THE SCREENING OF CROP, PASTURE AND WETLAND SPECIES FOR TOLERANCE OF POLLUTED WATER ORIGINATING IN COAL MINES

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REPORT TO THE WATER RESEARCH COMMISSION

Project Leader: Prof R O Barnard

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EXECUTIVE SUMMARY

BACKGROUND

The total area of South Africa comprises some 120 million hectares, of which only 13% (14 million ha) is arable. Of this, only a third (4,5 million ha) is regarded as being of high potential. In addition, South Africa has a low and variable rainfall. With the steady increase in population, a figure of 0,2 ha arable land per capita is fast being approached, whereas a norm of 0,4 ha per capita is often considered desirable.

The coal fields of the eastern Highveld region of South Africa underlie one of the most important high potential agricultural areas in the country. Against this background, the importance of maintenance and effective utilization of agricultural potential becomes paramount. This includes not only soil, effective and adequate rehabilitation of open cast mining sites, but also treatment, management and utilization of associated waters.

The area in which the coal fields occur is a major catchment for rivers supplying water to the industrial and mining heartland of Gauteng, the national ESCOM power grid, important irrigation schemes and the Kruger National Park. Several coal mines are currently being exploited in the Witbank area, as well as in other areas.

Most South African coal deposits contain pyritic formations. When exposed, iron pyrite is oxidised to sulphuric acid and iron sulphate, in the presence of oxygen, water and the catalytic action of *Thiobacillus ferrooxidans* bacteria. This results in the occurrence of large quantities of acid mine drainage (AMD) being formed. Extremely high acidity of this water (pH ~ 2) precludes discharge into natural streams as the environmental impact would be catastrophic. This is, of course, not only a local problem, but is found world-wide where similar deposits are found.

Current measures to prevent pollution of the environment include pumping these waters into previously excavated areas or treating them with bulk hydrated lime ($Ca(OH)_2$) in order to neutralize the acidity. The major portion of $CaSO_4$ formed is precipitated in sedimentation basins, but the resulting effluent is saline water with an electrical conductivity (EC) = 200 mSm^{-1}, due mainly to Ca and SO_4 in solution. Such waters could result in salinization of soils, rivers, dams and catchment areas if freely discharged into the natural environment.

PROBLEM WATERS

Disposal of mine waste water has become a problem of increasing importance from an ecological point of view. Lime treated AMD has been used so far for dust alleviation on dirt roads and irrigation of lawns. The idea was to investigate the possible use of lime treated AMD for irrigation of agricultural crops. In this way, large amounts of waste water could become useful for irrigation of high potential soils on the Mpumalanga Highveld region. Moreover, filtering saline water through the soil and precipitating gypsum in the profile could limit environmental pollution hazards. Contamination of water supplies for other potential users could be minimized. The high costs of AMD amelioration could to some extent be alleviated by achieving profits through agricultural production.

There are, of course, other types of waters emanating from coal mines, depending largely on the respective geological properties of the coal and other material with which waters come into contact. These would have different effects on crops irrigated with them, as well as on soils with which they come into contact.

The stated aim of the project was to identify suitable plant species for use where: polluted mine water is used for irrigation, or wetlands are used to improve the quality of polluted mine water. With the envisaged programme, one of the biggest anticipated benefits would be utilization "on site", which would have the following advantages:

- Prevention of contamination of water supplies for other potential uses (irrigation, power generating complexes, industries, urban areas, etc.).
- Productive use as irrigation water in an area characterized by high potential soils and a suitable climate.

IRRIGATION

Selected crops and pastures suitable for cultivation under prevailing climatic conditions and under irrigation were therefore investigated under applicable glasshouse, growth chamber and field conditions for their tolerance to lime treated AMD. Other high sulphate and sodic-saline waters were also investigated under controlled conditions. In addition some wetland species were investigated, as well as some tentative studies conducted on possible soil changes with treated AMD. The latter was conducted in soil columns, as well as through modelling of the field trial.

Although the main thrust of the study was the screening of crops and pastures, it is clear that several originally peripheral matters received increasing attention during the investigation. This is understandable, as the implications of irrigation with water of sub-optimal quality are far greater than only the resistance, or otherwise, of plants.

GERMINATION AND SEEDLING GROWTH

Generally germination of most cultivars of both the subtropical and temperate annual crops was not influenced by either the high sulphate or sodic-saline mine water. There were, however, exceptions where germination of the odd cultivar of sorghum and pearl millet was suppressed with the sulphate salinity, while the same was true for lucerne with the sodic-saline water.

Germination should not be a problem if these crops are irrigated with comparable waters; where it was suppressed, it ranged from 5 to 16%, which could early be compensated for by sowing more densely.

Seedling growth on the actual 'worst case' mine waters showed that the subtropical cereal crops exhibited more cultivar differences and sensitivity to the neutral high sulphate water than did the legumes evaluated. Soybean and drybean grew exceptionally well on the sulphate-saline water. Generally the seedling growth of the annual temperate crops was more tolerant to the sulphate water than that of the subtropicals except for one sensitive wheat and one triticale cultivar. Wheat seedling growth was, however, less sensitive to the sulphate water when N was partly supplied as NH_4. Lucerne cultivars were generally sensitive to the sulphate mine water, with the relative seedling growth of different cultivars ranging from 55% to 76%.

On the sodic-saline 'worst case', actual, mine water the seedling growth of the annual cereal crops was somewhat suppressed; again the subtropicals were influenced to a greater extent than the temperate annuals. Cultivar differences were generally limited to differences between the most tolerant and the most sensitive cultivar. All lucerne cultivars were very sensitive, however. The growth of soybean, dry bean and cowpea seedlings was generally less suppressed than that of the subtropical cereals, with some cultivar differences, where soybean Ibis and dry bean (PAN 127) stood out as the most tolerant.

There is a relatively wide choice of cultivars that should be able to successfully bridge the sensitive seedling stage by irrigation with sulphate-saline waters originating from coal mines in the Highveld region. The choice of cultivars to be grown under irrigation with the sodic-saline mine waters is limited. There are, however, some cultivars (except for lucerne) that should be tolerant enough to bridge the sensitive seedling growth stage.

With increasing sulphate concentrations of a simulated sulphate mine water there was a general tendency for seedling growth to be increasingly suppressed to a point usually in the vicinity of 2000 to 3000 $mg\ell^{-1}$ sulphate. In the treatments where the gypsum was either not dissolved or started precipitating, the seedling growth either increased up to a point above which in some cases it decreased, or did not decrease any further. Where salinity was, however, due to increasing sodium sulphate content, seedling growth generally decreased further.

With increasing $Na/Cl/SO_4$ concentrations, simulating a sodic-saline mine water, seedling growth generally decreased in a linear fashion in line with the Maas & Hoffman theory (Maas & Hoffman, 1977).

VEGETATIVE GROWTH

The vegetative growth of both the subtropical and temperate annuals was mostly not significantly influenced by the lime treated AMD and sodic-saline mine waters. The vegetative growth of bermuda grass cultivars, a subtropical perennial species, was tolerant to the lime treated AMD water, but cultivars differed significantly with the sodic-saline water.

Vegetative growth of the temperate perennial forage crops was tolerant to the lime treated AMD water; lucerne grew exceptionally well. The vegetative growth of lucerne, tall fescue and cocksfoot was also tolerant to the sodic-saline water evaluated, but crown vetch and white clover were very sensitive.

When extrapolating these results to field conditions it must be remembered that salt tolerance varies for different growth stages and is dependant on a multitude of soil, climatic and other factors. Tolerance found in the seedling and vegetative stages is not always a reliable guide for predicting seed or grain yields. When comparing results, the electrical conductivity of the growth medium can be equated to the mean seasonal EC of the soil water in the rooting zone. Furthermore it must also be remembered that the apparently more sensitive, subtropical crops are produced during the rainy summer growing season. In an area that receives 600-700 mm of summer rainfall, this 'clean' water can have a diluting effect and reduce the need for supplementary irrigation except for periodic drought conditions, thus inferring that one can go much further with relatively poor quality irrigation water.

FIELD TRIAL

The screening field trial determined which species are the most suitable for the specific environmental conditions, which were representative of the Mpumalanga Highveld. From a potential production point of view, legumes (soybean and cowpeas) among the subtropical and triticale among the temperate crops proved to be the most suitable. This confirms the glasshouse results.

Shallow rooting depth was observed for all crops, possibly due to high soil acidity, soil compaction and P deficiency in deeper layers. Under these conditions, leaching of nutrients out of the reach of the rooting system is likely to occur if irrigation and fertilization practices are not properly approached. Nutritional problems were experienced for some crops. In particular, maize was the crop that mainly suffered from nutrient deficiency and soil acidity. High frequency irrigation and application of fertilizers several times during the growing season in smaller amounts are recommended. In particular, potassium fertilization is critical due to the low content of this element in the soil and the added problem of displacement with the high gypsum content of the treated AMD. Magnesium nutrition also requires monitoring, for identical reasons.

For the purpose of lime treated AMD disposal, fast growing species that use a lot of water are recommended (pearl millet in combination with a winter cereal, or a lucerne/fescue mixed pasture). It is important to have as large a transpiring canopy as possible throughout the year.

Soil salinity parameters did not show any real trend during the three years of the trial. It is not therefore expected, in the short-term, that there will be an increase in soil salinity while irrigating with lime treated AMD. On the other hand, soil pH could be considerably increased when irrigation water with a pH of about 8.0 is applied.

PASTURE SPECIES

Sub-tropical, perennial grass species which are well adapted to local soil and climatic conditions respond very well to irrigation with gypsiferous water, as typified by lime treated acid mine drainage, on the well drained sandy soil used in this investigation. From the range of species and cultivars evaluated it is evident that reclamationists can incorporate several hitherto unused grasses into seeding mixtures, which will benefit both bio-diversity and productivity. This investigation did, however, place the emphasis on plant x water interaction and the influence on soil parameters received minimal attention. It was, however, evident that the effect of gypsiferous water on pH, Ca and SO_4 concentrations was in proportion to the level of irrigation and that these influences were not restricted to the upper 20 cm of the profile. Future work should, therefore, place the emphasis on the long term implications for the whole eco-system including plant, soil, leachate, etc.

The preliminary screening work with leguminous woody species found large differences with respect to climatic adaptation, disease resistance, productivity, leaf retention and persistence, and several species warrant further investigation. The lack of response to an irrigation gradient was surprising and may be linked to the high variability in a relatively small population and/or the strong limit on root development in all but the upper horizon of the experimental soil.

WETLAND SPECIES

Within the limits of preliminary studies on wetland species it would appear that there is a wide range of species adapted to, or tolerant to, moderate deviations from neutrality and reasonably high salt loads provided that such salinity be characterized by high calcium and sulphate. This might, to some extent, be explained by the fact that plants adapted to edaphic factors of the Mpumalanga Highveld would be adapted to growing in soils which are often very acid. In such agro-ecological areas the highest "salt" concentrations would also be commonly found in the bottomland sites, which are often the sink for leachate from the surrounding landscapes.

The fact is that, in developing and using wetland areas as part of water treatment programmes, there are possibilities of enriching bio-diversity using indigenous species. In some cases there might even be the possibility of using forage species (such as *Panicum*, *Paspalum* and *Echinochloa*) or a genus such as *Sphagnum* for commercial purposes.

MODELLING

A simple water movement - soil salinity model (SWB - Soil Water Balance) was developed for management of irrigation with lime treated AMD. It proved a useful tool for crop growth simulations and irrigation scheduling.

Simulations using the calculated crop growth coefficients fitted measured data of water balance and crop growth parameters fairly well. The mechanistic solution of the model worked well both under good water supply and crop water stress conditions. It needs, however, to be tested using independent data sets.

The SWB should give a good first approximation of the movement of water in well drained fairly uniform profiles. The limitations of such soil water balance models need to be borne in mind, however.

The SWB model was specifically developed to solve problems concerning the use of lime treated AMD. The predictions of soil solution electrical conductivity were in good agreement with observed data. Combined with a weather data generator, this model could be a useful tool for predicting the long-term environmental impact due to irrigation with lime treated AMD.

The model could also be used to determine crop salt tolerance. The advantage of doing this with a mechanistic crop growth model is that yield depression can be calculated under specific conditions of soil water supply and evaporative demand of the atmosphere.

It could be developed further by introducing sub-routines describing other aspects of the possible chemical reactions in the rooting zone. The necessary sensitivity analyses would have to be included.

COLUMN STUDY

A preliminary column study was also carried out on two soils, in an attempt to evaluate the suitability of different treatments of AMD for soil application. Adequate neutralization proved necessary.

Lower levels of neutralization investigated gave inconclusive results, with dolomitic lime tending to be superior. Efficiency of neutralization needs to receive adequate attention, however. Soil application of relatively large amounts of calcitic or dolomitic lime prior to direct application of AMD also proved questionable, with dolomitic lime again appearing superior. The efficiency of neutralization under these conditions warrants further investigation.

The extremely negative effect of direct application of AMD illustrates the problems that are currently occurring wherever this material comes into contact with soil.

This investigation covered only the application of 1000 mm of water, and was of necessity fairly preliminary. Even so, quite dramatic effects of application of different materials were apparent. It is obviously not possible to say what the effect of prolonged treatment would be.

The method could be used to estimate the effect of longer term treatment, although drying of the soil as occurs over time in practice would be difficult to accelerate.

CONCLUSION

Although the main thrust of the investigation was the screening of plants for utilization with treated AMD, several other related aspects also received attention, including other types of coal mine water, crop growth modelling and soil related aspects.

It is clear that with adequate neutralization of AMD, it should be possible to irrigate a large spectrum of agronomic and pasture species. At the same time changes in soil conditions should not be unfavourable.

It is recommended that these observations, based on laboratory, growth chamber, glasshouse and a preliminary field trial, but also on modelling, be further tested under practical field conditions. Careful monitoring of plant growth, soil conditions - both chemical and plant nutritional - and drainage water would be required. Other aspects relating to treated AMD, such as wetland dynamics, could also be followed up.

With the necessary knowledge and management it is likely that treated AMD could play an important role in at least augmenting irrigation water, of which both the supply and quality are steadily decreasing in the RSA, in an environmentally acceptable manner.

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The steering committee responsible for this project consisted of the following persons:

Mr H M du Plessis	Water Research Commission (Chairman)
Mr F P Marais	Water Research Commission (Secretary)
Dr G C Green	Water Research Commission
Prof P J Robbertse	University of Pretoria
Prof F D I Hodgson	University of the Orange Free State
Prof A L P Cairns	University of Natal
Dr P Manders	Forestek, CSIR
Mr F C van Zyl	Water Quality Management, DWAF
Mr J J van Wyk	Water Quality Management, DWAF
Mr S Jooste	Institute Water Quality Studies, DWAF
Dr P D Tanner	Amcoal Environmental Services
Mr B J Cook	Consultant
Mr K Kellner	Potchefstroom University for CHE

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LIST OF APPENDICES

LIST OF SYMBOLS

A - Parameter associated with absolute temperature and dielectric constant of the solvent
a - Campbell's value of a log-log water retention function
a_i - Ionic activity (mol l^{-1})
Alt - Altitude (m)
Alt_o - Altitude at sea level (m)
AMD - Acid mine drainage
a_n - Leaf absorptance in the near infrared range of solar radiation
a_p - Leaf absorptance in the range of photosynthetically active radiation
b - Campbell's value of a log-log water retention function
C_s - Solute concentration (mol kg^{-1})
C_{dw} - Concentration of drainage water (mg kg^{-1})
C_i - Molar ionic concentration (mol l^{-1})
C_{iw} - Concentration of irrigation water (mg kg^{-1})
C_p - Specific heat of moist air at constant pressure (J kg^{-1} $°C^{-1}$)
D - Drainage (mm)
Dec - Solar declination (rad)
DM - Dry mass
DMWR - Dry matter water ratio (Pa)
DOY - Day of year
dz - Soil layer thickness (m)
E - Actual evaporation (mm)
e_a - Actual atmospheric vapour pressure (kPa)
e_s - Atmospheric vapour pressure at saturation (kPa)
EC - Electrical conductivity (mS m^{-1})
E_c - Radiation conversion efficiency (kg MJ^{-1})
EC_e - Electrical conductivity of saturated soil extract (mS m^{-1})
E_p - Potential evaporation (kg m^{-2} s^{-1})
ET - Actual crop evapotranspiration (mm)
evapD - Maximum dimensionless soil water loss rate
f - Factor for weighted root distribution in a soil layer
FC - Field capacity
FI - Radiation fractional interception
f_l - Leaf partitioning factor
FLDD - Day degrees at end of vegetative growth
FM - Fresh mass
f_r - Fraction of dry matter partitioned to roots
G - Soil heat flux (W m^{-2})
g - Gravitational acceleration (9.8 m s^{-2})

LIST OF SYMBOLS (continued)

GDD - Growing degree days
GPDD - Day degrees of transition period from vegetative to reproductive growth
GPF - Grain partition fraction
G_{sc} - Solar constant (118.08 MJ m^{-2} day^{-1})
HDM - Harvestable dry matter (kg m^{-2})
I - Irrigation amount (mm)
I_s - Ionic strength of solution (mol l^{-1})
K_{bd} - Black leaves canopy extinction coefficient for diffuse radiation
KC - Canopy radiation extinction coefficient
K_s - Canopy extinction coefficient for total solar radiation
K_{sp} - Solubility product (mol^2 l^{-2})
LAI - Leaf area index
Lat - Latitude (rad)
LDM - Dry matter partitioned to leaves (kg m^{-2})
LF - Leaching fraction
M_i - Molar mass of ionic species per unit area (mol m^{-2})
NIR - Near infrared range of solar radiation (0.7-3 μm wavelength)
P - Precipitation (mm)
P_a - Atmospheric pressure at a given altitude (kPa)
PAR - Photosynthetically active radiation (0.4-0.7 μm wavelength)
PART - Stem-leaf partition parameter
PET - Potential evapotranspiration (mm)
P_0 - Standard atmospheric pressure at sea level (101.3 kPa)
R - Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})
R_c - Root resistance factor under soil salinity conditions (J kg^{-1})
RD - Root depth (m)
RDM - Root dry matter (kg m^{-2})
R_g - Gas constant (8.314 J K^{-1} mol^{-1})
RGR - Root growth rate (m^2 $kg^{-0.5}$)
RH - Air relative humidity
Rn - Net radiation (W m^{-2})
Rni - Isothermal net radiation (W m^{-2})
R_u - Runoff (mm)
rootU - Dimensionless root water uptake rate
RRES - Crop specific root resistance increase coefficient under soil salinity conditions
S - Runoff curve number (mm)
s - Slope of the saturation vapour pressure curve (Pa °C^{-1})
SDM - Stem dry matter (kg m^{-2})
SI - Stress index

Continued

LIST OF SYMBOLS (continued)

SLA	-	Specific leaf area (m^2 kg^{-1})
SWB	-	"Soil Water Balance" model
SWC	-	Soil moisture content
S_o	-	Incoming solar radiation on a horizontal surface outside the earth's atmosphere (MJ m^{-2} day^{-1})
S_{o30}	-	Extraterrestrial solar radiation 30 days previous to the simulation day (MJ m^{-2} day^{-1})
S_t	-	Daily incoming solar radiation on earth's surface (MJ m^{-2} day^{-1})
T	-	Actual transpiration (mm)
T_a	-	Air temperature (K)
T_{avg}	-	Daily average air temperature (°C)
T_b	-	Base temperature for crop growth (°C)
T_{cutoff}	-	Cutoff temperature for crop growth (°C)
TDM	-	Total dry matter (kg m^{-2})
TDS	-	Total dissolved salts (mg kg^{-1})
T_f	-	Temperature factor for light limited crop growth
T_{lt}	-	Temperature for optimum light-limited growth (°C)
T_{max}	-	Daily maximum air temperature (°C)
T_{min}	-	Daily minimum air temperature (°C)
Tr_{max}	-	Maximum possible transpiration rate (mm day^{-1})
T_s	-	Temperature of solution (K)
T_t	-	Daily atmospheric transmission coefficient
T_0	-	Standard temperature at sea level (K)
T^*	-	Dimensionless actual water uptake
V	-	Volume of gypsum precipitated in the soil
V_{dw}	-	Volume of drainage water (kg m^{-2})
V_{iw}	-	Volume of irrigation water (kg m^{-2})
VPD	-	Vapour pressure deficit (Pa)
z	-	Soil depth (m)
z_i	-	Charge of ionic species
α	-	Albedo; Priestley-Taylor coefficient; Adiabatic lapse rate (K m^{-1})
α_d	-	Parameter in the function of ion diameter
α_v	-	Priestley-Taylor coefficient corrected for vapour pressure deficit
β	-	Parameter associated with absolute temperature and dielectric constant of the solvent

LIST OF SYMBOLS (continued)

γ - Psychrometer constant (kPa °C^{-1})
γ_i - Ionic activity coefficient
ΔQ - Soil water storage (mm)
ΔS - Salt balance (mg m^{-2})
ε - Ratio of the molecular masses of air to water
ε_a - Clear sky emissivity
ε_{sc} - Sky emissivity
ε_s - Emissivity of the surface
Θ - Actual volumetric soil water content
Θ_{ad} - Air dry volumetric soil water content
Θ_{fc} - Volumetric soil water content at field capacity
Θ_{pwp} - Volumetric soil water content at permanent wilting point
λ - Latent heat of vaporization (MJ kg^{-1})
ρ_b - Bulk density (Mg m^{-3})
ρ_w - Water density (Mg m^{-3})
σ - Stefan-Boltzmann constant (5.67 10^{-8} W m^{-2} °K^{-4})
ν - Number of ions per molecule of ionizing solute
χ - Osmotic coefficient
Ψ_{fc} - Soil matric potential at field capacity (J kg^{-1})
Ψ_g - Gravitational potential (J kg^{-1})
Ψ_{lmin} - Leaf water potential at maximum transpiration (J kg^{-1})
Ψ_m - Soil matric potential (J kg^{-1})
Ψ_o - Osmotic potential (J kg^{-1})
Ψ_{pwp} - Soil matric potential at permanent wilting point (J kg^{-1})
Ψ_x - Xylem water potential (J kg^{-1})
Ψ^* - Root weighted average soil matric potential (J kg^{-1})
ω_s - Sunset hour angle (rad)

LIST OF TABLES (continued)

CHAPTER 1

GENERAL INTRODUCTION

The coal fields of the eastern Highveld region of the Mpumalanga Province in South Africa lie on a plateau with an elevation of 1500 - 1800 m.a.s.l. They have been the primary source of energy generation in the country since the previous century.

They underlie one of the most important high potential agricultural areas in the country, with a summer rainfall and an average precipitation of some 600-700 mm. This is of particular significance when viewed against the fact that South Africa has a very low percentage of arable land (some 14 out of 120 million ha), of which only a third (4,5 million ha) is regarded as being of high potential.

In addition, South Africa has a low and variable rainfall (66% of the country is classified as semi-arid to arid). Add to this the steady increase in population (0,2 ha arable land per capita is already being approached whereas 0,4 ha per capita is considered desirable) and the importance of maintenance, and effective utilization of agricultural potential becomes paramount.

The area in which the coal fields occur is a major catchment for rivers supplying water to the industrial and mining heartland of Gauteng, the national ESCOM power grid, important irrigation schemes and the Kruger National Park. Several coal mines are currently being exploited in the Witbank area, as well as in other areas.

Most South African coal deposits contain pyritic formations. When exposed, iron pyrite is oxidised to sulphuric acid and iron sulphate, in the presence of oxygen, water and the catalytic action of *Thiobacillus ferrooxidans* bacteria (Kempe, 1983). This results in the occurrence of large quantities of acid mine drainage (AMD) being formed. This is frequently neutralized by other strata present, but where it occurs as a seep, extremely high acidity precludes discharge into natural streams due to the potential vegetative environmental impact. The actual composition not only depends on the origin of the water, but also on such aspects as dilution due to mixing with natural groundwater. This is, of course, not only a local problem, but is found world-wide, where similar deposits are found.

Current measures to prevent pollution of the environment include pumping these waters into previously excavated areas or treating them with bulk hydrated lime ($Ca(OH)_2$) or calcite lime in order to neutralize the acidity (Van Staden, 1979). It is estimated (1985) that a third of the lime mined in South Africa is used for the neutralization of acid mine waters. The major portion of $CaSO_4$ formed is precipitated in sedimentation basins, but the resulting effluent is saline water (with an electrical conductivity EC $\approx$ 200 mSm^{-1}), due mainly to Ca and SO_4 in solution. Such waters could result in salinization of soils, rivers, dams and catchment areas if freely discharged into the natural environment.

Disposal of mine waste water has become a problem of increasing importance from an ecological point of view (Van Niekerk, 1992). Lime treated AMD has been used so far for dust alleviation on dirt roads and irrigation of lawns. The idea was to investigate the possible use of lime treated AMD for irrigation of agricultural crops (Du Plessis, 1983a). The volumes on the Mpumalanga Highveld have been estimated at between 14 and 30 Mℓ/day (P. Tanner, AMCOAL Environmental Services, personal communication). In this way, large amounts of waste water could become useful for irrigation of high potential soils on the Highveld. Moreover, filtering saline water through the soil and precipitating gypsum in the profile could limit environmental pollution hazards. Contamination of water supplies for other potential users could be minimized. High costs of AMD amelioration could be alleviated by achieving profits through agricultural practice.

There are, of course, other types of waters emanating from coal mines, depending largely on the respective geological properties of the coal and other material with which waters come into contact.

The project being reported on has as its objective the use of different waters originating in coal mines for possible irrigation of crops and pastures on or near the mining sites, and especially the screening of crops and cultivars that are already recommended for cultivation in these regions for their tolerance to grow sufficiently well for commercial purposes.

The main thrust of the investigation was the selection of crops and pastures for their tolerance to lime-treated AMD, and a "worst case" high sulphate water. Sodic-saline water was also investigated. This was conducted under glasshouse, growth chamber and field conditions. In addition some wetland species were investigated.

As the study progressed it became clear that some additional aspects warranted attention. The field trial was used to develop a simple water movement - soil salinity model for management of irrigation with lime-treated AMD. Predicting the long-term environmental impact due to irrigation with this water, as well as the determination of crop salt tolerance, were envisaged in the development of this model.

Furthermore the possible effect of adding AMD, treated in different ways, to two soils was studied in a preliminary column experiment.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter deals mainly with the literature of plant response to salinity in the growth medium. A brief background sketch is followed by the motivation for correct irrigation management and for modelling of salinity effects on crop yield and soil properties (2.3 & 2.4). The influence of salinity on the general and more specific aspects of growth (2.5.1), the physiological effects and the possible mechanisms by which growth is affected (2.5.2), are subsequently presented.

Apart from salt concentration and composition, the salt tolerance/sensitivity of plants is dependant on many other factors; these are discussed under the section dealing with environmental and plant factors (2.5.3).

Crop salt tolerance has been of commercial importance for many decades, but with the increasing use of marginal soil and poor quality water for agriculture, it has gained importance. The following section (2.5.4) thus deals with the evaluation of the salt tolerance of crops, the criteria used, the parameters and some yield response functions available to predict growth and yields of crops under saline conditions.

The chapter concludes with the general trends of salt tolerance found for the agronomic groups investigated in this study, namely the cereal and forage crops (2.5.5.).

2.2 BACKGROUND TO THE STUDY

The irrigation of plants with waters of varying quality is probably as old as the practice of agriculture itself. In areas of high evapotranspiration it is essential to irrigate crops to ensure adequate yields. Unfortunately there is usually little choice or control over the quality of available water and, for various reasons, water quality is generally declining. As this occurs to an increasing degree, the choice of crop, the management of the irrigation process or method and of the soil itself becomes increasingly important (Hoffman, Rhoades, Letey & Sheng Fang, 1990; Rhoades & Loveday, 1990).

At the same time it needs to be realized that treated waters, such as those emanating from coal mines and the mining industry, are potential sources of an extremely scarce commodity and also contain chemical components that could have both a negative and a positive effect on plant nutrition and growth as well as on soil properties. Furthermore the spectrum of possible chemical constituents and their relative occurrence is enormous, making predictions of their effects virtually impossible.

There are also divergent ideas as to the relative importance of aspects such as "total" salinity, determined osmotically by soluble salt concentration, and toxicities/imbalances of various ions.

2.3 MANAGEMENT OF IRRIGATION APPLICATION METHODS

Permissable levels of salinity in soils and irrigation waters are highly affected by irrigation management (Rhoades, 1976), cultivars and phenological stages (Maas & Hoffman, 1977). Factors such as higher soil evaporation, larger amounts of applied saline water and increase in salinity of upper soil layers could occur when adopting high-frequency irrigation (Van Schilfgaarde, Bernstein, Rhoades & Rawlins, 1974). Correct management of saline irrigation water is therefore required in order to obtain satisfactory profits from agricultural practice.

2.4 EFFECTS ON SOIL

Another aspect that is of great importance is monitoring the long-term impact of specific irrigation waters on soil. Long-term changes in soil chemical properties can be experimentally measured, but the set-up of long-term experiments monitoring slow environmental processes is not attractive, both from practical and financial considerations. It is for this reason that modelling is being increasingly used in order to predict crop growth and soil properties using specific waters (Campbell, 1985; Maas & Hoffman, 1977; Bresler, McNeal & Carter, 1982; Du Plessis, 1983b; Wagenet, 1984; Maas, 1986).

Waste products from mining and industrial activities have been used for the reclamation of sodic soils (Miyamoto, Ryan & Stroehlein, 1975; Moolman & Weber, 1979; Keren & Shainberg, 1981).

There are also other possibilities. Waters containing Ca, such as lime treated acid mine drainage, could contribute to the amelioration of acid soils (Sumner, 1993). Irrigated soils seldom remain acid, but this contribution could make them more acceptable in the initial stages.

2.5 PLANT RESPONSE TO SALINITY

Plants differ in their ability to grow under saline conditions. Greenway and Munns (1980) suggested four groups of plant species according to their growth under saline conditions: Halophytes, where growth is optimal under sodic and/or saline conditions. Secondly there are a few crop species termed halophylics, where growth is slightly stimulated by low salinity levels. The third and fourth groups are non-halophytes (glycophytes) that range from salt-tolerant to salt-sensitive. Most crop species fall under the last two groups which are, however, not clearly defined.

2.5.1 GROWTH RESPONSES

Although salinity affects plants physiologically in many different ways, injury is not readily seen morphologically except at extreme salt concentrations. The most general effect is a reduction in growth and growth rate. Plants that are salt-sensitive or moderately tolerant show a progressive decline in growth and yield as salinity levels increase (Bernstein, 1964, 1974) and may also be stunted.

Plant parts are not all equally affected: shoot growth is usually influenced more than root growth with a concomitant decrease in the shoot to root ratio. The leaf to stem ratio is also often affected, which could be important for forage quality (Maas & Hoffman, 1977).

2.5.1.1 Leaf growth

The initial response of a non-halophyte to salinity is that its leaves grow more slowly (Munns & Thermaat, 1986). With low or moderate salinity levels leaves do not necessarily show specific symptoms such as scorching or chlorosis. Leaves are often smaller and a darker green than control plants. Marginal chlorosis, necrosis (leaf burn) and defoliation occur in some herbaceous and in most woody species with NaCl salinity; this is mostly due to toxic accumulation of Na and/or Cl (if Na > 0,25%; Cl > 0,5% dry mass, Bernstein, 1964). Leaf analyses have shown Cl-toxicity to be the major cause. These effects start at the tips or margins of the leaves resulting in death of the tissues. The affected parts become brownish and are sharply separated from the healthy part of the leaf, which usually retains its normal colour. The more salt accumulated the bigger the leaf area affected. In citrus and some shrubs a general bronzing of the leaves followed by leaf drop can also occur, without leaf burn developing. Leaf burn can, however, also be caused by excess boron (Bernstein, 1964; Maas, 1986), which sometimes occurs in problem waters.

Most herbaceous plants do not develop such leaf injury symptoms even though Na and Cl accumulation can be as high as that causing injury to woody species. Vegetable, forage and field crops often accumulate these elements up to 5 and sometimes 10% of their leaf dry mass without showing leaf injury symptoms (Bernstein, 1974). Leaf injury under saline conditions can also sometimes be caused by nutritional imbalances leading to specific nutrient-deficiency symptoms.

Salinity can either increase or decrease the leaf area, but generally salinity and leaf area are inversely related (Flowers & Yeo, 1989; Marschner, 1986). In glycophytes leaf area is usually decreased by any significant increase in salinity, while for halophytes this will depend on the relationship between the external salinity and the growth optimum; above this optimum halophytes can be expected to respond similarly to glycophytes. In the case of natrophylic species, Na can stimulate growth mainly by its positive effect on cell expansion and water balance.

In sugarbeet, a tolerant forage crop, Na increased the leaf area, succulence, and the number of stomata per unit leaf area but the chlorophyll content was less.

Changes in leaf area can influence the overall water loss of the plant. "Salinity generally reduces the rate of transpiration by mimicking a water deficit, causing stomatal closure and reducing leaf area, but the gains made by stomatal closure seem to outweigh the costs" (Flowers & Yeo, 1989). The rate of water loss is also decreased by anatomical and morphological changes in the plant. Leaf surface properties such as hairs (impede vapour exchange), succulence (generally reduces the number of stomata per unit area) and the properties of the cuticle, may all contribute in reducing the rate of water movement (and consequently also accumulation of salts) through the plant (Ahmad & Wainwright, 1976; Hajibagheri, Hall & Flowers, 1983).

Leaf thickness and succulence (water content per unit leaf area) have been observed as a typical morphological response to high substrate salinity and water stress (Jennings, 1968, 1976). It is usually observed in salt tolerant species growing in saline substrates (Jennings, 1976), and in most dicotyledons as an adaptation to high substrate salinity both in salt 'excluders' and 'includers' (Longstreth & Nobel, 1979). Succulence can be caused by a decrease in surface area and/or an increase in tissue water content. Apart from salinity, succulence can also be induced by a water deficit and hormone related changes (Marschner, 1986).

2.5.1.2 Root growth

Generally root growth is affected less by salinity than shoot growth. At low salinity it may not be influenced or may even show an increase (Munns & Termaat, 1986). These observations are, however, mostly based on root dry mass; root length, which is important for nutrient and water uptake, has recently been shown to be a more sensitive parameter than root dry mass for the influence of salinity on root growth (Shalhevet, Huck & Schroeder, 1995).

Root cell elongation can, however, be very sensitive to salt at low Ca concentrations in the growth medium. Ca stimulates and Na inhibits root cell elongation (Kurth, Cramer, Laüchli & Epstein, 1986). Addition of Ca to the root medium ameliorated salt stress on maize root growth (Cramer, Epstein & Laüchli, 1988), and in peas (Solomon, Gedalovich, Mayer & Poljakoff-Mayber, 1986). The yields of storage roots may, however be decreased much more than those of fibrous roots (Maas & Hoffman, 1977).

2.5.2 PHYSIOLOGICAL RESPONSES (Mechanisms of adverse effects)

2.5.2.1 General (mainly for NaCl salinity)

Salinity in the root zone can adversely affect growth due to two main properties of the soil solution: (i) the lowered osmotic potential (lowered water availability) caused by the high concentration of soluble ions; and (ii) specific ion effects, which include toxicity of specific ions and/or unfavourable ratios of ions such as Na/Ca, Na/K and Ca/Mg; also lowered activity (availability) and imbalances of nutrient ions and thus a disturbance in inorganic nutrition.

The earlier belief that it was the actual lack of water that limited growth with a saline root medium, has generally been rejected because plants have been shown to adjust osmotically (Maas & Nieman, 1978). More recent literature suggests that in short-term responses of whole plants to salinity, shoot growth is regulated by the water status of the root, through some "messenger system" to the shoots which could include hormonal substances, e.g. abscisic acid or other antitranspirants (Rengel, 1992).

Osmotic potential or specific ion effects?

From the literature it seems that there are two schools of thought on the relative importance of osmotic potential and/or ion excess on growth. Although the toxic influences of some ions, such as B and Cl, and nutritional imbalances are recognised, some authors maintain that it is mainly the total salt concentration of the soil solution that causes growth reduction (e.g. Bernstein, 1964, 1974; Maas & Nieman, 1978). Evidence connected to the direct toxic influence of some ions, e.g. Cl, or the accumulation of toxic amounts of salts in the leaf tissues, leads others to attach more importance to growth inhibition through ion toxicity (Maas, 1990; Munns, 1993; Marschner, 1986). It is generally recognized that both these adverse effects could simultaneously be responsible for growth reduction, but the relative contribution of ion excess and osmotic potential is difficult to assess (Marschner, 1986; Jacoby, 1994). However, the earlier opinion that growth reduction was primarily due to the osmotic potential, is being reviewed as many nutritional and also membrane related studies indicate other possibilities (Läuchli & Epstein, 1990; Grattan & Grieve, 1992; Reinhold, Braun, Hassidim & Lerner, 1989; Rengel, 1992).

Much effort has been made in understanding the primary physiological causes of growth reduction in saline environments. Munns (1993) reviewed work on turgor, photosynthesis and effects on particular metabolites which directly influence growth, and concludes: (i) "Although turgor is essential for growth ... it does not control growth; the rate of cell wall expansion is controlled by the rheological properties of the cell wall and not directly by turgor." The decrease in turgor is sensed by a "turgor sensor", probably in the plasma membrane. The sensor emits an error signal that activates biochemical processes necessary for solute accumulation or synthesis. This results in the recovery of the turgor pressure (Bisson & Gutknecht, 1980). (ii) "Salinity affects carbon assimilation per plant via a smaller leaf area rather than a reduced rate of photosynthesis." Concentrations of sugars often increase with exposure to salinity indicating a blockage in utilization. (iii) Growth reduction and death is mainly due to eventual accumulation of salts in the vacuole above a concentration that the specific specie or cultivar can tolerate and "the cell dies of salt poisoning or dehydration depending on whether salts build up in the cytoplasm or cell wall."

Munns and Termaat (1986) suggested a hypothesis of a biphasic model where the external osmotic potential could be the main growth inhibitory factor for seedlings in the first weeks of growth (Munns, 1993). "This phase of growth reduction is a water stress effect and is regulated by inhibitory signals from the roots." In the following vegetative growth stage accumulation and/or specific ion effects are increasingly important in the leaves and can eventually lead to the death of the older leaves when the vacuoles can no longer isolate incoming salts. The supply of assimilates and growth regulators to the growing leaves will depend on the rate of leaf death to that of new leaf formation.

This two-stage process bears similarities to the "short"- and "long-term" effects suggested by other authors (Cramer & Bowman, 1991). The duration of the "short-term" differs for the different authors, but there seems to be agreement that later growth stages are affected more by the specific ion effects of salt accumulation and toxicity than by the osmotic potential of the external solution (Munns, 1993). Plant species and cultivars differ in their ability to compartmentalise at the cell, tissue and whole plant level and thus in their salt tolerance or sensitivity.

Recent reviews stress the nutritional effects of salinity (Grattan & Grieve, 1992, 1994) and the almost immediate effect of excess Na on the Ca-homeostasis of root and leaf cells (Rengel, 1992). Rengel suggested that "the Na-related changes of the normal pattern of Ca fluxes at the plasma membrane is the primary signal of salt stress perceived by roots and translated into almost immediate changes of the leaf cell environment, at least together, if not preceding, the osmotic changes". With this in mind the hypothesis of Munns and Termaat (1993) of osmotic potential being the main or only growth inhibitor for seedling growth, and of others on "short-term" effects, can be questioned.

Nutritional disorders

Salinity disrupts nutrition by (i) decreased activity of nutrient ions due to the ionic strength of the substrate, regardless of its composition; and (ii) extreme ratios of Na/Ca, Na/K, Ca/Mg and Cl/NO_3, that can lead to reduced uptake and disrupted translocation through competition. It can also affect the membrane selectivity and efficiency (Reinhold, Braun, Hassidim & Lesner, 1989; Grattan & Grieve, 1992; Rengel, 1992).

Nutritional disorders most commonly found with saline soils are reduced uptake or disturbed internal distribution of K, Ca, and Ca induced Mg deficiencies (Claassens, 1973; Marschner, 1986). High Ca concentrations in the soil solution usually result in an increased Ca and decreased Mg content of the leaves (Bernstein & Hayward, 1958). There are, however, only a few studies where fertilisation with these nutrients increased growth in sodic/saline conditions. (Growth is determined by the most limiting factor, in this case salinity versus nutrition.) The amounts needed for correction are probably too large and not economical, especially for K (Grattan & Grieve, 1992, 1994).

Species and cultivars can vary widely in their nutrient requirements and in their ability to absorb individual nutrients. These nutritional disorders are thus highly dependent on genetic variation.

2.5.2.2 Sulphate salinity

Most findings in the foregoing section have been based on studies with NaCl or NaCl/$CaCl_2$ mixtures. Although not so extensively, sulphate salinity has been investigated where high sulphate concentrations (up to 30 000 mgℓ^{-1}!) are found in soils and waters of e.g. Solonetzic soils and soils associated with cretaceous geological formations (Curtin, Steppuhn & Selles, 1993; Mayland & Robbins, 1994). The influence of the sulphate anion relative to other anions has also been included in a number of nutritional and salinity studies (e.g. Magistad, 1943, Curtin *et al.*, 1993). If SO_4 and Cl are given at iso-osmotic concentrations (equal osmotic potentials) SO_4 salinitiy can suppress growth more than Cl salinity (Mengel & Kirkby, 1987).

Plants are generally tolerant to high sulphate concentrations in the growth medium, and are usually only affected when SO_4 is in the order of 50 mmolℓ^{-1} (4800 mgℓ^{-1}). The responses are typical of salt affected plants (Mengel & Kirkby, 1987). The effect of excess sulphur on plant growth was reviewed by Rennenburg (1984). He concludes: "Survival in a sulphur rich environment is seldom achieved through the avoidance of the intake of sulphur. The presence of excess sulphur in the soil or in the air usually results in an intake of excess sulphur into plants. An immediate injury by the excess sulphur taken up, is however prevented by a series of metabolic processes. Storage of excess sulphur in ... the vacuole, appears to occur in most plants." Sulphate can be translocated in both xylem and phloem, and can thus be stored in plant parts not directly exposed to the excess. With increasing accumulation of sulphate, an increase of storage glutathione was found, suggesting that with increasing accumulation of sulphate its reduction also increases.

Furthermore sulphate can also be decreased in plants by emission of volatile sulphur compounds. It is thus improbable that excess sulphate *per se* would influence growth through ion toxicity (Rennenburg, 1984).

Ca and Mg

Excess sulphate in the soil solution can, however, also have nutritional implications, the most well-known being a Ca or Mg deficiency where very high sulphate salinity is accompanied by low Ca and Mg levels; Ca and Mg deficiency can also be caused by competition with other cations simultaneously present in excess concentrations, especially by Na. On the solonetzic soils of the Canadian prairie, nutrient problems arise from high Na and low Ca together with the high sulphate content (Curtin *et al.*, 1993). Ca deficiency was found to be severe for barley on these soils if the ratio of Ca to Mg/or total cations in the tissues were below 0,15 (Carter, Webster & Cairns, 1979).

Ca requirement has been estimated more accurately as the molar ratio of Ca to the total sum of cations, rather than the Ca concentration of the soil solution *per se*. Generally reduced growth is likely to occur when the molar ratio of Ca to the total cations in plant tissues, falls below 0,10 (Curtin *et al.*, 1993), but as was seen above, this value could be higher, especially if high Na concentrations are also present. A concentration of 10 mmolℓ^{-1} Ca was, however, enough to reverse Ca deficiency effects on pea roots (Solomon, Gedalovich, Mayer, & Poljakoff-Mayber, 1986).

In sulphate salt solutions Ca decreases as the sulphate content increases. Salinity of $CaCl_2$/NaCl was compared with $CaSO_4$/Na_2SO_4 in barley and *kochia* (Curtin *et al.*, 1993). Their results indicated that at the EC values compatible for most crops' growth (< 800 mSm^{-1}) Ca-deficiency by sulphate salinity should not repress growth except for a limited number of crop species that are inefficient in absorbing or utilizing Ca. They also concluded that "response functions generated by the $CaCl_2$/NaCl salinisation probably provide an acceptable measure of the tolerance of most crops to SO_4 salinity" (Curtin *et al*, 1993).

High Mg as part of the Ca/total cations ratio can be partly or largely responsible for a decrease in Ca uptake. If the molcharge ratio ($me\ell^{-1}$) of Mg to Ca, in the growth medium exceeds 1.0 growth can be negatively influenced (Claassens, 1973). On the other hand the rate of uptake of Mg can be depressed by other cations, especially by high levels of K (Claassens, 1973), Ca, and Mn (Heenan & Campbell, 1981) and also by H^+ (low pH) (Marschner, 1986). Some studies with increased $CaSO_4$ in the root medium indicated Mg decreases in plant tissues (Grattan & Grieve, 1992).

N, P and K

Sulphate salinity can also affect the N, P and K content of plants. NO_3 absorption can be decreased but to a lesser extent with excess SO_4 than with Cl when present at equal osmotic potentials. Although salinity reduces N accumulation in plants, additional N above that considered optimal for normal conditions has not proved to increase growth or yield under saline conditions (Grattan & Grieve, 1992).

The influence of salinity on K content mainly pertains to the competitive effects of Na on K uptake, regardless of the anion being Cl or SO_4. Cortical root cells have the ability to selectively absorb K in preference to Na, but the degree of this selectivity varies both among species and cultivars (Grattan & Grieve, 1992).

Crop species also vary in their ability for P-uptake under saline conditions (Champagnol, 1979). It can either be increased, decreased or not affected. Decreases have mostly been found with soil studies (probably due to a reduced activity of the phosphate ions in the saline conditions) and increases in sand or solution studies. In one investigation both Cl and SO_4 salts reduced P-uptake in barley and sunflower (Grattan & Grieve, 1992).

Cl versus SO_4 salinity effects

Some of the differences between Cl and SO_4 have already been touched on. Experiments by Magistad and co-workers (1939-1943) in outdoor sand cultures included a comparison of NaCl versus Na_2SO_4 salinity. They found that "for some crops chlorides and sulphates at equal osmotic concentrations are equally harmful, while with other crops chlorides are more toxic than sulphate at approximately equal osmotic values". This is probably a reflection of either an osmotic potential effect or of chloride toxicity. He goes on to say that "more equivalents of sulphate are needed to produce a given osmotic value which explains why plants can withstand far greater amounts of sulphate than chloride on a part per million ($mg\ell^{-1}$) basis" (Magistad, Ayers, Wadleigh & Gauch, 1943).

NaCl could also have a greater effect on membrane integrity/leakage than Na_2SO_4 (Jacoby, 1994), but comparisons are made difficult because different concentrations are needed to acquire treatments with equal osmotic potentials.

Micronutrients

The influence of salinity on the micronutrient concentration in plants is inconsistent for Fe, Zn and Mn; it varies with species, increasing in some crops and decreasing in others (Grattan & Grieve, 1992).

High sulphate can, however, reduce the Mo uptake and/or transport (Stout, Meagher, Pearson & Johnson, 1951). Barnard and Fölscher (unpublished data) found that the Mo content of the top growth of wheat doubled in the absence of SO_4; Mo was also diminished by other anions in the order of $S > B > P > Cl > NO_3$ (Barnard, 1978).

Although an essential element for livestock, Mo can be toxic to especially ruminants at higher concentrations. The critical amount of Mo that animals can tolerate depends on the Cu and sulphate level and can be as little as 5 $mgkg^{-1}$ in dry plant tissues if the Cu is low. The toxicity of Mo is essentially a deficiency of Cu; this Mo/Cu interaction is strongly influenced by the surrounding sulphate level.

Plants can tolerate higher levels of Mo in the tissues than the usual 2 $mgkg^{-1}$ dry mass. Forage crops with a high Mo content can therefore be unfit as fodder. Plant Mo availability is low on acid soils and increases to a maximum near neutrality, whereas Cu availability decreases with increasing pH. Sulphate can, however, reduce molibdate uptake by competition. Thus, although Mo would be more available in the pH range of lime treated AMD, the high sulphate content should help to prevent excessive levels in forage crops. Crop species have varying Mo requirements, but generally legumes need two to three times more Mo than non-legumes for the N-fixing nodules. High sulphate levels can induce Mo deficiency, especially in legumes (Albasal & Pratt, 1989).

2.5.2.3 Adaptation to adverse affects

Plants have the ability to adapt osmotically to low osmotic potentials of the soil solution. Much work has been done to understand the mechanisms by which plants adapt. Such an understanding is important for the genetic breeding of salt tolerant plants, but will not be discussed here in detail. Adaptive mechanisms include osmotic adjustment via increased synthesis of organic compounds, (e.g. glycine betaine and proline), increased tissue salt tolerance and/or compartmentation at the cell, tissue or organ level. The salt content can also be controlled by excretion and leaf drop (see Maas & Nieman, 1978; Greenway & Munns, 1980; Cheeseman, 1988; Jacoby, 1994 for reviews).

The effects of salt stress on growth can be summarised in terms of energy needed to adapt to saline conditions: "Salt stress essentially increases the energy that must be expended by the plant to extract water from the soil and to make the biochemical adjustments necessary to grow relative to the nonsaline condition" (Rhoades & Loveday, 1990). Energy is thus diverted from processes needed for normal growth to adapting mechanisms.

2.5.3 FACTORS THAT INFLUENCE SALT TOLERANCE

Salt tolerance data in the literature can only be used as a general guideline for crop selection. Such data are mostly average values for different cultivars grown in a variety of, although usually the commercially acceptable, conditions for a specific crop species (Maas & Hoffman, 1977). Salt tolerance depends, not only on salinity, but also on many other factors such as soil, climate, plant variety and growth stage, agronomic and irrigation practices. Salt tolerance data in the literature therefore cannot provide quantitative predictions of crop yield losses from salinity for every situation.

2.5.3.1 Environmental factors

Soil environment

Chemical and exchange reactions and moisture retentivity can influence growth on saline soils. The physical structure of the soil influences drainage and aeration. Poor soil aeration amplifies the detrimental effects of soil salinity. Extraction of water from the underlying water table can also influence the salt tolerance of crops, depending on the quality of that water and the crop's rooting pattern. The application of gypsum under such conditions can increase the salt tolerance by improving soil structure and aeration (Frenkel & Meiri, 1985; Oster & Frenkel, 1980).

The fertility and fertilization of soil can result in an 'apparent' relative salt tolerance, that can be misleading (Bernstein, Francois & Clark, 1974; Grattan & Grieve, 1994). Crops grown at low fertility levels may show an apparently high salt tolerance (Feigin, 1985), because yields on non-saline soils can be relatively more affected by infertile conditions than on saline soils, resulting in an apparently higher relative salt tolerance. Improving nutrition by fertilization could, on the other hand, improve growth proportionately more under moderate or non-saline conditions than under saline conditions and result in an apparently lower relative salt tolerance. It was concluded that at moderate nutrient deficiency and salinity the effects on cereals are independent and additive. At higher stress levels the growth is, however, determined by the more limiting salinity factor (Bernstein *et al.*, 1974). Nutrient/salinity interaction can thus differ substantially as salinity increases from low to high levels (Grattan & Grieve, 1992). This is probably why most plants do not respond positively to N and P fertilization at high salinity. Feigin (1985) also reviewed data on fertilization of crops irrigated with saline water and concluded that standard fertilization for non-saline conditions is also suitable for saline conditions.

Salt tolerance also depends on the combination of specific salts in the soil solution. Different ions have different toxic levels and influence osmotic potential differently. This depends *inter alia* on the osmotic coefficient of the specific salt of which $NaCl > Mg$ and $CaCl_2 > Na_2SO_4 > MgSO_4$, depending on the concentration of the particular salt (Robinson & Stokes, 1959). The proportion of $Cl/SO_4/HCO_3$ and Na/Ca/Mg are important for the effect on plant growth. "Generally, however, plants respond similarly to salinity over a wide range of salt combinations." (Maas, 1990).

Although there is much evidence that Na dominated solutions reduce K and Ca uptake by plants, only a few studies show increased growth with their addition to sodic or saline-sodic soils (Grattan & Grieve, 1992).

Climate

Climate is probably the factor that has the greatest influence on the salt tolerance of crops. Temperature, irradiation, atmospheric humidity and pollution can influence salt tolerance. Generally, studies show that crops are more tolerant to salinity under cool, humid conditions than in a hot, dry climate (Magistad *et al.*, 1943). Crops and cultivars can, however, vary in their reaction. Lucerne and bean salinity tolerance decreased at higher temperatures (Ahi & Powers, 1938); barley, bean and corn were more sensitive to salinity at low than high air humidity (Maas, 1990), while humidity did not greatly affect the salt tolerance of wheat (Hoffman & Jobes, 1978). High humidity causes greater yield increases in salt-sensitive than in salt tolerant crops (Maas & Hoffman, 1977).

Ozone, a major air pollutant, has a greater effect on the growth of oxidant-sensitive (leafy and forage) crops under non-saline than saline conditions. Such crops may thus seem relatively more tolerant to salinity in such areas (Maas, 1990).

Agronomic and irrigation practices

Agronomic and irrigation practices can also cause increased injury with saline water. In raised seedbeds with furrow irrigation seeds should be planted on the shoulders away from the areas of salt accumulation (Ayers & Westcot, 1985). The frequency of irrigation influences sensitivity as plants are exposed to increased salinity with time between applications. Species also differ in their response to sprinkled irrigation. This depends on leaf characteristics and rate of absorption of salts. The Solonaceae family, e.g. potato and tomato, are most sensitive to leaf injury by salts. Greenhouse tests indicated sensitivity in the following order: Sugarbeet < cotton, sunflower < barley, sorghum < alfalfa < potato and tomato (Maas, Grattan & Ogata, 1982).

2.5.3.2 Plant factors

Species, cultivars and rootstocks

Plant species and cultivars differ in their ability to grow under saline conditions. With the greater emphasis on the genetic breeding of salt- and other stress tolerant cultivars, agronomical varieties now originate from a more diverse genetic base than in the past. There is thus a greater probability of cultivars differing in salt tolerance than in the past and this is an important basis for screening (Francois & Maas, 1994).

Rootstocks of fruit and vine crops furthermore play an important role in the sensitivity to toxic accumulation of Na and Cl in the leaves. This is mainly due to the exclusion and transport effects of the rootstocks on these ions (Maas & Hoffman, 1977).

Growth stage

The sensitivity of species and cultivars can change during their ontological development. It is important to separate the effects of growth stage from those related to duration of exposure to salinity (Lunin, Gallatin & Batchelder, 1961). There is, however, little data on specific effects of salinity at the different growth stages of crops. In most studies crops are subjected to salinity either from planting or after the early seedling stage (Francois & Maas, 1994).

Germination: Germination can be influenced by salinity through a decreased entry of water (lower osmotic potential) and/or the intake of ions to toxic levels. However, the percentage of germination is generally not decreased by salinity, but the rate of germination and emergence have been delayed (Francois & Maas, 1994). Exceptions are sugar-beet, lucerne, cotton and sunflower where germination is sensitive to soluble salts (Läuchli & Epstein, 1990). Pearl millet is sensitive to sodicity during germination (Ray, 1988). It is also interesting that some halophytes, that grow optimally at relatively high NaCl levels, appear to be salt sensitive during germination (Ungar, 1978).

Emergence and seedling stages: Plants are usually most sensitive during emergence and early seedling stages and become more tolerant as growth proceeds from the vegetative to the reproductive and grain-filling stages (Francois & Maas, 1994). Leaf and spikelet primordia and tiller buds of cereals are formed during the early vegetative stage. Salinity stress at this stage can thus significantly affect the eventual seed yield.

Sensitivity at these early stages, and thus the crop stand, can be greatly enhanced because of the exposure of juvenile roots to intensified salt and water stresses by evaporation from the soil surface.

The **vegetative growth stage** of non-halophytes is generally sensitive to salinity.

Pollination and fertilization: Although very limited, there are some indications that this could be a sensitive growth stage, e.g. for rice (Pearson & Bernstein, 1959) although this was not confirmed by a subsequent investigation by Kaddah (1963). In maize, salt sensitivity was found to be particularly high at tasselling (Maas, Hoffman, Chaba & Shannon, 1983). During **reproductive development** salt tolerance can, however, increase dramatically (e.g. cotton yields, Rains, 1981).

Comparing the sensitivity of a particular cultivar at different growth stages is complicated by the criteria used at these stages: germination and emergence is usually determined by survival percentage and thereafter salt tolerance is based on relative growth or yield.

When screening for salt tolerance of different cultivars of a specie, the most sensitive growth stage would obviously be studied, but within one genotype there could also be shifts in the relative salt tolerance of cultivars at different development stages. "Salt resistance of three barley cultivars changed over time, the cultivar most sensitive to early salinisation proved rather resistant at maturity, and the one that had the greatest initial resistance ... was more sensitive at maturity." (Lynch, Epstein & Läuchli, 1982).

2.5.3.3 Microbiological factors

Other biological factors are the sensitivities of *Rhizobium* species, and also possibly that of mycorrhiza. Soil salinities above the threshold values of legume species may severely affect the survival and N-fixing abilities of *Rhizobium* species. Chloride salts of Na, K and Mg appear to have specific ion effects on *Rhizobium* growth and are more toxic than the sulphate salts. Magnesium inhibits *Rhizobium* growth at lower concentrations than Na and K (Francois & Maas, 1994).

The Rhizobia species vary in their salt tolerance, from some being able to survive 4600 mSm^{-1} down to 1200 mSm^{-1}: *R. meliloti* (4600) > *R. trifolii* > *R. leguminosarum* > *R. japonicum* (grows poorly at 1200 mSm^{-1}) (Francois & Maas, 1994).

In conclusion then, these environmental and plant factors should be thoroughly kept in mind when evaluating salt tolerance data of a particular crop for recommendations for specific conditions.

2.5.4 EVALUATION OF CROP SALT TOLERANCE

The agricultural productivity of a crop can be limited by excessive concentrations of soluble salts in the growth medium; this is more pronounced in arid and semi-arid regions, where low quality water is the only source. One of the primary options available to ensure agricultural productivity under such conditions, is the choice of suitably tolerant crops or cultivars.

"Salt tolerance" has generally been defined as a plant's capacity to endure the effects of excess salts in the root growth medium (Maas, 1990). Salt tolerance can be appraised in several ways: survival under saline conditions; absolute growth or yield reduction for specific salinity levels; or growth in saline- relative to that in non-saline (control) conditions (Maas, 1990). Survival is important for ecological studies and perhaps also for revegetation of problem soils, but not for commercial production. The absolute yield reduction at specific salt concentrations can be useful for farmers, but is complicated by the fact that these yields are influenced by a multitude of other factors pertaining to the climate, environment, soil and the plant itself (see 2.4.3). Furthermore yields of different crop species cannot be compared on an absolute basis. These problems are largely overcome by expressing yield or growth on a relative basis. Relative growth or yield is defined by Maas (1990) as "the growth of a crop grown under saline conditions expressed as a fraction of that achieved under non saline, but otherwise comparable, conditions". Relative salt tolerances can, however, also be misleading (Bernstein, Francois & Clark, 1974), leading to 'apparent' salt tolerances that can be higher or lower depending on the proportionate influence of other limiting factors on the control (see factors 2.4.3.1).

2.5.4.1 Criteria used for salt tolerance evaluation

Many criteria have been used to evaluate the salt tolerance of crops, of which survival (germination), shoot dry mass and seed or fruit yield are the most common. The most recent salt tolerance lists of Maas and Francois (1994), include data on the specific parameter used such as grain yield, shoot growth and tuber yield. Depending on the criteria used, differing salt tolerance responses can be elicited. Vegetative shoot growth has been the most widely used parameter with non-halophytic crops. Experience has shown that increased biomass can result in increased economic yields (Arnon, 1977). It is important to note that tolerance can differ at different growth stages (see 2.4.3.2) and it is for this reason that selection for salt tolerance has sometimes been evaluated over the entire growth cycle. In many cases, however, salinity is imposed from the late seedling stage to maturity. Another approach is to evaluate for salt tolerance at the most sensitive growth stage. This could, however, lead to erroneous deductions for the salt tolerance of the total growth cycle of a specie (Ray, 1988; Munns, 1993).

2.5.4.2 Salt tolerance data and yield response functions

In the earliest salt tolerance data crops were listed according to their yield in the order of their tolerance (Magistad & Christiansen, 1943); or subsequently more qualitatively by placing crops in groups from sensitive to tolerant (*inter alia* United States Salinity Laboratory Staff, 1954). In a later approach, semi-quantitative data was given by listing crops with the salinity values at which different yield percentage decreases could be expected (e.g. Bernstein, 1964, 1974).

In 1977 there was a breakthrough for quantitative evaluation of salt tolerance when Maas and Hoffman reviewed all available salt tolerance information and it became apparent "that, in general, yield was not decreased significantly until a threshold salinity level was exceeded, and that yield decreased approximately linearly as salinity increased beyond the threshold" (Maas & Hoffman, 1977). To obtain the numerical values of the "threshold" and "slope" least square linear equations were fitted to the data of each experiment for the datapoints beyond the threshold salinity and these 'new' parameters computed from the average regression coefficients.

The relative yield (Y_r) could now be calculated for any given soil salinity exceeding the threshold, if the threshold and slope values were known, by using the equation

$$Y_r \quad = \quad 100 - B(EC_e - A)$$

where A = the salinity threshold expressed in dSm^{-1} ($1\ dSm^{-1} = 100\ mSm^{-1}$)

B = the slope expressed in yield decrease % per dSm^{-1}

and EC_e = the mean electrical conductivity of the saturated soil extract of the root zone at 25°C in dSm^{-1} (over the growth period)

According to Van Genuchten (1983), salinity can also be expressed as concentration (see Hoffman, Rhoades, Letey & Sheng, 1990, for conversion from EC_e), osmotic potential (see Maas, 1990) and the electrical conductivity of the soil water *per se* (EC_{sw}). (In this study EC of the growth medium can be more or less equated to EC_{sw}.)

A comprehensive list of crop salt tolerances with these "new" parameters was presented in Maas and Hoffman (1977) and these have been updated with ongoing research in expanded lists in Maas (1986, 1990) and Francois & Maas (1994). These lists include results from different countries and should thus be applicable as guidelines anywhere.

When using values in these lists for yield prediction, the following points must be kept in mind:

(a) These values are averages - not only from different countries but also with different soil types and for different cultivars.

(b) The listed values are based on data where salinity treatments were often started after seedling establishment, and thus not representative of sensitivity with germination and seedling stages included (although such information is noted when available).

(c) Soil salinity was mostly maintained at a relatively uniform value throughout the root zone, by irrigating with a high leaching fraction, thus minimizing salinity variations in concentration over time and space (Hoffman *et al.*, 1990).

(d) Data in these tables mostly apply to soils where Cl is the main anion. Due to the dissolution of gypsum when preparing saturated soil extracts, the corresponding EC_e values of gypsiferous soils (non-sodic, low Mg) generally ranges "from 1 to 3 dSm^{-1} (100 to 300 mSm^{-1}) higher than that of the nongypsiferous soils having the same conductivity in the soil water at field capacity. Therefore, plants grown on gypsiferous soils will tolerate EC_e values "approximately" 200 mSm^{-1} "higher than those indicated in the tables" (Maas, 1986).

(e) The lists in 1977 only included crop responses to total soluble salts in the root medium. In subsequent reviews salt tolerance data and limits for specific ion effects such as for B, Cl and Na were also included (e.g. Maas, 1986).

For quick qualitative rating, Maas and Hoffman (1977) grouped crops into five groups according to the salinities where yield starts to decrease (threshold EC_e) and where zero yield is expected:

Sensitive	EC_e < 130 mSm^{-1}
Moderately sensitive	EC_e 130 - 300 mSm^{-1}
Moderately tolerant	EC_e 300 - 600 mSm^{-1}
Tolerant	EC_e 600 - 1000 mSm^{-1}
Unsuitable for most crops (unless reduced yield accepted)	EC_e > 1000 mSm^{-1}

(Ayers & Westcot, 1985)

The threshold hypothesis of the popular two-section linear, yield/salinity response function was confirmed by Feinerman, Yaron and Bielorai (1982), using a switching regression method instead of the least squares approach to estimate the parameters in the two-section linear response curve.

Van Genuchten (1983) developed a computer program, entitled SALT which facilitates the calculation of the parameters of the stepwise linear and other nonlinear yield-salinity response functions with limited data points.

The threshold and slope parameters were subsequently implemented in a crop-water production function in which three yield relationships were combined, i.e.: (1) yield and evapotranspiration; (2) yield and average root zone salinity; and (3) average rootzone salinity and leaching (Letey & Dinar, 1986).

2.5.4.3 "Salinity"

The term "salinity" requires clarification: in many studies it is equated with NaCl, with or without $CaCl_2$, as the sole salinizing agent. Soil and irrigation waters are, however, made up of diverse contributions of various salts. The major ions present are chloride, sulphate, and bicarbonate salts of sodium, calcium and magnesium (Bernstein, 1964, 1974). The proportions can vary widely (Epstein & Rains, 1987) but the concentrations of some ions, e.g. Na and Cl can exceed those of essential nutrients by many orders. The most abundant kinds of salinity are nevertheless that of NaCl and Na_2SO_4 sometimes together with Mg salts (Poljakoff-Mayber &

Lerner, 1994). Soils with very high SO_4 content (e.g. 30 000 mgℓ^{-1}) are found on Solonetzic and cretaceous soils, e.g. Australia and the prairies of North America and Canada. In this report, when not stated otherwise, 'salinity' generally also refers to NaCl salinity.

Soils are considered saline if the EC of the saturated soil extract (EC_e) exceeds 400 mSm^{-1}. Due to a possible salt build-up in the longterm use of saline irrigation water, guidelines for the salinity of irrigation water are low: in the RSA the salinity hazard of irrigation water with an EC_{iw} of 90 to 270 mSm^{-1} is considered 'high' and 'very high' when from 270 - 540 mSm^{-1} (Dept. Water Affairs & Forestry, 1993).

2.5.5 SALT TOLERANCE OF AGRONOMIC GROUPS

The general salt tolerance trends for agronomic groups such as cereal, forage, vegetable, fruit and ornamental crops are summarised in Francois and Maas (1994). Most of the crops investigated in the current study fall into the cereal or forage groups.

2.5.5.1 Cereal crops

With the exception of maize and rice, most cereal crops are tolerant to soil salinity. Sorghum, wheat, triticale, rye, oats and barley fall into this group.

All cereals seem to follow the same tendencies of sensitivity or tolerance with regard to their growth stage. Seedling and early vegetative stages ('seedling' and 'tillering' stages of Tottman & Makepeace, 1979) are usually the most sensitive, while subsequent stages are increasingly salt tolerant. (This has been shown to be the case for sorghum, wheat, barley, corn and rice and can also be expected with the other cereal crops.)

Developmental events during the life cycle of cereals have been separated into three major developmental phases: "In the first phase, which encompasses the early vegetative stage" (i.e. 'seedling' and 'tiller' stages) "leaf and spikelet primordia are initiated, leaf growth occurs and tiller buds are produced in the axils of the leaves. High soil salinity at this time reduces the number of leaves per culm, the number of spikelets per spike and the number of tillers per plant".

"During phase II (which includes 'Stem elongation, booting and inflorescence emergence' of Tottman & Makepeace (1979)) "the tillers grow, mainstem and tiller culms elongate and the final number of florets is set" (Francois & Maas, 1994). Tiller survival and the number of functional florets per spikelet can be reduced by salinity stress during this phase which ends at anthesis (flowering). In the final phase of fertilization and grain filling, seed number and size can be affected by salinity.

Salinity has a greater influence on yield through its effect on spikelet and tiller number during phase I than through the yield components of the subsequent two phases (Francois & Maas, 1994).

2.5.5.2 Forage crops

Forage crops are mainly from the grass and legume families. Generally the grasses are more tolerant and the legumes more sensitive to saline conditions.

Like the cereals, grasses are most sensitive during the early seedling growth; as many forage grasses are mostly kept in the vegetative stage by grazing or cutting, "it appears that these grasses, once beyond the early seedling stage and well established, are less sensitive to soil salinity" (Francois & Maas, 1994).

Legumes mostly used for forage or fodder are clovers (*Trifolium* and *Melilotus* species) and lucerne (*Medicago sativa* L.). The salt tolerance of these crops depends very much on the stage of growth when salinity is imposed. Dark green leaves, and decreased leaf area and plant size are typical of the salt effect on these legumes. Due to the genetic variability of the grass and legume species and cultivars, differences in salt tolerance are possible (Francois & Maas, 1994).

From this literature survey it should be clear that plant response to salinity should not be over-simplified. Different environmental and plant factors, mechanisms and evaluation methods are involved and should be kept in mind when evaluating and predicting crop response to saline conditions.

CHAPTER 3

EXPERIMENTAL METHODS AND MATERIALS OF LABORATORY SCREENING

3.1 INTRODUCTION

In this chapter the different culture methods, mine waters and treatments used are described. Culture methods are described for germination, comparison of cultivars in the seedling growth stage, the effect of gradients of simulated mine water on seedling growth and finally for growth responses in the vegetative growth stage. Crops and cultivars to be evaluated, were recommended mainly on the basis of irrigation and/or the climate of the eastern Highveld region (a plateau with an elevation of 1500 - 1800 m.a.s.l. and a summer rainfall area). Information of the plant materials used is presented in Appendix A. The chemical composition of the mine waters differs with treatment, time and location; the composition of specific waters and treatments used is therefore presented. Finally the units are clarified.

3.2 CULTURE METHODS

3.2.1 GERMINATION

Germination percentages were determined by using germination paper rolls (Anchor germination and absorbent paper from Multasaad) (Similar to the method of Covell, Ellis, Roberts and Summerfield, 1986). The rolls were prepared by using three paper sheets (28 x 30cm) with absorbent paper towelling between two and a third to cover the seeds.

The rolls were first soaked in the respective treatment waters and then wrung by hand until dry enough not to make a shiny liquid film when pressed with a finger. Seeds were chosen at random and spread uniformly; the rolls were sealed inside a plastic bag with an elastic band. The tests were conducted in a growth chamber in total darkness and at a constant temperature of 20°C for both the subtropical and temperate crops.

The rolls were opened on the fourth day to use some of the germinated seedlings for the seedling trials. The final number not germinated was counted on the twelfth day. Seeds were considered germinated if at least a healthy radicle had formed. In a few cases growth ceased when the radicule was 1-2 cm long: these were included in the number not germinated. There were three replicates for each treatment with 40 seeds in each roll.

The treatments were: Control, deionized water; Mine A, a lime treated acid mine drainage (AMD) water or C, an untreated neutral high sulphate water with high Ca and Mg; Mine B, a water with high sodium, chloride and sulphate. No supplementary nutrients were added to these treatments.

3.2.2 SEEDLING GROWTH

3.2.2.1 Comparison and growth response of cultivars in glasshouse on actual mine waters

The seedling growth was evaluated in water culture in a glasshouse; subtropical crops were evaluated from October to February and the temperate crops from March to August. In summer the mean temperatures were: 28°C by day and 14°C by night; in winter 28°C and 6°C. Lighting was the natural sunlight; humidity was not measured, but the glasshouse was cooled by fans causing a suction of air through a layer of wet coke. In winter temperature was raised by underfloor heating.

Germinated seedlings were taken from the paper rolls on the fourth day and "planted" (secured with foam strips) in seedling trays, resting on a 28 liter black plastic container filled with the appropriate treatment solutions. Seedlings damaged in planting were replaced on the following morning. The containers were placed on a rotating table. Aeration was given for 3 minutes every 30 minutes through three black plastic pipelets in each container.

There were two replicates with 10 plants of each cultivar per replicate (except in the case of dry beans 15 plants and for cowpea 8 plants were used). The cultivars were placed throughout the seedling tray with the help of random numbers.

The treatments were: Control, ⅕ strength of modified Hoagland No 2 with NH_4 and NO_3; Mine A or C, a high sulphate mine water - either lime treated (A) or untreated with high sulphate and calcium (C) with additional nutrients to approximate the control; Mine B a high $Na/Cl/SO_4$ mine water with additional nutrients to approximate the control.

The analyses of the waters used are given in Table 3.1 (p. 38). All micronutrients were given at ⅕ strength Hoagland No. 2 with the exception of Mn for Mine A or C. Nutrients were added weekly, that is on the first and eighth day.

The top growth was harvested 14 days after 'planting' (17 days of growth), at the three to four leaf stage, dried at 65°C for 48 hours and the dry mass of the top and root growth determined. Root masses were not always accurate due to entangling and these results are thus not given.

The number of plants that survived was noted, and the mass per 10 plants calculated where necessary.

Seed companies were consulted and asked to recommend cultivars of crops adapted to the eastern Highveld climate and/or to irrigation. The seed was donated by PANNAR, SENSAKO, and CARNIA (now OMNIA). The Small Grain Centre of the Agricultural Research Council recommended and provided seed for the annual temperate crops.

The statistical analyses for both germination and seedling growth were conducted with the computer package SAS (Statistical Analyses System) using the General Linear Models (GLM) procedure, which fitted linear models to the data. The influence on the growth was determined by comparing absolute growth on a mine water to that of the control. Differences of growth on the mine waters relative to the control for each cultivar are indicated by asterisks:

- * Tending to significant difference from control ($P<0,1$).
- ** Significant difference from control ($P<0,05$); this usually includes $P<0,01$.

The relative growth % was calculated by a random combination of replicates of the treatments and controls. Least significant differences (LSD_T) were determined separately for the absolute and relative growth %, with Fisher's LSD test and where applicable the differences were indicated by alphabetical letters.

3.2.2.2 Seedling growth on gradients of artificially mixed mine waters in a growth chamber

The objective of these trials was to determine salt tolerance parameters for selected crop cultivars in the seedling growth stage with increasing concentrations of artificially mixed, simulated mine waters. The parameters are: the threshold value, i.e. the maximum allowable salinity without growth reduction, relative to that achieved under non-saline control conditions; and the 'slope', the percentage growth decrease per 100 mSm^{-1} increase beyond the threshold. From these parameters relative growth for a given salinity exceeding the threshold can be calculated.

To achieve this objective sand culture experiments were conducted in growth chambers. Seeds were planted in washed quartz sand in 250 ml polystyrene cups with enough holes to allow free drainage of treatment solutions. Due to the size of the cups, solutions only drained to the saturated volume (± 75 mℓ/cup). This did not, however, prove to be detrimental to growth.

The temperatures and light/dark periods were chosen to simulate conditions at the time of planting/seedling growth in the field. Crops were grown with 12 hours dark and 12 hours light (except for subtropical annuals with simulated sodic-saline water, where a day/night period of 14 hours light to 10 hours dark was followed), and day/night temperatures of 25°C/15°C for the subtropical and 23°C/12°C for the temperate annuals.

Two types of mine water were simulated: Mine C 3/95 was used as a basis for sulphate and Mine B 3/95 for sodic-saline (Na/Cl/SO_4) salinity (Table 3.1, p. 38). In the case of the high sulphate water, salinity was attained by increasing the SO_4, Ca and Mg, while maintaining the Ca:Mg ratio of the mine water simulated. With the sodic-saline water Na, Cl and SO_4 was increased. $CaSO_4$ (0,861 $g\ell^{-1}$) was added to all treatments of the simulated sodic-saline water in order to prevent a Ca effect on salt tolerance.

The chemical composition of the simulated sulphate mine water treatment solutions is presented in Table 3.2 (p. 39) and that of the sodic-saline water in Table 3.3 (p. 40). The EC, pH (H_2O) and concentration of sulphate in solution were determined in the supernatant of these solutions. Estimated osmotic potential values (ψ_o) of the treatment solutions were calculated with the equation

$$\psi_o \quad = \quad -C\,\phi\,v\,R\,T \qquad \text{(Campbell, 1977)}$$

where C = concentration of solute taken as the total $mol\ell^{-1}$ of ions in the treatment solution

ϕ = the osmotic coefficient taken as 1

v = number of ions per mole (e.g. 2 for NaCl, 3 for $CaCl_2$) taken as 1

R = gas constant (8,3143 J $mol^{-1}K^{-1}$)

T = Kelvin temperature taken as the average of the day and night temperature.

The limited solubility of $CaSO_4$ (gypsum) posed a problem in acquiring high soluble sulphate concentrations. Two ranges of treatments were thus planned:

1. The sulphate was provided by increasing Ca and Mg sulphate; the composition ranged from 226 to 5000 or 6000 '$mg\ell^{-1}$' sulphate (this includes the undissolved gypsum which was also applied as a suspension). The concentra-

tion in the mine water (2300 $mg\ell^{-1}$ sulphate) is in the vicinity of the maximum solubility of gypsum; from about this value calcium sulphate could start precipitating or remain undissolved (Arslan & Dutt, 1993). The actual concentration of the soluble sulphates in these solutions were determined by analyses of the supernatant (Treatment solutions 2 - 9, Table 3.2, p. 39).

2. In order to obtain solutions containing higher soluble sulphates the composition of the 2300 $mg\ell^{-1}$ sulphate treatment (treatment 5) (more or less at maximum solubility of gypsum) was kept constant and the sulphate increased with Na_2SO_4 (Treatment solutions 10 - 13, or 11 - 14, Table 3.2, p. 39).

There were four replicates of each treatment.

A mass of 280 grams of dry quartz sand, washed with deionized water, was weighed into each cup. The seeds were planted directly, then wet with 75 ml of the respective solutions, drained and the mass determined. Until emergence the water was replenished daily to the original masses with deionized water. At and after emergence the solutions were replaced every third day, with 120 ml treatment solution and between this replenished daily with deionized water to the original masses. By this procedure it was endeavoured to minimize daily salinity variations in concentration.

Where the gypsum had not completely dissolved the solutions were shaken and applied as a suspension. (This was done so that an idea could be formed of a possible influence of undissolved/precipitated gypsum in the root system medium.) The top growth was clipped at sand level 21 days after planting, at the three to four leaf stage; the stems were rinsed four times with deionized water. The top growth was dried for 48 hours at 65°C and the dry masses per cup determined. The number of plants per cup varied for the different crops from 3 plants for dry beans to ± 20 plants for ryegrass. Results are given as DM/10 plants. This can be easily compared to data in literature which is often given as DM/plant.

The statistical analysis was conducted with the computer package SAS (Statistical Analysis System) using the General Linear Models procedure which fitted linear models to the data. Asterisks indicate differences from the control (treatment 1):

* $P<0,1$, a tendency to differ, and ** $P<0,05$, a significant difference on the 5% level.

The computer programme, SALT (Van Genuchten, 1983, 1984) was used to statistically fit the unknown coefficients of threshold and slope to the experimental data (see 2.5.4.2, p. 22). Where growth decrease was not linear, some problems were experienced to acquire a good fit for some regression curves. This programme was successful mainly for the NaCl salinity.

3.2.3 Vegetative growth stage

Two trials were conducted with subtropical and temperate crops respectively to determine the influence of a lime treated AMD water and a sodic-saline water on the vegetative growth stage (28 to 56 days after planting).

In the first trial, a sand culture experiment was conducted with maize (*Zea mays* SNK 2340), sorghum (Sorghum hybrid PAN 888), soybean (*Glycine max* Ibis), pearl millet (babala) (*Pennisetum glaucum* common), cowpea (*Vigna unguiculata* Dr Saunders); and four bermuda grass cultivars (*Cynodon dactylon*), Coast Cross 2 K11 hybrid, Primavera, Tierra Verde and Sahara, and also with alkali sacaton grass (*Sporobolus airoides*).

This trial was conducted on a rotating table in a glasshouse from February to March, using 6 kg of washed quartz sand in Mitscherlich vegetation vessels. The mine waters with added nutrients were compared with a third strength modified Hoagland No. 2 (NH_4^+ and NO_3^-) solution over four replications. The seeds were germinated in the quartz sand with half strength modified Hoagland No 2 (NH_4 + NO_3). The seedlings, after thinning to three plants per pot at the three leaf stage, were allowed to grow in the same nutrient solution for a further two weeks before the commencement of the comparative study. Full salinization was from day 26 to day 52 after planting. During the study solutions were replenished and circulated twice daily with deionized water and replaced weekly to maintain salinity and nutrient levels. In this way it was endeavoured to keep the water content at 'field capacity' throughout the experiment. Plants were harvested after 25 days of treatment. The total fresh mass was determined directly after clipping at 'ground' level. Leaf areas were determined using the LI

3100 leaf area meter. Dry mass of both top growth and root components was determined after oven drying at 65°C for 48 hours. The total top growth was milled, wet ashed and N, P, K, Ca, Mg, Na, S as sulphate (% DM), as well as Fe, Mn, Cu and Zn (mg/kg DM) determined by atomic absorption spectrophotometric techniques and Cl by titration with silver nitrate ($AgNO_3$). The ratios of top growth:roots and leaves:stems (DM) were calculated, as well as the moisture content in the fresh material and the relative growth (as a percentage of the control) of both leaf and total top growth.

In May to June a second trial was conducted, using water culture to evaluate the tolerance of rye (*Secale cereale* SSR 1), oats (*Avena sativa* Overberg), Triticale (*Triticosecale* CLOC 1), wheat (*Triticum aestivum* Inia), ryegrass (*Lolium multiflorum* Midmar), lucerne (*Medicago sativa* PAN 4860), tall fescue grass (*Festuca elatior* Au Triumph) crown vetch (*Coronilla varia* Penngift), cocksfoot (*Dactylis glomerata* Hera) and white clover (*Trifolium repens* Dusi).

This experiment was also conducted on rotating tables in a glasshouse. Mitscherlich pots (5 ℓ), lined with plastic bags, and with black plastic covers, were used. The solutions were aerated for three minutes every 30 minutes. Seeds were sown in vermiculite and three seedlings were 'planted' in each pot ten days later (5 species, 3 treatments and 4 replicates). Plants were grown out to the four-leaf stage in a half strength Hoagland No. 2 nutrient solution. Treatments with the mine waters with added nutrients and one third strength modified Hoagland No. 2 were started four weeks after planting. Treatment solutions were replaced weekly. The water level was topped up twice daily to maintain the concentrations. After four weeks of treatment (28 to 56 days after planting) top and root growth were harvested. Fresh mass, dry mass and leaf areas were determined as in the first trial and ratios between different growth components were calculated. Statistical analyses were again conducted with the SAS (Statistical Analyses System) using the GLM procedure as previously (p. 30). Asterisks in Tables indicate significance of differences from control.

3.3 MINE WATERS USED IN TRIALS

Three types of mine waters were used in the evaluation of the tolerance of crops

(Mines A, B & C). With the help of routine analyses data of mine waters in the Highveld area, made available by Amcoal environmental services, 'worst case' waters were identified. Initially a lime treated acid mine water (Mine A Kromdraai) and a high Na/Cl/SO_4 water (Mine B New Denmark) were used for the vegetative evaluations. The lime treated water was also used in the field trial, but it was not really a 'problem' water in relation to plant growth. Subsequent seedling growth evaluations were conducted with a more concentrated neutral sulphate water from another location (Mine C Kleinkopje).

Neutralization of AMD through the addition of lime produces a water (Mine A) with a high Ca content which can theoretically be advantageous to plant growth in saline environments. Furthermore dissolved metals such as Fe and Mn precipitate and settle out of the lime treated water, thus the possibility of toxic amounts of these metals in this type of water is decreased. The Mine A water was used to determine its effect on the vegetative growth of crops, for the comparison of the maize cultivars and for the field trial. The Mg content of this water was relatively low (average 1994 to 1996 was 20,7 $\mathrm{mg}\ell^{-1}$).

To form an idea of how the water varied over the three year period, the chemical analyses of the lime treated AMD water from 1994 to 1996 is presented in APPENDIX B.

Mine C water is a more or less neutral water that is pumped directly from old underground workings via a borehole. The sulphate content is relatively high, *ca* 2500 $\mathrm{mg}\ell^{-1}$ SO_4, as well as the Ca and Mg ($\sim$ 350 $\mathrm{mg}\ell^{-1}$ and 200 $\mathrm{mg}\ell^{-1}$ respectively). The Mn content of *ca* 3,5 $\mathrm{mg}\ell^{-1}$ is higher than recommended by water quality guidelines, a maximum of 0,20 $\mathrm{mg}\ell^{-1}$ Mn being suggested (Dept of Forestry & Water Affairs, 1993).

Mine B is a 'worst case' Na/Cl/SO_4 sodic-saline water of this area. The ratio of Na:Cl:SO_4 varies considerably, especially of Cl:SO_4. This water, however, contains 2 $\mathrm{mg}\ell^{-1}$ F which can eventually be detrimental to animal health. The recommended maximum concentration for irrigation water on acid sandy soils is 1 $\mathrm{mg}\ell^{-1}$ (Dept of Forestry & Water Affairs, 1993).

The chemical composition of the different waters denoted by the specific Mine (A, B or C) and date of collection that were used in the evaluations of crop salt tolerance, is presented in Table 3.1 (p. 38), together with the control treatments. All values include supplementary nutrients added to approximate the one third strength modified Hoagland No. 2 (NH_4 & NO_3) of the controls.

A final sample of the three types of water was taken in October 1996. These were analysed by the Institute for Water Quality Studies in order to determine metal contents. This did not prove to be problematic. The analysis is given in Appendix C.

3.4 UNITS USED FOR SALINITY

Salinity of soil water for salt tolerance parameters is usually presented as the electrical conductivity of a saturated soil extract (EC_e) in dSm^{-1}. Threshold values are thus usually given as EC_e dSm^{-1}, and slope values as % yield decrease per dSm^{-1}. Although we have used the International unit of mSm^{-1}, 1 dSm^{-1} = 100 mSm^{-1}, it is still easy to compare with values given in the literature. EC of the soil solution is denoted as EC_{sw}, and of irrigation water as EC_{iw}. In this study salinity of the growth medium is used and simply termed EC. Slope is given as % yield decrease per 100 mSm^{-1}.

When comparing the results in this report with other investigations, it must be taken into account that in the literature the threshold value, is mostly given as the electrical conductivity of a saturated soil extract (EC_e) of soil samples from the root zone where maximum water is taken up. The EC_e value is about half that of the soil solution (EC_{sw}) at field capacity (Marschner, 1986), which is comparable to the EC of the growth medium used in this report. Values in this report are thus about twice the concentration of what it would be if measured in a saturated soil extract, e.g. of a threshold of 200 mSm^{-1} was found for maize seedlings in the growth medium it would be equivalent to an EC_e of 100 mSm^{-1}.

Table 3.1 **Chemical composition of mine waters[1] and controls used in the salt tolerance evaluations**

Mine/ Controls	pH (H_2O)	EC mSm^{-1}	NH_4	NO_3	P	K	Ca	Mg	SO_4	Na	Cl
			mg ℓ$^{-1}$							mmolℓ$^{-1}$	
Control 1	5,6	96	30	310	10	78	66	28	221	0,7	
A 2/94	6,5	274	30	310	10	78	646	16	1609		
A 5/94	7,0	274	30	310	10	78	400	35	998	0,3	
B 3/94	7,8	407	30	310	10	78	32	30	885	33,5	(15,5)[2]
B 4/94	8,5	407	30	310	10	70	41	40	802	30,4	(17,2)[2]
Control 2	5,2	92	31	316	10	78	67	28	227	0,7	
A 7/94[4]	6,5	278	31	316	10	81	257	40	1371	0,3	2,4
B 7/94	8,4	(405)	31	316	10	86	41	14	575	40,3	27,8
Control 3	(5,6)	110	30	207	10	78	67	16	225		
C 10/94	(7,5)	(420)	30	207	10	80	297	186	2533	2,6	
C 12/94	(7,5)	(370)	30	207	10	81	419	221	2360	2,3	
B 11/94	8,1	590	30	207	10	79	110	44	1135	52,3	(35)[2]
B 12/94	(8,1)	(590)	30	207	10	77	73	21	879	44,8	(29,1)[2]
Control 4	5,6	153	30	207	10	90	66	30	255	1,1	
C 3/95[5]	7,3	394	30	207	10	90	425	217	2248	4,6	0,1
B 3/95	7,9	534	30	207	10	90	67	30	732	39,8	26

Mine A Lime treated acid mine drainage water
Mine B Na/Cl/SO_4 mine water pumped from shaft
Mine C High sulphate mine water pumped from old underground workings

1. All analyses include the supplemental nutrients; controls are one third strength of a modified Hoagland No 2 (NH_4 + NO_3) solution
2. Calculated
3. Other brackets : estimated
4. Mine A 7/94 Mn 1,84 mg ℓ$^{-1}$; Average values 1994 to 1995: Fe 0,41 Mn 2,85 mgℓ$^{-1}$
5. Mine C 3/95 HCO_3 74 Fe 0,44 Mn 3,54 Cu 0,016 Zn 0,027 mg ℓ$^{-1}$

Table 3.2 Chemical composition of simulated gradients of sulphate salinity[1]

Treatment[2]	Sulphate mgℓ^{-1}		EC mSm^{-1}	pH (H_2O)	Osmotic Potential[3] J kg^{-1}		Ca	Mg	K	Na[4]	NH_4^+	NO_3	P
	Planned	Supernatant Analysed			Sub-tropicals	Tem-perates	mgℓ^{-1}						
1. Control	226	243	104	5,7	-52	51	66	16	81	0/48	31	205	10
2.	1500	1420	300	5,5	-97	-97	342	171	81	0/48	31	205	10
3.	2000	2070	361	6,2	-124	-121	454	230	81	0/48	31	205	10
4.	2150	2195	381	5,3	-131	-128	489	247	81	0/48	31	205	10
5.	2300	2310	412	5,3	-138	-135	524	264	81	0/48	31	205	10
6.	2500	2435	400	5,2	-150	-147	570	286	81	0/48	31	205	10
7.	3000	2975	436	5,4	-184	-180	682	345	81	0/48	31	205	10
8.	4000	3288	460	5,5	-217	-212	911	459	81	0/48	31	205	10
9.	5000	3850	523	6,0	-205	-201	1136	575	81	0/48	31	205	10
10.	2500	2713	432	5,7	-155	-153	524	264	81	97	31	205	10
11.	3000	3200	512	5,5	-193	-190	524	264	81	336	31	205	10
12.	4000	4150	678	6,7	-238	-234	524	264	81	814	31	205	10
13.	5000	4988	840	5,6	-302	-297	524	264	81	1292	31	205	10
Mine C 3/95		2248	335	7,0	-124	-122	425	217	12	48	0	0	0

1. After the preliminary trial using treatments 1 - 13, an extra treatment with a total sulphate content ($CaSO_4$) of 6000 'mg ℓ^{-1}' was included (10); 11 - 14 then coincided with 10 - 13.
2. Treatments 2 - 9: salinity increased mainly with $CaSO_4$; 10-13 salinity increased with Na_2SO_4 from 2500 mg$\ell^{-1}SO_4$.
3. Estimated value by calculation (3.2.2.2, p. 31).
4. No Na was added to treatments 1 - 9 for maize CRN 4403, sorghum PAN 888, pearl millet common and sunflower SNK43; for all other crops 48 mgℓ^{-1} Na was added to treatments 1 - 9.

Table 3.3 Chemical composition of simulated gradients of Na/Cl/SO_4 mine water

Treatment	pH^1 (H_2O)	EC^1 mSm^{-1}	Osmotic Potential^2 J kg^{-1}		Na	Cl	SO_4 ^{3}	Ca ^{3}	Mg	K	NH_4 ^{1}	NO_3 ^{1}	P
			Sub-tropicals	Tem-perates	$mmol\ell^{-1}$		$mg\ell^{-1}$						
1. Control	6,2	241/168	-64	-63	0,02	0	1137	210	30	90	31/19	205/247	10
2.	5,9	308/286	-111	-110	10	10	1170	196	30	90	31/19	205/247	10
3.	5,9	396/372	-154	-153	20	16	1308	189	30	90	31/19	205/247	10
4.	5,7	581/565	-244	-241	40	29	1440	190	30	90	31/19	205/247	10
5.	5,9	678/664	-287	-284	50	35	1949	189	30	90	31/19	205/247	10
6.	5,8	770/756	-333	-330	60	42	2213	193	30	90	31/19	205/247	10
7.	5,8	958/934	-420	-416	80	54	2396	194	30	90	31/19	205/247	10
Mine B 3/95	7,8	503	-202	-200	40	26	732	19	30	8	0	0	0

1. Less NH_4 was used for the winter crops and more NO_3; the first value is for summer crops and the second for winter crops.
2. Estimated values by calculation (3.2.2.2, p. 31).
3. $CaSO_4$ was added to all treatment solutions to prevent a Ca effect on salt tolerance.

Ch3-Tab3.3

CHAPTER 4

RESULTS OF LABORATORY SCREENING OF AGRONOMIC AND PASTURE SPECIES

4.1 INTRODUCTION

In this chapter the results of the laboratory screening of agronomic and pasture crops for tolerance to two types of mine waters, are presented. The crops have been subdivided into four groups: the subtropical or summer annual crops; some subtropical perennials; the temperate or winter annual crops and lastly the temperate perennial crops.

The vegetative growth (28-56 days after planting) of all the groups was evaluated, whereas, the germination and seedling growth of only the annual crops and lucerne were investigated. Seedling response included firstly the growth response and a comparison of the recommended cultivars of the different species on the actual mine waters relative to a Hoagland control. Secondly selected cultivars were subjected to increasing concentrations of simulated mine waters in the seedling growth stage.

In the results one crop out of each group is fully discussed. As salt tolerance can, however, be crop and cultivar specific, the results for each species should be individually studied. For this reason and for easy reference the tables and figures of specific crops are grouped together at the end of this chapter.

A summary of salt tolerance parameters found in literature for the crops involved are given in Tables 4.1 to 4.6 (pp. 88 to 93).

Finally, some possible mechanisms by which growth of the specific crops could have been affected, is looked into. This could be a help and give some guidelines for mechanistic crop growth modelling.

The chapter concludes with an overview of the tolerance of the evaluated crops and pastures to sulphate and sodium chloride mine waters in the different growth stages.

4.2 SUBTROPICAL ANNUALS

The subtropical annual crops evaluated were maize, sorghum, pearl millet (babala), soybean and cowpea; sunflower, beans and potato were only partly evaluated. Maize and soybean will be discussed as examples of this group. Where applicable, specific responses of other crops will be pointed out.

The salt tolerance parameters found in the literature for this group are summarised in Tables 4.1 and 4.2 (pp. 88 & 89), and 4.6 (p. 93); these are, however, mostly for NaCl or NaCl/$CaCl_2$ salinity and often do not include the seedling growth stage.

4.2.1 MAIZE (sorghum and babala)

4.2.1.1 Introduction

Maize has been classified as a moderately salt sensitive crop plant. Maas and Hoffman (1977) calculated a threshold of EC_e[1] 170 mSm^{-1} for yield decrease. The yield decrease % per 100 mSm^{-1} salinity increase was calculated at 7,4% for forage, and 12% for grain and sweetcorn. A yield decrease of 50% is expected at 590 mSm^{-1} (Maas, 1986). The salt tolerance of maize has also been thought to be site-specific and a study on organic soils yielded a threshold value slightly higher than the above value (Hoffman, Maas, Pritchard and Meyer, 1983). These values are mostly for NaCl salinity; on gypsiferous soils, plants will tolerate EC_e's from 100 to 300 mSm^{-1} higher than for non-gypsiferous soils (Maas, 1986).

Studies of Maas *et al.* (1983) on the sensitivities of the growth stages of maize indicate that seedling growth up to 21 days is the most sensitive stage with a threshold value of EC_{sw} 100 mSm^{-1} (EC_e = 50 mSm^{-1}) and a slope of 4,9%. Germination was relatively tolerant up to EC_{sw} of 930 mSm^{-1}. Although emergence was delayed, the final percentage emerging was not significantly affected. The salt tolerance thresholds for growth after 21 days, and for the

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[1] EC_e electrical conductance of the saturated soil extract; EC_{sw} conductance of the soil water in the root zone. In this study the salinity of the growth medium either in water or sand culture is termed EC and can be compared to the EC_{sw}. EC_{sw} at field capacity is about twice that of EC_e (Marschner, 1986).

ear and grain yields were, however, much higher and yield decrements greater per unit increase in EC_{sw} (FM ears threshold $EC_e \simeq 290\ mSm^{-1}$; dry grain $EC_e \simeq 225\ mSm^{-1}$) than for seedling growth. The response of shoot growth compared to grain yield at harvest did not differ in some reports, while in others grain yields were more sensitive than the vegetative top growth (Kaddah and Ghowail, 1964).

The irrigation method, flood or sprinkle, does not influence the salt tolerance of maize but the response is dependant on how much and how frequently water was applied (Cramer, 1994).

The mechanisms of the adverse effects of salinity on the growth of maize were summarised by Cramer (1994): There have been many investigations on specific ion toxicity of Na on the growth of maize. Work by Cramer and his colleagues, however, questions the toxic influence of Na on the basis of their own findings that Na exclusion is negatively correlated with salt tolerance; they do, however, note that the cytoplasmic Na was not investigated and that the influence of Na requires more rigorous testing. The role of chloride in possible toxicity has also been investigated in maize: in two reports chloride exclusion was found not to be a factor in salt tolerance whereas in another higher cytoplasmic chloride was found in two salt sensitive cultivars. Cramer (1994) concludes that for most saline conditions specific ion effects play a minor role, but that for soil types or irrigation waters with unusual ion ratios it could be a more important growth inhibitory mechanism. Finally there is also a report that long term exposure to salinity can also cause an increase of growth inhibitors in maize leaves (Khan, Khan & Khizar, 1976).

The reduction of growth in maize by salinity appears to be caused by a reduced leaf area, which seems to be primarily due to an osmotic potential effect. The possible role of increased abscisic acid levels in maize leaves in restricting leaf elongation, is currently being researched in the laboratory of Cramer and colleagues.

4.2.1.2 **Germination** (Mine A 7/94, Mine B 7/94)

The results comparing the germination of maize hybrids are given in

Table 4.13 (p. 98) and those of sorghum and pearl millet in Table 4.17 (p. 104). The germination of the 18 recommended maize hybrids was not significantly influenced by either the lime treated acid mine drainage (AMD) water or the sodic-saline mine water.

This was also true for most sorghum cultivars and pearl millet (common), except for three higher forage producing cultivars SENTOP, CRN 7686 and SENFOR, where there was a higher incidence of early seedling deaths (radicle 1-2 cm). This could indicate a sensitivity in very early seedling growth for SENTOP and CRN 7686. Germination of pearl millet PAN 911 was significantly less by 11% on the high sulphate water.

4.2.1.3 Seedling growth

A. Screening of maize hybrids in the seedling growth stage

Eighteen recommended maize hybrids were screened for their salt tolerance in the seedling stage (0-18 days; 3 to 4 leaf stage) with the two types of mine water in water culture in the glasshouse. Results are given in Table 4.18 (p. 105) and for sorghum and babala in Table 4.24 (p. 111).

a) **Lime treated AMD mine water** (Mine A 7/94, EC 278 mSm^{-1})

The top growth dry mass of five hybrids (SNK 2266, SNK 2151, SNK 2665, PAN 6552 and Pan 6549) was significantly depressed by this water. As the primordia of reproductive organs are probably initiated in this growth stage (Cheng, Greyson & Walden, 1983), the sensitivity of these hybrids in the seedling growth stage could eventually result in lower yields. Most of the hybrids were, however, not significantly influenced. Probably due to dilution by heavy rains in this particular season, this was not really a problem water. In the subsequent trials a high sulphate untreated water, pumped from old underground workings from another location (Mine C), was used.

The hybrid SNK 2340 (also used in the sand culture and field trials) of which the seed was not available for this trial, was evaluated with the sorghum cultivars on the more concentrated water from Mine C (10/94) (EC 420 mSm^{-1}, sulphate 2533 mgℓ^{-1}). In the latter water the seedling growth was significantly reduced by 25%. (In the gradient experiments the seedling growth of this hybrid was not significantly decreased at EC values below 368 mSm^{-1} for a simulated high sulphate mine water. This could be an indication that the seedling growth of SNK 2340 would also not have been significantly influenced by the lime treated AMD water with an EC of 278 mSm^{-1}.)

The most tolerant hybrids were CRN 4403 and CRN 3631; and the most sensitive SNK 2151, SNK 2665, PAN 6552 and PAN 6549. Generally, cultivars did not differ significantly except the most tolerant from the most sensitive hybrids: relative seedling growth of CRN 4403 was significantly better than SNK 2042, SNK 2266, SNK 2151, SNK 2665, PAN 6552 and PAN 6549; and that of CRN 3631 was significantly higher than the above-mentioned four most sensitive cultivars (Table 4.18, p. 105).

b) **Sodic-saline mine water** (Mine B 7/94, EC 405 mSm^{-1})

The seedling growth of three hybrids, CRN 3414, CRN 3818 and PAN 6480, was not significantly influenced by the sodic-saline mine water. The last two did, however, show a tendency to suppressed growth.

The most tolerant maize hybrids with this sodic-saline mine water were SNK 2042 and PAN 6480; and the most sensitive PAN 6363. The only significant cultivar difference is between the most tolerant, SNK 2042, and the most sensitive, PAN 6363, hybrids.

Cultivars of sorghum and babala also differed in their response to the two mine waters in the seedling growth stage (Table 4.24, p. 111).

B. Seedling growth on gradients of two types of simulated mine water in a growth chamber

a) Simulated high sulphate mine water (Mine C 3/95)

The chemical analyses of the gradient treatments are given in Table 3.2 (p. 39). The results of seedling growth of maize hybrids SNK 2340 and CRN 4403 on gradients of simulated sulphate saline mine water are given in Table 4.15 (p. 100) and Figure 4.1 (p. 101) (and of sorghum PAN 888 and pearl millet (common) in Tables 4.19 and 4.21, pp. 106 & 108 and Figures 4.3 and 4.4, pp. 107 & 109 respectively). The seedling growth was evaluated on two ranges of simulated Mine C water (3/95). In one range (treatments 1 to 9) the sulphate was increased with mainly $CaSO_4$ and in the other supplemented (10 to 13) with Na_2SO_4.

The seedling growth for CRN 4403 did not decrease significantly for any of the increased sulphate treatments in the range with $CaSO_4$ (EC of the growth medium ranged from 104 to 523 mSm^{-1} and the total sulphate in the system from 226 to 5000 '$mg\ell^{-1}$'). Growth was least at 2300 $mg\ell^{-1}$ sulphate (EC 412 mSm^{-1}) (Table 4.15, p. 100). It is interesting to note that the salt concentration and composition at this point coincides with the actual mine water. In this range when sulphate content > 2300 $mg\ell^{-1}$ the salts start precipitating or gypsum remains undissolved. Even where the EC of the supernatant solution still increases, there is an initial growth increase and then a second growth decrease. These tendencies are, however, statistically insignificant for CRN 4403. SNK 2340 followed similar tendencies but with a significant depression at 2300 and 2500 $mg\ell^{-1}SO_4$ and a lower absolute and relative seedling growth than CRN 4403 (Figure 4.1, p. 101). CRN 4403 was thus more tolerant to increasing $CaSO_4$ concentrations than SNK 2340.

In the range where sulphate was increased with Na_2SO_4, the addition of sodium seems to be beneficial for CRN 4403 at the lower Na concentrations (4 and 15 mmolℓ^{-1} Na) compared to $CaSO_4$ treatments with similar EC values (Figure 4.1, p. 101). For SNK 2340, however, the Na_2SO_4 treatments seemed to suppress seedling growth at similar EC values to the $CaSO_4$ treatments. The beneficial effect could possibly be due to an osmotic adaptation of CRN 4403 by uptake of the Na.

There were no significant regression results for these two maize hybrids on the simulated high sulphate waters.

b) **Simulated sodic-saline mine water** (Mine B 3/95)

The chemical composition of the $Na/Cl/SO_4$ gradient treatments are given in Table 3.3 (p. 40). The results of seedling growth of maize hybrids SNK 2340 and SNK 2042 on gradients of a simulated sodic-saline mine water are given in Table 4.16 (p. 102) and Figure 4.2 (p. 103) (and of sorghum in Table 4.20 and Figure 4.3, pp. 106 & 107; pearl millet Table 4.22 and Figure 4.4, pp. 108 & 109). The gradients were achieved by increasing the Na, Cl and sulphate keeping the same ratio as in the mine water. The seedling growth of SNK 2340 and SNK 2402 decreased significantly from the 20 mmolℓ^{-1} Na and 40 mmolℓ^{-1} Na respectively with significant linear and non-linear regressions for both hybrids.

Threshold and growth decrease % per 100 mSm^{-1} for these two hybrids on the NaCl treatments were determined with option 1 of the SALT programme of Van Genuchten (1983) using the Maas & Hoffman equation: Thresholds for SNK 2340 and SNK 2042 on the sodic-saline water were 205 and 230 mSm^{-1} respectively, and the slopes for relative growth data 5,1% and 8,2% (Figure 4.2, p. 103).

Comparisons of these two hybrids showed that SNK 2340 had a higher absolute yield, but that there were no significant differences between the relative yields of the two hybrids with the increasing concentrations of this simulated sodic-saline mine water.

The salt tolerance parameters of maize, sorghum and babala on the Na/Cl/SO_4 gradients are summarised in Table 4.2 (p. 89).

4.2.1.4 Vegetative Growth Stage

The maize hybrid chosen for the field trial, SNK 2340, was evaluated for its vegetative growth with the two types of mine water in a sand culture experiment conducted in the glasshouse. Full strength salinization was imposed from the 27th day after planting, when the plants had approximately four leaves. Plants were harvested 52 days after planting at the beginning of the tasselling stage, i.e. 25 days after full strength treatment had begun. The analyses of the minewaters and control used are given in Table 3.1 (p. 38).

A. Growth results

Results of growth parameters for maize, sorghum and babala are given in Table 4.7 (p. 94) and some calculated growth ratios in Table 4.8 (p. 95).

a) **Lime treated AMD mine water** (Mine A 2/94, EC 274 mSm^{-1}, SO_4 1609 $mg\ell^{-1}$)

The total dry mass of the top growth of maize SNK 2340 did not differ significantly from that of the control. Only dry stem mass was significantly decreased by 20% which was reflected in a higher leaf to stem ratio. This decrease in stem mass was probably due to shorter but not thinner stems (growth observations).

In a preliminary experiment with SNK 2340 on sand culture to determine acceptable minimal nutrient levels (results not given), this hybrid was classified as very sensitive because of a relative growth of about 40%. Furthermore the first mature leaves showed long areas of soft dying tissue spread randomly, although these symptoms disappeared as the plant developed further. This was more apparent with the lower nutrient treatment and it was concluded that the nutrient status, was probably an additional limiting factor. When ⅓ strength Hoagland (replaced weekly) was used in the second sand culture trial, instead of $^{1}/_{22}$ (every second day) or $^{1}/_{8}$ strength weekly, there were no such external symptoms.

It can thus be concluded that at an EC of 278 mSm^{-1} of the growth medium ($EC_e \simeq 189$ mSm^{-1}), the total top growth of SNK 2340, and also of sorghum PAN 888 and babala (common), was not significantly influenced by the lime treated AMD water except for a significant decrease in stem masses with maize and sorghum.

b) **Sodic-saline mine water** (Mine B 3/94, EC 407 mSm^{-1}, Na 34 $mmol\ell^{-1}$, Cl 15,5 $mmol\ell^{-1}$)

The hybrid SNK 2340 exhibited no significant decrease in the vegetative growth stage, on the $Na/Cl/SO_4$ mine water. Highly significant increases of the succulence of the leaves, despite a significant *increase* in leaf area, probably points to an osmotic adaptation to salinity by this particular hybrid. There was also no influence of this water on sorghum top or root growth; in the case of babala, top growth was increased by an increase in stem mass due to earlier maturity with this water (Table 4.7, p. 94).

B. Chemical analyses of top growth

Chemical analyses were conducted on the composited material of the stems, leaves and spikes. The concentration and total uptake of nutrient elements in the total top growth of maize SNK 2340, harvested at the tasselling stage, sorghum and babala are given in Tables 4.11 and 4.12 (pp. 96 & 97) respectively.

a) **High sulphate water** (Mine A 2/94)

Analyses of the total top growth of maize hybrid SNK 2340 reveal that there are significant increases in uptake of Ca, SO_4 and Mn on this water. The N uptake was, however, significantly decreased by 0,135%.

b) **Sodic saline water** (Mine B 3/94)

Maize SNK 2340 exhibited significant increases in tissue content of K, Mg, Na, Fe and chloride. The N, P and S uptake was, however, significantly less, relative to the control.

c) **Discussion**

N

The N content was in the low range for maize (Chapman, 1966), but even though there were significant decreases of N on both waters, there were no obvious signs of deficiency except perhaps in the shorter stems. The greater decrease of N content obtained with the sodium chloride water could be due to competition between chloride and nitrate ions for uptake (Grattan & Grieve, 1993).

P

Studies with maize in solution cultures have shown that P concentrations that are optimal under non-saline conditions, could adversely affect growth of maize when grown in saline conditions (Nieman & Clark, 1976). This was, however, not the case in the current investigation for the vegetative growth stage on either the high sulphate or sodium chloride water.

S

Although the sulphate concentrations in the top-growth of maize was significantly increased with the high sulphate water, it probably did not have a direct effect on the biomass (Rennenburg, 1984)(see 2.5.2.2, p. 12). Sulphate can compete with molybdate for uptake. As molybdate is necessary for protein synthesis this could reduce growth (Barnard, 1978; Albasel & Pratt, 1989).

Ca

Sulphate salinity can reduce plant available Ca by precipitation of $CaSO_4$. The molar ratio of Ca to the sum of cations in the maize top-growth was increased from 0,12 in the control to 0,18 with the sulphate water and decreased to 0,11 with the NaCl water. Curtin *et al*. (1993) noted that reduced growth would likely occur when the molar ratio of Ca:sum of the cations in the plant tissues, fell below 0,10. The ratio of Ca to the sum of the total cations in these waters were thus high enough to prevent Ca deficiency.

Mg

Plaut and Grieve (1988) found that the photosynthetic rate and water use efficiency for maize decreased as the external Ca:Mg ratio increased. The high Ca:Mg ratio (24,6) in the lime treated AMD water did, however, not significantly affect the Mg content of the top growth of this hybrid. In contrast the significant increase in Mg uptake with the NaCl water could be due to a higher external Mg:Ca ratio. It has been found that if the exchangeable Mg:Ca ratio is > 1 the growth of maize was reduced (Key, Kurtz & Teicher, 1962). The increase of the molar ratio of Mg:Ca was from 0,4 in the control to 0,9 in the NaCl water where the top growth of maize hybrid SNK 2340 was not significantly decreased.

K

The uptake of K was not significantly influenced by the lime treated AMD water. With the sodic-saline water, however, the uptake of K was significantly increased in the top-growth of SNK 2340. This efficient uptake of potassium could be partly responsible for the tolerance of this hybrid to the sodic-saline water.

Na

The sodium content of the top growth of maize hybrid SNK 2340 was 0,63% which compares well to that found for maize in previous work (0,49 on 25 & 50 mmolℓ^{-1} NaCl and 0,69 on 100 mmolℓ^{-1} NaCl, Marschner, 1986). It is also low compared to the amounts that can accumulate in herbaceous species without showing leaf injury symptoms (Bernstein, 1964). The vegetative growth on this water was not negatively influenced. Maize has been classified as a natrophobic crop species with a low uptake potential for Na (Marschner, 1986, 1971), with a possible Na exclusion mechanism in the roots (Cramer, 1994). The effect of sprinkling with the NaCl water was not determined, but 10 to 20 $\text{mmol}\ell^{-1}$ Na or Cl is given as a guideline for susceptibility to foliar injury for maize (Tanji, 1990).

Cl

Concentration of chloride in the top growth was significantly increased with the sodic-saline water (2,75%). Toxicity concentrations of chloride range from 0,35% in sensitive species to 2,0 - 3,0% of leaf dry mass in tolerant species (Marschner, 1986). Growth was not negatively affected in the vegetative stage of hybrid SNK 2340, which thus seems to be tolerant to the chloride concentration (15,5 $\text{mmol}\ell^{-1}$) in this mine water. The threshold Cl concentration without yield loss for maize is given as 15 $\text{mmol}\ell^{-1}$ in a saturated soil extract which is ± 30 $\text{mmol}\ell^{-1}$ in the soil water at field capacity (= growth medium) (Maas, 1990) (Table 4.6, p. 93).

Micronutrients

There was a significant increase in the Mn uptake and concentration with the lime-treated AMD water, but it was still well below toxicity levels ($\text{Mn} > 1000\ \text{mgkg}^{-1}$) (Chapman, 1966); however, for soybean toxicity could be induced at only 160 mgkg^{-1} (Mengel & Kirkby, 1987). (Manganese was also added with the nutrients without which the uptake would have been less. In subsequent seedling experiments manganese was not supplemented with the high sulphate mine waters.)

The Fe uptake was significantly increased with the sodic-saline water. This is in contrast to results on maize, reported by Hassan, Drew, Knudsen and Olsen (1970) where NaCl-salinity decreased the Fe concentration in the shoots of maize. Reports on the influence of salinity on Mn, Zn and Fe are, however, inconsistent and depend, *inter alia*, on plant type, concentrations and environment (Grattan and Grieve, 1993).

4.2.1.5 Conclusion for maize, sorghum and pearl millet

The **germination** % of maize hybrids was not affected by either the sulphate or sodic-saline mine water. Some high forage producing sorghum cultivars seemed to be sensitive in very early seedling growth; and the germination of one hybrid forage millet was decreased on the sulphate water. In the **seedling growth** stage there were significant differences between some hybrids/cultivars of maize, sorghum and pearl millet on both waters, which could possibly lead to a reduced eventual grain yield. The seedlings of the hybrid forage pearl millet grew well on the $CaSO_4$ water, but that of the common variety seemed very sensitive. As the variation for pearl millet was high, however, these results should be tested by follow-up trials. Pearl millet cultivars were both very sensitive to the sodic-saline water. The total top growth in the **vegetative growth stage** of selected maize and sorghum cultivars was not depressed by either type of water, except for a decrease in stem growth (shorter stems) with the lime-treated AMD, and a significant increase in leaf area of maize with the sodic-saline waters. The common variety of pearl millet matured earlier on the sodic-saline water.

With **increasing concentrations** of **simulated sulphate mine water**, the growth of maize seedlings tended to decrease between 2300 to 2500 $mg\ell^{-1}SO_4$ in the growth medium; common pearl millet between 2000 to 3000 $mg\ell^{-1}SO_4$ and sorghum from 2300 to 3000 $mg\ell^{-1}$; at concentrations higher than this seedling growth was not suppressed any further with the simulated $CaSO_4$ water. Na_2SO_4, however, had a greater effect at the higher concentrations of SO_4.

In contrast, the seedling growth of maize, sorghum and pearl millet decreased linearly with increasing concentrations of **sodic-saline waters** with seemingly lower threshold values than with the $CaSO_4$ gradients.

The vegetative growth of these three species was not influenced greatly by the sodic-saline water used. Accumulation of salts was apparently not a major growth depressing mechanism in this more mature stage with the particular water used.

The increased tissue concentrations of Na, Cl and K in the maize hybrid, with the sodic-saline mine water, coupled with an increased leaf area and succulence, seems to indicate an osmotic adaptation by the inclusion of these inorganic ions. As could be expected the seedling growth stage of SNK 2340 proved more sensitive to the sulphate and sodic-saline water than the vegetative growth stage.

4.2.2 LEGUMES (Soybean, dry bean & cowpea)

4.2.2.1 Introduction

The majority of legumes are sensitive to soil salinity (Francois & Maas, 1994). **Soybean** has, however, been classified as moderately tolerant with a seed yield decrease starting at a threshold EC_e value of 500 mSm^{-1} (Maas & Hoffman, 1977) and 50% seed yield decrease at 900 mSm^{-1} (Bernstein, 1974). Germination % and rate of emergence decreased when the EC_e of the soil exceeded 810 mSm^{-1} (Abel & McKenzie, 1964). **Dry bean** has been classified as sensitive with a threshold EC_e value of 100 mSm^{-1} and 50% yield at 350 mSm^{-1}; and **cowpea** as moderately sensitive for forage and moderately tolerant for yield with a threshold of EC_e 160 mSm^{-1} for vegetative growth and 490 mSm^{-1} for seed yield; vegetative growth was reduced 9% and yield 12% for each 100 mSm^{-1} salinity increase. Germination was reduced when the EC in sand cultures ($\approx EC_{sw}$) exceeded 1200 mSm^{-1} (29°C) (West & Francois, 1982).

An indication of sensitivity of the seedling/early vegetative growth stage of **soybean** was found by Grattan and Maas (1984). Soybean seedlings were salinized from 10 days after planting in solution culture in a glasshouse and harvested at 32 days. Shoot yield decreased by 50% at an osmotic potential of $-0{,}38$ MPa in the growth medium (EC 1056 $mSm^{-1} = EC_e$ 528 mSm^{-1}) and root yield at $-0{,}33$ MPa (EC 917 $mSm^{-1} = EC_e$ 458 mSm^{-1}) (Grattan & Maas, 1984; Shalhevet *et al*, 1995). Comparing this value with the 900 mSm^{-1} for the seed yield, early shoot growth of soybean thus also appears to be more sensitive than the later stages.

Significant differences among cultivars have been observed for soybean (Abel and McKenzie, 1964). Sensitivity is mainly related to Cl toxicity in the shoots (Abel & McKenzie, 1964; Parker, Gascho & Gaines, 1983), with growth inhibition occurring at low levels of Cl where it is improbable that osmotic potential is a constraint (Greenway & Munns, 1980). It has been possible, however, to breed tolerant cultivars that prevent or restrict the transport of Cl to the shoots.

There has also been indications of cultivar differences in salt tolerance of **beans** for germination (some are affected at EC values of about 1000 mSm^{-1}) (Zaiter, Marroush & Nimah, 1992), for seedling growth (Zaiter & Mahfouz, 1993) and also generally (Pessarakli, 1994). Retardation of bean growth is dependent on the rate, the ultimate level and the duration of salinity. Growth is mainly suppressed through a smaller leaf area and number of leaves. The adverse effect is due mainly to a reduction in transpiration. Under constant salinity beans showed a slight adaptation to saline conditions (Meiri & Poljakoff-Mayber, 1970). Beans could also have a low capacity of discrimination for K uptake in the presence of high Na levels (Benlloch, Ojeda, Ramos & Rodriquez-Navarro, 1994).

Wignarajah (1990) found that bean plants adjusted osmotically to salt stress resulting in increased leaf water content and suggested that "two major physiological traits enable plants to tolerate salinity: (a) compensatory growth following adjustment to salinity, and (b) ability to increase both leaf area ratio (LAR) and net assimilation rate (NAR) to achieve this increased growth".

Cowpeas grow well under hot, dry conditions as well as under irrigation. Cultivar California Blackeye No 5 was found to be moderately tolerant to salinity. The vegetative stage was more sensitive to salinity than dry seed yield; the reduction of yield was mostly due to fewer pods per plant while the seed mass was not affected (West & Francois, 1982).

4.2.2.2 **Germination** (Mine C 10/94, EC 420 mSm^{-1}, Mine B 11/94, EC 590 mSm^{-1})

The germination results of the 15 soybean, 1 cowpea and 4 dry bean cultivars with the two types of mine water are given in Table 4.23 (p. 110). Germination of the soybean cultivars was not significantly influenced by the **high sulphate water**. A5409 showed a tendency to a germination decrease of 6%. Except for Hutcheson (which was infected by a fungus) there were no significant differences in germination between the different cultivars with this water. Cowpea Dr Saunders germination was significantly higher on the sulphate water relative to deionized water and dry bean germination was not affected.

The **sodic-saline water** suppressed the germination of Bakgat (by 8%), Hutcheson (16%), A2233 (11%) and A5409 (10%); cultivars did not, however, differ significantly from each other. Cowpea and dry bean germination was not affected by the sodic-saline water.

4.2.2.3 Seedling growth

A. Screening of legume cultivars

Nine recommended soybean, four dry bean and one cowpea cultivars were screened for their tolerance in the seedling stage on the actual mine waters in the glasshouse (0-18 days; 3 to 4 leaf stage). Results are presented in Table 4.24 (p. 111).

a) Sulphate mine water (Mine C 10/94, EC 420 mSm^{-1}, SO_4 2533 $mg\ell^{-1}$)

This water did not significantly affect the seedling growth of any of the **soybean** cultivars. PAN 494 produced the highest (92%) and A 7119 the lowest (77%) relative growth values; these differences were, however, not significant.

The **dry bean** cultivars grew exceptionally well on the high sulphate water; 3 dry bean cultivars were significantly increased with this water, PAN 127 being the most and PAN 122 the least tolerant.

The seedling growth of **cowpea** seemed to be sensitive and was significantly suppressed. Variation was, however, high.

b) **Sodic-saline water** (Mine B 11/94, EC 590 mSm^{-1}, Cl 35 $mmol\ell^{-1}$)

The seedling growth of **soybean** cultivars Ibis, Hutcheson and A 2233 was not significantly influenced by this water. The relative growth of the latter two, however, could have been influenced by a fungus infection. Prima, PAN 494, A 5409, Bakgat and A 7119 were significantly suppressed with this water, with a relative growth ranging from 61 to 64%. The relative seedling growth of A 2233 (102%) was significantly higher than all the cultivars except Ibis, but again the growth of A 2233 could have been influenced by the infection. Although the seedling growth of the rest of the cultivars varied from 61% (Prima) to 80% (Ibis) no significance was indicated between these cultivars.

Of the **dry beans** PAN 127 was the most tolerant and PAN 122 the most sensitive with the sodic-saline water. **Cowpea** was also relatively tolerant to this water.

B. Seedling growth on gradients of simulated mine water in a growth chamber

a) **Simulated high sulphate mine water** (Mine C 3/95 simulated)

The chemical composition of the gradients of the simulated sulphate water is presented in Table 3.2 (p. 39). The results of the seedling growth of soybean Ibis (inoculated) on the simulated sulphate gradients are presented in Table 4.25 and Figure 4.5 (pp. 112 & 113); results of dry bean PAN 122 and cowpea Dr Saunders are presented in Tables

4.27 and 4.29 (pp. 114 & 116) respectively, and in Figures 4.6 and 4.7 (pp. 115 & 117).

Soybean: Where salinity was increased mainly with **$CaSO_4$** there was an initial significant decrease in relative growth at EC 265 mSm^{-1} and SO_4 1500 $mg\ell^{-1}$, after which the relative growth increased up to an EC of 443 mSm^{-1} (4000 '$mg\ell^{-1}$' SO_4), above which growth again decreased (Figure 4.5, p. 113). Apart from the initial decrease soybeen seedling growth was, however, not significantly influenced by the $CaSO_4$ high sulphate water.

With **Na_2SO_4** the seedling growth at the 2500 and 3000 $mg\ell^{-1}$ was similar to that of the gypsum water at similar EC values. Above 4000 $mg\ell^{-1}$ with Na_2SO_4 seedling growth was significantly less than with the $CaSO_4$ treatments at similar SO_4 contents; this seems to be due mainly to an EC (osmotic) effect.

Soybean was also evaluated on these gradients without inoculation (results not given). It was interesting to note that without *Rhizobium* the seedling growth with the Na_2SO_4 was suppressed much more than when inoculated, despite a supply of NH_4 and NO_3-N (results not given). From this one could deduct that the host plant Ibis is sensitive to Na, but that this sensitivity is relieved by the *Rhizobium* symbioses. This emphasizes the importance of matching host plants with appropriate salt tolerant *Rhizobia* (Velagaleti & Schweitzer, 1994).

Dry bean seedling growth varied between 91 and 108%, with the **$CaSO_4$** salinity up to ± 440 mSm^{-1} (± 5000 '$mg\ell^{-1}$' SO_4) above which it decreased. With **Na_2SO_4** seedling growth was notably less than with $CaSO_4$. THis could be due to a lower K uptake efficiency in the presence of Na (Benlloch *et al*, 1993).

Cowpea seedling growth decreased with increasing **$CaSO_4$** salinity to about 80% at EC 364 mSm^{-1}, above which seedling growth did not decrease any further. The presence of Na as **Na_2SO_4** did not notably influence the seedling growth at similar EC's to the $CaSO_4$ (see possible mechanisms 4.6., p. 83).

b) **Simulated sodic-saline water** (Mine B 3/95 simulated)

The chemical composition of the $Na/Cl/SO_4$ gradient treatments is presented in Table 3.3 (p. 40). The results for soybean Ibis with the sodic-saline gradient are presented in Table 4.26 and Figure 4.5 (pp. 112 & 113); and for dry bean PAN 127 and cowpea Dr Saunders in Tables 4.28 and 4.30 (pp. 114 & 116), and figures 4.6 and 4.7 (pp. 115 & 117) respectively. Linear regression for soybean Ibis, cowpea Dr Saunders and dry bean PAN 127 on the simulated sodic-saline water was significant. The salt tolerance parameters calculated with these results are presented in Table 4.2 (p. 89).

Although the threshold values of soybean, dry bean and cowpea are on the sensitive side, the growth decrease is gradual. If these values are used in the equation of Maas and Hoffman (1977), a 50% decrease in seedling growth is reached at EC values of 1412, 1191 and 1011 mSm^{-1}, which are EC_e values of *ca* 703, 595 and 505 mSm^{-1} respectively.

This mine water ranged from 405 to 590 mSm^{-1}. At these salinities 50% or more seedling growth for these crops is still possible. This may be sufficient to bridge the sensitive seedling stage to the more tolerant mature growth stage in periodic drought and still produce a profitable yield as the thresholds given for yield in literature is higher than for seedling growth.

4.2.2.4 Vegetative growth stage

This growth stage was evaluated with soybean Ibis and cowpea Dr Saunders on sand culture in the glasshouse. The waters used were diluted by rain and thus not 'worst case' mine waters. Dry bean cultivar PAN 122 was evaluated separately on sand culture with a high sulphate water (Mine C 12/94) only for seed yield.

A. Growth results

The growth results for soybean Ibis and cowpea Dr Saunders are presented in Table 4.7 and 4.8 (pp. 94 & 95); the results for the influence of a high sulphate mine water on the dry seed yield of dry bean PAN 122 are presented in Table 4.10 (p. 95) and for sunflower vegetative growth in Table 4.9 (p. 95).

a) **Lime treated AMD water** (Mine A 2/94, EC 274 mSm^{-1}, SO_4 1609 $\text{mg}\ell^{-1}$)

Growth on this water was not significantly different from that of the control. **Soybean**, however, developed a white marginal chlorosis on some of the younger mature leaves after two to three weeks of salinization (Figure 4.5, p. 113). This could be a possible Mo deficiency due to sulphate competition; in the field trial where this cultivar was irrigated with a similar water, these symptoms did, however, not occur. In the field trial the seed yield of soybean Ibis was also exceptionally high with this water.

The seed yield of **dry bean** PAN 122 was significantly increased by 34% on the high sulphate water (Table 4.10, p. 95). Although the leaf area of **cowpea** decreased significantly together with an increase in succulence (a possible adaptation), the leaf mass and relative top growth was not significantly depressed.

b) **Sodic-saline water** (Mine B 3/94, EC 407 mSm^{-1}, Na 30 $\text{mmol}\ell^{-1}$, Cl 17 $\text{mmol}\ell^{-1}$)

Although the top growth of **soybean** was not significantly affected, stress was indicated by chlorosis and death of the older leaves, a significant decrease in dry root mass and leaf area. Drought stress was also indicated by the vertical angle of the leaf pinnates. The significant increase of pod dry masses with this water could partly be due to increased pod numbers (results not given).

The leaf area of **cowpea** decreased significantly with a concomitant significant increase of succulence; this was probably an osmotic adaptation that was responsible for the tolerance of this cowpea cultivar. Pod numbers were not significantly influenced at these NaCl concentrations.

B. Chemical analyses of top growth

Chemical analysis was conducted on the composited material of the total top growth for each replica. The concentrations and total uptake of nutrient elements in the total top growth of soybean and cowpea, harvested in the flowering/early pod stage are presented in Tables 4.11 and 4.12 (pp. 96 & 97) respectively.

a) **Lime treated AMD water** (Mine A 2/94)

The total N, P and K uptake of the top growth of soybean and cowpea were not influenced, while Ca, Mg, SO_4, Mn and Zn concentrations and total uptake (with the exception of Mg) were significantly increased.

b) **Sodic-saline water** (Mine B 3/94)

The K, Ca, Mg, Na and Cl contents of the top growth were significantly increased, N and P not influenced and the SO_4 and Mn contents decreased.

Although the Na (0,06%) and Cl (0,8%) content were not particularly high and the total top growth of soybean Ibis was not significantly influenced, the death and chlorosis of the older leaves are probably due to Na and/or Cl accumulation. The majority of the leaves were, however, green at harvest and did not show signs of necrosis.

It must be remembered that soybean, as the other subtropical crops in this group, are produced during the rainy summer growing season that will have a diluting effect on these waters.

4.2.2.5 Conclusion for subtropical legumes

Germination of soybeans, dry beans and cowpeas were not suppressed by the sulphate mine water; that of cowpea was stimulated. On the sodic-saline water germination of four soybean cultivars were suppressed and that of dry bean and cowpea not affected.

The **seedling growth** of soybean was not affected by the **sulphate mine waters** used. In the presence of Na, innoculation is, however, important. Drybean seedlings grew exceptionally well on an actual sulphate mine water, but at higher concentrations of $CaSO_4$ and with Na_2SO_4 seedlings were affected to a greater degree. Cowpea seemed to be sensitive to the actual sulphate mine water, but with increasing $CaSO_4$ concentrations growth was not suppressed more than 20%. With sodium sulphates the suppressing effect was greater at higher concentrations, probably due to its greater effect on osmotic potential.

On the actual **sodic-saline mine waters** the tolerance of soybean and dry bean cultivars differed. With increasing $Na/Cl/SO_4$ concentrations seedling growth was linearly suppressed for all three legume crops. The threshold values calculated all fell into the sensitive group, but at the concentrations generally found in these particular mine waters these crops could still produce a 50% yield. However, the determining factor in using this water, would be its long-term influence on the soil.

In the **vegetative growth stage** the total top growth of soybean was not suppressed by either the high sulphate or NaCl waters, but there were indications of nutrient deficiency with the sulphate and of other stress symptoms with the NaCl water. The total top growth of cowpea was not influenced by either types of water used. Dry bean grew very well on the sulphate water with a significantly increased dry seed yield.

4.2.3 SUNFLOWER

No threshold and yield decrease values for sunflower were found in the salt tolerance lists. The influence of salinity on yield is thus unknown except that sunflower has been classified as moderately tolerant (Francois & Maas, 1994).

4.2.3.1 Germination and seedling growth (Mine C 10/94, EC 420 mSm^{-1}, Mine B 7/94, EC 405 mSm^{-1})

The results of sunflower germination is presented in Table 4.31 (p. 118) and of the relative tolerance of cultivars in the seedling stage on the actual mine waters in Table 4.32 (p. 118). Seedling growth with gradients of simulated high sulphate and $Na/Cl/SO_4$ mine waters are presented in Tables 4.33 and 4.34 (pp. 119) respectively.

Nine sunflower cultivars were evaluated in the germination and seedling stage and cultivar SNK 43 with simulated mine waters in a growth chamber.

Germination was not influenced by either mine water. In the water culture evaluation of sunflower cultivars, **seedling growth** was severely affected and chlorotic with both the high sulphate and $Na/Cl/SO_4$ mine waters. **Cultivars** differed significantly, with PAN 7369 being the most tolerant on both waters; A 1006 was the most sensitive with the sulphate and PAN 7392 with the NaCl water (see Table 4.32, p. 118). However, when evaluated on sand culture both in the glasshouse and growth chamber, no chlorosis was observed for SNK 43 in the seedling stage. The phenomenon that water culture was a more severe screening method than sand culture was also found for beans (Zaiter & Mahfouz, 1993). Sunflower SNK 43 seedling growth was not significantly affected by the simulated sulphate water. The threshold for NaCl-salinity for this simulated $Na/Cl/SO_4$ mine water was 302 mSm^{-1} and the growth decrease

5,3% per 100 mSm^{-1}; 50% growth decrease is expected at an EC value of 1245 mSm^{-1} (≃ EC_e 622 mSm^{-1}) (Figure 4.8, p. 120).

4.2.3.2 **Vegetative growth** (Mine C 10/94 & 12/94, Mine B 11/94 & 12/94)

The effect of the two mine waters on sunflower growth from planting to 52 days (before flower bud appeared), was evaluated on sand culture in Mitscherlich vessels in the glasshouse. The results are presented in Table 4.9 (p. 95).

The high sulphate water increased the top growth significantly by 32% whereas the sodic-saline water did not affect the vegetative growth.[1]

4.2.3.3 Conclusion for sunflower

On sand culture sunflower SNK 43 seedlings were tolerant to the high sulphate water and grew very well in the vegetative stage. Seedling growth was also relatively tolerant to the sodic-saline water, whereas the vegetative growth was not affected.[1] There were significant cultivar differences in the seedling stage with both types of mine water when evaluated in water culture. However, seedlings grew much better in the sand compared to the water culture.

4.2.4 POTATO

Potato (*Solanum tuberosum* L.) was classified by Maas & Hoffman (1977) as moderately sensitive to salinity with tuber yield as the criterium (Table 4.1, p. 88). The average threshold was calculated as 170 mSm^{-1} and the yield decrease per 100 mSm^{-1} as 12%. Potato is, however, one of the most sensitive crops to sprinkling with saline water (Maas *et al.*, 1982).

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[1] This particular sodic-saline water (B 12/94), however, seemed to 'improve' with time probably due to the presence of a black colloidal substance that settled, leaving a supernatant solution that was not at all saline, with low Na, Cl and SO_4 contents.

Varying responses of potato cultivars have been found depending on the types of salts present in the growth medium (Bilski, Nelson & Conlon, 1988; Levy, 1992). The addition of gypsum to saline soils has increased tuber yields (Marschner, 1986).

The effect of the two types of mine water on the emergence, growth and tuber yield of four potato cultivars, **Herta**, **Buffelspoort**, **BP1** and **Up-to-date** were investigated on sand culture in Mitscherlich vessels in the glasshouse.

The material used, however, proved variable (results not given), but some tendencies were observed: the leaves of all four cultivars appeared larger with the high $CaSO_4$ water compared to the control. Flowering was also earlier for all the cultivars on the sulphate water. Although tuber growth was generally increased with the sulphate water, some of Herta and Up-to-date were malformed (this could also be due to the environmental conditions prevailing in this experiment which were not optimal for potato growth, e.g. high temperature and root zone water levels). The skin quality with this $CaSO_4$ water was, however, very noticeably improved and could be economically advantageous. Ca and Mg contents of tubers tended to increase, whereas SO_4 content was not influenced.

These results with high $CaSO_4$ water agrees with observations found by Abdullah and Ahmad (1982) that "potato yield was improved at each level of salinity amended with gypsum over non-amended saline soils".

With the sodic-saline water, tuber growth was severely depressed with tubers being small and of poor quality.

Buffelspoort stood out as the cultivar with the best emergence, the lowest variation and a significantly increased tuber yield of higher skin quality with the sulphate water. Therefore Buffelspoort (and possibly also the other cultivars under more favourable conditions) warrant further investigation, especially as potato is a crop that does very well in this region and in acid soils.

The effect of sprinkling with the saline waters was, however, not investigated, but as none of the other crops were affected by sprinkling with the sulphate water, this is also possibly true for potato.

4.3 SUBTROPICAL PERENNIALS

In this group four bermuda grass (*Cynodon dactylon*) cultivars and alkali sacaton (*Sporobolus airoides*) were evaluated for vegetative growth in sand culture in a glasshouse. Salinity was imposed after seedling establishment, at the four leaf stage and plants harvested after four weeks of salinization (28 - 56 days after emergence).

4.3.1 INTRODUCTION

Bermuda grass has long been known to exhibit significant salt tolerance differences among cultivars (Bernstein, 1964). Generally it is classified as tolerant to salinity with an average threshold of EC_e 690 mSm^{-1} and a 6,4% yield decrease per 100 mSm^{-1} (Table 4.1, p. 88). A 50% yield decrease is expected at an average EC_e value of 1800 mSm^{-1}. Tolerant varieties can be 20% more tolerant, and sensitive varieties 20% less tolerant than the average values (Bernstein, 1974).

It has been found that with Bermuda grass, increasing NaCl salinity decreased top growth linearly with a concurrent increasing root growth (Youngner & Lunt, 1967; Dudeck, Singh, Giordano, Nell & McConnell, 1983). The increased root growth can be an adaptive mechanism to saline conditions through which the water and nutrient absorbing surface is increased. "The concurrent increased root growth and decreased top growth may allow bermuda grass to survive osmotic and nutritional stresses caused by salinity" (Harivandi, Butler & Wu, 1992).

Alkali sacaton (*Sporobolus airoides*) has been estimated as tolerant to salinity (US Salinity laboratory, 1954. In: Francois and Maas, 1994), but no quantitative values were found in the general salt tolerance lists.

4.3.2 RESULTS

4.3.2.1 Growth results

The growth parameters and ratios are presented in Table 4.35 and 4.36 (pp. 121 & 122) respectively; and the chemical composition of the control and mine waters used in Table 3.1 (p. 38).

a) Lime treated AMD water (Mine A 3/94, EC 274 mSm^{-1}, SO_4 1609 mgℓ^{-1})

All bermuda grass cultivars grew just as well, or better, on the lime-treated AMD water relative to the control treatments. The top growth of Tierra Verde increased significantly and that as well as leaf area of Sahara tended to increase. With Coast Cross 2 (K11) the leaves:stems ratio increased significantly. Root growth was generally not affected by this water, except in the case of Coast Cross 2 (K11) where it tended to increase.

Alkali sacaton (*Sporobolus airoides*) also grew just as well on the lime-treated water with its root growth tending to increase. In a preliminary sand culture experiment (results not given) *Sporobolus* also exhibited healthy growth and inflorescences on a similar but more concentrated water with $^1/_6$ strength modified Hoagland No 2 (NH_4 + NO_3).

b) Sodic-saline water (Mine B 3/94, EC 407 mSm^{-1}, Na 34 mmolℓ^{-1}, Cl 15 mmolℓ^{-1})

Bermuda grass cultivars Coast Cross 2 (K11) and Sahara were tolerant to this water with no significant differences in dry masses of top growth relative to the controls. The root growth of K11 was significantly increased, indicating a possible adaptive mechanism to the NaCl salinity. The leaf:stem ratio of K11 was, however, significantly less on this water relative to the control. The cultivar Tierra Verde was also sensitive to this water with a significant growth decrease of 20%. Tierra Verde, however, proved to be the strongest grower of these cultivars with the absolute growth, though decreased, still greater than that of the tolerant K11.

Cynodon cultivar Primavera was the most sensitive to this sodic-saline water with both top and root growth very significantly decreased.

Alkali sacaton was sensitive to this water: the top growth was significantly suppressed.

4.3.2.2 Chemical analysis of top growth of bermuda grass cultivars

The concentrations of nutrient elements in the total top growth of four bermuda grass cultivars are given in Table 4.37 (p. 123). The total uptake per pot (3 plants per pot) is given in Table 4.38 (p. 124).

a) Lime treated AMD water (Mine A 2/94)

The uptake of nutrient elements was not adversely affected by this water. The increased growth of Tierra Verde and Sahara was accompanied by an increase of P in Tierra Verde and of K by Sahara; the SO_4 uptake of these two cultivars was also higher than that of K11 and Primavera where growth was not significantly affected. The tissue concentrations of Mn increased significantly for all four cultivars, but were still within acceptable levels for plant growth.

b) Sodic-saline water (Mine B 3/94)

Growth of Primavera was severely suppressed and chlorosis very apparent with this water. The P, Ca, S, Cu and Mn tissue levels were also decreased. Mg, Na and Cl levels were significantly higher than in the control.

Tierra Verde also showed a significant but much less severe growth decrease with this water. In this case the Ca uptake was less in contrast to Sahara (Ca increased) and K11 where Ca uptake was not affected. It thus seems possible that part of the tolerance of bermuda grass cultivars could be related to efficient Ca uptake.

4.3.3 CONCLUSION FOR SUBTROPICAL PERENNIALS

All four the bermuda grass cultivars can be recommended for use with lime-treated AMD water. Sahara and Tierra Verde showed increased top growth and that of Coast Cross 2 (K11) and Primavera grew just as well on this water relative to the control.

Coast Cross 2 (K11) and Sahara can also be recommended for a sodic-saline water of similar composition to that used in this evaluation. Although Tierra Verde was sensitive to the sodic-saline water with a 20% growth suppression, the absolute biomass was still comparable or higher than that of the other three cultivars with this water.

Alkali sacaton can be recommended for the lime-treated AMD water, but showed a significant decrease in top growth biomass with the sodic-saline water used.

4.4 TEMPERATE ANNUALS

The temperate annuals evaluated were wheat, rye, oats, triticale and ryegrass; barley was only studied in the germination and seedling growth stage. Wheat response to a high sulphate and a saline-sodic mine water will be discussed as an example of this crop group. As salt tolerance can be crop and cultivar specific the results of rye, oats, triticale, ryegrass and barley should be individually evaluated. General trends will, however, be pointed out as also specific responses of crops where applicable.

The salt tolerance parameters for total salt concentrations found in literature are presented in Table 4.3 (p. 90) and for Cl tolerance in Table 4.6 (p. 93).

4.4.1 INTRODUCTION

Wheat (*Triticum aestivum* L.) has been classified as moderately tolerant with both grain and shoot dry mass as criteria. The average EC_e value at which grain yield starts to decrease has been calculated as 600 mSm^{-1} with a 7,1% yield decrease for every 100 mSm^{-1} increase in salinity; for forage these values are lower, i.e. 450 mSm^{-1} and 2,6% (Maas & Hoffman, 1977; Francois & Maas, 1994).

The tolerance of a semi-dwarf cultivar (Probred) was found to be higher with a threshold of 860 mSm^{-1} and a 3,0% yield decrease per 100 mSm^{-1} with grain yield as criterium (Francois, Maas, Donovan and Youngs, 1986).

As with other cereals the germination of wheat can be delayed by salinity but with full emergence occurring (Maas and Poss, 1989). The seedling and vegetative stages are the most sensitive, also affecting yield by a decreased seed number through its influence on spike differentiation (Maas & Poss, 1989). Generally the sensitivity of wheat as of other cereals decreases with age (Francois & Maas, 1994; Maas & Poss, 1989). 50% grain yield decrease was found at EC_e 1400 mSm^{-1} (Bernstein, 1964, 1974). The maximum Cl that can be tolerated by wheat without yield loss is given as 60 $\text{mmol}\ell^{-1}$ Cl in the saturated soil extract with a 0,7% yield decrease per $\text{mmol}\ell^{-1}$ Cl (Maas, 1990). This would be comparable to *ca* 120 $\text{mmol}\ell^{-1}$ in the growth medium. The Cl concentration in the sodic-saline mine water used for wheat was 26 $\text{mmol}\ell^{-1}$ and is far below that which wheat can tolerate. The chloride in these mine waters varied between 15 to 35 $\text{mmol}\ell^{-1}$ and should thus not create problems for wheat.

4.4.2 GERMINATION

The results of the influence of the two types of mine waters (Mine C 3/95; Mine B 3/95) on germination % of different wheat cultivars are given in Table 4.43 (p. 129); and that of oats and barley in Table 4.47 (p. 132), triticale in Table 4.53 (p. 137) and rye and ryegrass in Table 4.57 (p. 142).

Generally both waters did not significantly affect germination except a 16% decrease for Rye SSR 1 with the sodic-saline water. This could, however, have been partly due to the seed possibly having aged.

4.4.3 SEEDLING GROWTH

A. Screening of cultivars (Mine C 3/95, EC 394 mSm^{-1}, SO_4 2248 $\text{mg}\ell^{-1}$;
Mine B 3/95, EC 534 mSm^{-1}, Na 40 $\text{mmol}\ell^{-1}$,
Cl 26 $\text{mmol}\ell^{-1}$)

The seedling growth results of wheat cultivars are presented in Table 4.44 (p. 129).

The data for oats and barley, triticale, rye and ryegrass are given in Tables 4.48, 4.54 and 4.57 (pp. 132, 137 & 142) respectively.

The high sulphate water did not affect seedling growth significantly in 6 of the 7 cultivars evaluated. The NaCl mine water suppressed the seedling growth of all the cultivars significantly, ranging from a relative growth of 42% for SST 822 to 61% for Marico.

There were few significant cultivar differences with the sulphate water. SST 882 was the most sensitive to this water and Inia the most tolerant. With the NaCl salinity SST 822 was also the most sensitive.

Growth observations of the seedlings, however, indicated a possible toxic NH_4 effect on the control plants (EC 153 mSm^{-1}, 30 $mg\ell^{-1}$ NH_4 and 207 $mg\ell^{-1}$ NO_3). Especially the first emerging leaf of some cultivars was bronze coloured. Growth on the sulphate water was healthy and showed no signs of bronzing or chlorosis. The apparent relative growth %'s could thus be higher due to possible suppressed growth of the controls. The wheat cultivars were subsequently rescreened with half the NH_4 and an equivalent increase in NO_3-N (results not given). In this case the controls were a healthy green and the top growth dry masses generally higher than with the higher NH_4 (except for SST 822). It was, however, very notable that with the lower NH_4, the seedlings on the SO_4 water were generally very chlorotic in contrast to the healthy green seedlings of the previous evaluation. It thus seems possible that N uptake/assimilation was not sufficient with the high sulphate water despite the increased NO_3 concentration. This could possibly result from competition between NO_3 and SO_4 anions, which seems to be remedied by the higher NH_4 in the first screening. The only cultivar that did not follow this response was SST 822 where the absolute growth of the control was depressed with less NH_4. SST 822 is a cultivar that is sensitive to water stress and also responds more to increasing N (personal communication, SENSAKO). This could explain the response to the saline waters: growth could be suppressed more due to water availability (osmotic potential); and competition of either SO_4 or Cl with NO_3 in N-nutrition. In practice this could mean that when irrigating wheat with high sulphate or NaCl water the inclusion of NH_4 for N-fertilization could be advantageous for most cultivars.

B. Seedling growth on gradients of two types of simulated mine waters in a growth chamber

a) Simulated high sulphate mine water (Mine C 3/95 simulated)

The chemical composition of the gradient treatments are given in Table 3.2 (p. 39). The results of the seedling growth of wheat cultivar Inia with the sulphate gradients are given in Table 4.45 and Figure 4.9 (pp. 130 & 131); and of oats, barley, triticale, rye and ryegrass, in Tables 4.49, 4.51, 4.55, 4.59 and 4.61 (pp. 133, 135, 138, 143 & 145 respectively); and Figures 4.10 to 4.15 (pp. 134, 136, 139, 141, 144 & 146 respectively).

In the range where salinity was increased mainly with $CaSO_4$ there were gradual but not significant decreases of relative seedling growth from 1500 to 2300 $\text{mg}\ell^{-1}$ total sulphate in the growth medium. Above this value the general trend was that the depression stayed between 86 and 100% relative growth up to 6000 '$\text{mg}\ell^{-1}$' total SO_4 in the system (Figure 4.9, p. 131). Oats and barley (Figures 4.10 and 4.11, pp. 134 & 136) followed this same trend whereas with triticale and rye the seedling growth started to gradually decrease above 4000 and 5000 '$\text{mg}\ell^{-1}$' SO_4 in the system, respectively. This was probably due to increased clogging of the pores by undissolved or precipitated $CaSO_4$ and can possibly be an indication of sensitivity of root growth to such conditions.

Both ryegrass cultivars showed an almost inverse reaction to the $CaSO_4$ gradient than the other temperate annuals: a general increase in seedling growth up to 3000 $\text{mg}\ell^{-1}$ SO_4 for Midmar and 4000 $\text{mg}\ell^{-1}$ SO_4 for Dargle (Figure 4.15, p. 146). Above these concentrations there was an initial decrease and then levelling off of seedling growth to *ca.* 110% for Midmar and *ca.* 120% for Dargle. This could be due to the genetic make-up of these two cultivars which were probably bred for acid soils, and thus grows exceptionally well on a neutral water?

Where salinity was achieved with Na_2SO_4, the growth decrease of wheat seemed to be linear with increasing EC, but very gradually up to 5000 $\text{mg}\ell^{-1}$ SO_4. Triticale Rex and ryegrass shows the same tendency whereas the increase of EC with Na_2SO_4 seems to have very little or no influence on seedling growth of oats and barley up to 5000 $mg\ell^{-1}$ SO_4 or EC 755 - 782 mSm^{-1} (Figures 4.9, 4.10 and 4.11, pp. 131, 134 & 136).

b) Sodic-saline water

The seedling growth of Inia wheat with the sodic-saline gradient is presented in Table 4.46 and Figure 4.9 (pp. 130 & 131); and for oats, barley, triticale, rye and ryegrass in Tables 4.50, 4.52, 4.56, 4.60 and 4.61 (pp. 133, 135, 140, 143 & 145) and Figures 4.10, 4.11, 4.13, 4.14 and 4.16 respectively (pp. 134, 136, 141, 144 & 148).

On this $Na/Cl/SO_4$ gradient all the temperate annuals responded with linear growth curves. Regression was significant for wheat Inia, oats Overberg, ryegrass Midmar, barley Stirling, triticale Rex and rye SSR1; although also linear, the regression of triticale Cloc 1 was not significant indicating a high tolerance to these waters.

The threshold and yield decrease values calculated by the best fitting options of the SALT computer programme, are given in Table 4.4 (p. 91).

The temperate annuals that were the most tolerant to the sodic-saline water in the seedling growth stage were triticale Cloc1, barley Stirling and triticale Rex; their threshold values are the highest and yield decrease values the lowest. Rye SSR1, wheat Inia, ryegrass Midmar and oats follow in order of tolerance, with oats being the most sensitive (threshold 182 mSm^{-1} with the highest growth decrease %). (Overberg was probably bred for a winter rainfall area.) The EC values of the growth medium where a 50% growth decrease is expected (lowest for oats, 840 mSm^{-1}) is still well above the general salinity values of these mine waters. It must, however, be kept in mind that with this particular water the $Cl:SO_4$ ratios can differ markedly and that the Cl concentration (e.g. higher chloride and lower SO_4) could be a growth limiting factor; generally, however, herbaceous crops can tolerate these Cl concentrations.

It can thus be concluded that, barring soil factors, these temperate annual crop cultivars could grow with reasonable success at their most sensitive stage with this type of Na/Cl/SO_4 sodic-saline mine waters.

The important question, however, still remains what this type of water would do to soil physical and nutrient properties.

4.4.4 VEGETATIVE GROWTH

The growth parameters and growth ratios for the annual temperate crop species with the mine waters on water culture in the glasshouse are respectively given in Tables 4.39 and 4.40 (pp. 125 & 126). The chemical composition of the mine waters and controls used are presented in Table 3.1 (p. 38).

4.4.4.1 Growth results

a) **Lime treated AMD water** (Mine A 5/94, EC 274 mSm^{-1}, SO_4 998 $mg\ell^{-1}$)

Growth of both the wheat cultivars Inia and the cultivar bred as a "nursecrop" for mine spoils appeared normal and more luxuriant than on the control. There were no significant influences on any of the growth parameters or ratios for wheat Inia; only a tendency to a decreased root dry mass. The nursecrop produced significant increases in most of the growth parameters except for root dry mass. Growth ratios were unchanged with this cultivar.

The annual temperate crops produced very few significant effects on either growth parameters or ratios. The notable exception was **rye SSR1** where lime treated AMD water had a significant beneficial effect on total top growth, the mass of roots and leaves produced, and the top growth:root ratio. Lime treated water produced 24% more leaf material and 26% more top growth than the control nutrient solution. This treatment also improved the leaf yield of **oats** and the leaf:stem ratio of **ryegrass** Midmar, both aspects of importance where these crops are used as forages. **Triticale** was not significantly influenced in any way although most growth parameters seemed to improve on this lime treated AMD water.

b) **Sodic-saline mine water** (Mine B 4/94, EC 407 mSm^{-1},
Na 30 $\text{mmol}\ell^{-1}$, Cl 17 $\text{mmol}\ell^{-1}$,
SO_4 610 $\text{mg}\ell^{-1}$)

The growth parameters and ratios of **wheat** Inia were not greatly influenced by this water. The leaf dry mass tended to increase, and the roots to decrease. Tiller numbers were increased significantly for both the wheat cultivars as well as oats, but without a concomitant increase in tiller dry mass (thinner stems).

It seems that **rye SSR1**, **triticale Cloc1** and **ryegrass** Midmar adapted osmotically to this water, as in these cases, leaf dry mass, leaf area or succulence were influenced to a greater or lesser degree without relative growth %'s being significantly influenced.

Although still maintaining a top growth of 83%, **oats** seemed the most sensitive of these winter annuals to the sodic-saline water as the leaf, top growth and root dry masses were significantly suppressed. This coincides with its sensitivity to this water in the seedling growth stage.

4.4.4.2 Chemical analyses of top growth

Chemical analyses were conducted on the composited replicates of the leaves and stems respectively. Analyses were conducted only for Ca, Mg, SO_4, Na and Cl. The concentration of these nutrient elements are given in Table 4.41 and the total uptake per pot (3 plants) in Table 4.42 (pp. 127 & 128 respectively).

a) **Lime treated AMD water** (Mine A 5/94)

As in the case of subtropical species there was an increased uptake of Ca; concentrations ranged from 1,28% in oats to 3,17% in the wheat nursecrop for leaves and 0,67% in stems of wheat Inia to 1,86% in the nursecrop; it also increased in the young ears of wheat Inia. This compares well with the average Ca content of plants (Marschner, 1986). As Ca is a non-toxic mineral nutrient, also at high concentrations, and can also detoxify high concentrations of other mineral elements (Marschner, 1986) this can be a positive attribute of this water.

In contrast to the subtropical annuals the Mg uptake was decreased to about ½ that of the control in rye, oats, triticale and wheat Inia and apparently not greatly influenced in ryegrass and the wheat nursecrop. The concentrations ranged from 0,02% in wheat leaves to 0,09% in rye (controls 0,04 to 0,13%) which is low compared to the average 0,5% of the dry mass of the vegetative parts for optimal plant growth (Marschner, 1986).

S uptake was increased in both the leaves and stems; the SO_4 concentration in the leaves increased by 0,5 to 1,0% ranging from 1,92% in ryegrass to 2,24% in rye; this is higher than the critical requirement of cool season grasses of 0,2 to 0,26% (Martin and Walker, 1966), but these levels should not be detrimental to plant growth (See 2.5.2.2, p. 12).

Ruminant-animal health problems have been associated with high S intake (Mayland & Robbins, 1994) which is usually associated with high SO_4 in drinking water, but the S or SO_4 ingested from forage could be an additive factor and should also be taken into account when calculating the amount of S ingested. This is especially applicable when animal drinking water also contains high amounts of SO_4 (Mayland and Robbins, 1994).

b) **Sodic-saline mine water** (Mine B 4/94)

The total Ca-uptake per pot did not seem to differ from the control except for the wheat nursecrop where Ca content was increased indicating an efficient Ca uptake of this cultivar.

The Mg and SO_4 uptake was generally not influenced by the composition of this water. The Na and Cl uptake was least for wheat Inia and high for oats Overberg. This corresponds with a tolerance of Inia and a sensitivity of oats for NaCl water (Table 4.42, p. 128). The Cl content was the least for the two wheat species, which could be due to exclusion from the shoots. Ryegrass seems to be unaffected by the high concentrations of Na and Cl in the top growth.

4.4.5 CONCLUSION FOR TEMPERATE ANNUALS

The temperate annuals were generally more tolerant to both types of mine water than the subtropical annuals. Germination of most cultivars was not influenced by either the sulphate or sodic-saline mine water. Exceptions were odd cultivars of oats (sulphate salinity) and rye with the sodic-saline waters.

The seedling growth of the temperate annuals was more tolerant to the sulphate water than the subtropicals except for one sensitive wheat and one triticale cultivar. Wheat seedlings were, however, less sensitive to the sulphate water when N was partly supplied as NH_4. On the sodic-saline water temperate annuals were more tolerant than the subtropicals. Significant cultivar differences were generally between the most tolerant and sensitive cultivars. Oats was the only crop where one of the cultivars was sensitive to this particular sodic-saline water used (which was, however, not very concentrated due to heavy rain).

Although oats was sensitive to sodic-saline waters (lowest threshold) at low concentrations of the actual mine water, the seedling growth of all the cultivars grew the best of all the temperate annual crops.

4.5 TEMPERATE PERENNIALS

The winter perennials lucerne (*Medicago sativa* L.) Pan 4860, tall fescue (*Festuca elatior* L.) Au Triumph, crown vetch (*Coronilla varia*) Penngift, cocksfoot (*Dactylis glomerata* L.) Hera, and white clover (*Trifolium repens* L.) Dusi were evaluated for their vegetative growth in water culture in the glasshouse. This material was analysed for nutrient and salt uptake. Lucerne cultivars were also screened in the seedling stage in the glasshouse, and lucerne PAN 4860 seedling growth evaluated on the sulphate and sodic-saline gradients, and will thus be discussed more fully. The chemical composition of the mine waters used are presented in Table 3.1 (p. 38).

4.5.1 INTRODUCTION

Lucerne was classified by Maas and Hoffman (1977) as a moderately sensitive crop with a threshold of 200 mSm^{-1} and a slope of 7,3% per 100 mSm^{-1}. A 50% yield decrease is expected at 800 mSm^{-1} (Bernstein, 1974). Lucerne is more sensitive to salt at germination and in young seedlings than at later growth stages. Cultivars differ in their capacity to germinate under saline conditions, and can also vary in tolerance at later growth stages (Noble, Halloran & West, 1984). Tolerance can be correlated with chloride exclusion from the shoots and/or the level of chloride tolerated by the shoots before leaf damage is evident.

4.5.2 GERMINATION (Mine C 3/95, EC 394 mSm^{-1}, SO_4 2248 $mg\ell^{-1}$; Mine B 3/95, EC 534 mSm^{-1}, Na 40, Cl 26 $mmol\ell^{-1}$)

The germination was not suppressed on the high sulphate mine water, except for Topaz that tended to a decrease by 11%. On the sodic-saline water the germination of only Diamond was significantly depressed by 12% (Table 4.67, p. 153).

4.5.3 SEEDLING GROWTH

4.5.3.1 Screening of cultivars (Mine C 3/95, EC 394 mSm^{-1}, SO_4 2248 mgℓ^{-1}; Mine B 3/95, EC 534 mSm^{-1}, Cl 26 mmolℓ^{-1})

The cultivars PAN 4860, PAN 4581, Baronet, Topaz and Diamond were compared on the two types of mine water in the seedling growth stage. The results are presented in Table 4.68 (p. 153).

Seedling growth was depressed on both waters. On the high sulphate water Diamond was the most tolerant (76%) and was significantly higher than the most sensitive PAN 4580 (55%), but did not differ significantly from the other cultivars.

Growth was severely restricted and chlorotic on the sodic-saline water and all cultivars responded in a similar way. The Cl concentration of the mine water was above that of the Cl threshold given for lucerne (Table 4.6, p. 93).

4.5.3.2 Seedling growth on gradients of two types of mine water in a growth chamber

a) **Simulated high sulphate mine water** (Mine C 3/95 simulated)

The chemical composition of the gradient treatments are given in Table 3.2 (p. 39). The results for lucerne PAN 4860 are given in Table 4.69 and Figure 4.17 (pp. 154 & 155).

In the range where salinity was achieved mainly with $CaSO_4$ the relative seedling growth decreased significantly above a total sulphate content of 2150 up to 3000 mgℓ^{-1} (EC $>$ 381 to 436 mSm^{-1}); when the total SO_4 was above 3000 up to 5000 mgℓ^{-1} growth increased despite an increasing EC of the growth medium; as was the case with the temperate annuals growth again decreased when the total SO_4 exceeded 5000 'mgℓ^{-1}' (clogging of pores?) (Figure 4.17, p. 155).

Where salinity was obtained with Na_2SO_4, growth seemed to decrease linearly with increasing SO_4. Due to the greater solubility of Na_2SO_4 the EC increases in this case were greater. The decrease of growth seems to correlate with the increasing EC values (Figure 4.17, p. 155).

b) **Saline-sodic water** (Mine B 3/95 simulated)

The chemical composition of the gradient treatments are given in Table 3.3 (p. 40) and the results in Table 4.70 (p. 154). Growth decreased linearly with increasing $Na/Cl/SO_4$ content with a first significant decrease at EC 286 mSm^{-1} and NaCl 10 $mmol\ell^{-1}$ (Figure 4.17, p. 155). The threshold value calculated by the SALT programme was EC 170 mSm^{-1} and 6,6% growth decrease per 100 mSm^{-1} which is lower than the average threshold for lucerne (Table 4.4, p. 91). A 50% shoot dry mass decrease can be expected at 757 mSm^{-1}. This cultivar may thus be more sensitive to Cl than the average cultivars.

Lucerne is thus more sensitive to the NaCl than the $CaSO_4$ salinity: growth decreased significantly at a lower EC value (286 mSm^{-1}) with NaCl than with the SO_4 salinity (338 mSm^{-1}). Cl can be toxic to lucerne from 40 $mmol\ell^{-1}$ in the growth medium (Maas, 1990). The growth decline here at the lower Cl concentrations is thus probably caused by other mechanisms. When the seedling growth on $CaSO_4$, Na_2SO_4 and NaCl salinity was simultaneously plotted against the estimated osmotic potential values, the latter seemed to be the main growth inhibiting mechanism for lucerne (Figure 4.17, p. 155).

4.5.4 VEGETATIVE GROWTH OF TEMPERATE PERENNIALS

Growth responses of the perennial temperate forage species with the two mine waters are presented in Tables 4.63 and 4.64 (pp. 149 & 150). The concentration and total uptake of Ca, Mg, SO_4, Na and Cl are presented in Tables 4.65 and 4.66 (pp. 151 & 152) respectively.

a) **Lime treated AMD water** (Mine A 5/94, EC 274 mSm^{-1}, 998 mgℓ^{-1} SO_4)

Lucerne and **white clover** grew exceptionally well on this water. Lucerne leaf, stem and root masses increased significantly (there were, however, a few 'cupped' leaves with a thin marginal necrosis); the total top growth of **white clover** increased, which was mostly due to higher stem masses. The top growth dry mass of **tall fescue** tended to increase and the leaf area was very significantly increased with this water but without a concomitant increase in dry mass; the leaves were markedly wider than those of the control.

Crown vetch and **cocksfoot** showed no significant growth increases with this water. The leaf to stem ratio, however, increased significantly for crown vetch and decreased for cocksfoot. Cocksfoot also tended to an increased top:root ratio.

b) **Growth on saline-sodic water** (Mine B 4/94, EC 407 mSm^{-1}, Na 30, Cl 17 mmolℓ^{-1})

Lucerne top growth was not significantly affected by this water; the root dry mass was, however, significantly less and the succulence of the leaves increased. This indicates a possible osmotic adaptation to salinity. The Na content (2,01%) of leaves was the highest of these perennials. The upright angles of some leaves at harvest, however, indicated a drought stress effect and leaves also showed some signs of interveinal chlorosis. The Cl concentration of the growth medium was, however, below the threshold value of 40 mmolℓ^{-1} Cl for lucerne in the growth medium (Table 4.6, p. 93).

Tall fescue grew exceptionally well on the saline-sodic water with a highly significant increase in top growth leaf dry mass, and leaf area; the stem mass was also increased significantly, probably due to the significant increase of stem numbers. Root growth was unaffected with a resultant increase in top:root ratio. The threshold for Tall Fescue, a moderately tolerant crop, calculated by Maas and Hoffman (1977) is an EC_e of 390 mSm^{-1} with a 5,3% yield decrease. The EC of this water was 407 mSm^{-1}; the increased growth of tall fescue Au Triumph could be an indication that this cultivar is more tolerant than the average tall fescue cultivars. Tall fescue is relatively tolerant to Cl with a threshold of 80 mmolℓ^{-1} Cl in the growth medium (Table 4.6, p. 93).

The top growth dry mass of **Cocksfoot** Hera was not affected, but there was a decrease in root growth and stem number (not so the stem mass - stems stronger), resulting in a significant increase in top:root ratio. There was, however, a marked number of dead leaves with this water, and also a number of leaves halfway necrotic, which indicates a salt sensitivity through accumulated salt in the older leaves.

The sodic-saline water very significantly decreased all growth parameters of **crown vetch** Penngift and **white clover** Dusi.

4.5.5 CONCLUSION FOR TEMPERATE PERENNIALS

On the **high sulphate mine water** the germination % of one out of the five **lucerne** cultivars was suppressed. Although lucerne cultivars were sensitive to the sulphate water in the seedling stage, the growth should still be enough to survive to the less sensitive vegetative growth stage. Lucerne PAN 4860 grew exceptionally well in the vegetative stage at EC 274 mSm^{-} ($EC_e \simeq 137\ mSm^{-1}$) which was to be expected as the general threshold for lucerne is an EC_e of 200 mSm^{-1}. This was confirmed by the field trial.

White clover Dusi and **tall fescue** Au Triumph also grew exceptionally well on the lime treated AMD water in the vegetative growth stage. **Crown Vetch** Penngift and **cocksfoot** Hera also showed no growth suppression by this water. The increased leaf to stem ratio of crown vetch could be advantageous in its use as a forage. With cocksfoot the decreased leaf to root ratio as well as suppressed root growth could be an indication of a sensitivity to this water.

On the **sodic-saline water** the germination % of one **lucerne** cultivar was decreased. Seedling growth of all lucerne cultivars was very sensitive to the NaCl mine water. In the vegetative stage lucerne growth was, however, not significantly reduced by the actual sodic-saline mine water, where the Cl concentration was below that of lucerne's threshold Cl value. There were, however, signs of stress which might increase in intensity with repeated cuttings, especially because the root growth of lucerne was significantly suppressed by this water.

Tall fescue Au Triumph grew exceptionally well on the sodic-saline water with increases in all top growth parameters. This specific cultivar seems to be more tolerant to NaCl salinity than the average tall fescue cultivars. Although the top growth of **cocksfoot** Hera was not significantly suppressed, there was 50% necroses in the older leaves which indicates an increasing sensitivity by accumulation of salts with age. **Crown vetch** Penngift and **white clover** Dusi were very sensitive to this sodic-saline mine water.

4.6 POSSIBLE MECHANISMS BY WHICH THE SALINITY OF DIFFERENT MINE WATERS INFLUENCED CROP SEEDLING GROWTH

This study was not designed to determine the mechanisms by which the different saline mine waters influenced growth; however, a knowledge of these mechanisms could give some guidelines for crop growth modelling. Therefore, in an attempt to form an idea of the mechanisms involved, the relative seedling growth on the gradients of $CaSO_4$, Na_2SO_4 and NaCl salinities was plotted simultaneously against estimated osmotic potential values (Tables 3.2 and 3.3, pp. 39 & 40).

These influences on growth can be due to one or more of the following mechanisms:

(a) decreasing osmotic potential (a decrease in the availability of water due to increases in salt concentration) together with the genetic potential of osmotic adaptation to salinity,

(b) toxicity of specific ions, especially of Na and Cl, and

(c) SO_4 nutrient effects which could either suppress growth by SO_4 competition with NO_3 or MoO_4 for uptake and thus N-nutrition, or by a positive S-nutritional effect. The latter could be more applicable to legumes that have a greater S requirement than other crops (Pasricha & Fox, 1993).

From the plots mainly mechanisms (a) and (c) seemed to be active with these waters: **Firstly**, there were crops where the **decreasing osmotic potential** generally seemed to be the main growth inhibiting mechanism for all three types of salinity: this could possibly be the case with lucerne PAN 4860 (Figure 4.17, p. 155), oats Overberg (Figure 4.10, p. 134), common pearl millet (babala) (Figure 4.4, p. 109), wheat Inia (Figure 4.9, p. 131), cowpea Dr Saunders (Figure 4.7, p. 117) and possibly also sorghum PAN 888 (Figure 4.3, p. 107).

Decreasing osmotic potential may further be a contributing mechanism for NaCl and Na_2SO_4 salinity for soybean Ibis, sorghum PAN 888 and dry bean (Figures 4.5, p. 113; 4.3, p. 107 & 4.6, p. 115 respectively); and for NaCl salinity for sunflower and ryegrass (Figures 4.8, p. 120 & 4.16, p. 148).

Secondly, growth decreases could also be due to **specific ion effects** of Na and/or Cl; Na could *inter alia* influence K uptake and Cl can inhibit growth at low levels, "where a water deficit is not a constraint. Many legumes belong to this group" (Marschner, 1986). Maas (1990) lists threshold values of Cl for some crops above which growth decreases (Table 4.6, p. 115); according to these values it is improbable that Cl toxicity is active with these waters in most of the crops evaluated. The higher Cl concentrations may, however, have been detrimental to maize (Figure 4.2, p. 103), dry beans (Figure 4.6, p. 115) and lucerne growth (Figure 4.17, p. 155).

The maximum Cl concentration that the other crops could tolerate without a yield reduction is generally higher than the Cl in the actual (15 to 35 $\mathrm{mmol}\ell^{-1}$ Cl in the growth medium) or simulated (0 to 54 $\mathrm{mmol}\ell^{-1}$ Cl) mine waters.

The thresholds given by Maas (1990) is, however, for yield losses in the mature growth stage. It must be kept in mind that the current study was conducted in the seedling growth stage. There was only one crop, namely dry bean where NaCl salinity could possibly have had a toxic effect, but even here it is more probably due to decreasing osmotic potential as seedling growth responds in a similar way to both the NaCl and Na_2SO_4 salinity (Figure 4.6, p. 115).

In some cases the presence of Na and/or Cl (especially at the lower concentrations evaluated) could also stimulate growth and tolerance due to its possible role in osmotic adaptation (e.g. as in barley Stirling, Figure 4.11, p. 136).

Thirdly, high sulphate (especially the $CaSO_4$ treatments) could have had nutrient effects on growth - either negative or positive. Much more SO_4 than NaCl is needed to achieve a specific osmotic potential; with some crops SO_4 had a greater suppressing effect on seedling growth than NaCl at similar osmotic potentials. This could be due to competition of SO_4 with NO_3 or MoO_4 uptake thus influencing nitrogen nutrition; this seemed to be the case for rye SSR 1 (Figure 4.14, p. 144) and sorghum PAN 888 (Figure 4.3, p. 107). (In the case of sorghum, however, the simulated $CaSO_4$ treatments contained no Na and the weaker seedling growth may also be due to a lack of Na for osmotic adaptation, as Na_2SO_4 and NaCl gave rise to similar seedling growth at similar osmotic potentials). This suppressing effect of SO_4 on N nutrition could also be partly responsible for reducing seedling growth of maize SNK 2340 and triticale (Figures 4.2, p. 103 & 4.13, p. 141).

In some cases increasing sulphate ($CaSO_4$) concentrations seemed to stimulate seedling growth despite decreasing osmotic potentials (high total salt concentrations). Soybean Ibis (Figure 4.5, p. 113), dry bean PAN 122 (Figure 4.6, p. 115) and perhaps cowpea (Figure 4.7, p. 117) seemed to partly respond in this way; also triticale Rex (Figure 4.13, p. 141) and ryegrass Dargle (Figure 4.16, p. 148).

The different responses of the crops to the different types of saline mine waters again illustrates the uniqueness of each species in its salt tolerance. One should, however, remember that these responses were for seedling growth (0-21 days) and that other mechanisms could be active in the following phenological growth stages. This could either be negative such as the effect of increasing accumulation of salts in the leaves, or positive when the plant adapts increasingly to the saline root environment.

4.7 GENERAL CONCLUSION

Generally **germination** of most cultivars of both the subtropical and temperate annual crops was not influenced by either the high sulphate or sodic-saline mine water. There were, however, exceptions where germination of the odd cultivar of sorghum, pearl millet and soybean was suppressed with the sulphate salinity, the same being true for soybean and lucerne with the sodic-saline water. Germination was influenced more where there were fungus infections, e.g. with some soybean and oats cultivars. With some cultivars of triticale and sorghum there seemed to be a sensitivity of very early seedling growth with the radicle dying after about one centimeter's growth. Where seed had possibly aged (> 2 years) germination was affected to a greater extent by NaCl salinity.

Germination should, however, not be a problem if these crops are irrigated with these waters; where it was suppressed, it ranged from 5 to 12%, which could be compensated for by sowing more densely.

Seedling growth on the actual 'worst case' mine waters showed that the subtropical cereal crops exhibited more cultivar differences and sensitivity to the neutral high sulphate water than the legumes. Soybean and dry bean grew exceptionally well on the **sulphate water**. Generally the seedling growth of the annual temperate crops was more tolerant to the sulphate water than that of the subtropicals except for one sensitive wheat and one triticale cultivar. Wheat seedling growth was less sensitive to the sulphate water when N was partly supplied as NH_4. Lucerne cultivars were generally sensitive to the sulphate mine water, with the relative seedling growth of cultivars ranging from 55 to 76%.

There is thus a relatively wide choice of cultivars that should be able to successfully bridge the sensitive seedling stage by irrigation with sulphate-saline waters originating from coal mines in the Highveld region.

On the **sodic-saline** 'worst case', actual mine water the seedling growth of the annual cereal crops was generally suppressed; again the subtropicals were influenced to a greater extent than the temperate annuals. Cultivar differences were generally limited to differences between the most tolerant and the most sensitive cultivar. Oats seedling growth was exceptional in that none of the cultivars were sensitive to this particular concentration of sodic-saline water. All lucerne cultivars were very sensitive. The relative growth of soybean, dry bean and cowpea seedlings was generally less suppressed than that of the subtropical cereals, with some cultivar differences, where soybean Ibis and dry bean PAN 127 stood out as the most tolerant.

The choice of cultivars to be grown under irrigation with the sodic-saline mine waters is limited. There are, however, some cultivars (except for lucerne) that should be tolerant enough to grow successfully in the sensitive seedling growth stage.

With **increasing sulphate concentrations** of a simulated sulphate mine water there was a general tendency for seedling growth to be increasingly suppressed to a point usually somewhere between 2000 and 3000 mgℓ^{-1} SO_4. In the treatments where the gypsum was not dissolved or started precipitating, the seedling growth either increased or did not decrease any further. Where salinity was, however, due to increasing Na_2SO_4 content, seedling growth was generally increasingly suppressed.

With **increasing Na/Cl/SO_4 concentrations**, simulating a sodic-saline mine water, seedling growth generally decreased in a linear fashion according to the Maas & Hoffman (1977) theory.

The **vegetative growth** of both the subtropical and temperate annuals was mostly not suppressed by the specific lime treated AMD and sodic-saline mine waters used. The vegetative growth of bermuda grass cultivars, a subtropical perennial species, was tolerant to the lime treated AMD water, but cultivars differed significantly with the sodic-saline water. It must, however, be stressed that the concentration of the mine waters used for the vegetative growth stage was not very high due to dilution by good rains.

The vegetative growth of the temperate perennial forage crops was tolerant to the lime treated AMD water; lucerne grew exceptionally well. With the sodic-saline mine water lucerne, tall fescue and cocksfoot were also tolerant, but crown vetch and white clover were very sensitive.

When extrapolating these results to field conditions it should be kept in mind that salt tolerance varies for different growth stages and is dependent on a multitude of soil, climatic and other factors. Tolerance found in the seedling and vegetative growth stages is not always a reliable guide for predicting seed or grain yields. To use results for field conditions it should be taken into account that the EC of the growth medium, as used in this report, can be roughly equated to the mean seasonal EC of the *soil water* in the root zone where maximum water uptake occurs. Furthermore, although the subtropical crops tended to be more sensitive to salinity, in this area they are grown in the rainy summer season that can have a diluting effect and reduce the need for supplementary irrigation except for periodic drought conditions. It is also advantageous that the generally more tolerant temperate crops are grown in the dry winter season when irrigation would be profitable.

SALT TOLERANCE PARAMETERS

TABLE 4.1 Salt tolerance parameters for subtropical annuals and perennials found in literature

Crop Common name	Botanical name	Criteria	Threshold EC$_e$ mSm^{-1}	Slope % yield decrease /100 mSm^{-1}	Rating[1]	EC$_e$ at which yield decrease expected[2] mSm^{-1}			Reference
						10%	25%	50%	
Maize	*Zea mays* L.	Ear FM	170	12	MS			590	Maas, 1980
Maize (forage)		Shoot DM	180	7.4	MS				Francois & Maas, 1994
Maize		Grain	170	12	MS	500	600	700	Maas & Hoffman, 1977
Maize (sweetcorn)		Ear FM	170	12	MS				Bernstein, 1974
Sorghum	*Sorghum bicolor* (L.) Moench	grain	680	16	MT			(992)	Francois & Maas, 1994
	Sorghum vulgare					600	900	1200	Bernstein 1974
Sudan grass (forage)	*Sorghum sudanense* (Piper) Stapf.	Shoot DM	280	4.3	MT			(1442)	Maas, 1986
Soybean	*Glycine max* (L.) Merrill	Seed yield	500	20	MT			(750)	Maas & Hoffman, 1977
						550	700	900	Bernstein, 1974
Cowpea (forage)	*Vigna unguiculata* (L.) Walp.	Vegetative growth	160	9					West & Francois, 1982
Cowpea (yield)		Shoot DM	250	11	MS				Maas, 1990
		Seed yield	490	12	MT				Maas, 1986
Bean	*Phaseolus vulgaris* L.	Seed/pods	100	19	S				Maas & Hoffman, 1977
Bean (field bean)		Seed/pods				150	200	350	Bernstein, 1974
		Greenbeans				150	200	350	Bernstein, 1974
Sunflower	*Helianthus annuus* L.	Seed			MT				Francois & Maas, 1994
Potato	*Solanum tuberosum* L.	Tuber yield	170	12	MS				Francois & Maas, 1994
						250	400	600	Bernstein, 1974
Bermuda grass (forage)	*Cynodon dactylon* L.	Shoot DM	690	6.4	T				Maas & Hoffman, 1977
						1300	1600	1800	Bernstein, 1974
Alkali sacaton	*Sporobolus airoides* Torr.	Shoot DM			(T)				Francois & Maas, 1994

[1] S sensitive MS moderately sensitive MT moderately tolerant T tolerant (see 2.5.4.2, p. 24).

[2] This data does not include the germination and early seedling stage (Bernstein, 1974).

[3] Brackets: calculated with Maas & Hoffman function (p. 23).

TABLE 4.2 **Salt tolerance parameters for seedling growth stage of annual subtropical crops with a simulated sodic-saline mine water calculated by the SALT computer programme**

Crop	Salt tolerance parameters				
	Threshold mSm^{-1}		Growth decrease per 100 mSm^{-1} %	EC at which 50% growth decrease expected mSm^{-1}	
	EC	~EC$_e$		EC	~EC$_e$
Maize SNK 2340	205	103	5.1	1185	593
Maize SNK 2042	230	115	8.2	840	420
Sorghum PAN 888	240	120	6.6	998	499
Pearl millet (babala) common	223	112	9.4	755	378
Soybean Ibis	162	81	4.0	1412	706
Cowpea Dr Saunders	230	115	6.4	1011	506
Bean PAN 127	80	40	4.5	1191	596
Sunflower SNK 43	302	151	5.3	1245	623

Ch4-Tab4.02

TABLE 4.3 Salt tolerance parameters for annual temperate crops

Common name	Botanical name	Criteria	Threshold EC_e mSm^{-1}	Slope % yield decrease per 100 mSm^{-1}	Rating[1]	EC_e at which yield decrease expected mSm^{-1}			Reference
						10%	25%	50%	
Wheat	*Triticum aestivum* L.	Grain	600	7.1	MT	700	1000	1400	Maas & Hoffman, 1977 Bernstein, 1974
Wheat (semidwarf)	*Triticum aestivum* L.	Grain	860	3.0	T				Francois & Maas, 1994
Wheat (forage)	*Triticum aestivum* L.	Shoot DM	450	2.6	MT				Francois & Maas, 1994
Rye	*Secale cereale* L.	Grain	1140	10.8	T				Francois & Maas, 1994
Rye (forage)	*Secale cereale* L.	Shoot DM	760	4.9	T				Francois & Maas, 1994
Oats	*Avena sativa* L.	Grain	-	-	T				Francois & Maas, 1994
Oats (forage)	*Avena sativa* L.	Straw DM	-	-	T				Francois & Maas, 1994
Triticale	x *Triticosecale* Wittmack	Grain	610	2.5	T				Francois & Maas, 1994
Ryegrass (Italian)	*Lolium italicum multiflorum* Lam.	Shoot DM	-	-	MT				Maas & Hoffman, 1977
Ryegrass (perennial)	Lolium perenne L.	Shoot DM	560	7.6	MT	800	1000	1300	Bernstein, 1974
Barley	*Hordeum vulgare* L.	Grain	800	5.0	T	1200	1600	1800	Maas & Hoffman, 1977
Barley (forage)	*Hordeum vulgare* L.	Shoot DM	600	7.1	MT	800	1100	1380	Bernstein, 1974

[1] S sensitive MS moderately sensitive MT moderately tolerant T tolerant (see 2.5.4.2, p. 24)

TABLE 4.4 Salt tolerance parameters for seedling growth of annual temperate cereal crops with a simulated sodic-saline mine water calculated by the SALT computer programme

Crop	Salt tolerance parameters				
	Threshold mSm^{-1}		Growth decrease per 100 mSm^{-1} %	EC at which 50% growth decrease expected mSm^{-1}	
	EC	$\sim EC_e$		EC	$\sim EC_e$
Wheat Inia	313	156	3.1	1925	963
Rye SSR 1	339	169	6.1	1072	536
Oats Overberg	182	91	7.6	840	420
Triticale Cloc 1	500	250	3.0	1782	891
Triticale Rex	286	143	3.9	1568	784
Ryegrass Midmar	240	120	6.6	998	499
Barley Stirling	569	284	4.3	1731	865
Lucerne	170	85	6.6	757	379

Ch4-Tab4.04

TABLE 4.5 Salt tolerance parameters for temperate perennial crops

Common Name	Botanical name	Criteria	Threshold EC_e mSm^{-1}	Slope % Yield decrease /100 mSm^{-1}	EC_e at which yield decrease expected mSm^{-1}			Rating[1]	Reference
					10%	25%	50%		
Lucerne (alfalfa)	*Medicago sativa* L.	Shoot DM	200	7.3	300	500	800	MS	Maas & Hoffman, 1977 Bernstein, 1974
Tall fescue	*Festuca elatior* L.	Shoot DM	390	5.3	700	1050	14500	MT	Maas & Hoffman, 1977 Bernstein, 1974
Cocksfoot (Orchard grass)	*Dactylis glomerata* L.	Shoot DM	150	6.2	250	450	800	MS	Maas & Hoffman, 1977 Bernstein, 1974
White clover (Dutch)	*Trifolium repens* L.	Shoot DM						MS	Francois & Maas, 1994
Clover, ladino	*Trifolium repens* L.	Shoot DM	150	12				MS	Francois & Maas, 1994

[1] S sensitive MS moderately sensitive MT moderately tolerant T tolerant (see 2.5.4.2, p. 25)

Ch4 Tab4.05

TABLE 4.6 Chloride tolerance of some agricultural crops (Adapted from Maas, 1990)[1]

Crop	Threshold Maximum Cl in saturated soil extract from rootzone, without yield loss $\text{mmol}\ell^{-1}$	Threshold Maximum Cl in soil water at field capacity[2] ~ $\text{mmol}\ell^{-1}$	% Decrease in yield at Cl concentrations above the threshold $\%/\text{mmol}\ell^{-1}$
SUBTROPICAL CROPS			
Maize	15	30	1.2
Sorghum	70	140	1.6
Sudan grass	30	60	0.4
Bean	10[3]	20	1.9
Potato	15	30	1.2
Cowpea	50	100	1.2
Bermuda grass	70	140	0.6
TEMPERATE CROPS			
Wheat[4]	60	120	0.7
Barley[4]	80	160	0.5
Barley (forage)[4]	60	120	0.7
Tall fescue	40	80	0.5
Clover, ladino (*Trifolium repens* L.)	15	30	1.2
Lucerne	20	40	0.7
Cocksfoot (Orchard grass)	15	30	0.6
Ryegrass, perennial	55	110	0.8

[1] These data only serve as a guideline to relative crop tolerances. Absolute tolerance varies according to climate, soil and cultural factors.

[2] Estimated values for soil water; this value is roughly comparable to the concentrations of the growth medium in the current evaluations.

[3] Wignaraja (1989) found a threshold of 48 $\text{mmol}\ell^{-1}$ NaCl.

[4] Less tolerant during emergence and seedling stage.

1. SUBTROPICAL ANNUALS

Vegetative Growth

Table 4.7 Growth parameters for subtropical annuals in the vegetative growth stage

Crop	Treatment	Dry mass top growth g				Dry mass roots	Leaf Area
		Stems	Leaves	Pods/ spikes	Total	g	cm^2
Maize *Zea mays* SNK 2340	Control	47.64	41.26	3.92	92.81	26.45	8764
	Mine A	38.17**	39.00	3.51	80.68*	26.16	8571
	Mine B	46.29	43.70	4.45	94.43	29.77	9811**
c.v. %		13.08	7.13	25.72	9.54	13.62	5.75
Sorghum hybrid PAN 888	Control	55.18	18.92	6.53	80.63	23.68	4872
	Mine A	51.84**	19.34	6.85	78.03	23.80	4980
	Mine B	54.34	19.91	6.31	80.55	21.87	5345
c.v. %		3.72	6.83	17.69	3.19	7.53	8.50
Soybean *Glycine max* Ibis	Control	16.40	17.15	4.89	38.43	8.66	6158
	Mine A	16.36	16.75	4.67	37.78	7.11*	6318
	Mine B	15.05	16.61	7.09***	38.75	6.72**	5523*
c.v. %		15.60	9.33	16.24	9.09	15.68	7.33
Pearl millet *Pennisetum glaucum* common (babala)	Control	33.67	17.55	5.58	56.79	16.75	4229
	Mine A	31.27	17.32	6.50	55.09	15.96	3881
	Mine B	44.11**	18.23	9.48	72.05***[1]	14.00	4281
c.v. %		12.85	16.82	59.15	9.61	15.02	12.47
Cowpea *Vigna unguiculata* Dr Saunders	Control	38.14	20.40	3.81	62.35	6.09	7606
	Mine A	34.33	19.58	4.14	58.04	6.89	6331***
	Mine B	35.73	21.34	4.50	61.56	6.70	6238***
c.v. %		10.84	9.95	16.93	9.38	17.64	5.39

*	Tends to significant difference from control ($P<0.10$)
**	Significant difference from control ($P<0.05$)
***	Highly significant difference from control ($P<0.01$)

Mine A 2/94
Mine B 3/94

[1] This increase was due to earlier maturity of pearl millet on this water.

TABLE 4.8 Growth ratios of subtropical annuals in the vegetative growth stage

Species	Treatment	Water % in top growth	Succulence mg H_2O/cm^3 leaves	Leaves/ Stems	Top growth/ Roots	Relative growth %	
						Leaves	Top growth
Maize *Zea mays* SNK 2340	Control	83.91	16.69	0.87	3.59	100	100
	Mine A	84.08	17.36	1.03**	3.09	94.52	86.93*
	Mine B	85.77***	18.75***	0.96	3.18	105.91	101.43
Sorghum hybrid PAN 888	Control	79.70	13.44	0.34	3.41	100	100
	Mine A	79.32	12.83	0.37	3.28	102.22	96.78
	Mine B	80.73	13.54	0.37	3.71	105.23	99.90
Soybean *Glycine max* Ibis	Control	79.40	9.90	1.06	4.52	100	100
	Mine A	80.13	10.28	1.03	5.35	97.67	98.33
	Mine B	79.34	10.39	1.11	5.82**	96.85	100.83
Pearl millet *Pennisetum glaucum* common (babala)	Control	81.36	22.27	0.53	3.40	100	100
	Mine A	82.71	21.88	0.56	3.49	98.69	97.01
	Mine B	81.05	21.15*	0.41	5.23***	103.87	126.87***
Cowpea *Vigna unguiculata* Dr Saunders	Control	83.46	17.96	0.53	10.34	100	100
	Mine A	83.44	19.17**	0.57	8.50***	95.98	93.09
	Mine B	84.11	20.22***	0.61	9.53	104.60	98.73

Mine A 2/94 Mine B 3/94

TABLE 4.9 The influence of two mine waters on the vegetative top growth of sunflower cultivar SNK 43

Cultivar	Dry mass of topgrowth g/pot			Relative growth %		c.v. %
	Control	Mine C	Mine B	Mine C	Mine B[1]	
SNK 43	41.85	55.38	43.50	132**	103	5.2

Mine C 10/94; Mine B 7/94 & 11/94

[1] See 4.2.3.2, p. 63

TABLE 4.10 The influence of two mine waters on the yield of dry bean PAN 122

Cultivar	Yield (65°C) g/pot		Relative yield %	c.v.
	Control	Mine C	Mine C	%
PAN 122	34.17	45.71**	134*	26.7

Mine C 12/94

* Tends to significant difference from control ($P<0.10$)
** Significant difference from control ($P<0.05$)
*** Highly significant difference from control ($P<0.01$)

TABLE 4.11 Concentration of nutrient elements in the top growth of subtropical annuals with two mine waters in the vegetative growth stage

Species	Treatment	N	P	K	Ca	Mg	Na	Sulphate	Cl	Fe	Mn	Cu	Zn
		%								mg kg^{-1}			
Maize *Zea mays* SNK 2340	Control	0.955	0.145	0.983	0.173	0.138	0.00	0.813	0.072	18	45	3	6
	Mine A	0.820*	0.140	1.183	0.337*	0.163	0.00	1.080*	0.158	21	131*	2	12*
	Mine B	0.688*	0.118*	1.178	0.213	0.323*	0.63*	0.210*	2.752*	35*	30*	3	3
	c.v. %	7.01	6.92	12.27	12.59	12.51	30.00	14.45	20.0	50.78	9.17	42.42	34.62
Sorghum hybrid PAN 888	Control	1.088	0.145	0.855	0.213	0.165	0.00	0.965	0.079	30	89	6	13
	Mine A	0.943	0.140	1.123*	0.370*	0.250*	0.00	1.428*	0.144	51	221*	6	25*
	Mine B	1.100	0.155	1.033*	0.283*	0.443*	0.058*	0.240*	2.634*	59*	33*	5	11
	c.v. %	13.09	9.64	7.64	9.21	10.67	45.18	12.27	4.41	48	8.03	25.53	17.89
Soybean *Glycine max* Ibis	Control	2.23	0.263	1.648	0.703	0.330	0.00	1.410	0.077	68	188	8	29
	Mine A	2.46	0.293	1.868	1.493*	0.408*	0.00	2.565*	0.122	77	316*	8	52*
	Mine B	2.29	0.308	1.995*	1.263*	0.625*	0.058*	0.518*	0.800*	75	99*	6	26
	c.v. %	14.01	9.15	11.58	4.31	6.47	66.79	4.99	10.96	12.81	6.64	17.00	10.85
Pearl millet *Pennisetum glaucum* common (Babala)	Control	1.298	0.208	1.525	0.243	0.268	0.00	1.405	0.088	47	128	4	17
	Mine A	1.258	0.215	1.763	0.383*	0.435*	0.10*	1.755*	0.180	41	350*	4	33*
	Mine B	1.178	0.193	1.595	0.218	0.423*	0.24*	0.385*	2.12*	31*	55*	4	11
	c.v. %	20.65	14.03	17.24	22.34	16.45	27.84	11.22	16.64	31.70	20.96	19.76	36.69
Cowpea *Vigna unguiculata* Dr Saunders	Control	2.523	0.198	1.425	0.685	0.235	0.00	1.613	0.077	71	302	5	21
	Mine A	3.235*	0.215	1.428	1.143*	0.308*	0.00	2.205*	0.134*	72	486*	2*	37*
	Mine B	3.060	0.193	1.490	1.048*	0.465*	0.255*	0.973*	0.866*	67	132*	4	12*
	c.v. %	12.40	9.71	9.59	18.01	9.76	19.61	7.87	9.52	18.65	16.22	15.38	18.96

* Significant difference from control ($P < 0.05$)

Ch4 Tab4.11

TABLE 4.12 Total uptake of nutrients in the top growth of subtropical annuals with two mine waters in the vegetative growth stage

Crop	Treatment	N	P	K	Ca	Mg	Na	Sulphate	Chloride	Fe	Mn	Cu	Zn
		g/pot								mg/pot			
Maize *Zea mays* SNK 2340	Control	0.884	0.135	0.909	0.159	0.127	0.00	0.748	0.067	1.63	4.17	0.24	0.58
	Mine A	0.662*	0.113*	0.940	0.270*	0.132	0.00	0.869*	0.127	1.68	10.57*	0.18	0.97
	Mine B	0.648*	0.111*	1.105*	0.199	0.303*	0.591*	0.196*	2.580*	3.18*	2.78	0.24	0.24
Sorghum hybrid PAN 888	Control	0.877	0.117	0.689	0.171	0.133	0.00	0.777	0.063	2.39	7.12	0.51	1.07
	Mine A	0.733	0.109	0.875	0.289*	0.195*	0.00	1.113*	0.112	3.38	17.25*	0.44	1.96*
	Mine B	0.889	0.125	0.831	0.228*	0.356*	0.046*	0.193*	2.121*	4.78*	2.69*	0.39*	0.85
Soybean *Glycine max* Ibis	Control	0.861	0.101	0.624	0.269	0.126	0.00	0.543	0.031	2.61	7.26	0.32	1.08
	Mine A	0.928	0.110	0.705	0.564*	0.154	0.00	0.969*	0.046	2.90	11.94*	0.30	1.97*
	Mine B	0.882	0.118	0.768	0.488*	0.241*	0.022	0.198*	0.308*	2.92	3.85*	0.25	1.01
Pearl millet *Pennisetum glaucum* common (Babala)	Control	0.742	0.117	0.857	0.135	0.150	0.00	0.786	0.049	2.56	7.19	0.23	0.94
	Mine A	0.699	0.119	0.978	0.210*	0.241*	0.056*	0.969*	0.100	2.26	19.40*	0.21	0.84
	Mine B	0.843	0.138*	1.144*	0.157	0.305*	0.170*	0.277*	1.525*	2.22	3.96*	0.30	0.82
Cowpea *Vigna unguiculata* Dr Saunders	Control	1.577	0.123	0.883	0.423	0.146	0.00	1.002	0.048	4.40	18.62	0.28	1.33
	Mine A	1.875	0.125	0.828	0.663*	0.178	0.00	1.280*	0.077	4.18	28.21*	0.09*	2.15*
	Mine B	1.868	0.117	0.913	0.633*	0.283*	0.159*	0.598*	0.531*	4.12	8.12*	0.23	0.75

* Significant difference from control ($P < 0.05$)

Ch4-Tab4.12

MAIZE

Germination and Seedling Growth

TABLE 4.13 The influence of two mine waters on the germination percentage of maize hybrids

Hybrids	Germination %			Relative germination %		c.v. %
	Deionised water	Mine A	Mine B	Mine A	Mine B	
MAIZE						
SNK 2042	100	100	100	100	100	0
SNK 2888	100	100	100	100	100	0
SNK 2266	100	100	98	100	98	1.7
SNK 2151	100	100	100	100	100	0
SNK 2665	100	100	99	100	100	0.8
PAN 6480	99	100	100	101	101	0.8
PAN 6364	100	100	100	100	100	0
PAN 6552	100	100	100	100	100	0
PAN 6363	100	100	100	100	100	0
PAN 6549	97	100*	99	103*	102	1.9
PAN 6479	100	98	100	98	100	1.7
CRN 3816	100	100	100	100	100	-[1]
CRN 3414	100	100	98	100	98	-
CRN 3818	100	100	99	100	99	-
CRN 3631	99	98	100	99	101	-
CRN 4403	100	100	100	100	100	-
CRN 4523	98	100	100	102	102	-
SNK 2340[2]	94	94	93	100	99	-

c.v. 1.09 %

* Tending to significant difference from control ($P < 0.1$)

Mine A 7/94

Mine B 7/94

1. The CRN hybrids could not be statistically analysed as there was only enough seed for one replicate.
2. This hybrid (SNK 2340) was evaluated with more concentrated water from Mine C (10/94) 2 533 $\text{mg}\ell^{-1}$ sulphate and Mine B (11/94) 52 mmol ℓ^{-1} Na, 35 mmol ℓ^{-1} Cl and 1 135 $\text{mg}\ell^{-1}$ sulphate.

TABLE 4.14 The influence of two types of mine water on the growth of maize hybrid seedlings

Maize Hybrids	Dry mass of top growth per 10 plants (g)			c.v. %	Relative growth %	
	Control	Mine A	Mine B		Mine A	Mine B
SNK 2042	3.99	3.19	3.08**	13.9	80 bc	77 a
SNK 2888	4.26	3.62	2.76**	16.3	85 abc	65 ab
SNK 2266	4.43	3.45**	2.81**	10.3	78 bc	63 ab
SNK 2151	3.87	2.59**	2.14**	20.8	69 c	55 ab
SNK 2665	4.32	3.11**	2.21**	13.9	73 c	51 ab
PAN 6480	3.09	2.48	2.30*	12.9	80 abc	74 ab
PAN 6364	4.14	3.76	2.37**	20.1	94 abc	57 ab
PAN 6552	3.23	2.25**	1.84**	13.0	70 c	57 ab
PAN 6363	3.65	3.03	1.78**	7.1	83 abc	49 b
PAN 6549	3.11	2.21**	1.77**	13.2	71 c	57 ab
PAN 6479	2.98	2.38	1.91**	11.2	80 abc	64 ab
CRN 3816	2.43	2.17	1.57**	8.8	90 abc	65 ab
CRN 3414	2.00	1.71	1.37	12.1	85 abc	69 ab
CRN 3818	2.37	2.21	1.55*	13.0	95 abc	65 ab
CRN 3631	3.25	3.59	1.93**	18.6	110 ab	59 ab
CRN 4403	4.16	4.66	2.35**	14.7	113 a	56 ab
CRN 4523	3.91	3.54	2.07**	7.3	91 abc	53 ab
SNK 2340[1]	2.30	1.73**	1.33*	13.7	75 –	58 –
c.v. %	14.6				18.7	20.6
LSD$_T$					33	26

* Tending to significant difference from control ($P < 0.1$)
** Significant difference from control ($P < 0.05$)
Mine A 7/94
Mine B 7/94

[1] This hybrid was not included with Mine A water, but was evaluated with the Sorghums on more concentrated waters: Mine C water (10/94) EC 402 mSm^{-1}; 2533 $mg\ell^{-1}$ sulphate and Mine B (11/94) EC 590 mSm^{-1}, 52 $mmol\ \ell^{-1}$ Na, 35 $mmol\ \ell^{-1}$ Cl and 1135 $mg\ell^{-1}$ sulphate, (Table 3.1).

TABLE 4.15 **The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of maize seedlings (Figure 4.1, p. 101)**

Maize Hybrid	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
		EC_w[2] mSm^{-1}	Sulphate[3] mg ℓ^{-1}	g	%
SNK 2340	1.	95	226	2.05	100
	2.	265	1500	1.94	95
	3.	321	2000	1.88	92
	4.	337	2150	1.89	93
	5.	362	2300	1.59**	78 **
	6.	364	2500	1.59**	78 **
	7.	398	3000	1.89	92
	8.	443	4000	1.99	97
	9.	429	5000	1.48**	72 **
	10.	517	6000	1.77	86
	11.	356	2500	1.48**	73 **
	12.	435	3000	1.77	86
	13.	587	4000	1.38**	67 **
	14.	736	5000	1.38**	67 **

c.v. 13.3%

CRN 4403	1.	104	226	2.29	100
	2.	300	1500	2.34	102
	3.	361	2000	2.19	96
	4.	381	2150	2.42	106
	5.	412	2300	2.06	90 *
	6.	400	2500	2.30	101
	7.	436	3000	2.44	107
	8.	460	4000	2.34	102
	9.	523	5000	2.16	94
	10.	432	2500	2.61**	114 **
	11.	512	3000	2.52*	110 *
	12.	678	4000	2.08*	91 *
	13.	840	5000	2.09	91

c.v. 7.6%

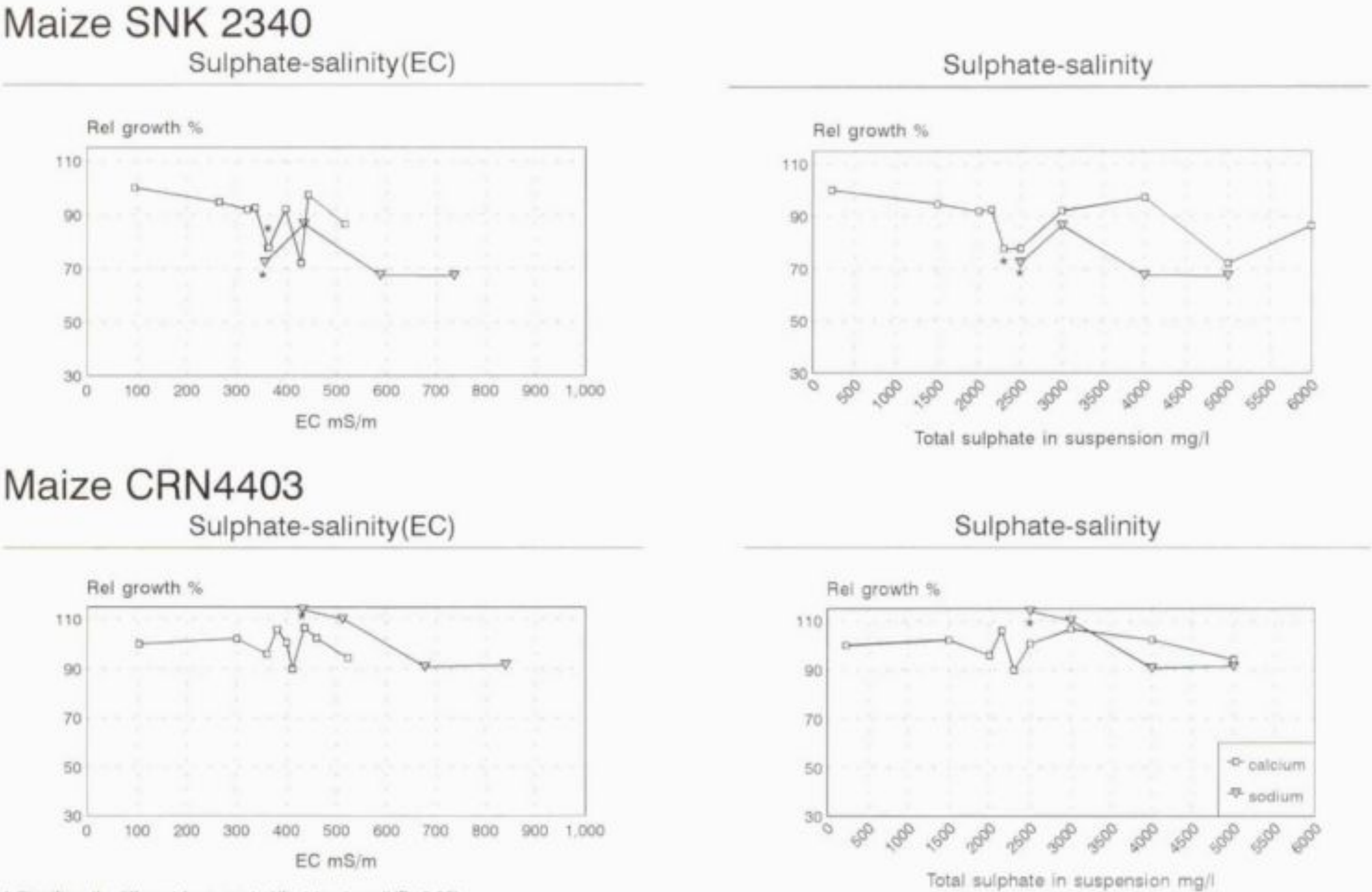
* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

[1] Treatment 1-10 and 1-9 salinity with mainly $CaSO_4$; 11-14 and 10-13 with added Na_2SO_4.

[2] EC electrical conductance measured in supernatant of treatment solutions.

[3] Total sulphate in suspension.



* Significantly different from control(first treatment)(P<0.05)

Legend:Ca=salinity increased mainly with gypsum;Na=salinity mainly increased withNa-sulphate

FIGURE 4.1 **The influence of increasing concentrations of a simulated high sulphate mine water on the seedling growth (0-18 days) of maize hybrids SNK 2340 (top) and CRN 4403 in a growth chamber (25°C day/15°C night)**

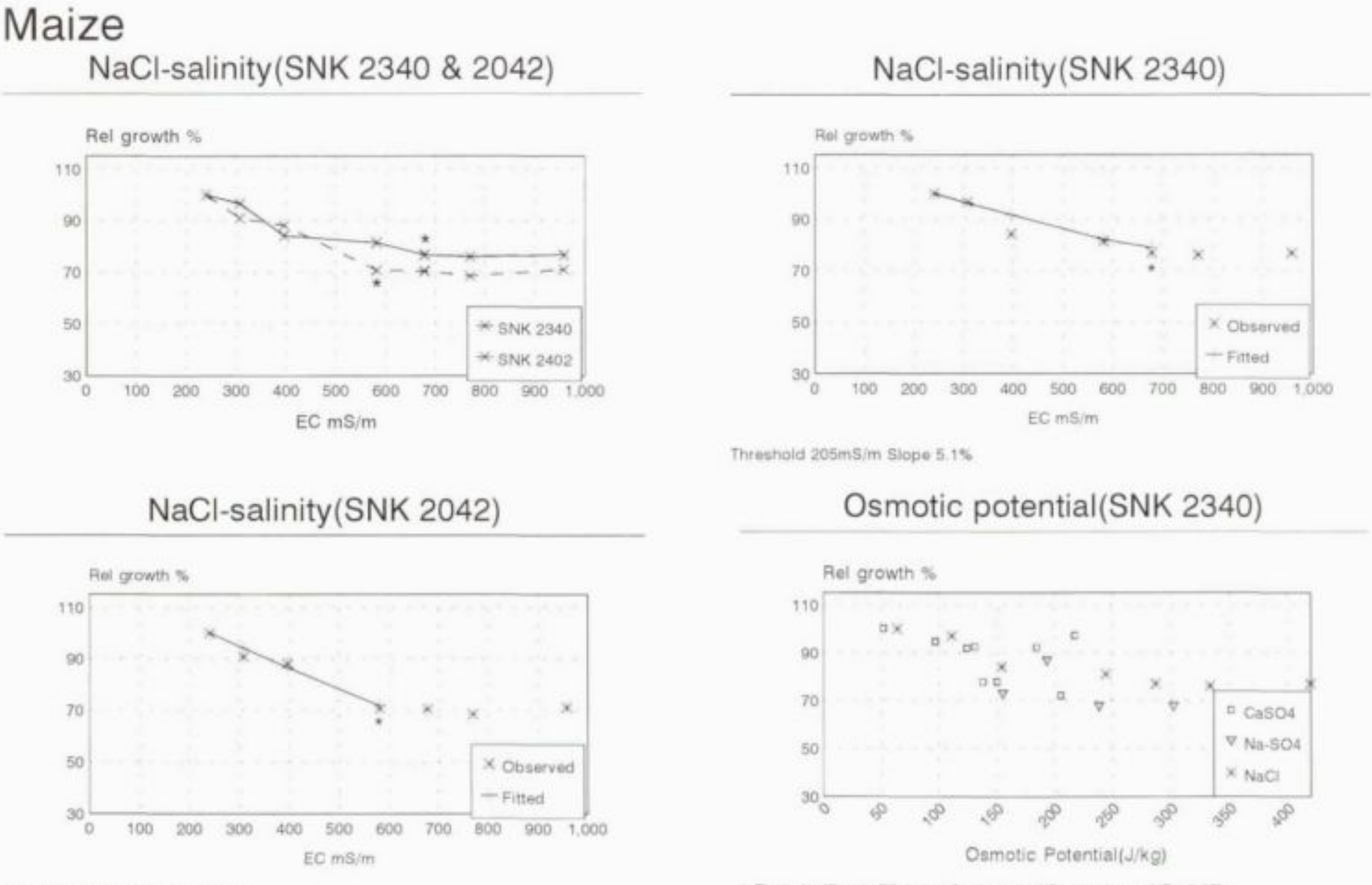
TABLE 4.16 **The influence of a gradient of a simulated sodic-saline mine water on the top growth of maize seedlings (Figure 4.2, p. 103)**

Hybrid	Treatment				Dry mass of top growth/ 10 plants	Relative Growth
	EC[1] mSm^{-1}	Na	Cl	SO_4		
		mmolℓ^{-1}			g	%
SNK 2340	1. 241	0	0	12	3.39	100
	2. 308	10	10	12	3.28	97
	3. 396	20	16	13.8	2.85**	84**
	4. 581	40	29	17.5	2.76**	81**
	5. 678	50	35	19.3	2.60**	77**
	6. 770	60	42	21.1	2.58**	76**
	7. 958	80	54	24.8	2.60**	77**
c.v. 8.07%						
LSD$_5$					0.34	
SNK 2042	1. 241	0	0	12	2.89	100
	2. 308	10	10	12	2.63	91
	3. 396	20	16	13.8	2.55*	88*
	4. 581	40	29	17.5	2.04**	71**
	5. 678	50	35	19.3	2.04**	70**
	6. 770	60	42	21.1	1.98**	68**
	7. 958	80	54	24.8	2.06**	71**
c.v. 10.01%						

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

[1] EC electrical conductance measured in supernatant of treatment solutions.



Threshold 205mS/m Slope 5.1%

Threshold 230mS/m slope 8.2%

* First significant difference from control(first treatment)(P<0.05)

FIGURE 4.2 The influence of increasing concentrations of Na/Cl/SO_4 in a simulated sodic-saline mine water on the seedling growth of maize hybrids SNK 2340 and SNK 2042 in a growth chamber (25°C day/15°C night)

SORGHUM
PEARL MILLET

Germination and Seedling Growth

TABLE 4.17 The influence of two mine waters on the germination percentage[1] of sorghum and pearl millet cultivars

Cultivars	Germination %			c.v. %	Relative germination %	
	Deionised water	Mine C	Mine B		Mine C	Mine B
SORGHUM						
1. SNK 3860	93	93	93	2.2	100	100
2. SNK 3939	97	97	94	2.1	100	97
3. SENFOR[1]	80	84	92**	5.8	105	115**
4. SENTOP[1]	97	91*	92	3.1	94*	95
5. SNK 3000	88	91	95	6.6	103	108
6. PAN 8494	88	85	83	4.4	97	94
7. PAN 8501	93	90	91	4.4	97	98
8. PAN 8522	89	91	88	3.5	102	99
9. PAN 8564	99	98	98	1.9	99	99
10. PAN 8591	98	98	98	1.9	100	100
11. NK 283	96	92	94	5.1	96	98
12. PAN 888	99	98	98	1.9	99	99
13. CRN 776W	95	98	92	2.3	103	97
14. CRN 7686[1]	82	80	74**	10.7	98	90**
PEARL MILLET						
PAN 911	95	85**	98	3.8	89**	103
Common	91	92	92	4.6	101	101

cv 4.3%

* Tending to significant difference from control ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

Mine C 10/94.

Mine B 11/94.

[1] This includes seedlings that died after the radicle grew to 1-2 cm; more apparent with control for SENFOR and sodic-saline water for CRN 7686.

TABLE 4.18 The influence of two types of mine water on the seedling growth of sorghum and pearl millet cultivars

Cultivars	Dry mass of top growth/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
SORGHUM						
SNK 3860	1.11	0.64**	0.37**	9.5	58 cd	33 cd
SNK 3939	0.79	0.70	0.37**	14.3	81abc	43abc
SENFOR	0.71	0.57	0.33**	16.2	82abc	47abc
SENTOP	0.97	0.66**	0.47**	8.8	68bcd	48abc
SNK 3000	0.75	0.59	0.36**	25.6	83abc	51abc
PAN 8494	0.67	0.44**	0.36**	14.7	66bcd	55 ab
PAN 8501	0.83	0.55**	0.32**	6.8	66bcd	38bcd
PAN 8522	0.58	0.56	0.32**	13.5	97abc	54 ab
PAN 8564	0.73	0.69	0.36**	5.0	95abc	50abc
PAN 8591	0.89	0.82	0.47**	6.5	92abc	52abc
NK 283	0.90	0.87	0.50**	12.5	99abc	55 ab
PAN 888	0.45	0.47	0.23**	10.7	104abc	52abc
CRN 776W	0.73	0.72	0.34**	12.0	98abc	47abc
CRN 7686	0.61	0.62	0.32**	19.0	105 ab	48abc
PEARL MILLET						
PAN 911	0.51	0.61	0.11**	31.5	120 a	22 d
Common	0.82	0.26**	0.32**	23.4	32 d	39abcd
c.v. %	15.7				26.6	19.8
LSD$_T$					47	19

* Tendency to differ from control ($P < 0.1$)
** Significant difference from control ($P < 0.05$)
Mine C 10/94.
Mine B 11/94.

TABLE 4.19 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of sorghum PAN 888 (Figure 4.3, p. 107)

Cultivars	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
		EC[2] mSm^{-1}	Sulphate[3] mg ℓ^{-1}	g	%
PAN 888	1.	104	226	1.39	100
	2.	300	1500	1.33	96
	3.	361	2000	1.26	91
	4.	381	2150	1.20*	87*
	5.	412	2300	1.03**	74**
	6.	400	2500	1.07**	77**
	7.	436	3000	1.01**	73**
	8.	460	4000	1.30	94
	9.	523	5000	1.05**	76**
	10.	432	2500	1.26	91
	11.	512	3000	1.20**	86**
	12.	678	4000	1.09**	79**
	13.	840	5000	0.95**	68**

c.v. 15.2%

TABLE 4.20 The influence of a gradient of a simulated sodic-saline mine water on the seedling top growth of sorghum PAN 888 (Figure 4.3, p. 107)

Cultivar	Treatment					Dry mass of top growth/ 10 plants	Relative Growth
	EC		Na	Cl	SO_4		
	mSm^{-1}		mmolℓ^{-1}			g	%
PAN 888	1.	241	0	0	12	1.34	100
	2.	308	10	10	12	1.30	97
	3.	396	20	16	13.8	1.14**	85**
	4.	581	40	29	17.5	1.13**	84**
	5.	678	50	35	19.3	0.91**	68**
	6.	770	60	42	21.1	0.88**	66**
	7.	958	80	54	24.8	0.70**	52**

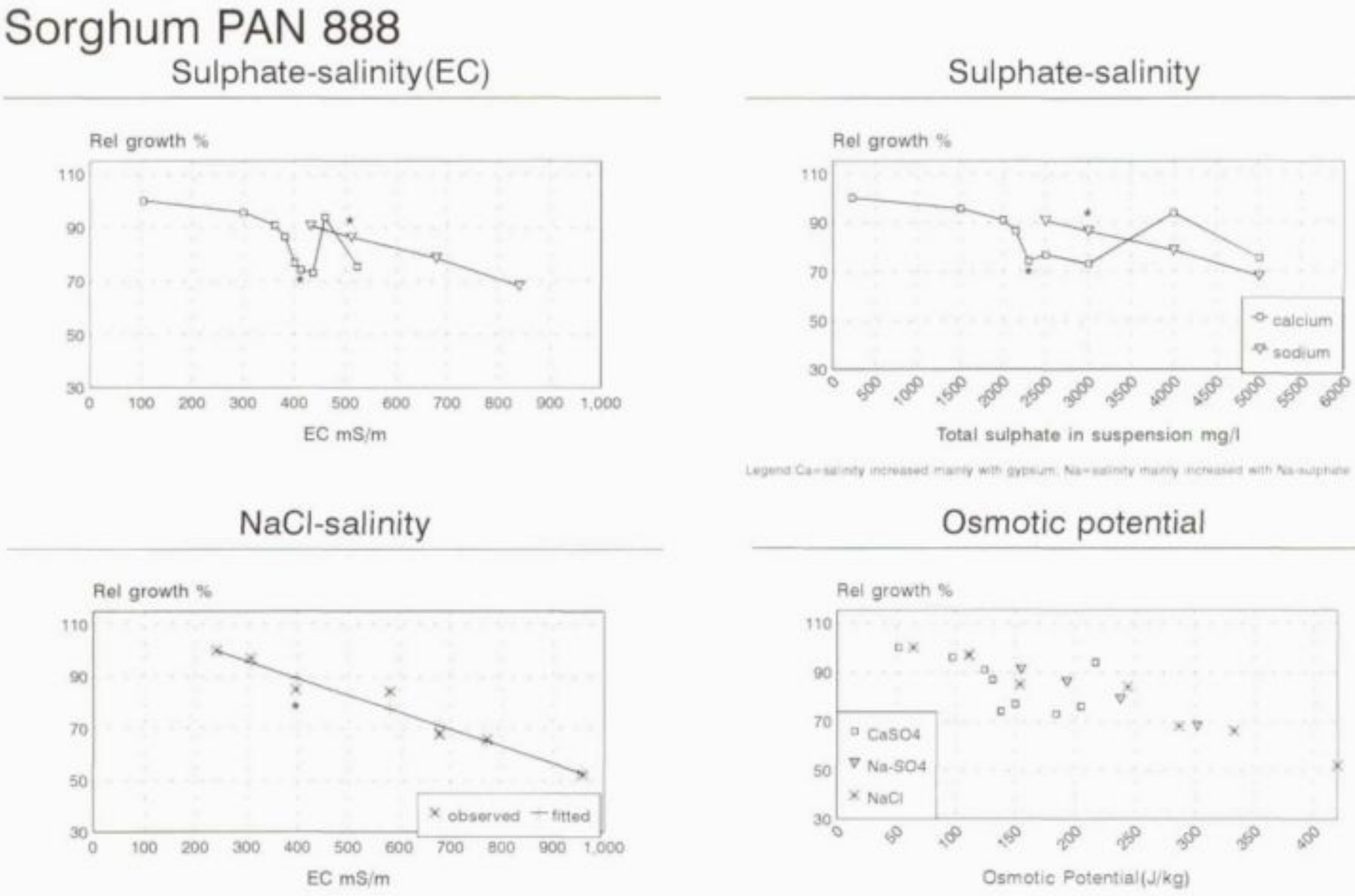
c.v. 12.4%

LSD$_T$ 0.19

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-9 salinity with mainly $CaSO_4$; 10-13 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.



threshold 240mS/m slope 6.6%

* First significant difference from control(first treatment)(EC)

FIGURE 4.3 The influence of increasing concentrations of a simulated sulphate (top) and a sodic-saline (bottom) mine water on the seedling growth (0-18 days) of sorghum PAN 888 in a growth chamber (25°C day/15°C night)

TABLE 4.21 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of pearl millet (babala) (common) (Figure 4.4, p. 109)

Crop Cultivar	Treatment[1]		Dry mass of top growth/ 10 plants	Relative Growth
	EC[2] mSm^{-1}	Sulphate[3] mg ℓ^{-1}	g	%
Pearl millet common	1. 104	226	1.09	100
	2. 300	1500	1.09	100
	3. 361	2000	0.91**	83.5 **
	4. 381	2150	0.94	86.2
	5. 412	2300	0.90**	82.6 **
	6. 400	2500	0.93 *	85.3 *
	7. 436	3000	0.92 *	84.4 *
	8. 460	4000	0.96	88.1
	9. 523	5000	0.92	84.4
	10. 432	2500	0.92 *	84.4 *
	11. 512	3000	0.98	89.9
	12. 678	4000	0.86**	78.9 **
	13. 840	5000	0.64**	58.7 **

c.v. 12.6%

TABLE 4.22 The influence of a gradient of simulated sodic-saline mine water on the seedling top growth of pearl millet (babala) (common) (Figure 4.4, p. 109)

Cultivar	Simulated sodic-saline mine water				Dry mass of top growth/ 10 plants	Relative Growth
	EC	Na	Cl	SO_4		
	mSm^{-1}	mmolℓ^{-1}			g	%
Pearl millet common	1. 241	0	0	12	1.04	100
	2. 308	10	10	12	0.98	94
	3. 396	20	16	13.8	0.88**	85**
	4. 581	40	29	17.5	0.70**	67**
	5. 678	50	35	19.3	0.45**	44**
	6. 770	60	42	21.1	0.52**	50**
	7. 958	80	54	24.8	0.39**	38**

c.v. 10.28%

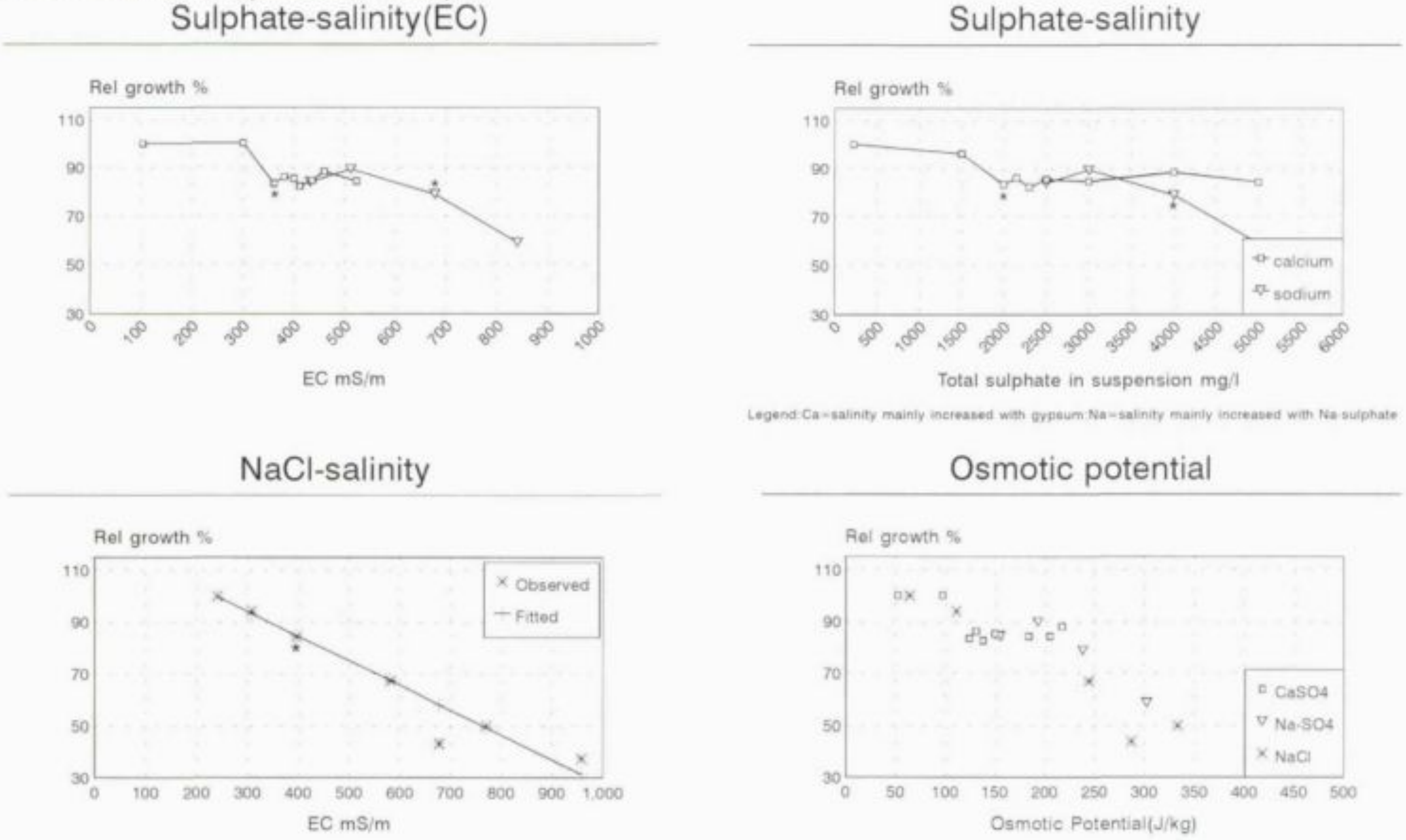
LSD$_T$ 0.10

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-9 salinity with mainly $CaSO_4$; 10-13 with added Na_2SO_4.
2. EC measured in supernatant of treatment solutions.
3. Total sulphate in suspension.

Pearl Millet(common)



Legend:Ca-salinity mainly increased with gypsum:Na-salinity mainly increased with Na-sulphate

Threshold 223 mS/m Slope 9.3%

* First significant difference from control(first treatment)($P<0.05$)

FIGURE 4.4 **The influence of increasing concentrations of a simulated sulphate (top) and a sodic-saline (bottom) mine water on the seedling growth of Pearl millet (common variety) in a growth chamber (25°C day/15°C night)**

SOYBEAN
DRY BEAN
COWPEA

Germination and Seedling Growth

TABLE 4.23 The influence of two mine waters on the germination percentage of soybean, dry bean and cow pea cultivars

Cultivar	Germination %			c.v. %	Relative germination %	
	Deionized water	Mine C	Mine B		Mine C	Mine B
SOYBEAN						
1. Bakgat	82	79	75**	7.3	96 a	92 a
2. Ibis	88	90	92	5.6	104 a	106 a
3. PAN 494	100	98	99	1.7	98 a	99 a
4. PAN 577G	99	98	99	2.1	99 a	100 a
5. Prima	98	99	100	1.9	101 a	102 a
6. Hutcheson	(38)	(25)**	(28)**	25.8	(68)[1] b	(74)[1] b
7. A2233	(88)	(86)	(80)**	9.0	(98)[1] a	(89)[1] ab
8. A5409	95	89*	86**	2.1	94 a	90 ab
9. A7119	85	83	86	3.6	97 a	101 a
COWPEA						
1. Dr Saunders	95	100**	97	1.7	105 a	102 a
c.v. %	4.4				11.1	10.7

[1] Brackets indicate that values were probably influenced by an infection.

DRY BEANS						
1. PAN 122	93	94	96	1.5	101 a	103 a
2. PAN 127	99	98	100	2.1	99 a	101 a
3. Mkuzi	98	99	100	1.9	101 a	102 a
4. Nandi	98	99	95	2.4	101 a	97 a
c.v. %	4.4				11.1	10.7

Mine C 10/94 (soybean & cowpea); 3/95 (dry bean)
Mine B 11/94 (soybean & cowpea); 3/95 (dry bean)

* Tendency ($P < 0.1$)
** Significant ($P < 0.05$)

TABLE 4.24 The influence of two mine waters on the seedling top growth of soybean, dry bean and cow pea cultivars

Cultivar	Dry mass top growth/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
SOYBEAN						
1. Bakgat	3.01	2.40	1.90**	8.3	80abc	63 cd
2. Ibis	3.00	2.47	2.42	10.7	82abc	80 abcd
3. PAN 494	2.79	2.53	1.74**	14.2	92 ab	62 d
4. PAN 577 G	2.98	2.62	2.06**	5.1	88 ab	69bcd
5. Prima	2.61	2.29	1.61**	14.2	89 ab	61 d
6. Hutcheson[1]	(2.15)	(1.78)	(1.44)	21.4	(89) ab	(70) bcd
7. A2233[1,2]	(3.24)	(3.05)	(3.31)	10.6	(95) ab	(102) a
8. A5409	3.90	3.21	2.45**	7.2	83abc	63 d
9. A7119	2.73	2.11	1.74**	13.2	77 bc	64 cd
COW PEA						
1. Dr Saunders[5]	2.87	1.73**	2.13*	26.5	65	80
DRY BEANS[3]						
1. PAN 122	6.16	5.12	3.61**	13.4	83 c	59 c
2. PAN 127	7.26	9.55**	6.54	5.3	131 a	90 a
3. Mkusi	6.78	8.10**	5.59**	5.3	119 ab	82 ab
4. Nandi	7.22	8.56**	5.37**	7.5	119 ab	74 b

c.v. %

c.v. %

* Tendency to differ from control ($P < 0.1$)
** Significant difference from control ($P < 0.05$)

Mine C 10/94 (soybean & cowpea); 3/95 (dry bean)
Mine B 11/94 (soybean & cowpea); 3/95 (dry bean)

1. Germination affected in all treatments by infections. The seedlings planted were very weak.
2. Less plants survived, especially in the control, probably due to infection; more plants survived with the salt treatments.
3. Dry beans were evaluated with 15 plants per replicate.
4. Brackets indicate that growth could have been influenced by infection of the seeds and young seedlings.
5. The number of surviving plants varied, as well as growth between individual plants; this is probably an indication of sensitivty in the seedling stage.

TABLE 4.25 The influence of a gradient of a simulated sulphate mine water on the top growth of soybean Ibis seedlings (Figure 4.5, p. 113)

Cultivar	Treatment^{1}		Dry mass of top growth/ 10 plants	Relative Growth
	EC^{2} mSm^{-1}	Sulphate^{3} mgℓ$^{-1}$	g	%
Soybean Ibis	1. 95	226	2.17	100
	2. 265	1500	1.64**	75**
	3. 321	2000	1.93	89
	4. 337	2150	1.79*	82*
	5. 362	2300	1.83	84
	6. 364	2500	1.83	84
	7. 398	3000	1.89	87
	8. 443	4000	2.17	100
	9. 429	5000	2.05	94
	10. 517	6000	1.95	90
	11. 356	2500	1.81	83
	12. 435	3000	2.02	93
	13. 587	4000	1.66**	77**
	14. 736	5000	1.73*	80*

c.v. 17.0%

TABLE 4.26 The influence of a gradient of a simulated sodic-saline mine water on the top growth of soybean Ibis seedlings (Figure 4.5, p. 113)

Cultivar	Treatment				Dry mass of top growth/ 10 plants	Relative Growth
	EC^{1}	Na	Cl	SO_4		
	mSm^{-1}	mmolℓ$^{-1}$			g	%
Soybean Ibis	1. 241	0	0	12	3.53	100
	2. 308	10	10	12	3.43	97
	3. 396	20	16	13.8	3.09	88
	4. 581	40	29	17.5	2.88*	82*
	5. 678	50	35	19.3	2.46**	70**
	6. 770	60	42	21.1	2.79*	79*
	7. 958	80	54	24.8	2.55**	72**

c.v. 19.3%

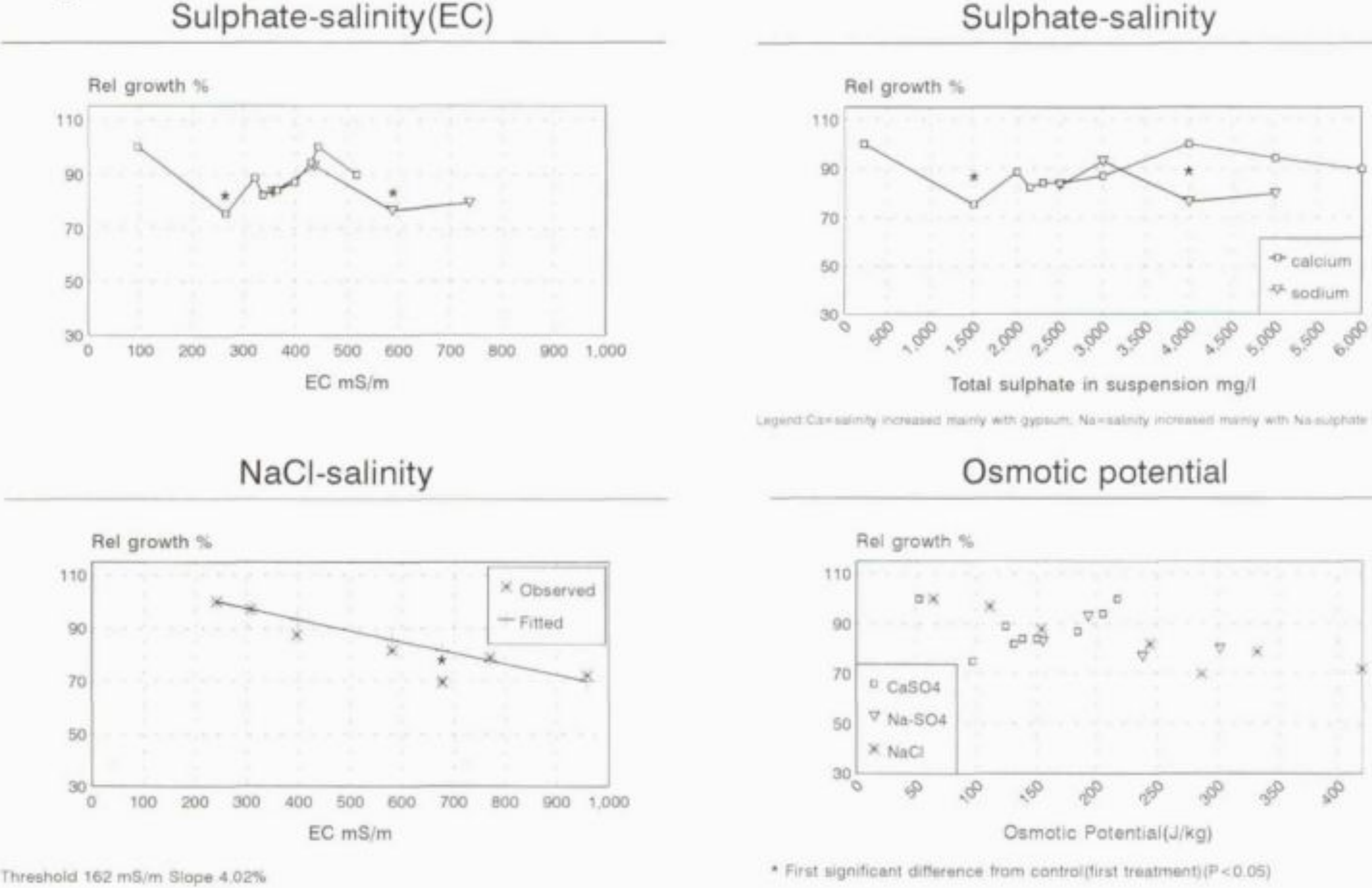
LSD$_T$ 0.75

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.

Soybean Ibis



Sulphate-salinity(EC)

Sulphate-salinity

Legend:Ca=salinity increased mainly with gypsum; Na=salinity increased mainly with Na-sulphate

NaCl-salinity

Osmotic potential

Threshold 162 mS/m Slope 4.02%

* First significant difference from control(first treatment)(P<0.05)

FIGURE 4.5 **The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth (0-18 days) of soybean Ibis in a growth chamber (25°C day/15°C night)**

TABLE 4.27 The influence of a gradient of a simulated sulphate mine water on the top growth of drybean PAN 122 seedlings (Figure 4.6, p. 115)

Crop Cultivar	Treatment^{1}		Dry mass of top growth/ 10 plants g	Relative Growth %
	EC^{2} mSm^{-1}	Sulphate^{3} mgℓ$^{-1}$		
Drybean PAN 122	1. 90	226	1.86	100
	2. 266	1500	1.94	104
	3. 317	2000	1.78	96
	4. 308	2150	1.68	91
	5. 334	2300	2.00	108
	6. 370	2500	1.84	99
	7. 390	3000	1.75	94
	8. 440	4000	1.76	95
	9. 424	5000	1.86	100
	10. 494	6000	1.38 *	74*
	11. 372	2500	1.46	79*
	12. 450	3000	1.58	85
	13. 564	4000	1.28 **	69**
	14. 740	5000	1.31 **	70**

c.v. 21.1%

TABLE 4.28 The influence of a gradient of a simulated sodic-saline mine water on the top growth of drybean PAN 127 seedlings (Figure 4.6, p. 115)

Crop Cultivar	Treatment				Dry mass of top growth/ 10 plants g	Relative Growth %
	EC^{1}	Na	Cl	SO_4		
	mSm^{-1}	mmolℓ$^{-1}$				
Drybean PAN 127	1. 241	0.02	0.02	12	3.98	100
	2. 308	10	10	12	3.43	86
	3. 396	20	16	13.8	3.26*	82*
	4. 581	40	29	17.5	3.20**	80**
	5. 678	50	35	19.3	2.74**	69**
	6. 770	60	42	21.1	2.58**	65**
	7. 958	80	54	24.8	2.62**	66**

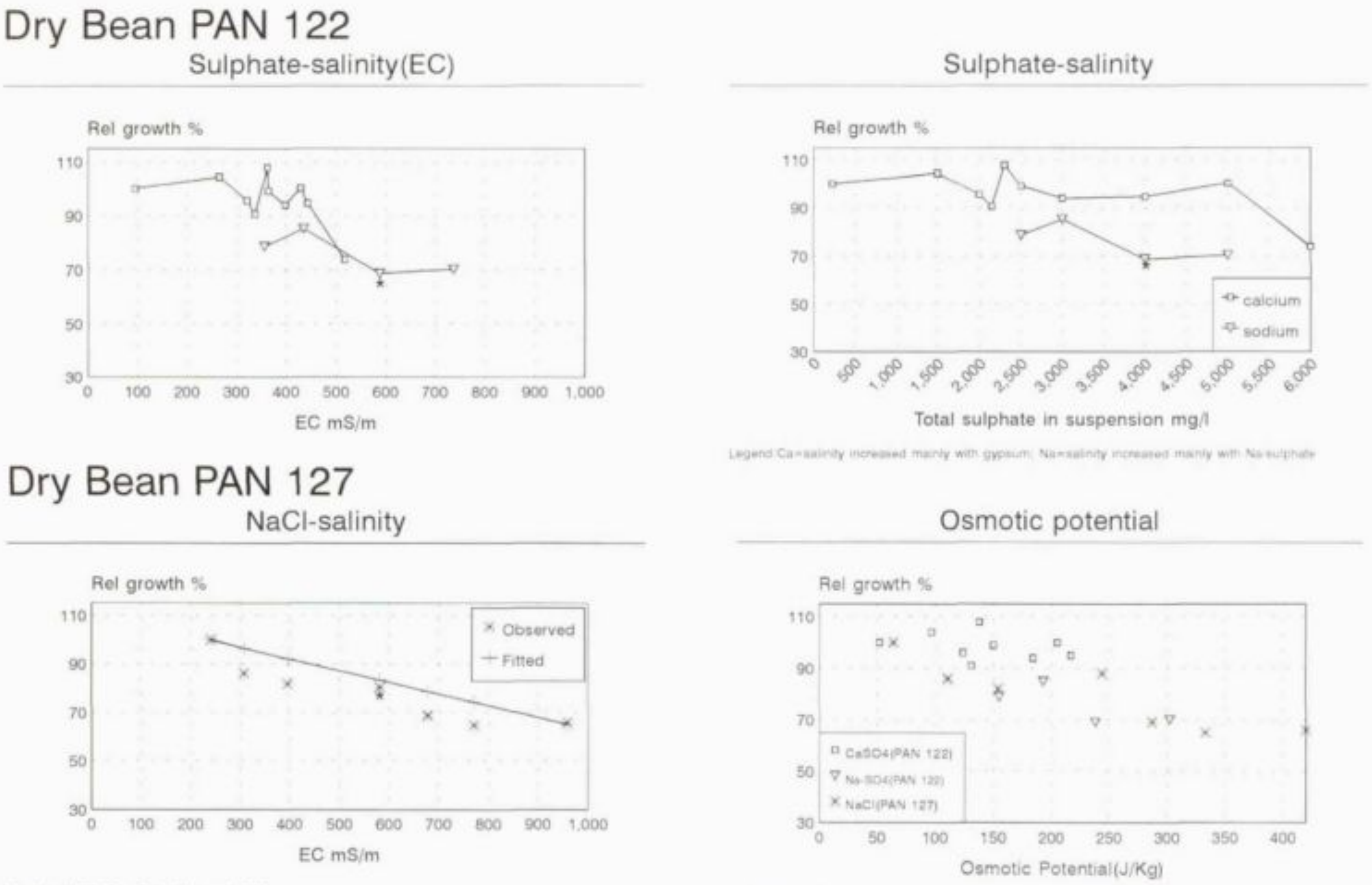
c.v. 15.9%

LSD$_{T}$ 0.72

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.



Dry Bean PAN 122

Sulphate-salinity(EC)

Sulphate-salinity

Legend Ca=salinity increased mainly with gypsum; Na=salinity increased mainly with Na-sulphate

Dry Bean PAN 127

NaCl-salinity

Osmotic potential

Threshold 79.81mS/m Slope 4.49%

*First significant difference from control(first treatment)(P=0.05)

FIGURE 4.6 **The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth (0-18 days) of dry bean cultivars PAN 122 and PAN 127 in a growth chamber (25°C day/15°C night)**

TABLE 4.29 **The influence of a gradient of a simulated sulphate mine water on the top growth of cowpea Dr Saunders seedlings (Figure 4.7, p. 117)**

Crop Cultivar	Treatment[1]			Dry mass of top growth/ 10 plants g	Relative Growth %
		EC[2] mSm^{-1}	Sulphate[3] mgℓ^{-1}		
Cowpea Dr Saunders	1.	95	226	2.54	100
	2.	265	1500	2.64	104
	3.	321	2000	2.37	93
	4.	337	2150	2.36	93
	5.	362	2300	2.27	89
	6.	364	2500	2.03 *	80*
	7.	398	3000	2.36	93
	8.	443	4000	2.48	98
	9.	429	5000	2.04 *	80*
	10.	517	6000	2.25	89
	11.	356	2500	2.56	101
	12.	435	3000	2.08 *	82*
	13.	587	4000	1.81 **	71**
	14.	736	5000	2.10	83

c.v. 15.8%

TABLE 4.30 **The influence of a gradient of simulated sodic-saline mine water on the top growth of cowpea Dr Saunders seedlings (Figure 4.7, p. 117)**

Crop Cultivar	Treatment					Dry mass of top growth/ 10 plants g	Relative Growth %
		EC[1]	Na	Cl	SO_4		
		mSm^{-1}	mmolℓ^{-1}				
Cowpea Dr Saunders	1.	241	0.02	0.02	12	3.62	100
	2.	308	10	10	12	3.53	97
	3.	396	20	16	13.8	3.18**	88**
	4.	581	40	29	17.5	2.63**	76**
	5.	678	50	35	19.3	2.59**	72**
	6.	770	60	42	21.1	2.46**	68**
	7.	958	80	54	24.8	1.95**	54**

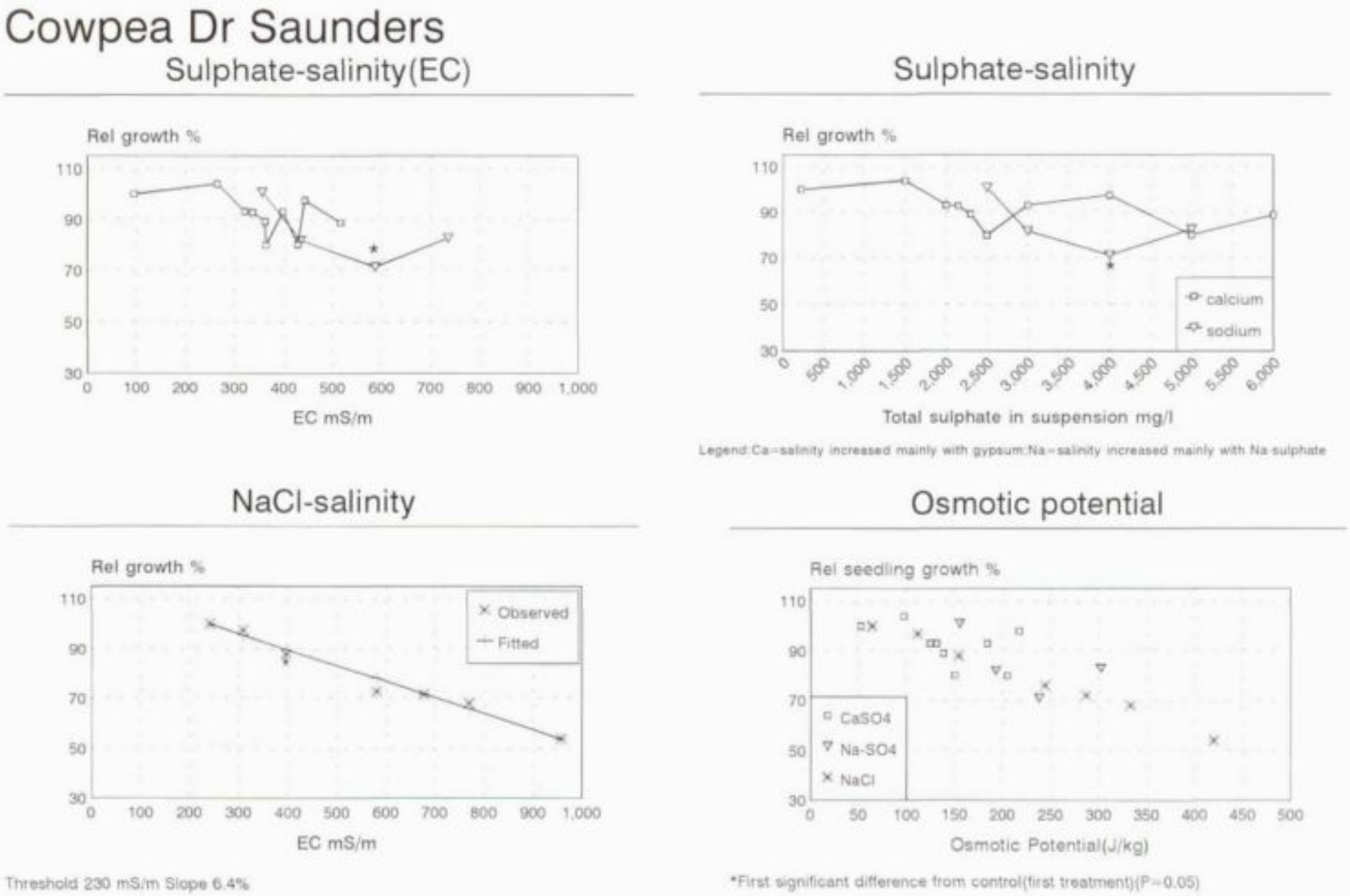
c.v. 7.8%

LSD$_T$ 0.32

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.



Legend:Ca=salinity increased mainly with gypsum;Na=salinity increased mainly with Na-sulphate

Threshold 230 mS/m Slope 6.4%

*First significant difference from control(first treatment)(P=0.05)

FIGURE 4.7 The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth (0-18 days) of cowpea Dr Saunders in a growth chamber (25°C day/15°C night)

SUNFLOWER

Germination and Seedling Growth

TABLE 4.31 The influence of two mine waters on the germination percentage of sunflower cultivars

Cultivars	Germination %			Relative germination %		c.v. %
	Deionized water	Mine C	Mine B	Mine C	Mine B	
SNK 43[1]	83	93	89	112	107	8.5
SNK 34	95	100*	97	105*	102	3.1
SNK 37	86	85	78	99	91	20.1
PAN 7392	100	99	98	99	98	1.9
PAN 7411	98	99	96	101	98	2.8
PAN 7369	98	99	95	101	97	3.5
CRN 1445	94	93	89	99	95	5.1
CRN 543	99	98	100	99	101	1.9
A1006	90	95	93	106	103	4.8

c.v. 7.2%

TABLE 4.32 The influence of two mine waters on the seedling top growth of sunflower cultivars

Cultivars	Mass of topgrowth/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
SNK 43	4.78	2.77**	2.38**	9.5	58 abc	50 ab
SNK 34	3.44	2.13**	1.86**	2.4	62 ab	54 ab
SNK 37	2.35	1.38**	1.26**	12.7	59 abc	54 ab
PAN 7392	3.36	1.82**	1.52**	13.5	54 abc	45 b
PAN 7411	3.94	1.76**	1.86**	5.3	45 bc	47 b
PAN 7369	3.39	2.18**	2.00**	9.5	64 a	59 a
CRN 1445	3.32	2.03**	1.56**	5.2	61 ab	47 b
CRN 543	2.84	1.32**	1.29**	17.2	47 abc	46 b
A 1006	4.18	1.81**	2.08**	4.6	43 c	50 ab
c.v. %	9.2				14.36	9.70
LSD$_T$					17	11

* Tendency to differ from control ($P < 0.1$)
** Significant difference from control ($P < 0.05$)

Mine C 10/94
Mine B 7/94

1. SNK 43 seeds were infected with a fungus.

TABLE 4.33 The influence of a gradient of a simulated sulphate saline mine water on the top growth of sunflower SNK 43 seedlings (Figure 4.8, p. 120)

Crop Cultivar	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
		EC[2] mSm^{-1}	Sulphate[3] mgℓ^{-1}	g	%
Sunflower SNK 43	1.	104	226	2.50	100
	2.	300	1500	2.91 *	116*
	3.	361	2000	2.60	104
	4.	381	2150	2.66	106
	5.	412	2300	2.48	99
	6.	400	2500	2.66	106
	7.	436	3000	2.61	104
	8.	460	4000	2.54	102
	9.	523	5000	2.47	99
	10.	432	2500	2.57	103
	11.	512	3000	2.58	103
	12.	678	4000	1.58 **	63**
	13.	840	5000	2.00 *	80*

c.v. 13.1%

TABLE 4.34 The influence of a gradient of simulated sodic-saline mine water on the top growth of sunflower SNK 43 seedlings (Figure 4.8, p. 120)

Crop Cultivar	Treatment					Dry mass of top growth/ 10 plants	Relative Growth
		EC[1]	Na	Cl	SO_4		
		mSm^{-1}	mmolℓ^{-1}			g	%
Sunflower SNK 43	1.	241	0.02	0.02	12	2.45	100
	2.	308	10	10	12	2.55	104
	3.	396	20	16	13.8	2.28	93
	4.	581	40	29	17.5	2.01**	82**
	5.	678	50	35	19.3	1.83**	75**
	6.	770	60	42	21.1	1.93**	79**
	7.	958	80	54	24.8	1.64**	67**

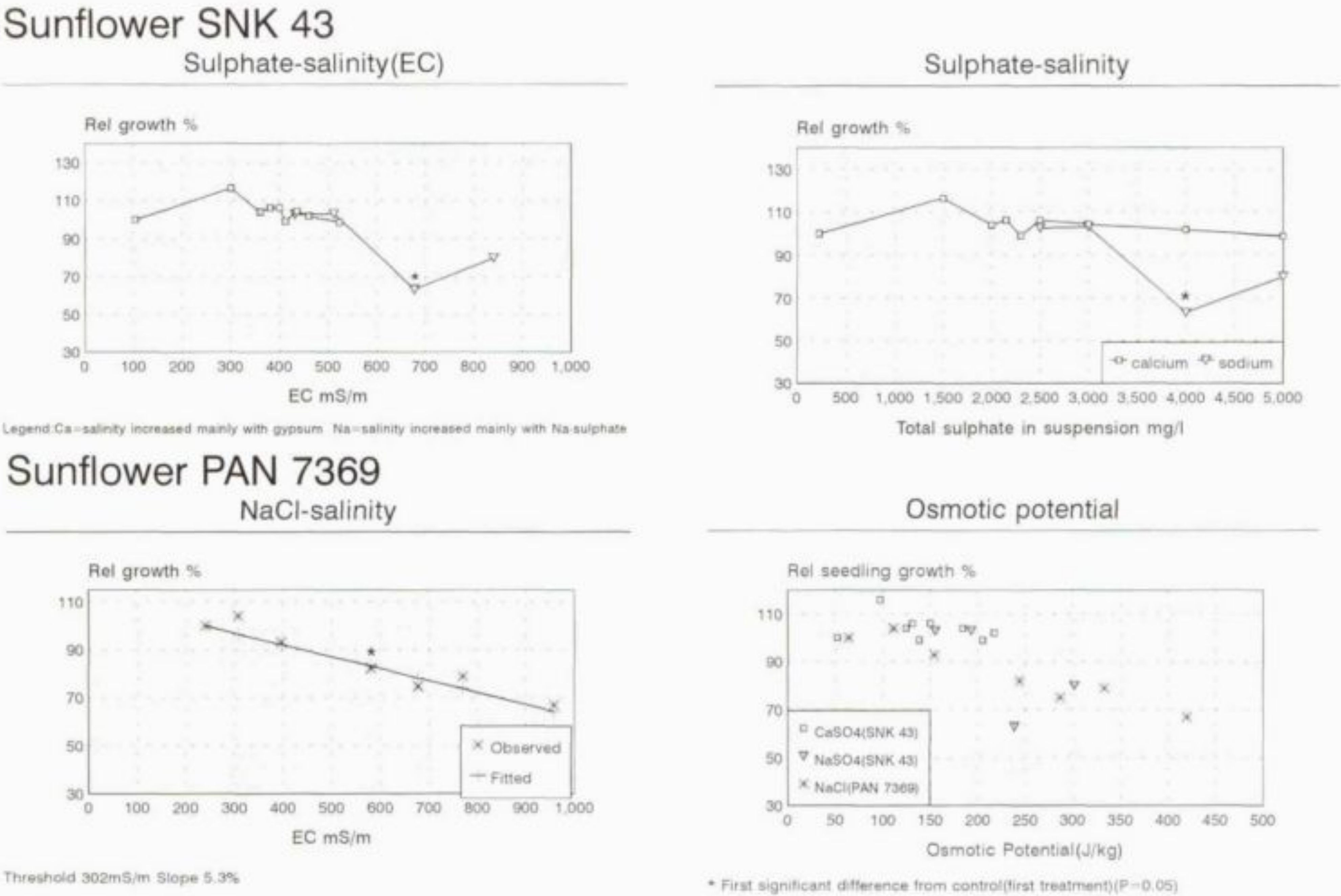
c.v. 7.2%

LSD$_T$ 0.22

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-9 salinity with mainly $CaSO_4$; 10-13 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.



Legend:Ca=salinity increased mainly with gypsum Na=salinity increased mainly with Na-sulphate

Threshold 302mS/m Slope 5.3%

* First significant difference from control(first treatment)(P=0.05)

FIGURE 4.8 The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth of sunflower SNK 43 in a growth chamber (25°C day/15°C night)

2. SUBTROPICAL PERENNIALS

Vegetative Growth

Table 4.35 Growth parameters for subtropical perennial grasses

Species	Treat-ment	Dry mass top growth g			Dry mass roots	Leaf & Stem area
		Stems	Leaves	TOTAL	g	cm^2
Cynodon hybrid Coast Cross 2 K11	Control	15.24	16.55	31.71	5.37	1566
	Mine A	13.77	18.30	32.45	6.62*	1806
	Mine B	19.15	17.10	36.47	6.80**	2034
c.v. %		24.00	20.22	20.72	13.24	24.27
Cynodon dactylon Primavera	Control	9.98	11.59	21.69	3.34	2604
	Mine A	11.42	12.07	23.36	3.25	2677
	Mine B	4.17***	4.71***	8.85***	1.90**	929***
c.v. %		27.17	15.81	19.32	22.32	14.58
Cynodon dactylon Tierra Verde	Control	21.41	24.29	44.69	12.20	4410
	Mine A	23.43	25.66	49.90**	9.95	4510
	Mine B	18.23**	19.59***	37.07***	9.30*	3785***
c.v. %		8.16	7.20	6.64	17.46	5.94
Cynodon dactylon Sahara	Control	12.89	12.24	25.26	3.23	2610
	Mine A	14.89	13.26	29.59*	3.45	2941*
	Mine B	11.53	11.46	23.35	3.23	2459
c.v. %		16.16	9.24	11.99	26.66	8.48
Sporobolus airoides	Control	-	-	2.31	0.34	192.41
	Mine A	-	-	2.56	0.48*	260.70
	Mine B	-	-	1.64**	0.38	152.41
c.v. %				18.16	23.12	18.18

* Tends to significant difference from control. $P<0.10$

** Significant difference from control. $P<0.05$

*** Highly significant difference from control. $P<0.01$

Mine A 2/94
Mine B 3/94

Table 4.36 Growth ratios for subtropical perennial grasses

Species	Treat-ment	Water % in top growth	Leaves/ Stems	Top growth/ Roots	Relative growth %	
					Leaves	Top growth
Cynodon hybrid Coast Cross 2 K11	Control	73.55	1.10	5.93	100	100
	Mine A	74.23	1.35***	5.08	110.57	102.33
	Mine B	73.05	0.91**	5.33	103.32	115.01
c.v. %		2.36	13.50	16.43	20.22	20.72
Cynodon dactylon Primavera	Control	79.41	1.17	6.55	100	100
	Mine A	78.48	1.11	7.61	104.14	107.70
	Mine B	78.81	1.19	4.84	40.64***	40.80***
c.v. %					20.12	19.32
Cynodon dactylon Tierra Verde	Control	75.74	1.14	3.84	100	100
	Mine A	75.55	1.10	5.01	105.64	111.66**
	Mine B	77.38**	1.08	4.15	80.65***	82.95***
c.v. %					7.20	6.64
Cynodon dactylon Sahara	Control	78.41	0.97	8.18	100	100
	Mine A	77.18	0.90	8.66	108.33	117.14*
	Mine B	78.91	1.00	7.29	93.63	92.44
c.v. %					9.24	11.99
Sporobolus airoides	Control	75.55	-	6.79	-	100
	Mine A	77.91***	-	5.33	-	110.82
	Mine B	75.84	-	4.32**	-	71.00**
c.v. %		1.34	14.57	26.88		18.16

* Tends to significant difference from control ($P<0.10$)
** Significant difference from control ($P<0.05$)
*** Highly significant difference from control ($P<0.01$)
Mine A 2/94
Mine B 3/94

TABLE 4.37 Concentration of nutrient elements in the top growth of subtropical perennials with two mine waters

Cultivars	Treatment	N	P	K	Ca	Mg	Na	Sulphate	Fe	Mn	Cu	Zn	Cl
		%							mgkg^{-1}				%
Cynodon hybrid Coast Cross 2 K11	Control	1.970	0.253	2.308	0.333	0.153	0.005	1.160	78	72	5	25	0.16
	Mine A	2.118	0.270	2.238	0.715*	0.210*	0.023	1.613*	83	432*	3*	32	0.29
	Mine B	1.828	0.180*	1.760	0.360	0.253*	0.245*	0.878*	71	45	3*	18	2.26*
	c.v. %	11.22	8.63	8.80	5.85	4.45	23.99	9.94	33.85	17.38	24.99	43.47	10.86
Cynodon dactylon Primavera	Control	3.338	0.478	3.283	0.428	0.243	0.005	2.288	106	227	9	30	0.15
	Mine A	3.210	0.433	3.115	0.688*	0.268	0.030	2.433	122	675*	8	44*	0.34*
	Mine B	3.188	0.340*	3.243	0.315*	0.283*	0.460*	1.420*	89	69*	5*	32	1.99*
	c.v. %	5.08	10.32	10.43	10.24	10.42	12.62	5.67	17.18	12.38	18.86	15.09	7.31
Cynodon dactylon Tierra Verde	Control	1.845	0.213	1.625	0.390	0.210	0.013	2.083	44	132	4	20	0.14
	Mine A	1.855	0.225	2.010*	0.433	0.175*	0.060*	2.268*	66*	273*	4	24	0.22
	Mine B	2.213*	0.243*	1.713	0.288*	0.230	0.643*	1.683*	52	75	4	26*	2.23*
	c.v. %	9.76	9.36	7.62	14.06	8.76	10.79	6.21	24.2	27.5	26.52	15.40	8.19
Cynodon dactylon Sahara	Control	3.468	0.390	2.595	0.453	0.263	0.013	2.463	103	176	6	25	0.19
	Mine A	2.968	0.353	2.928	0.533	0.218	0.030	2.473	98	523*	7	36	0.30
	Mine B	3.238	0.355	3.065	0.540	0.308	0.368*	2.250	93	125	8	48	2.09
	c.v. %	9.11	8.92	8.90	9.27	11.93	16.81	3.98	20.13	10.89	9.83	10.77	6.37

* Significant difference from control ($P < 0.05$)

Ch4 Tab4.37

TABLE 4.38 Total uptake of nutrient elements in the top growth of subtropical perennials

Cultivars	Treatment	N	P	K	Ca	Mg	Na	Sulphate	Fe	Mn	Cu	Zn	Cl
		g/pot[1]							mg/pot				g/pot
Cynodon hybrid Coast Cross 2 K11	Control	0.621	0.080	0.728	0.105	0.048	0.0016	0.371	3	2	0.17	0.8	0.05
	Mine A	0.679	0.087	0.719	0.231*	0.068	0.0072	0.521*	3	14*	0.10	1.0	0.09
	Mine B	0.656	0.065	0.635	0.130	0.091*	0.0912*	0.326	3	2	0.12	0.7	0.82*
Cynodon dactylon Primavera	Control	0.723	0.093	0.707	0.093	0.053	0.0011	0.496	2	5	0.19	0.7	0.03
	Mine A	0.756	0.099	0.718	0.159*	0.062	0.0070	0.566	3	16*	0.19	1.0*	0.08*
	Mine B	0.281*	0.030*	0.287*	0.029*	0.025*	0.0400*	0.127*	1*	1*	0.05*	0.3*	0.21*
Cynodon dactylon Tierra Verde	Control	0.821	0.095	0.724	0.174	0.094	0.0055	0.932	2	6	0.17	0.9	0.06
	Mine A	0.928	0.112*	1.002	0.216*	0.088	0.0299	1.129*	3*	14*	0.20	1.2*	0.11*
	Mine B	0.820	0.090	0.635	0.107*	0.085	0.2376*	0.624*	2	3	0.15	1.0	0.82*
Cynodon dactylon Sahara	Control	0.879	0.098	0.651	0.112	0.066	0.0031	0.623	3	4	0.15	0.6	0.05
	Mine A	0.875	0.104	0.862*	0.156*	0.065	0.0089	0.729*	3	15*	0.22*	1.1*	0.08
	Mine B	0.754	0.083*	0.716	0.126	0.072	0.0858*	0.525*	2*	3	0.18	1.1*	0.49*
c.v. %		17.83	13.44	12.90	18.44	19.35	21.29	12.94	30.27	36.72	21.60	22.50	

* Significant difference from control ($P < 0.05$)

[1] 3 plants per pot

3. *TEMPERATE ANNUALS*

Vegetative Growth

Table 4.39 The influence of two types of mine water on the vegetative growth parameters of annual temperate crops

Crops	Treat-ment	Leaves wet mass g/pot^2	Leaves dry mass g/pot	Tillers		Ears		Total dry mass top growth g/pot	Rel. Growth %	Roots dry mass g/pot	Leaf area cm^2/pot
				No.	Dry mass g/pot	No.	Dry mass g/pot				
1. Rye *Secale cereale* SSR1	Control	185.91	20.99	75	13.03			34.01		3.41	7182.06
	Mine A	187.27	26.01**	88	17.00			43.01*	126*	5.38**	7544.38
	Mine B	195.81	25.50*	74	15.13			40.63	119	3.53	8966.92**
c.v. %		8.93	12.56	19.34	21.33			14.51		27.22	6871.79
2. Oats *Avena sativa* Overberg	Control	188.56	24.85	23	30.81			55.66		5.05	6871.79
	Mine A	189.35	27.18*	25	30.15			57.33	103	4.64	6935.84
	Mine B	180.98	22.09**	28**	23.92*			46.01**	83**	3.42***	6389.17
c.v. %		6.21	6.50	11.51	15.63			10.91		15.90	7.16
3. Triticale *x Triticosecale* Cloc 1	Control	172.38	19.28	102	6.47			25.75		4.17	6536.34
	Mine A	177.01	21.14	111	7.18			28.32	110	3.99	6588.43
	Mine B	167.63	20.02	110	7.24			27.26	106	3.82	5880.44***
c.v. %		5.47	8.11	8.63	13.42			9.29		19.57	6.63
4. Wheat *Triticum aestivum* Inia	Control	43.24	8.81	26	14.80	17	4.62$^{1)}$	28.23		3.26	2349.61
	Mine A	46.14	9.03	29	14.37	20	4.66	28.06	99	2.76*	2414.01
	Mine B	48.67	9.95*	34***	13.39	16	3.34	26.68	95	2.76*	2527.73
c.v. %		10.23	9.09	5.53	10.7			10.48		10.99	10.51
5. Ryegrass *Lolium multiflorum* Midmar	Control	137.50	15.63	173	7.50			23.13		4.31	4985.77
	Mine A	140.48	15.18	167	6.22			21.40	93	4.04	5756.82
	Mine B	173.59**	18.47	173	9.57*			28.04	121	4.97	7256.26
c.v. %		13.15	18.39	26.17	22.65			19.16		37.61	26.69
6. Wheat (USA) Nursecrop for mine spoils	Control	127.81	17.50	45	8.05			25.55		3.55	4178.19
	Mine A	163.16***	20.58**	51	10.37**			30.95***	121***	3.98	5724.85**
	Mine B	143.53*	19.49*	72***	9.68*			29.17**	114**	3.61	4918.81
c.v. %		7.58	7.22	10.41	11.42			7.41		12.58	14.46

* Tendency to differ from control ($P < 0.1$)
** Significant difference from control ($P < 0.05$)
*** Highly significant difference from control ($P < 0.01$)

1. Mine A 5/94 Mine B 4/94 (Both waters diluted by rain)
2. 3 Plants per pot

Table 4.40 Growth ratios for temperate annuals

Crops	Treat-ment	Leaves/ Stems	Tops/ Roots	mg H_2O/cm^2 leaf area	Relative top growth %
1. Rye *Secale cereale* SSR1	Control	1.62	10.59	23.00	
	Mine A	1.60	8.23**	21.48	126*
	Mine B	1.69	11.97	19.51*	119
2. Oats *Avena sativa* Overberg	Control	0.81	11.19	23.81	
	Mine A	0.91	12.40	23.46	103
	Mine B	0.95	13.58**	24.87	83**
3. Triticale *x Triticosecale* Cloc 1	Control	3.00	6.24	23.51	
	Mine A	2.99	7.42	23.65	110
	Mine B	2.77	7.35	30.25***	106
4. Wheat *Triticum aestivum* Inia	Control	0.60	8.70	14.66	
	Mine A	0.63	10.31	15.17	99
	Mine B	0.74	9.71	15.33	95
5. Ryegrass *Lolium multiflorum* Midmar	Control	2.11	5.92	25.96	
	Mine A	2.49*	5.61	23.20	93
	Mine B	1.95	5.74	22.14*	121
6. Wheat (USA) Nursecrop on mine spoils	Control	2.18	7.20	26.46	
	Mine A	1.99	7.84	25.04	121***
	Mine B	2.04	8.21	25.60	114**
c.v. %		11.55	16.24	12.55	

*	Tendency to differ from control ($P < 0.1$)
**	Significant difference from control ($P < 0.05$)
***	Highly significant difference from control ($P < 0.01$)

Ch4-Tab4.40

Table 4.41 Concentration of some nutrient elements in the top growth of annual temperate crops with two types of mine water

Crops	Treatment	Ca			Mg			SO_4			Na			Cl		
		%														
		Leaves	Stems	Ears	Leaves	Stems	Ears	Leaves	Stems	Ears	Leaves	Stems	Ears	Leaves	Stems	Ears
1. Rye SSR 1 *Secale cereale*	Control	1.43	0.92		0.62	0.44		1.51	0.9		0.03	0.03		0.05	0.05	
	Mine A	1.99	1.37		0.35	0.27		2.24	1.68					0.20	0.19	
	Mine B	1.05	0.77		0.13	0.36		1.27	0.69		1.10	0.72		2.60	3.20	
2. Oats Overberg *Avena sativa*	Control	0.70	0.40		0.42	0.26		1.47	0.66		0.14	0.44		0.02	0.04	
	Mine A	1.28	0.85		0.20	0.16		2.12	1.40					0.10	0.17	
	Mine B	0.63	0.51		0.38	0.26		1.62	0.69		1.94	3.34		2.88	4.44	
3. Triticale Cloc 1 *x Triticosecale*	Control	0.85	0.69		0.40	0.38		1.59	1.03		0.02	0.04		0.06	0.07	
	Mine A	1.51	1.27		0.20	0.25		2.20	1.80					0.20	0.20	
	Mine B	0.73	0.50		0.33	0.28		1.48	0.79		1.12	1.06		2.09	2.73	
4. Wheat Inia *Triticum aestivum*	Control	1.31	0.37	0.48	0.45	0.14	0.23	1.57	0.87	0.70	0.01	0.02	0.03	0.03	0.06	0.15
	Mine A	2.03	0.67	0.55	0.22	0.09	0.14	2.00	1.52	1.88				0.14	0.23	0.17
	Mine B	0.99	0.37	0.34	0.65	0.26	0.24	1.65	0.96	0.87	0.39	0.33	0.02	0.99	1.27	0.27
5. Ryegrass Midmar *Lolium multiflorum*	Control	0.81	0.62		0.41	0.27		1.39	0.76		0.12	0.38		0.06	0.07	
	Mine A	1.35	1.06		0.32	0.31		1.92	1.48					0.19	0.19	
	Mine B	0.87	0.51		0.39	0.24		1.24	0.63		1.96	2.27		3.08	3.84	
6. Wheat (USA) Nursecrop for mine spoils	Control	2.19	1.20		0.28	0.13		1.49	0.60		0.06	0.06		0.05	0.04	
	Mine A	3.17	1.86		0.22	0.25		2.12	1.52					0.26	0.21	
	Mine B	3.29	1.37		0.38	0.27		1.06	0.90		1.95	1.93		0.59	0.62	

Mine A 5/94 Mine B 4/94

Ch4-Tab4.41

Table 4.42 Total uptake of nutrient elements by annual winter crops

Crops	Treat-ment	Ca			Mg			SO_4			Na			Cl		
		g/pot[1]														
		Leaves	Stems	Spikes	Leaves	Stems	Spikes	Leaves	Stems	Spikes	Leaves	Stems	Spikes	Leaves	Stems	Spikes
1. Rye SSR 1 *Secale cereale*	Control	0.30	0.12		0.13	0.06		0.32	0.12		0.006	0.004		0.01	0.007	
	Mine A	0.52	0.23		0.09	0.05		0.58	0.28					0.05	0.03	
	Mine B	0.27	0.12		0.03	0.05		0.32	0.10		0.28	0.11		0.66	0.48	
2. Oats Overberg *Avena sativa*	Control	0.17	0.12		0.10	0.08		0.37	0.20		0.03	0.14		0.005	0.01	
	Mine A	0.35	0.26		0.05	0.05		0.58	0.42					0.027	0.05	
	Mine B	0.14	0.12		0.08	0.06		0.36	0.17		0.43	0.80		0.64	1.06	
3. Triticale Cloc 1 *x Triticosecale*	Control	0.16	0.04		0.08	0.02		0.31	0.07		0.004	0.002		0.01	0.005	
	Mine A	0.32	0.09		0.04	0.02		0.47	0.13					0.04	0.01	
	Mine B	0.15	0.04		0.07	0.02		0.30	0.06		0.22	0.08		0.42	0.20	
4. Wheat Inia *Triticum aestivum*	Control	0.12	0.05	0.02	0.04	0.02	0.01	0.14	0.13	0.03	0.001	0.003	0.001	0.003	0.009	0.007
	Mine A	0.18	0.10	0.03	0.02	0.01	0.006	0.18	0.22	0.09				0.013	0.03	0.008
	Mine B	0.10	0.05	0.01	0.06	0.03	0.008	0.16	0.13	0.03	0.04	0.04	0.001	0.10	0.17	0.009
5. Ryegrass Midmar *Lolium multi-florum*	Control	0.13	0.05		0.06	0.02		0.22	0.06		0.02	0.03		0.009	0.005	
	Mine A	0.20	0.07		0.05	0.02		0.29	0.09					0.03	0.01	
	Mine B	0.16	0.05		0.07	0.02		0.23	0.06		0.36	0.23		0.57	0.37	
6. Wheat (USA) Nursecrop for mine spoils	Control	0.38	0.10		0.05	0.10		0.26	0.05		0.01	0.005		0.009	0.003	
	Mine A	0.65	0.19		0.05	0.03		0.44	0.16					0.05	0.02	
	Mine B	0.64	0.13		0.07	0.03		0.21	0.09		0.38	0.19		0.11	0.06	

Mine A 5/94 Mine B 4/94

[1] 3 plants per pot

Ch4 Tab4.42

WHEAT

Germination and Seedling Growth

TABLE 4.43 The influence of two mine waters on the germination percentage of wheat cultivars

Cultivar	Germination %			Relative germination %		c.v. %
	Deionized water	Mine C	Mine B	Mine C	Mine B	
1. SST 822	100	100	98	100	98	1.68
2. SST 825	99	98	100	99	101	1.19
3. Palmiet	100	98	100	98	100	1.68
4. Marico	100	100	99	100	99	0.84
5. Kariega	100	100	100	100	100	0
6. Inia	98	100	100	102	102	1.68
7. Nursecrop	100	98	98	98	98	1.88

c.v. 1.45%

TABLE 4.44 The influence of two mine waters on the seedling top growth of wheat cultivars

Cultivars	Top growth masses per 10 plants (g)			c.v. %	Relative growth %	
	Control	Mine C[1]	Mine B[2]		Mine C	Mine B
1. SST 822	1.56	1.05**	0.64**	23.2	69 b	42 b
2. SST 825	1.63	1.68	0.79**	10.20	103 a	48 ab
3. Palmiet	1.58	1.77	0.91**	12.03	113 a	57 ab
4. Marico	1.27	1.20	0.77**	10.9	95 ab	61 ab
5. Kariega	1.53	1.45	0.84**	8.4	94 ab	55 ab
6. Inia	1.56	1.82	0.86**	15.0	115 a	56 ab
7. Nursecrop	1.46	1.56	1.02**	3.11	107 a	70 a
c.v. %	11.5				13.7	20.0
LSD_T					31	25

** Significant difference from control ($P < 0.05$)

Mine C 3/95

Mine B 3/95

TABLE 4.45 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of wheat Inia (Figure 4.9, p. 131)

Cultivars	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
	EC[2] mSm^{-1}		Sulphate[3] mgℓ^{-1}	g	%
Wheat Inia	1.	97	226	0.55	100
	2.	263	1500	0.55	100
	3.	330	2000	0.52	95
	4.	332	2150	0.51	94
	5.	338	2300	0.50	92*
	6.	349	2500	0.55	100
	7.	364	3000	0.48	88**
	8.	398	4000	0.53	97
	9.	473	5000	0.47	86**
	10.	507	6000	0.52	95
	11.	352	2500	0.52	94
	12.	424	3000	0.50	91*
	13.	572	4000	0.49	90**
	14.	782	5000	0.43	79**

c.v. 6.8%

TABLE 4.46 The influence of a gradient of simulated sodic-saline mine water on the seedling top growth of wheat Inia (Figure 4.9, p. 131)

Crop Cultivar	Treatment					Dry mass of top growth/ 10 plants	Relative Growth
	EC[2]		Na	Cl	SO_4[3]		
	mSm^{-1}		mmolℓ^{-1}			g	%
Wheat Inia	1.	168	0.02	0.02	12	0.47	100
	2.	286	10	10	12	0.47	99
	3.	382	20	16	13.8	0.49	104
	4.	565	40	29	17.5	0.40**	85**
	5.	664	50	35	19.3	0.44	94
	6.	756	60	42	21.1	0.44	94
	7.	934	80	54	24.8	0.35**	75**

c.v. 10.3%

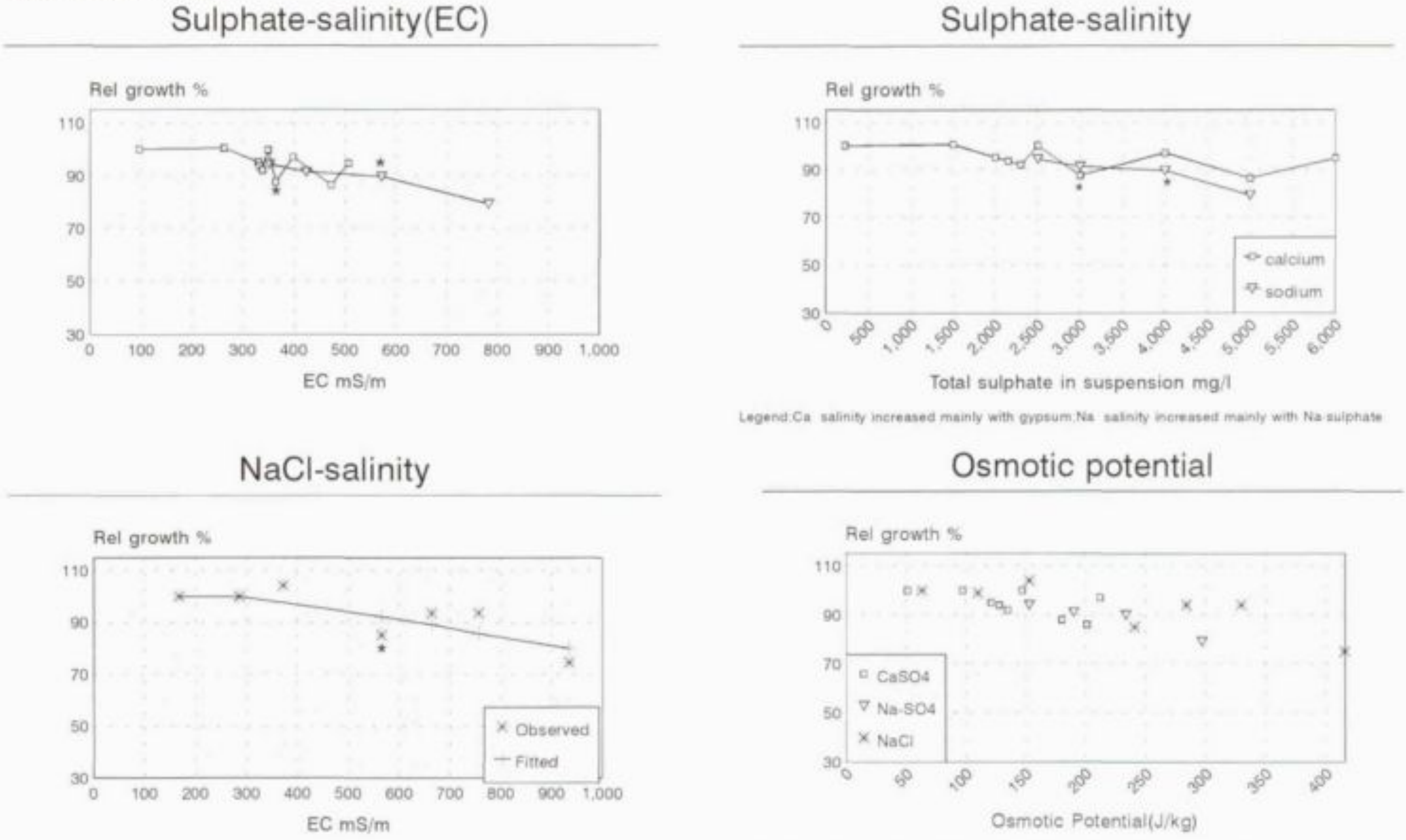
LSD_T 0.06

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.

Wheat Inia



Legend:Ca salinity increased mainly with gypsum;Na salinity increased mainly with Na-sulphate

Threshold 345mS/m Slope 3.45%

* First significant difference from control(first treatment)(P<0.05)

FIGURE 4.9 **The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth (0-18 days) of wheat Inia in a growth chamber (23°C day/12°C night)**

OATS
BARLEY

Germination and Seedling Growth

TABLE 4.47 The influence of two mine waters on the germination percentage of oats and barley cultivars

Cultivars	Germination %			Relative germination %		c.v. for cultivars %
	Deionized water	Mine C	Mine B	Mine C	Mine B	
OATS						
1. SSH 421	99	99	99	100	100	1.5
2. SSH 423	98	99	98	101	100	2.2
3. Witteberg	100	100	100	100	100	0.0
4. Perdeberg	98	99	99	101	101	2.8
5. Echidna	100	99	100	99	100	0.8
6. Overberg[1]	93	86**	88	92**	95	2.7
BARLEY						
1. Stirling	100	98	99	98	99	1.9

c.v. 2.6%

1. All treatments had a black powdery infection.

TABLE 4.48 The influence of two mine waters on the seedling top growth of oats and barley cultivars

Cultivars	Top growth/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
OATS						
1. SSH 421	1.12	1.10	1.13	17.6	98 abc	101 a
2. SSH 423	0.99	1.09	0.99	4.8	110 a	99 a
3. Witteberg	0.85	0.76	0.82	18.8	89 ab	96 ab
4. Perdeberg	1.26	1.26	1.16	9.2	100 abc	92 ab
5. Echidna	1.21	1.19	1.08	16.5	98 abc	89 ab
6. Overberg	1.36	1.45	1.28	16.7	107 ab	94 ab
BARLEY						
1. Stirling	2.32	2.04	1.85**	19.0	88 c	79 ab
c.v. %	17.6				7.8	27.0
LSD_T					17	53

* Tendency to differ from control ($P < 0.1$)

** Significant difference from control ($P < 0.05$)

Mine C 3/95

Mine B 3/95

Ch4-Tab4.47

TABLE 4.49 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of oats Overberg (Figure 4.10, p. 134)

Cultivars	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
		EC[2] mSm^{-1}	Sulphate[3] $mg\ell^{-1}$	g	%
Oats Overberg	1.	97	226	0.47	100
	2.	263	1500	0.46	99
	3.	330	2000	0.41 *	88*
	4.	332	2150	0.43	91
	5.	338	2300	0.45	96
	6.	349	2500	0.38 **	81**
	7.	364	3000	0.41 *	87**
	8.	398	4000	0.41 *	88*
	9.	473	5000	0.39 **	84**
	10.	507	6000	0.37 **	78**
	11.	352	2500	0.45	93
	12.	424	3000	0.39 **	82**
	13.	572	4000	0.40 **	86**
	14.	782	5000	0.38 **	82**

c.v. 10.4%

TABLE 4.50 The influence of a gradient of a simulated sodic-saline mine water on the seedling top growth of oats Overberg (Figure 4.10, p. 134)

Crop Cultivar	Treatment					Dry mass of top growth/ 10 plants	Relative Growth
		EC[2]	Na	Cl	SO_4[3]		
		mSm^{-1}	$mmol\ell^{-1}$			g	%
Oats Overberg	1.	168	0.02	0.02	12	0.64	100
	2.	286	10	10	12	0.61	95
	3.	382	20	16	13.8	0.49**	76**
	4.	565	40	29	17.5	0.51**	80**
	5.	664	50	35	19.3	0.40**	63**
	6.	756	60	42	21.1	0.34**	53**
	7.	934	80	54	24.8	0.34**	53**

c.v. 13.2%

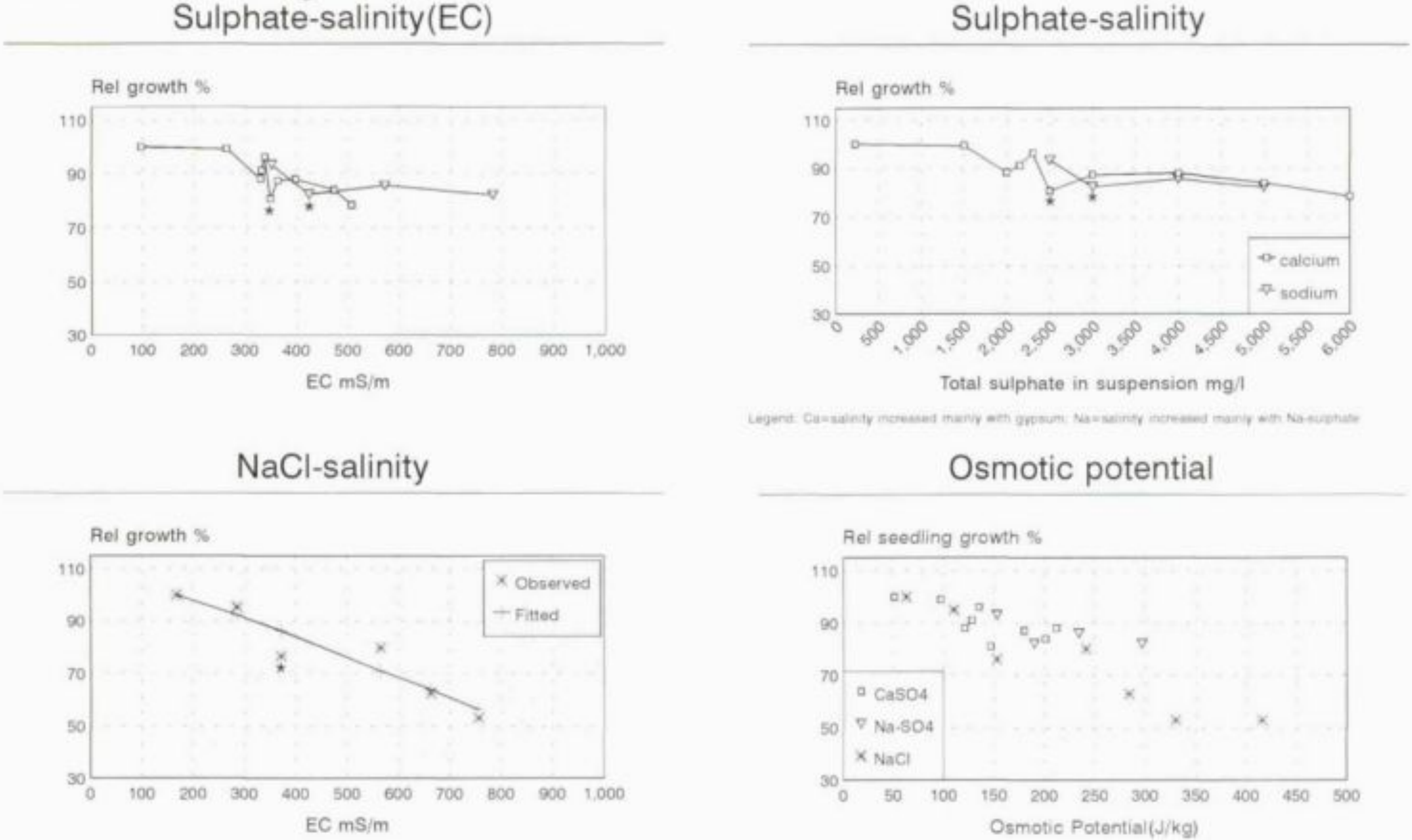
LSD$_y$ 0.09

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatments 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.

Oats Overberg



Legend: Ca=salinity increased mainly with gypsum; Na=salinity increased mainly with Na-sulphate

Threshold 182 mS/m Slope 7.6%

* First significant difference from control(first treatment)(P<0.05)

FIGURE 4.10 **The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth (0-18 days) of oats Overberg in a growth chamber**

TABLE 4.51 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of barley Stirling (Figure 4.11, p. 136)

Crop Cultivar	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
		EC[2] mSm^{-1}	Sulphate[3] mgℓ^{-1}	g	%
Barley Stirling	1.	112	226	0.79	100
	2.	252	1500	0.85	107
	3.	315	2000	0.75	95
	4.	327	2150	0.79	99
	5.	346	2300	0.71 *	90*
	6.	360	2500	0.76	95
	7.	377	3000	0.72	91
	8.	415	4000	0.77	98
	9.	448	5000	0.79	99
	10.	473	6000	0.74	94
	11.	378	2500	0.76	96
	12.	445	3000	0.73	93
	13.	690	4000	0.73	92
	14.	755	5000	0.70	89**

c.v. 8.7%

TABLE 4.52 The influence of a gradient of a simulated sodic-saline mine water on the seedling top growth of barley Stirling (Figure 4.11, p. 136)

Crop Cultivar	Treatment					Dry mass of top growth/ 10 plants	Relative Growth
	EC[2]		Na	Cl	SO$_4$		
	mSm^{-1}		mmolℓ^{-1}			g	%
Barley Stirling	1.	168	0.02	0.02	12	0.66	100
	2.	286	10	10	12	0.74**	112**
	3.	382	20	16	13.8	0.77	116
	4.	565	40	29	17.5	0.68	103
	5.	664	50	35	19.3	0.63	96
	6.	756	60	42	21.1	0.62	94
	7.	934	80	54	24.8	0.56	85**

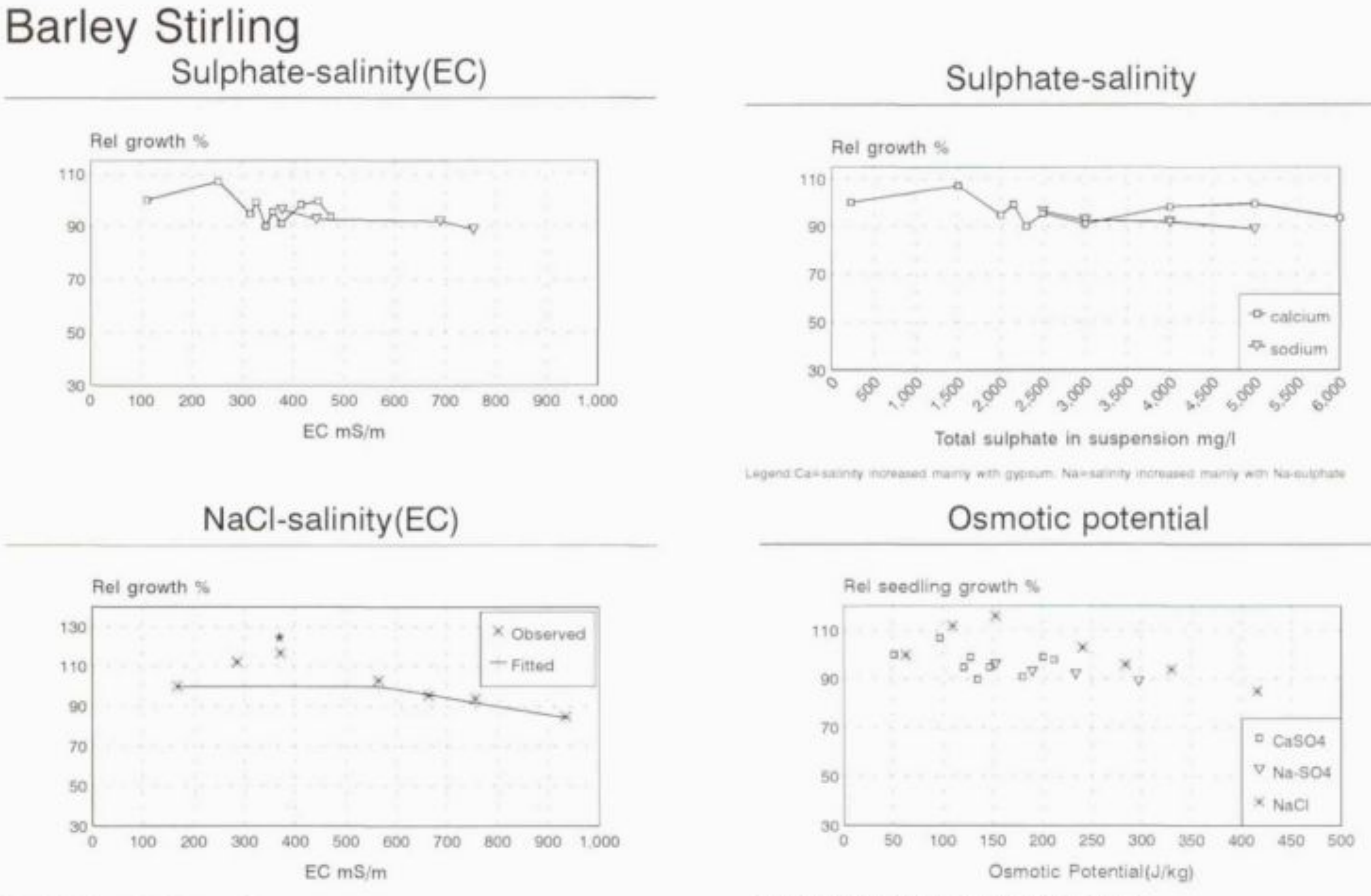
c.v. 10.6%

LSD$_T$ 0.10

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.



Legend:Ca=salinity increased mainly with gypsum. Na=salinity increased mainly with Na-sulphate

Threshold 569 mS/m Slope 4.37%

* First significant difference from control(P<0.05)

FIGURE 4.11 **The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth (0-18 days) of barley Stirling in a growth chamber**

TRITICALE

Germination and Seedling Growth

TABLE 4.53 The influence of two mine waters on the germination percentage of triticale cultivars

Cultivars	Germination %			Relative germination %		c.v. %
	Deionized water	Mine C	Mine B	Mine C	Mine B	
1. Kiewiet	100	99	99	99	99	1.2
2. SShRI	88	88	89	100	101	3.5
3. Rex	98	98	98	100	100	2.3
4. PAN 299[1]	57	63**	58	110**	102	11.1
5. SSKR 626	98	96	96	98	98	1.9
6. SSKR 628	98	98	94	100	96	3.5
7. Cloe 1	91	91	92	100	101	3.9

c.v. 3.4%

[1] These percentages included a marked number that had died when the radicle was ca 1 cm: more with the control than with the mine waters (Control 7.5-10 %, Mine C 2.5-5 % and Mine B2.5 %) giving an apparent increase in germination.

TABLE 4.54 The influence of two mine waters on the seedling top growth of triticale cultivars

Cultivars	Top growth/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
1. Kiewiet	1.66	1.41**	0.98**	9.9	86 a	59 b
2. SShR1	1.43	1.37	0.92**	6.7	97 ab	64 ab
3. Rex	1.40	1.51	1.19**	8.3	108 a	85 a
4. PAN 299	1.33	1.23	0.89**	4.9	92 ab	67 ab
5. SSKR 626	0.97	0.99	0.60**	14.5	103 ab	62 ab
6. SSKR 628	1.15	1.05	0.70**	6.1	91 ab	61 ab
7. Cloe 1	1.10	1.07	0.72**	3.5	97 ab	66 ab
c.v. %	8.2				9.1	14.72
LSD_T					19	23

* Tendency to differ from control ($P < 0.1$)
** Significant difference from control ($P < 0.5$)
Mine C 3/95
Mine B 3/95

TABLE 4.55 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of triticale cultivars (Figure 4.12, p. 139)

Crop Cultivar	Treatment[1]			Dry mass of top growth/ 10 plants g	Relative Growth %
		EC[2] mSm^{-1}	Sulphate[3] mgℓ^{-1}		
Triticale Cloc 1[4]	1.	97	226	0.33	100
	2.	263	1500	0.36	112
	3.	330	2000	0.22	68
	4.	332	2150	0.27	83
	5.	338	2300	0.29	88
	6.	349	2500	0.26	80
	7.	364	3000	0.29	88
	8.	398	4000	0.36	112
	9.	473	5000	0.32	99
	10.	507	6000	0.30	92
	11.	352	2500	0.23	72
	12.	424	3000	0.18**	55**
	13.	572	4000	0.24	74
	14.	782	5000	0.25	78
c.v. 31.9%					
Triticale Rex	1.	97	226	0.42	100
	2.	263	1500	0.36	87
	3.	330	2000	0.38	92
	4.	332	2150	0.35	85
	5.	338	2300	0.33	79
	6.	349	2500	0.37	88
	7.	364	3000	0.39	93
	8.	398	4000	0.40	95
	9.	473	5000	0.42	100
	10.	507	6000	0.37	90
	11.	352	2500	0.34	82
	12.	424	3000	0.36	88
	13.	572	4000	0.36	86
	14.	782	5000	0.32*	77*
c.v. 20.0%					

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

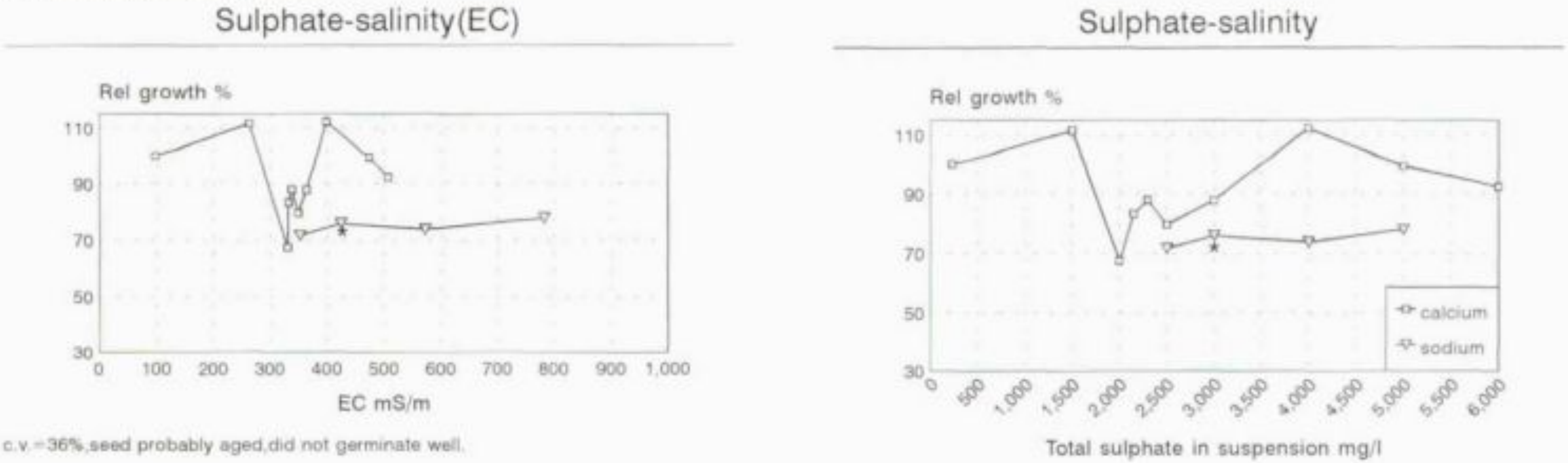
[1] Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.

[2] EC electrical conductance measured in supernatant of treatment solutions.

[3] Total sulphate in suspension.

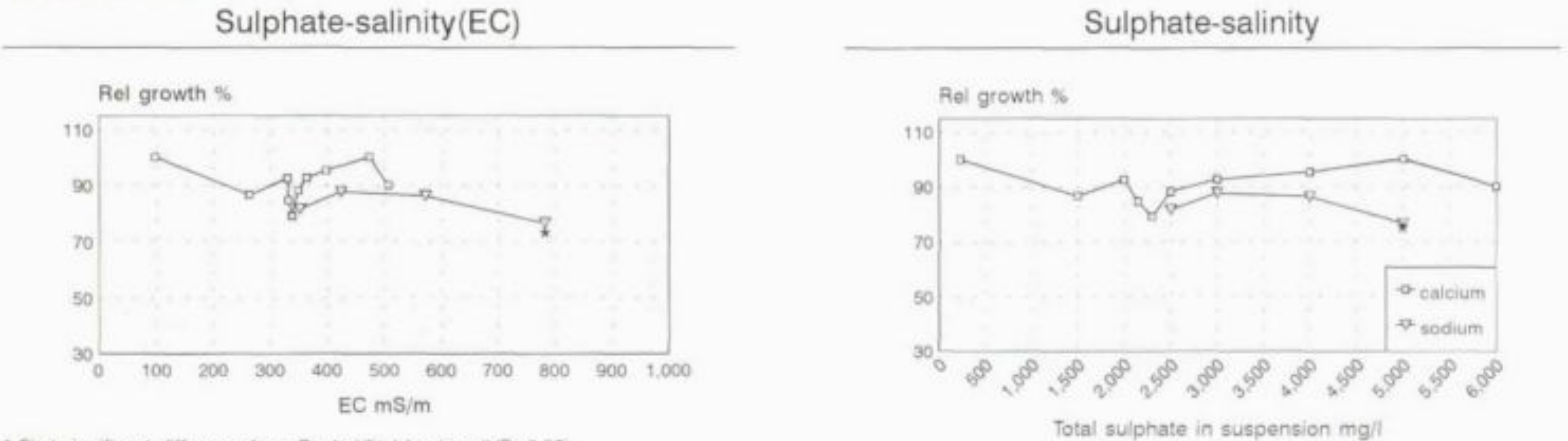
[4] High variation probably due to age of seed. Numbers of plants per container varied.

Triticale Cloc1



c.v.=36%,seed probably aged,did not germinate well.

Triticale Rex



* First significant difference from Control(first treatment)(P<0.05)

Legend:Ca=salinity increased mainly with gypsum;Na=salinity increased mainly with Na-sulphate

FIGURE 4.12 **The influence of increasing concentrations of a simulated high sulphate mine water on the seedling growth of triticale Cloc 1 (top) and triticale Rex (bottom) in a growth chamber**

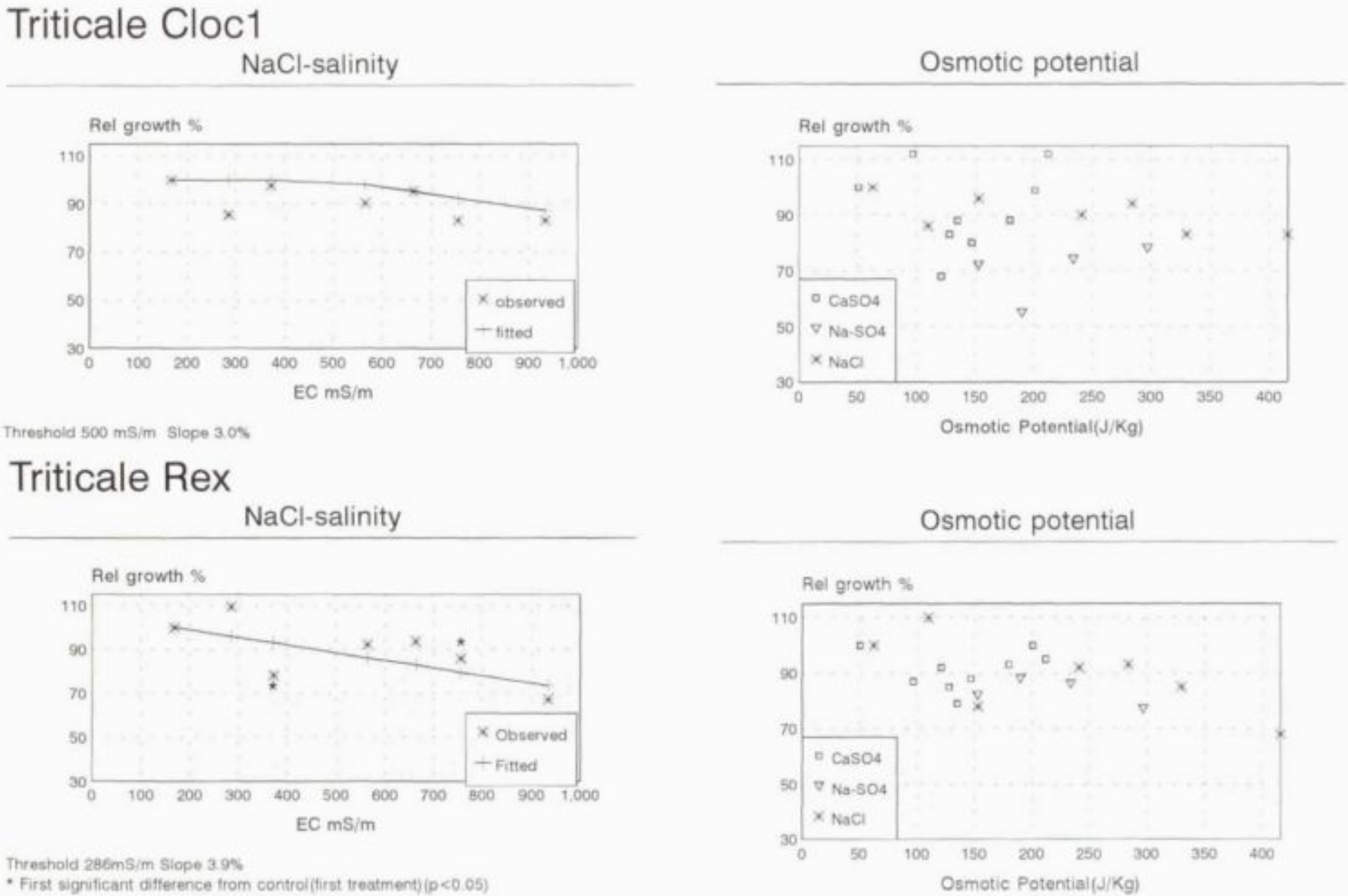
TABLE 4.56 **The influence of a gradient of a simulated sodic-saline mine water on the seedling top growth of triticale cultivars (Figure 4.13, p. 141)**

Crop Cultivar	Treatment				Dry mass of top growth/ 10 plants	Relative Growth
	EC[1]	Na	Cl	SO_4		
	mSm^{-1}	$mmol\ell^{-1}$			g	%
Triticale	1. 168	0.02	0.02	12	0.41	100
Cloe 1	2. 286	10	10	12	0.35	86
	3. 382	20	16	13.8	0.40	96
	4. 565	40	29	17.5	0.37	90
	5. 664	50	35	19.3	0.39	94
	6. 756	60	42	21.1	0.34	83
	7. 934	80	54	24.8	0.34	83
c.v. 16.1%						
Triticale	1. 168	0.02	0.02	12	0.64	100
Rex	2. 286	10	10	12	0.70	110
	3. 382	20	16	13.8	0.50	78**
	4. 565	40	29	17.5	0.59	92
	5. 664	50	35	19.3	0.60	93
	6. 756	60	42	21.1	0.55	85**
	7. 934	80	54	24.8	0.43	68**
c.v. 9.9%						
LSD$_{y}$					0.08	

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. EC electrical conductance measured in supernatant of treatment solutions.



Triticale Cloc1

NaCl-salinity

Osmotic potential

Threshold 500 mS/m Slope 3.0%

Triticale Rex

NaCl-salinity

Osmotic potential

Threshold 286mS/m Slope 3.9%

* First significant difference from control(first treatment)(p<0.05)

FIGURE 4.13 The influence of increasing concentrations of a simulated sodic-saline mine water on the seedling growth of Triticale Cloc 1 and Rex in a growth chamber

RYE
RYEGRASS

Germination and Seedling Growth

TABLE 4.57 The influence of two mine waters on the germination percentage of rye and ryegrass cultivars

Cultivars	Germination %			Relative germination %		c.v. %
	Deionized water	Mine C	Mine B	Mine C	Mine B	
RYE						
1. SSR 727	88	93	92	106	105	6.4
2. SSR 729	95	98	95	103	100	2.7
3. SSR 1[1]	63	60	53**	95	84**	16.6
4. Henoch	98	96	94	98	96	2.46
RYEGRASS						
1. Macho	75	71	70	95	93	10.26
2. Dargle	86	85	83	99	97	6.52
3. Apollo 64	94	93	95	99	101	2.94
4. Midmar	95	93	96	98	101	4.49

c.v. 6.06%

1. The low germination of SSR 1 could be due to aged seed.

TABLE 4.58 The influence of two mine waters on the seedling top growth of rye and ryegrass cultivars

Cultivars	Growth masses/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
RYE						
1. SSR 727	0.82	0.75	0.36**	4.9	91 a	43 ab
2. SSR 729	0.70	0.68	0.38**	14.1	98 a	54 a
3. SSR 1	0.65	0.65	0.28**	9.8	100 a	43 ab
4. Henoch	0.61	0.61	0.26**	19.3	104 a	43 ab
RYEGRASS						
1. Macho	0.55	0.48	0.19**	18.9	88 a	35 bc
2. Dargle	0.24	0.24	0.12**	14.7	100 a	52 a
3. Apollo 64	0.40	0.36	0.12**	9.9	89 a	30 bc
4. Midmar	0.33	0.25	0.06**	33.1	75 a	21 c
c.v.	13.4				19.1	17.2
LSD_T					40	16

* Tendency to differ from control (P < 0.1)
** Significant difference from control (P < 0.5)
Mine C 3/95
Mine B 3/95

TABLE 4.59 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of rye SSR 1[4] (Figure 4.14, p. 144)

Crop Cultivar	Treatment[1]		Dry mass of top growth/ 10 plants	Relative Growth
	EC[2] mSm^{-1}	Sulphate[3] mgℓ^{-1}	g	%
Rye SSR 1	1. 97	226	0.63	100
	2. 263	1500	0.58	91
	3. 330	2000	0.57	90
	4. 332	2150	0.54	86
	5. 338	2300	0.57	91
	6. 349	2500	0.55	87
	7. 364	3000	0.58	92
	8. 398	4000	0.57	90
	9. 473	5000	0.61	96
	10. 507	6000	0.48 *	76*
	11. 352	2500	0.52	82
	12. 424	3000	0.41 **	65**
	13. 572	4000	0.48 *	76*
	14. 782	5000	0.38 **	60**

c.v. 22.3%

TABLE 4.60 The influence of a gradient of simulated sodic-saline mine water on the seedling top growth of rye SSR 1 (Figure 4.14, p. 144)

Crop Cultivar	Treatment				Dry mass of top growth/ 10 plants	Relative Growth
	EC	Na	Cl	SO$_4$		
	mSm^{-1}	mmolℓ^{-1}			g	%
Rye SSR 1	1. 228	0.02	0.02	12	0.67	100
	2. 336	10	10	12	0.70	105
	3. 434	20	16	13.8	0.67	100
	4. 610	40	29	17.5	0.58*	88*
	5. 694	50	35	19.3	0.50**	75**
	6. 780	60	42	21.1	0.45**	68**
	7. 946	80	54	24.8	0.47**	71**

c.v. 9.9%

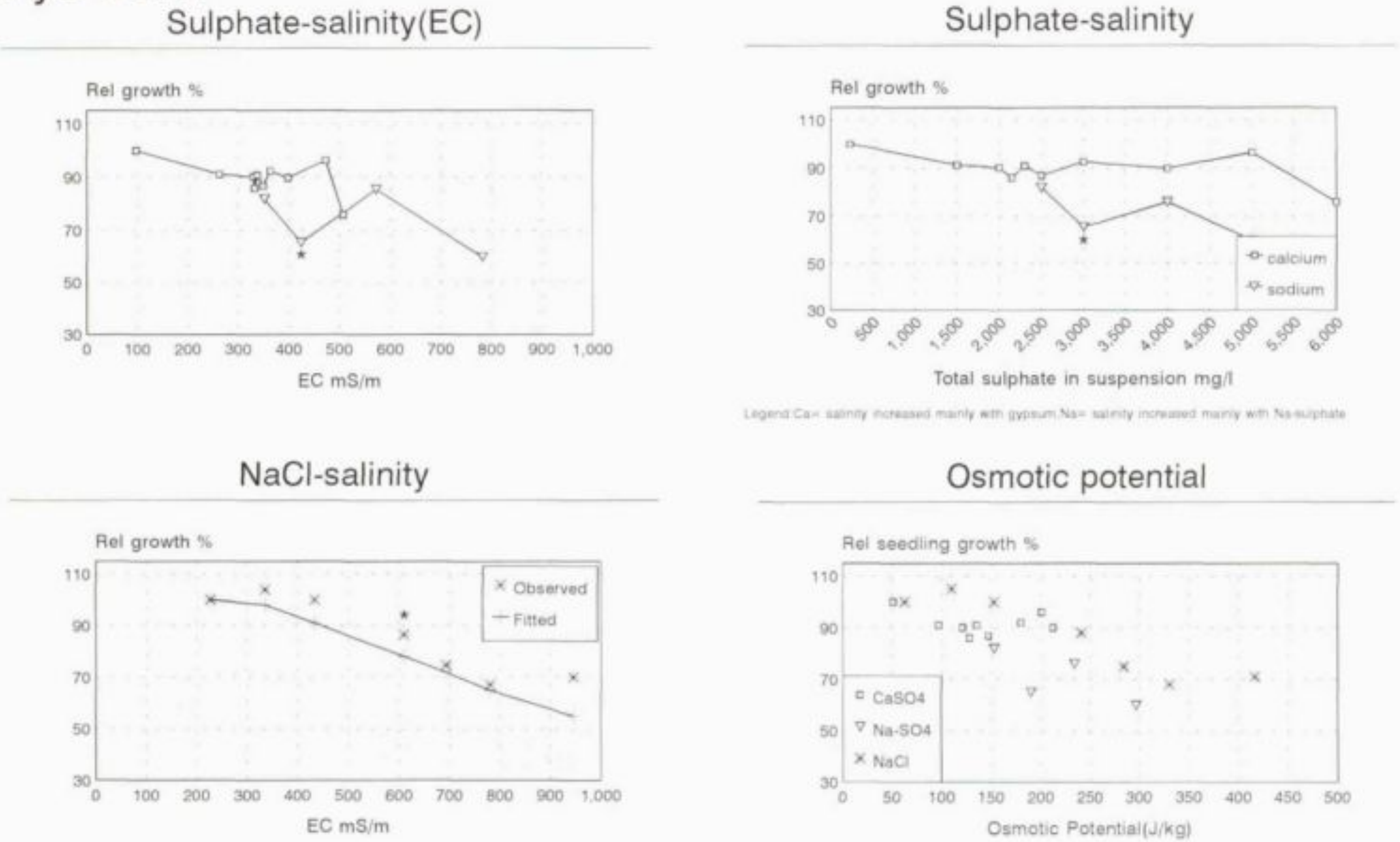
LSD$_T$ 0.08

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatments 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.
4. Did not germinate very well. possibly due to the age of the seed - high variation.

Rye SSR1



Legend:Ca= salinity increased mainly with gypsum.Na= salinity increased mainly with Na-sulphate

Threshold 339mS/m Slope 6.12%

* First significant difference from control(first treatment)(P<0.05)

FIGURE 4.14 **The influence of increasing concentrations of a simulated high sulphate (top) and sodic-saline (bottom) mine water on the seedling growth of Rye SSR1 in a growth chamber**

TABLE 4.61 **The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of ryegrass cultivars (Figure 4.15, p. 146)**

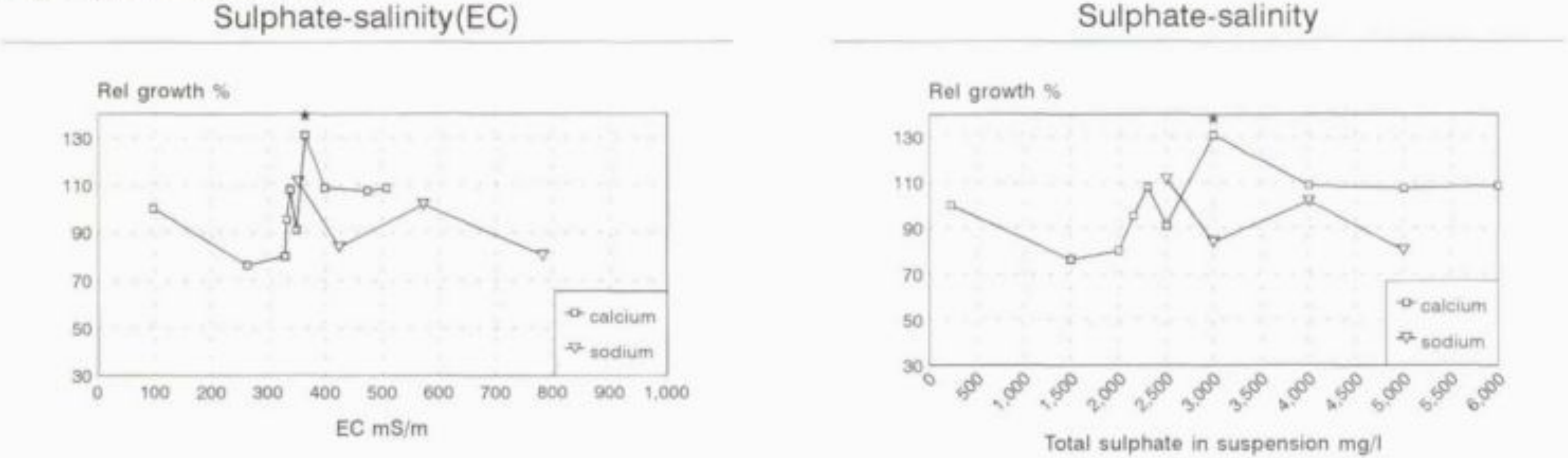
Crop Cultivar	Treatment[1]			Dry mass of top growth/ 10 plants g	Relative Growth %
		EC[2] mSm^{-1}	Sulphate[3] mgℓ^{-1}		
Ryegrass Midmar	1.	97	226	0.06	100
	2.	263	1500	0.04	76
	3.	330	2000	0.04	80
	4.	332	2150	0.05	95
	5.	338	2300	0.06	108
	6.	349	2500	0.05	91
	7.	364	3000	0.07**	131**
	8.	398	4000	0.06	109
	9.	473	5000	0.06	107
	10.	507	6000	0.06	109
	11.	352	2500	0.06	111
	12.	424	3000	0.05	84
	13.	572	4000	0.06	102
	14.	782	5000	0.04	81
c.v. 18.5%					
Ryegrass Dargle	1.	97	226	0.04	100
	2.	263	1500	0.04	99
	3.	330	2000	0.05	111
	4.	332	2150	0.06	131
	5.	338	2300	0.06	147
	6.	349	2500	0.07**	169**
	7.	364	3000	0.07**	154**
	8.	398	4000	0.05	116
	9.	473	5000	0.05	131
	10.	507	6000	0.05	122
	11.	352	2500	0.07**	159**
	12.	424	3000	0.07**	156**
	13.	572	4000	0.05	124
	14.	782	5000	0.06**	150**
c.v. 23.8%					

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

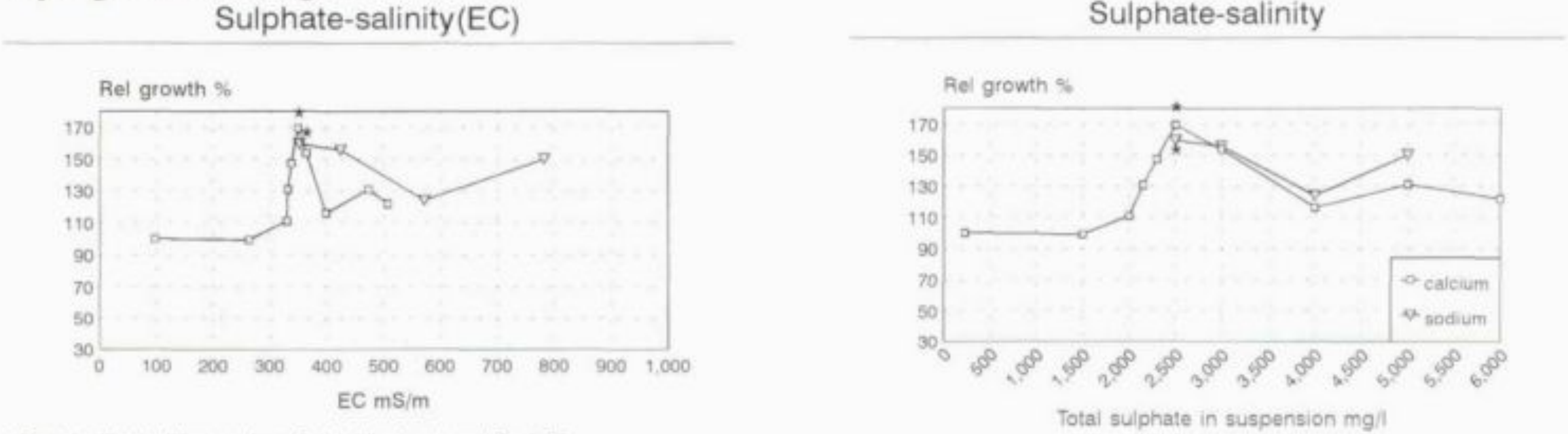
** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.

Ryegrass Midmar



Ryegrass Dargle



* First significant difference from Control (first treatment) (P=0.05)

Legend: Ca=salinity increased mainly with gypsum. Na=salinity increased mainly with Na-sulphate

FIGURE 4.15 The influence of increasing concentrations of a simulated high sulphate mine water on the seedling growth of ryegrass Midmar (top) and Dargle (bottom) in a growth chamber

TABLE 4.62 **The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of ryegrass Midmar (Figure 4.16, p. 148)**

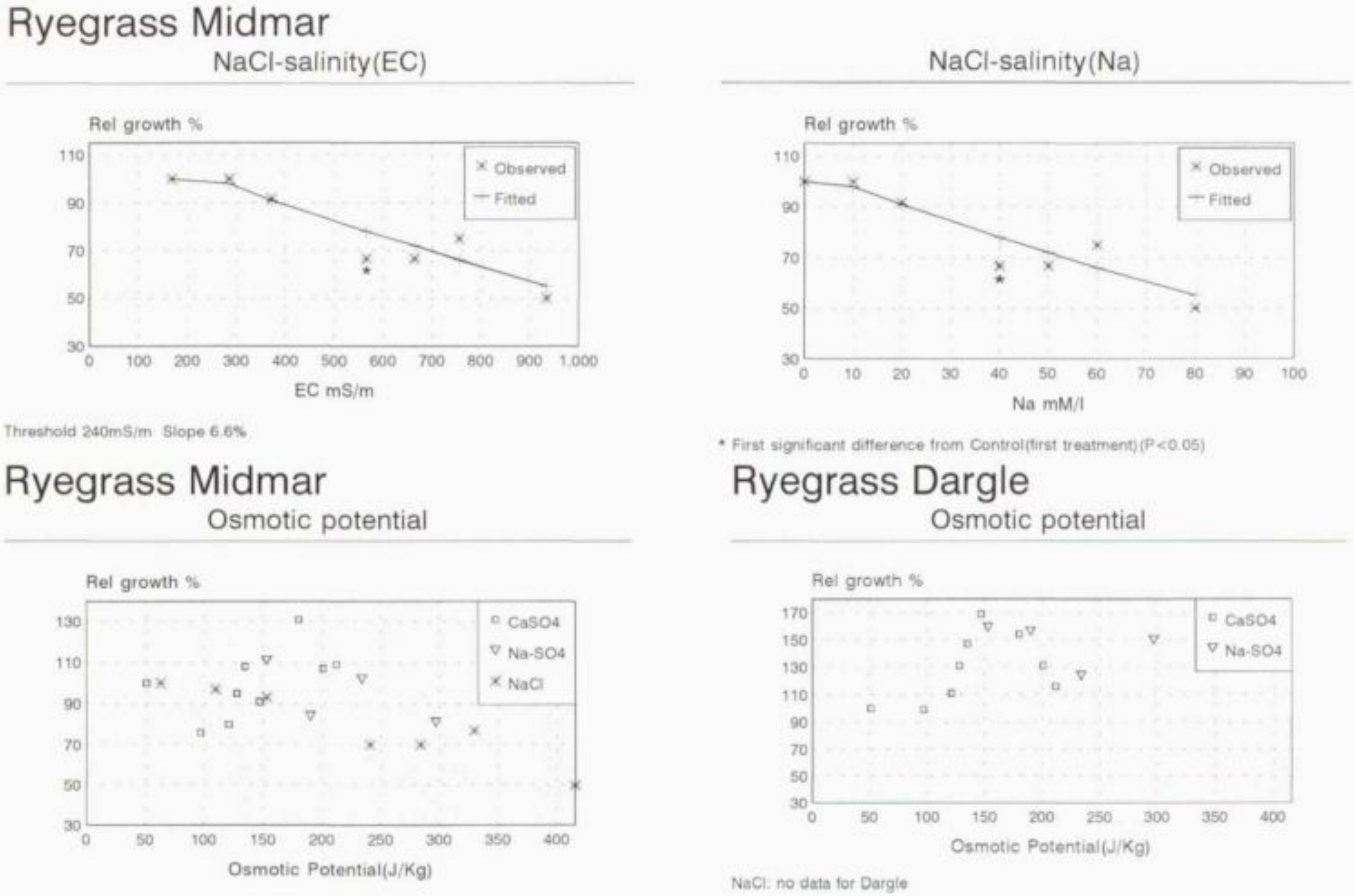
Crop Cultivar	Treatment				Dry mass of top growth/ 10 plants	Relative Growth
	EC[1]	Na	Cl	SO_4		
	mSm^{-1}	$mmol\ell^{-1}$			g	%
Ryegrass Midmar	1. 168	0.02	0.02	12	0.13	100
	2. 286	10	10	12	0.12	97
	3. 382	20	16	13.8	0.12	93
	4. 565	40	29	17.5	0.09**	70**
	5. 664	50	35	19.3	0.09**	70**
	6. 756	60	42	21.1	0.10**	77**
	7. 934	80	54	24.8	0.06**	50**

c.v. 15.2%

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. EC electrical conductance measured in supernatant of treatment solutions.



Ryegrass Midmar

NaCl-salinity(EC)

NaCl-salinity(Na)

Threshold 240mS/m Slope 6.6%

* First significant difference from Control(first treatment)(P<0.05)

Ryegrass Midmar

Osmotic potential

Ryegrass Dargle

Osmotic potential

NaCl: no data for Dargle

FIGURE 4.16 **The influence of increasing concentrations of a simulated sodic-saline mine water on the seedling growth of ryegrass in a growth chamber**

4. TEMPERATE PERENNIALS

Vegetative Growth

Table 4.63 Growth parameters for temperate perennials

Pastures	Treatment	Leaves wet mass g/pot[1]	Leaves dry mass g/pot	Stems		Total Dry mass Top growth g/pot	Rel. Top growth %	Roots dry mass g/pot	Leaf area cm^2/pot
				No/pot	Dry mass g/pot				
6. Lucerne[2] *Medicago sativa* PAN 4860	Control	51.73	8.65	30	7.68	16.33	100	3.97	
		43.08	5.98	-	7.90	13.88			2969.67
	Mine A	60.06*	11.55**	31	9.32*	20.87**	129**	5.85**	
		55.34	8.39	-	9.83	18.22			3364.25
	Mine B	42.80	7.66	24	6.49	14.15	95	2.91**	
		41.54	5.89	-	8.56	14.45			2412.36
c.v. %		14.64	14.79	-	16.02	13.77		12.47	24.10
7. Tall Fescue *Festuca elatior* Au Triumph	Control	163.58	27.83	87	11.44	39.27	100	8.77	5466.39
	Mine A	194.85**	31.70	91	15.70**	47.40*	121*	9.15	7645.16***
	Mine B	251.07***	40.13***	110**	15.78**	55.91***	142***	7.98	9844.86***
c.v. %		7.86	10.85	12.39	15.41	11.47		19.54	8.64
8. Crown Vetch *Coronilla varia* var. Penngift	Control	113.97	19.75		6.25	25.99	100	6.80	4388.53
	Mine A	100.76	17.20		4.60*	21.80	84	5.69	4174.98
	Mine B	59.07***	9.56***		2.69***	12.25***	47***	3.87**	2279.87***
c.v. %		13.48	16.88		26.46	18.53		31.95	13.03
9. Cocksfoot *Dactylis glomerata* var. Hera	Control	187.75	32.93	157	11.33	44.27	100	9.66	9738.06
	Mine A	182.62	31.68	144	12.98	44.66	101	7.61**	9600.60
	Mine B	159.05*	29.46	114**	11.93	41.39	94	4.64***	8342.67*
c.v. %		10.61	9.88	14.87	24.79	13.56		12.35	10.19
10. White Clover *Trifolium repens* Dusi	Control	62.91	11.72		15.97	27.69	100	4.19	3760.80
	Mine A	76.69	14.30		20.26**	34.56**	125**	3.63	4294.70
	Mine B	35.59**	5.27***		5.63***	10.90***	39**	1.30***	1790.49*
c.v. %		20.41	19.58		16.68	16.98		15.85	16.20

* Tends to significant difference from control $P<0.10$
** Significant difference from control $P<0.05$
*** Highly significant difference from control $P<0.01$
Mine A 5/94
Mine B 4/94

[1] 3 plants per pot

[2] Masses for two harvestings given. Total of two harvestings used for statistical analyses; the first cutting includes the seedling growth on a standard nutrient solution. When salinization was introduced there were 2 shoots 10-20 cm long.

Table 4.64 Growth ratios for temperate perennials

Pastures	Treat-ment	Leaves/ Stems	Tops/ Roots	mg H_2O/cm^2 leaf area	Relative Top-growth %
6. Lucerne *Medicago sativa* PAN 4860	Control	0.95	7.63	12.49	100
	Mine A	1.06	7.90	13.96	129**
	Mine B	0.89	9.87***	14.78**	95
7. Tall Fescue *Festuca elatior* Au Triumph	Control	2.44	4.56	24.61	100
	Mine A	2.04	5.21	21.62	121*
	Mine B	2.57	7.14***	21.45	142***
8. Crown Vetch *Coronilla varia* var. Penngift	Control	3.19	4.17	21.55	100
	Mine A	3.81**	3.88	19.99	84
	Mine B	3.77*	3.70	21.63	47***
9. Cocksfoot *Dactylis glomerata* var. Hera	Control	3.10	4.60	15.91	100
	Mine A	2.49**	5.95*	15.75	101
	Mine B	2.52*	9.02***	15.52	94
10. White Clover *Trifolium repens* Dusi	Control	0.73	6.57	13.60	100
	Mine A	0.71	9.63***	14.42	125**
	Mine B	0.95	8.53***	16.85*	39**
c.v. %		20.26	15.59	12.89	12.89

* Tends to significant difference from control $P<0.10$
** Significant difference from control $P<0.05$
*** Highly significant difference from control $P<0.01$

Ch4-Tab4.64

Table 4.65 Concentration of Ca, Mg, SO_4, Na and Cl in the top growth of perennial temperate crops with two types of mine water[1]

Pastures	Treat-ment	Ca		Mg		SO_4		Na		Cl	
		%									
		Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems
1. Lucerne *Medicago sativa* PAN 4860	Control	0.83	0.49	0.53	0.44	1.03	0.56	0.06	0.1	0.04	0.05
	Mine A	1.10	0.63	0.42	0.11	1.68	1.40			0.25	-
	Mine B	0.77	0.57	0.44	0.40	0.98	0.79	2.01	1.67	2.79	2.53
2. Tall Fescue *Festuca arundinaceae* Au Triumph	Control	2.48	1.08	0.42	0.26	0.70	0.63	0.27	0.1	-	0.03
	Mine A	4.14	1.95	0.25	0.36	2.04	2.12			0.29	0.14
	Mine B	2.46	1.18	0.37	0.21	0.99	0.79	0.38	1.13	0.89	0.84
3. Crown Vetch *Coronilla varia* Penngift	Control	0.88	0.59	0.43	0.26	1.08	0.57	0.07	0.07	0.03	0.07
	Mine A	1.29	0.87	0.34	0.16	1.68	1.44			0.16	0.28
	Mine B	0.61	0.55	0.30	0.27	0.98	0.72	1.51	1.56	1.47	2.55
4. Cocksfoot *Dactylis glomerata* Hera	Control	1.27	1.26	0.33	0.28	1.06	0.66	0.22	0.10	0.08	0.04
	Mine A	4.73	3.08	0.29	0.22	5.20	2.96			0.27	0.26
	Mine B	0.57	1.66	0.35	0.25	1.31	1.00	0.80	2.08	0.84	1.18
5. White Clover *Trifolium repens* Dusi	Control	0.49	0.38	0.26	0.18	1.14	0.52	0.02	0.04	0.06	0.09
	Mine A	1.17	0.65	0.23	0.19	2.32	1.68			0.14	0.19
	Mine B	1.69	0.34	0.29	0.22	1.31	0.68	1.79	0.99	2.04	3.04

Mine A 5/94
Mine B 4/94
1. Both these waters were diluted by heavy rain.

Ch4-Tab4.65

Table 4.66 Total uptake of Ca, Mg, SO_4, Na and Cl in the top growth of perennial temperate crops with two types of mine water

Crop Cultivar	**Treatment**	**Ca**		**Mg**		**SO_4**		**Na**		**Cl**	
		g/pot[1]									
		Leaves	**Stems**	**Leaves**	**Stems**	**Leaves**	**Stems**	**Leaves**	**Stems**	**Leaves**	**Stems**
1. Lucerne *Medicago sativa* PAN 4860	Control	0.12	0.08	0.08	0.07	0.15	0.09	0.01	0.02	0.006	0.008
	Mine A	0.22	0.12	0.08	0.02	0.33	0.27			0.05	–
	Mine B	0.10	0.09	0.06	0.06	0.13	0.12	0.27	0.25	0.38	0.38
2. Tall Fescue *Festuca elatior* Au Triumph	Control	0.69	0.12	0.12	0.03	0.19	0.07	0.08	0.01	–	0.003
	Mine A	1.31	0.31	0.08	0.06	0.65	0.33			0.09	0.02
	Mine B	0.99	0.19	0.15	0.03	0.40	0.12	0.15	0.18	0.36	0.13
3. Crown Vetch *Coronilla varia* Penngift	Control	0.17	0.04	0.08	0.02	0.21	0.04	0.01	0.004	0.006	0.004
	Mine A	0.22	0.04	0.06	0.01	0.29	0.07		0.04	0.03	0.01
	Mine B	0.06	0.01	0.03	0.01	0.09	0.02	0.14		0.14	0.07
4. Cocksfoot *Dactylis glomerata* Hera	Control	0.40	0.14	0.10	0.03	0.34	0.07	0.07	0.01	0.03	0.005
	Mine A	1.50	0.40	0.09	0.03	1.65	0.38			0.09	0.03
	Mine B	0.17	0.20	0.10	0.03	0.39	0.12	0.24	0.25	0.25	0.14
5. White Clover *Trifolium repens* Dusi	Control	0.06	0.06	0.03	0.03	0.13	0.08	0.002	0.006	0.007	0.01
	Mine A	0.17	0.13	0.03	0.04	0.33	0.34			0.02	0.04
	Mine B	0.09	0.02	0.02	0.01	0.07	0.04	0.09	0.06	0.11	0.17

Mine A 5/94
Mine B 4/94
[1] 3 plants per pot

LUCERNE

Germination and Seedling Growth

TABLE 4.67 The influence of two mine waters on the germination percentage of lucerne cultivars

Cultivars	Germination %			c.v. %	Relative germination %	
	Deionized water	Mine C	Mine B		Mine C	Mine B
1. PAN 4860	91	90	90	7.4	99	99
2. PAN 4581	93	96	94	3.9	104	102
3. Baronet	93	95	93	4.5	103	101
4. Topaz	71	63*	75	9.8	89*	106
5. Diamond	98	93	87**	4.0	94	88**

c.v. 5.9%

TABLE 4.68 The influence of two mine waters on the seedling top growth of Lucerne cultivars

Cultivars	Top growth/10 plants g			c.v. %	Relative growth %	
	Control	Mine C	Mine B		Mine C	Mine B
1. PAN 4860	0.46	0.34**	0.10**	8.0	72 ab	22 a
2. PAN 4581	0.36	0.19**	0.07**	15.4	55 b	21 a
3. Baronet	0.48	0.34**	0.10**	2.3	71 ab	21 a
4. Topaz	0.45	0.33**	0.11**	5.7	71 ab	25 a
5. Diamond	0.52	0.39**	0.11**	2.6	76 a	22 a
c.v. %	6.9				10.9	15.1
LSD$_T$					19	8

* Tendency to differ from control (P < 0.1)

** Significant difference from control (P < 0.5)

Mine C 3/95

Mine B 3/95

TABLE 4.69 The influence of a gradient of a simulated sulphate saline mine water on the seedling top growth of Lucerne cultivar PAN 4860 (Figure 4.17, p. 155)

Crop Cultivar	Treatment[1]			Dry mass of top growth/ 10 plants	Relative Growth
		EC[2] mSm^{-1}	Sulphate[3] mgℓ$^{-1}$	g	%
Lucerne PAN 4860	1.	97	226	0.23	100
	2.	263	1500	0.22	93
	3.	330	2000	0.21	90
	4.	332	2150	0.22	93
	5.	338	2300	0.19**	82**
	6.	349	2500	0.19**	80**
	7.	364	3000	0.18**	76**
	8.	398	4000	0.21	89
	9.	473	5000	0.21	89
	10.	507	6000	0.18**	78**
	11.	352	2500	0.21	91
	12.	424	3000	0.19**	81**
	13.	572	4000	0.18**	78**
	14.	782	5000	0.16**	67**

c.v. 11.8%

TABLE 4.70 The influence of a gradient of simulated sodic-saline mine water on the seedling top growth of Lucerne PAN 4860 (Figure 4.17, p. 155)

Crop Cultivar	Treatment					Dry mass of top growth/ 10 plants	Relative Growth
		EC	Na	Cl	SO_4		
		mSm^{-1}	mmolℓ$^{-1}$			g	%
Lucerne PAN 4860	1.	168	0.02	0.02	12	0.29	100
	2.	286	10	10	12	0.24**	82**
	3.	372	20	16	13.8	0.23**	79**
	4.	565	40	29	17.5	0.24**	84**
	5.	664	50	35	19.3	0.21**	72**
	6.	756	60	42	21.1	0.17**	59**
	7.	934	80	54	24.8	0.19**	66**

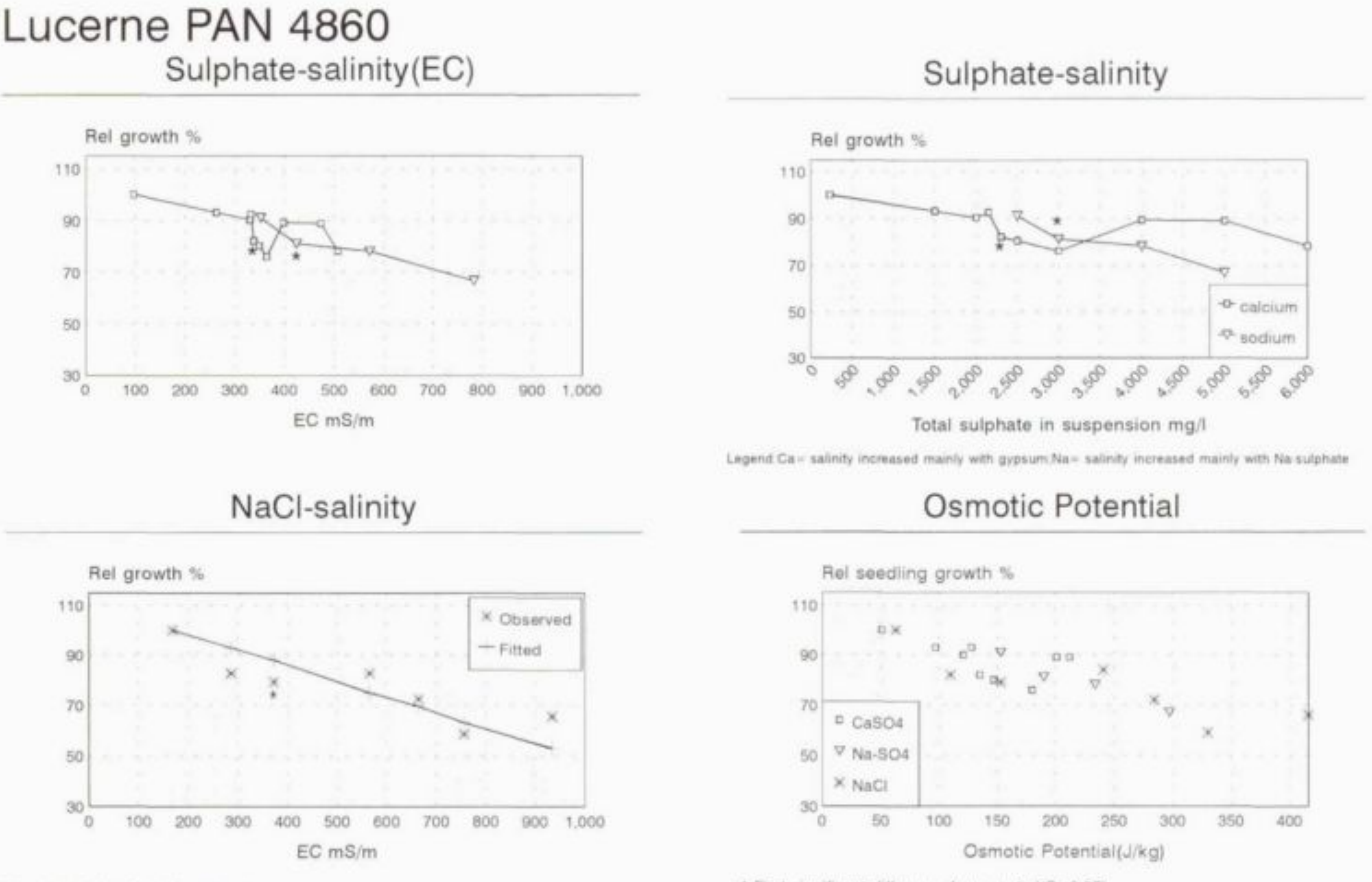
c.v. 9.8%

LSD$_P$ 0.03

* Tendency to differ from control (Treatment 1) ($P < 0.1$).

** Significant difference from control ($P < 0.05$).

1. Treatment 1-10 salinity with mainly $CaSO_4$; 11-14 with added Na_2SO_4.
2. EC electrical conductance measured in supernatant of treatment solutions.
3. Total sulphate in suspension.



Legend Ca = salinity increased mainly with gypsum Na = salinity increased mainly with Na sulphate

Threshold 170 mS/m Slope 6.2%

* First significant differance from control(P<0.05)

FIGURE 4.17 **The influence of increasing concentrations of a simulated high sulphate (top) and a sodic-saline (bottom) mine water on the seedling growth (0-18 days) of Lucerne PAN 4860 in a growth chamber**

CHAPTER 5

FIELD TRIAL AND SCREENING OF POTENTIAL FORAGE SPECIES

5.1 INTRODUCTION

Whereas previous chapters discuss the laboratory screening of agronomic and pasture species for tolerance to different mine waters, this chapter describes the screening trial conducted under field conditions in cooperation with the Kromdraai colliery. The field trial included a wide range of agronomic and pasture crops and potential forage species. Each species was irrigated with varying amounts of mine water of the same quality. In addition, the long-term impact of lime treated AMD on the soil was investigated.

5.2 LOCATION AND ENVIRONMENTAL CHARACTERISTICS

A field screening trial was established at Kromdraai opencast mine (lat. 25°48' S, long. 29°05' E, alt. 1510 m) in the highveld region, close to Witbank (Mpumalanga province).

The climate of the region is one of summer rainfall with an average rainfall of about 690 mm per annum. Carolina and Bethal are the nearest weather stations where historic data on air temperature, wind speed and direction are available. The average summer temperature range is from 12°C to 29°C with an average temperature of 20°C. The winter temperature varies from -3°C to 20°C with an average temperature of 9°C, the first frost being experienced in May and the last in August. The prevailing winds are from the Northwest with an average wind speed of 2.9 m s^{-1}. There are no suitable records of extreme weather conditions.

In Table 5.1 (p. 177), mean monthly rainfall and mean monthly evaporation data, measured in the Witbank area, are presented. Mean monthly rainfall has been measured at the Kromdraai liming plant from 1982 to 1992. Mean monthly pan evaporation has been measured at the Witbank Dam for the 1963-1989 period. Climatological data have been made available by S.A.C.E. (1993).

The soil is a sandy acid Hutton form 1200 (Soil classification working group, 1991), very common in the highveld region. It is over 2 m deep with good drainage characteristics. Prior to establishment of the trial, soil samples were taken on a grid basis to ascertain uniformity. Average data of soil physical and chemical properties are given in Tables 5.2 and 5.3 (p. 178). As there is a deep ground water table, no salt feeding of the root-zone was expected from deeper soil layers (van Schilfgaarde, 1976). Volumetric water content at field capacity (FC) and permanent wilting point (PWP) and bulk density values are represented in Table 5.4 (p. 179) for 20 cm layers down to 140 cm. FC was gravimetrically estimated, sampling from a plastic covered soil profile which was previously watered. Water content at PWP (-1500 J kg^{-1}) was determined in the laboratory.

5.3 EXPERIMENTAL SCHEME

The experimental field was 100 x 75 m in size. Each species was cropped on plots of 20 x 15 m as indicated in Figure 5.1 (p. 215). Potential forage species were grown on an adjacent plot of 75 x 20 m. Slope on the field necessitated the building of cut-off berms which facilitated drainage of excessive rain water into a shaped waterway down the one side of the field. The trial was carried out during three cropping seasons (from 1993 to 1996).

In a previous study (Hanks, Keller, Rasmussen & Wilson, 1976), a line source sprinkler irrigation system was successfully applied in order to properly manage both water and salt applications. This methodology has also been applied in this work and a stationary line source sprinkler irrigation system was set up on the experimental field.

Water from the liming plant at Kromdraai Colliery is accumulated in a dam, from where it is delivered to the users through a conveyance pressure pipe system and hydrants. The water source for the experimental field was provided through a main line which was directly connected to the conveyance pipe.

The experimental field irrigation scheme is presented in Figure 5.2 (p. 216). Each plot was provided with a sprinkler line control box containing a pressure regulator, a volumeter and a solenoid valve. Automated opening and closing of valves was set by regulating a clockwork system of potentiometers contained in the main irrigation system control box.

5.4 SCREENING OF POTENTIAL FORAGE SPECIES

5.4.1 Methodology

5.4.1.1 Screening of vegetative perennial sub-tropical grasses for adaptation to local (Mpumalanga Highveld) climatic and water conditions

During the 1993/94 season vegetative material of five perennial sub-tropical grasses was planted in replicated rows (20 m long) at right angles to a line-source irrigation system. In addition to basic liming and phosphate fertilization, applied before planting, nitrogen and potassium were applied at the rate of 100 kg N and 100 kg K ha^{-1} $season^{-1}$. During the 1994/95 season the upright growing Banagrass (*Pennisetum purpureum* x *P. glaucum*) was harvested twice, while the creeping species (Hybrid *Cynodon* K11, *Digitaria eriantha* P66, *Panicum repens* - torpedograss, *Paspalum vaginatum* - beach paspalum) were harvested only once, having allocated a major portion of photosynthate to horizontal spread in the early season. In the 1995/96 season the material was well established and three harvests (December, March and May) were obtained. While yields for banagrass were expressed in terms of g/tuft, those for the creeping grasses were harvested from quadrats and expressed as g m^{-1}. In the presentation of results the relative performance of species, rather than absolute yields per hectare, were emphasized. At the end of the 1995/96 season the soils on well irrigated, medium irrigated and non-irrigated portions of the line-source gradient were sampled at depths of 0-

20 cm, 20-40 cm and 40-60 cm. These samples were analysed for pH(H_2O), Ca, SO_4, Mg, P and K.

5.4.1.2 Screening of seeded perennial sub-tropical grasses for adaptation to local climatic and water conditions

In 1993/94 a range of *Bothriochloa*, *Eragrostis* and *Panicum* species and cultivars were planted in replicated 20 m rows at right angles to the line-source irrigation, using seedling plugs. Due to initial problems with irrigation an uneven stand was obtained and in the spring of 1994/95 blanks were filled and seedlings of *Digitaria eriantha*, *Cenchrus ciliaris* and *P. maximum* Gatton (which are the standard control species for such areas) were also planted. Although variability was high the yields were determined at the two ends of the irrigation spectrum (well irrigated and rainfed) in 1994/95 and expressed as g $tuft^{-1}$. During 1995/96 tufts were better established and three to four harvests (October, December, March and May) were possible at three points along the water gradient. Fertilization and liming was uniform throughout and were applied at the same rates as on the vegetative species. At the end of 1995/96 soils were sampled and analysed as described above.

5.4.1.3 Screening of fodder trees and shrubs for adaptation to local climatic and water conditions

During the latter half of the 1993/94 growing season a selection of fodder trees and shrubs, of both tropical and temperate origin, were planted in rows at right angles to the line-source irrigation. In the spring of 1994/95 dead plants were replaced and living plants hedged to a height of 50 cm, where applicable. Seasonal yields (total and edible proportions) were recorded at the end of the 1994/95 season and on three occasions (November, February and May) during the 1995/96 season. On each occasion "new" plants were harvested along the water gradient. Species such as *Sesbania* were replanted each spring after a virtual total kill each winter, while *Leucaena leucocephala*, which also suffered topkill with slow spring regeneration, was blanked.

At the end of the 1995/96 growing season root systems of surviving species were exposed to determine whether the nature of rooting systems might have a bearing on the above-ground results.

5.4.2 Results and Discussion

5.4.2.1 Vegetative grasses

Data presented in Tables 5.5, 5.6 and 5.7 (pp. 180, 179 & 182) are relevant. Although many reclamationists - and farmers - avoid establishing pastures with vegetative material, because of labour costs, there is no doubt that many of these species are particularly well suited for specific purposes. **Banagrass** - as representative of a wide selection of *Pennisetum* elephant grasses - is particularly well suited for use as a living contour hedgeplant to stabilize slopes. It is also an excellent pasture for use as grazing in summer and winter. In the first full growing season after planting (1994/95) Banagrass was already one of the best performers. Assuming only 5000 plants ha^{-1}, rainfed plants yielded the equivalent of 1.25 t DM ha^{-1} with a rainfall of less than 600 mm. The application of an additional 750 mm of irrigation (giving a total of 1330 mm) increased yields by 180% to 3.6 t DM ha^{-1}. In the second season after planting (1995/96) Banagrass literally stood head and shoulders above all other species evaluated. This season had a very good rainfall (± 1000 mm) and rainfed material yielded 27.6 t ha^{-1} compared with 47.3 t from intermediate irrigation and 52.6 t with full irrigation. It was particularly interesting to note that growth of this species was not detrimentally influenced by a heavy salt deposition on the hairy leaves where full irrigation was applied. The possible effect of such salt deposition on acceptability for livestock would be purely speculative at this stage.

K11, a *Cynodon* hybrid from the USA which is also known as Coast Cross II, **and P66**, a selection from *Digitaria eriantha*, which was identified in research conducted in Ermelo and Pretoria, are both creeping grasses well adapted to a wide range of moisture and temperature conditions. Under local conditions K11 established very much quicker and outperformed P66 in the

1994/95 season, with yields of 2.0 t ha^{-1} and 9.3 t ha^{-1} from rainfed and irrigated plots. This compared with 1.1 t ha^{-1} and 2,6 t ha^{-1} produced by P66. In the 1995/96 season differences between rainfed and irrigated plots and between these two species were less marked. P66 registered yields of 12.8 t and 20.0 t ha^{-1} compared with 11.1 t and 16.8 t ha^{-1} for K11. Irrigation had a marked beneficial effect on both the rate of vegetative cover and yield!

Torpedograss (*Panicum repens*) and **Beach Paspalum** (*Paspalum vaginatum*) clearly do not have the same production potential as the other vegetative species evaluated, but do respond well to (or tolerate) the gypsiferous water used in this trial (lime treated AMD). They are also well adapted to waterways and wetlands and, in contrast to the well drained sandy soil used in this trial, might be expected to do better in a "wetland" situation. In contrast *Pennisetum, Cynodon* and *Digitaria* are not well adapted to such wetland situations.

5.4.2.2 Seeded grasses

In contrast to the vegetative material, which was characterized by relatively uniform establishment, the establishment of these grasses was very variable, with certain species only being planted in 1994/95. In general the response to irrigation in the 1994/95 season was not as marked as that of vegetative grasses, but the response in 1995/96 was much better than expected (Tables 5.5 and 5.6, pp. 180 & 179), given the favourable rainfall conditions in the latter season.

The 1994/95 season was characterized by the very poor results obtained with Smutsfingergrass (*D. eriantha* Irene), Guineagrass (*P. maximum* Gatton) and the disappointing results from Molopo Buffelgrass (*C. ciliaris*). While the latter may be ascribed to the fact that this grass is not that well adapted to the relatively cool Highveld conditions, the results from Irene and Gatton are a result of only being planted in 1994/95. The relative performance of these two grasses improved considerably in 1995/96 and, on the basis of long experience on the Highveld, could be expected to improve further in the third and fourth seasons.

In terms of the relative performance of different seeded species (Table 5.7, p. 182) it is encouraging that there would appear to be a range of perennial summer grasses which are viable alternatives to the standard *Digitaria/Chloris* mixture, which is so widely used by reclamationists on the Mpumulanga Highveld. In the 1995/96 season the top group (Centario, Vencedor and Alamo) had an average production of 48.1 t ha^{-1}, when well irrigated, compared with 24.1 t ha^{-1} under dryland conditions (assuming a population of 15 000 tufts ha^{-1}). The next best group, which included Pollock, Ermelo, Bambatsi, Selection 75 and SDT, produced 20.3 t and 9.6 t ha^{-1} respectively, followed by Burnett, Verde and Gatton averaging 14.0 and 6.9 t ha^{-1} respectively. Molopo, Old World, Irene and Ironmaster were very disappointing with irrigated and dryland yields of only 8.1 and 4.0 t ha^{-1} respectively. The *Bothriochloa* cultivars Spar and Plains were the poorest, yielding only 3.8 t and 3.2 t ha^{-1}. There is little doubt that all four *Panicum* species evaluated are worthy of serious consideration for incorporation into reclamation mixtures. *Eragrostis curvula* also remains a winner for specialist purposes on the Eastern Highveld. Molopo should, however, only be considered for warmer sites (well drained northern aspects) and these particular *Bothriochloa* cultivars are unsuitable. Smutsfingergrass, although very disappointing and relatively slow to establish in this trial, has also been shown, in an adjacent trial, to have a potential comparable with that of Weeping Lovegrass once well established.

In the initial planning it was proposed to investigate the influence of mine water on both crops and soils. Although the latter aspect was not initially regarded as a priority certain soil analyses were made to determine whether soil parameters might be affected by irrigation with gypsiferous water, which might in turn affect plant performance. The results of replicated observations in the grass screening trial are presented in Table 5.8 (p. 183). It is evident from these results that the influence of gypsiferous water was in direct proportion to the level of irrigation and was restricted mainly to pH, Ca and SO_4. The influence with respect to all three parameters was most marked in the surface 20 cm, but was not limited to this cultivated zone. Over time the influence on the deeper horizons of well drained profiles could be additive, making such soils more suitable for crops which might be more sensitive to the chemical status of the sub-soil horizons. Sub-tropical grasses such as those evaluated, would appear to be capable of developing deep root systems on such soils and to be less sensitive to the chemical status of sub-soil horizons.

5.4.2.3 Fodder trees/shrubs

The results obtained with a selection of evergreen temperate and deciduous sub-tropical fodder trees are presented in Tables 5.9, 5.10 and 5.11 (pp. 184 & 185). **The most important finding was that there was no discernable pattern in productivity, which could be linked with the level of irrigation**. Results, therefore, represent the means of samples along the irrigation gradient.

In terms of productivity species such as *Cytisus maderiensis*, *Leucaena leucocephala*, *Lupinus arborea* and *Sesbania sesban*, which were all characterized by sensitivity to winter cold, disease or a poor persistence, generally had a good production over the short term. In contrast *Medicago arborescens* had neither good productivity or good persistence. The most persistent species at this site have proved to be *Albizzia julibrissen*, *Chamaecytisus palmensis*, *Leucaena pulverulenta* and *Teline stenopetala*. Unfortunately the tropical species (*Albizzia* and *L. pulverulenta*) have been very slow to develop and 28 months after planting are still characterized by poor productivity. It has been observed, however, that the coppice regrowth from such harvested plants appears to be very vigorous and the possibilities of using them in hedgerow systems is being actively pursued. At this stage *C. palmensis* and *T. stenopetala* appear to be promising with respect to yield, persistence and leaf retention in the winter. With a shrubby growth form and an acceptable proportion of edible material (Table 5.11, p. 185) these species should also be suited to the production of browse.

With respect to the root distribution of these woody species it was notable that there was little difference between species or level of irrigation. Virtually all roots were concentrated in the upper 25 cm of the profile. With the knowledge that these species are generally characterized by deep root systems it is evident that chemical soil characteristics of the deeper horizons inhibited deep root development. It is a possibility that irrigation with gypsiferous water would improve the chemical status of the sub-soil and hence root penetration (Table 5.8, p. 183).

5.4.3 Conclusions and Recommendations

Sub-tropical perennial grass species which are well adapted to local soil and climatic conditions respond very well to irrigation with gypsiferous water, as typified by lime treated acid mine drainage, on the well drained sandy soil used in this investigation. From the range of species and cultivars evaluated it is evident that reclamationists can incorporate several hitherto unused grasses into seeding mixtures, which will benefit both bio-diversity and productivity. This investigation did, however, place the emphasis on plant x water interaction and the influence on soil parameters received minimal attention. It was, however, evident that the effect of gypsiferous water on pH, Ca and SO_4 concentrations was in proportion to the level of irrigation and that these influences were not restricted to the upper 20 cm of the profile. Future work must, therefore, place the emphasis on the long term implications for the whole eco-system including plant, soil, leachate, etc.

The preliminary screening work with leguminous woody species found large differences with respect to climatic adaptation, disease resistance, productivity, leaf retention and persistence and several species warrant further investigation. The lack of response to an irrigation gradient was surprizing and may be linked to the high variability in a relatively small population and/or the strong limit on root development in all but the upper horizon of the experimental soil.

5.5 FIELD TRIAL

A large variety of species was selected according to their reported tolerance to salinity. Crops and pastures were divided into four groups (Figure 5.1, p. 215):

1) - ANNUAL SUBTROPICAL SPECIES

Maize	(*Zea mays* SNK 2340)
Soybean	(*Glycine max.* Ibis)
Sorghum	(*Sorghum* Pan 888)
Pearl millet	(*Pennisetum glaucum* SA standard)
Cowpea	(*Vigna unguiculata* Dr Saunders)

2) - ANNUAL TEMPERATE SPECIES

Rye	(*Secale cereale* SSR 1)
Oats	(*Avena sativa* Overberg)
Triticale	(*Triticum x Secale* Cloc 1)
Wheat	(*Triticum aestivum* Inia)
Rye grass	(*Lolium multiflorum* Midmar)

3) - PERENNIAL TEMPERATE SPECIES

Lucerne	(*Medicago sativa* Pan 4860)
Fescue	(*Festuca arundinacea* A.U.Triumph)
Crownvetch	(*Coronilla varia* Penngift)
Cocksfoot	(*Dactylis glomerata* Hera)
Milkvetch	(*Astragalus Cicer* Windsor)

4) - PERENNIAL SUBTROPICAL SPECIES

Weeping lovegrass	(*Eragrostis curvula* Ermelo)
Smuts finger	(*Digitaria eriantha* Irene)
Kikuyu	(*Pennisetum clandestinum*)
Panicum	(*Panicum maximum* Gattom)
Rhodes	(*Chloris gayana* Katambora)

5.5.1 Agronomic techniques

Agronomic techniques commonly used in the area were adopted. Planting dates, seeding density, distance between rows and cutting dates are summarized in Tables 5.12-5.13 (pp. 186 & 187). Inoculation material was applied to seeds of soybean and cowpeas before planting. The late planting date of subtropical crops in the 1993/94 season was due to technical problems encountered in the installation of the irrigation system (see section 5.3, p. 157). Sorghum and pearl millet (babala) did not re-grow after the first harvest and a second yield was not obtained. Due to difficulties in establishment, crownvetch was re-planted on 01-02-1995 using vegetative material. The original idea of growing white clover (*Trifolium repens* Dusi) was abandoned as the plants experienced difficulties in establishment. White clover was substituted with milkvetch which was planted at a later stage (01-12-1994). Panicum was planted on 05-10-1995 due to problems encountered in seed delivery. Good contact between soil and seed was ensured by rolling the plots of those perennial species that were established from seed.

On the basis of soil chemical analysis, the following fertilization treatments were recommended and applied before the beginning of the trial: 5 t ha^{-1} dolomitic lime, 1 t ha^{-1} superphosphate, 400 kg ha^{-1} 2-3-4 (30). Before the beginning of the second and third cropping season, 5 t ha^{-1} Dolomitic lime was applied for annual species in order to limit the effect of high soil acidity on the crops. Fertilizers were ploughed into the soil to a depth of 20 cm. Specific fertilization treatments during the three years of the trial are summarized in Tables 5.14-5.16 (subtropical annual species) (pp. 188 & 189), 5.17-5.18 (temperate annual species)(pp. 189 & 190) and 5.19 (subtropical and temperate perennial species)(p. 191).

5.5.2 Water supply scheme

Each plot was serviced by three G-Type 2 Hunter sprinklers. A central sprinkler covered an angle of 180°, while two edge sprinklers covered an angle of 90°.

A wide range of sprinkler nozzles of different sizes was tested in order to find the optimal water application rate pattern for the purpose of the experiment. The water application rate pattern for each plot is represented in Figure 5.3 (p. 217). This pattern has been drawn interpolating water application rates measured by a network of rain gauges set up on the plot. Rain gauges were set at a distance of 3 m from each other covering the whole plot. Measurement of water application rates was carried out under low wind conditions. The line source sprinkler system provided a water and salt application rate gradient. Maximum application rate of irrigation water was obtained close to the line source. The rate decreased toward the opposite edge of the plot. The sprinkler radius was not supposed to reach the opposite edge of the plot, so a narrow strip was maintained under rain fed conditions. A quite large distance between sprinklers (≈ 9 m) resulted in a satisfactory gradient uniformity under low wind conditions.

Irrigations were performed twice weekly in order to limit soil salinity effects on plants grown in the well-irrigated treatment (Rhoades & Merrill, 1976). The plots were irrigated under low wind conditions, generally during late afternoon, in order to avoid water drift and to improve distribution uniformity.

5.5.3 Field measurements

In Figure 5.3 (p. 217), six dots are indicated representing six positions where soil water content (SWC) measurements were carried out throughout the season. SWC was measured with a neutron moisture gauge, Model 503DR Hydroprobe. Readings were taken every few days for 20 cm soil layers down to 1.4 m. At the same positions indicated, rain gauges were installed in order to measure amounts of irrigation water and rainfall. Positions close to the sprinkler line (I and II) corresponded to a well-irrigated treatment (wet treatment). Amounts of irrigation water to be applied were calculated according to SWC readings at these two positions. SWC of the wet treatment was maintained close to FC values. No leaching fraction (LF) was applied in order to increase irrigation efficiency, as it was assumed that rainfall would leach a portion of the salts from the soil profile. Minimizing LF, maximization of gypsum precipitation and benefits with respect to the ground water pollution hazard were hereby achieved (Rhoades & Suarez, 1977; Redley, Darab & Esillag, 1980; Fey & Guy, 1993). Positions III and IV in the middle of the plot corresponded to a medium irrigated treatment (medium treatment). SWC of the medium treatment was maintained at levels below FC during the season. Positions V and VI corresponded to a rain fed dry treatment as they were not reached by the sprinkler jets under low wind conditions. In this way, three treatments of water and salt supply were differentiated on each plot and two replications adopted for SWC and irrigation and rainfall measurements.

The following measurements were carried out for each crop and each of the treatments:

- Radiation fractional interception (FI) every 3-4 days with a Decagon sunfleck ceptometer;
- Dry matter of plant organs every 2-3 weeks adopting common methodologies; and
- Leaf area index (LAI) every 2-3 weeks with a Li-Cor LI 3100 area meter.

Growth analyses (dry matter production and LAI) were carried out sampling 1 m^2 of plant material with no replications due to the small plot size and the large number of crops and options to be monitored. Root depth was estimated during the growing season from SWC measurement. At the end of the season, soil profiles were opened and root depth measured. Phenological development was also monitored for each crop and treatment.

During the second and third year of the trial, radiation fractional interception and leaf area index were additionally estimated with an LAI 2000 plant canopy analyzer. The LAI 2000 uses a fisheye sensor transmitting light onto five silicon detectors arranged in concentric rings. The detectors measure diffuse radiation simultaneously in five distinct angular bands about the zenith point. An optical filter restricts transmitted radiation to below 490 nm, minimizing the contribution of light that is scattered by foliage. Gap fractions (fraction of sky visible through the canopy) at five zenith angles are measured by making a reference reading above the canopy, and several readings beneath it, aiming the sensor skywards. Gap fraction analysis was used for indirect, non-destructive measurement of LAI (Welles, 1990). The plant canopy analyzer calculates LAI as a function of the logarithms of gap fractions measured at different zenith angles and path lengths of radiation through the canopy (Lang &

Xiang, 1986). Theoretical principles of the LAI 2000 plant canopy analyzer were reviewed by Welles & Norman (1991). The assumptions of the theoretical background are:

- Foliage is azimuthally randomly oriented;
- Measurement includes all opaque objects;
- Canopy elements neither reflect nor transmit radiation;
- Sky brightness is azimuthally uniform; and
- Foliage elements are small (smaller than four times the distance from the sensor to the closest leaves).

View restriction masks can be mounted on the sensor in order to remove the sun, operator, undesired objects or significant gaps in the canopy from the sensor's view. The masks can also be used to overcome lack of randomness in row canopies, limit the effect of canopy heterogeneity and restrict the view at edges of small plots. The use of view restriction caps is recommended when sky brightness is non-uniform in order to improve the accuracy of the reading.

The LAI 2000 senses canopy in all directions, making the measurement independent of solar orientation. It saves considerable time, being able to collect all necessary angular responses at once and doing all the computations immediately by means of a control unit which is easily carried by one operator. Another big advantage, especially for small plot experiments, is that the method is non destructive. A disadvantage of the instrument is that measurements must be made at dawn, at sunset or under cloudy conditions, since light scattering from sunlit foliage increases errors in measurement. LAI estimates with the plant canopy analyzer include all opaque objects (stem, fruit, branches), so foliage area index is a better description of what is measured. The sensor cannot distinguish between living tissue and dead tissue, so it is impossible to separate out photosynthetically active LAI. The instrument does not provide reliable measurements in grasses as it does not sense the portion of the canopy below its sensor. In this study, the objectives were to check the reliability of data provided by the LAI 2000 and suggest crop specific measurement techniques (number of measurements below the canopy, positions and orientation of the LAI 2000 sensor in rows, use of sensor view restriction caps). A reference reading above the canopy and six readings beneath it were made in order to determine FI and LAI with the plant canopy analyzer. Readings below the canopy were made along diagonal transects in the row, using 180° view restriction masks. Sampling involved one site per crop and treatment. Sampling sites were marked and plants harvested on the same day for growth analysis.

Soil samples were collected by augering from 20 cm soil layers down to 1 m depth. Three replications were taken for each water treatment at the end of the first season of subtropical annual crops. Soil electrical resistance, pH, SO_4 concentration in the soil solution and ammonium extractable cations were measured. Due to the amount of analyses to be carried out and the relatively high expense, it was decided to intensively monitor only two plots. During the second and third year of the trial, soil analysis was carried out for three water treatments of soybean and wheat, at the end of the growing season. Maas & Hoffman (1977) reported that soil solution chemical characteristics can be approximately estimated through measurement of the saturation extract. The following parameters were measured:

- Electrical conductivity of saturated soil extract (EC_e);
- Soil pH (H_2O);
- Bray I P;
- Ammonium acetate extractable Ca, Mg, K and Na;
- Concentrations of soluble Ca, Mg, K and Na; and
- SO_4, Cl, HCO_3 and CO_3 concentrations in saturated soil extract.

The intention was to describe vertical profile dynamics of soil solution electrical conductivity, pH and salts.

At the beginning of the 1995/96 season, samples were taken from the top 20 cm soil layer in order to determine nutrient status in the soil and carry out corrective fertilization where required. Three samples were taken from each plot, one for each water treatment. The samples were mixed and soil electrical resistance, pH (H_2O), Bray I P and ammonium acetate extractable cations measured.

At the end of the 1993/94 season, plant material of maize was sampled in order to determine crop salt uptake. Three replications of leaves, stem and cobs were taken for each water treatment. Plant material originating from different plant organs was mixed and complete chemical analyses were carried out to determine the content of macro- and micronutrients in plant tissue.

During the first year of the trial, the following weather data were collected at the Kromdraai mine meteorological station, approximately 100 m from the trial site:

- Solar radiation with a Li-Cor LI 200 sensor;

- Wind speed at 5 m and wind direction with an R M Young propeller anemometer;

- Atmospheric pressure with a PT 1 transducer;

- Rainfall with a TBR 87 tipping bucket rain gauge;

- Air temperature with a YSI 44203 temperature probe; and

- Air relative humidity with an XNAM 10205 sensor.

Ten minute average data were stored with an MM 950 data logger.

During the second year of the trial, an automatic weather station was installed next to the experimental plot. Grass was planted in the area around the station. The following meteorological parameters were recorded:

- Relative humidity and air temperature with a Vaisala HMP35C sensor;
- Wind speed with an R.M. Young 03101 cup anemometer;
- Wind direction with an R.M. Young 03301 vane;
- Solar radiation with an LI 200X pyranometer; and
- Rainfall with a Texas electronics TE 525 tipping bucket- rain gauge.

Data were recorded every 10 seconds and averaged or totalled hourly with a Campbell Scientific CR10 data logger.

Irrigation water chemical analysis was made during the first year of the field trial in order to take cognizance of water quality variability and salt balance in the soil. The following parameters were measured:

- Electrical conductivity (EC);
- pH; and
- Concentrations of Ca, Mg, K, Na, CO_3, HCO_3, Cl and SO_4.

5.5.4 Results and discussion

5.5.4.1 Irrigation water quality

Table 5.20 (p. 192) represents typical irrigation water properties measured during the 1994 season at Kromdraai. Data refer to the average of six samples of water. Large amounts of Ca and SO_4 in lime treated AMD were observed. Decreasing trends of EC, pH, Ca and SO_4 with time were due to management problems in the liming plant. Among the other ionic species present in lime treated AMD, Mg has the highest concentration. Variable but low concentrations of K and Cl were observed.

According to the Department of Water Affairs and Forestry (1993), use of water of such quality for irrigation is to be matched with LF applications of 0.15 and foliage wetting with fresh water. Optimal yields can nevertheless be expected irrigating moderately salt tolerant crops at high frequency. Measured pH, EC and ionic concentrations were in the range of those estimated by du Plessis (1983a).

5.5.4.2 Crop yield and water use

Tables 5.21-5.40 (pp. 193 to 205) represent aerial dry matter production (TDM), dry matter of cobs, pods or ears (HDM) and components of the seasonal soil water balance for 20 crop and pasture species and three water treatments.

TDM and HDM were measured at harvest. Root dry matter was not included in the estimation of TDM. ET + D was calculated as follows:

$$ET + D = P + I - R_o - \Delta Q$$

for a given time interval where ΔQ represents soil water storage in mm. A positive sign of ΔQ indicates gain in soil water storage. ΔQ was estimated from soil water measurements with a neutron moisture gauge. P and I were measured with rain gauges. Annual crops were planted in rows normal to the slope and runoff was neglected in the water balance equation.

Due to windy conditions and drifting of irrigation water, it was not possible to maintain the dry treatments under rainfed conditions throughout the season. An extremely rainy 1995/96 season prevented the differentiation of water treatments.

Previous work indicated that soil salinity suppresses top growth more than root growth (Eaton, 1942; Bernstein & Pearson, 1954; Ayers & Eberhard, 1960; Meiri & Poljakoff-Mayber, 1970). In this work, the root systems of most of the cropped species did not develop below 50 cm. The most probable reasons could have been unresolved soil acidity during seedbed preparation, soil compaction and P deficiency in deeper layers.

Nutritional problems were experienced for some crops due to shallow rooting depths. Sorghum and in particular maize were the crops that mainly suffered from nutrient deficiency under the specific environmental conditions. High frequency irrigation and careful fertilization practices are recommended in order to provide crops with the right amounts of available soil water and nutrients throughout the growing season.

Satisfactory yields were obtained for irrigated soybean, pearl millet, cowpeas and winter cereals. No second yield was obtained for sorghum and pearl millet during the 1993/94 season due to the late planting date. High yields of pearl millet were observed in all three treatments. Cowpeas flowered poorly in the 1994/95 and 1995/96 season. Ryegrass did not emerge in the dry treatment during the 1994 season as the soil was very dry. At the beginning of the 1995 season, the dry treatment of ryegrass was well watered before planting.

Among the temperate pastures, lucerne and fescue yielded better than cocksfoot. Difficulties in establishment were experienced for crownvetch and milkvetch, but the crops yielded well during the 1995/96 season.

Eragrostis, Smuts and Kikuyu were the only three species with root systems reaching depths below 140 cm. Differentiation between water treatments was poor as the root system of these three species in the medium-irrigated and dry treatment was able to reach soil water in deeper layers.

Excellent yields of subtropical pastures were achieved during the 1995/96 season, after full establishment. Panicum was planted late and did not establish properly until the trial was terminated.

In previous studies, risk of foliar injury was indicated due to irrigation with saline water by sprinkling. A wide range of crops suffered due to foliar absorption of sodium and chloride (Ehlig & Bernstein, 1959; Bernstein & Francois, 1975; Maas, Clark & Francois, 1982; Maas, Grattan & Ogata, 1982). Soil solutions with high sulphate contents provoked nutritional imbalances and Ca deficiency plant symptoms (Maas & Hoffman, 1977). No symptoms of foliar injury due to irrigation with saline water rich in $CaSO_4$ were noted in this work, however.

5.5.4.3 Soil properties

Soil chemical properties at the end of the 1993/94 season for subtropical annual crops are summarized in Tables 5.41-5.42 (pp. 206 & 207). Detailed soil analysis carried out on soybean and wheat plots in the following two years of the trial are presented in Tables 5.43-5.48 (pp. 208 to 213). Table 5.49 (p. 214) includes measured values of soil chemical properties in the top 20 cm soil layer at the beginning of the 1995/96 season. Corrective fertilization treatments were applied according to the results of chemical analyses shown in Table 5.49 (p. 214). Soil analysis data were not statistically processed due to the small number of replications.

The dominant ions in the soil were Ca and SO_4, the main ionic species present in lime treated AMD. Very low values of other ionic species were measured in the soil. The low content of K is particularly worrying. In fact, symptoms of a lack of K were observed in maize and sorghum. Symptoms of K deficiency appeared also in lucerne, before fertilization was applied at the beginning of the 1995/96 season.

Figure 5.4 (p. 218) represents measured values of EC_e in the soil profile of soybean (well irrigated and dry treatment) at the end of the 1994/95 and 1995/96 season. Decrease in EC_e values at the end of the extremely rainy 1995/96 season, indicated that fluctuations in soil salinity levels could be expected depending on rainfall pattern. No increasing trend in soil salinity levels should be expected to occur due to irrigation with lime treated AMD.

Figure 5.5 (p. 219) represents measured values of pH in the soil profile of soybean (well irrigated and dry treatment) at the end of each growing season. A dramatic increase in soil pH values was observed at the end of the 1995/96 season, probably as a result of accumulation of Ca over time.

5.5.5 Conclusions

The field trial determined which species are the most suitable for the specific environmental conditions. From a potential production point of view, legumes (soybean and cowpeas) among the subtropical and triticale among the temperate crops proved to be the most suitable.

Shallow rooting depth was observed in all crops, probably due to high soil acidity, soil compaction or P deficiency in deeper layers. Under these conditions, leaching of nutrients out of the reach of the rooting system is likely to occur if irrigation and fertilization practices are not properly approached. Nutritional problems were experienced for some crops. In particular, maize was the crop that mainly suffered from nutrient deficiency and soil acidity. High frequency irrigation and application of fertilizers several times during the growing season in smaller amounts are recommended. In particular, potassium fertilization is critical due to the low content of this element in the soil and the added problem of displacement with the high gypsum content of the treated AMD.

For the purpose of lime treated AMD usage, fast growing species that use a lot of water are recommended (pearl millet in combination with a winter cereal, or a lucerne/fescue mixed pasture). It is important to have as large a transpiring canopy as possible throughout the year.

The line source sprinkler system proved to be a convenient means for developing crop production functions.

Soil salinity parameters did not show any trend during the three years of the trial. It is not therefore expected, in the short-term, that there will be an increase in soil salinity while irrigating with lime treated AMD. On the other hand, soil pH could be considerably increased when irrigation water with a pH of about 8.0 is applied.

TABLE 5.1 Mean monthly rainfall at Kromdraai liming plant (1982-1992) and pan evaporation at Witbank dam (1963-1989)

Month	Rainfall mm	Pan evaporation mm
January	112	178
February	92	144
March	100	136
April	22	100
May	5	81
June	14	68
July	5	74
August	8	100
September	16	136
October	78	170
November	124	165
December	111	174
Total	689	1526

TABLE 5.2 Average soil textural characteristics

Textural fractions		Depth cm		
		0-20	20-40	40-60
Sand (%)	Coarse	44.3	36.8	35.1
	Medium	28.8	32.5	30.0
	Fine	10.2	11.8	12.2
Total sand (%)		83.3	81.1	77.3
Silt (%)		4.0	4.7	5.9
Clay (%)		11.8	13.6	16.1

TABLE 5.3 Average soil chemical characteristics prior to commencement of trial

Chemical properties		Depth cm		
		0-20	20-40	40-60
pH (H_2O)		4.45	4.15	4.2
Electrical resistance (ohm)		797	2632	1922
Bray I P (mg kg^{-1})		32	4	3
Ammonium acetate extractable cations ($cmol_c$ kg^{-1})	Ca	1.163	0.574	0.454
	Mg	0.083	0.066	0.074
	K	0.056	0.049	0.049
	Na	0.039	0.035	0.030

TABLE 5.4 Volumetric water content at field capacity (FC) and permanent wilting point (PWP) and bulk density

Depth cm	**Field capacity** % vol.	**Permanent wilting point % vol.**	**Bulk density** Mg m^{-3}
0-20	12.9	8.0	1.76
20-40	15.8	8.0	1.74
40-60	17.5	9.0	1.70
60-80	18.4	9.0	1.62
80-100	16.3	9.0	1.50
100-120	17.9	9.0	1.43
120-140	16.3	9.0	1.41

TABLE 5.6 Mean yield indices of perennial summer grasses at different levels of irrigation with gypsiferous water

	Mean yield indices	**Precip + Irrigation mm**	**(Mean Moisture Indices)**
1994/95			
No irrigation	100	587	(100)
Medium irrigation	-	898	(153)
Well irrigated	192	1328	(226)
1995/96			
No irrigation	100	1023	(100)
Medium irrigation	157	1217	(119)
Well irrigated	210	1407	(138)

TABLE 5.5 **Yields of perennial summer grasses established to assess the adaptation to local conditions and response to level of irrigation with gypsiferous water (Index relative to rainfed conditions) (g tuft^{-1} unless specified)**

1994/95 Season		**Well irrigated**	**Rainfed**
Vegetative species			
Digitaria eriantha	(P66)	258 (235)	110 (100) gm^{-1}
Cynodon hybrid	(K11)	925 (474)	195 (100) gm^{-1}
Panicum repens		350 (200)	175 (100) gm^{-1}
Paspalum vaginatum		130 (200)	65 (100) gm^{-1}
Pennisetum hybrid	(Banagrass)	718 (279)	257 (100) gm^{-1}
Seeded species			
Bothriochloa	(Ironmaster)	86 (215)	40 (100)
	(Old World)	236 (113)	208 (100)
	(Plains)	61 (103)	59 (100)
	(Spar)	59 (84)	70 (100)
Cenchrus ciliaris	(Molopo)	310 (161)	193 (100)
Digitaria eriantha	(Irene)	43 (67)	64 (100)
Eragrostis curvula	(Ermelo)	517 (149)	348 (100)
Panicum antidotale	(SDT)	402 (402)	100 (100)
P. coloratum	(Bambatsi)	467 (316)	148 (100)
	(Burnett)	303 (155)	195 (100)
	(Pollock)	527 (177)	297 (100)
	(Selection 75)	327 (168)	195 (100)
	(Verde)	352 (201)	175 (100)
P. maximum	(Centario)	963 (223)	432 (100)
	(Gatton)	60 (85)	71 (100)
	(Vencedor)	985 (112)	883 (100)
P. virgatum	(Alamo)	288 (114)	252 (100)

TABLE 5.5 (continued)

1995/96 Season		**Well irrigated**		**Medium irrigation**		**Rainfed**	
Vegetative species							
Digitaria eriantha	(P66)	2004	(157)	1720	(134)	1280	(100) gm^{-1}
Cynodon hybrid	(K11)	1676	(151)	1396	(126)	1108	(100) gm^{-1}
Panicum repens		1020	(96)	1036	(97)	1064	(100) gm^{-1}
Paspalum vaginatum		1148	(252)	1104	(242)	456	(100) gm^{-1}
Pennisetum hybrid	(Banagrass)	10528	(191)	9462	(172)	5522	(100) gm^{-1}
Seeded species							
Bothriochloa	(Ironmaster)	444	(281)	456	(155)	158	(100)
	(Old World)	546	(127)	770	(179)	429	(100)
	(Plains)	236	(92)	200	(78)	256	(100)
	(Spar)	263	(153)	270	(157)	172	(100)
Cenchrus ciliaris	(Molopo)	706	(353)	250	(125)	200	(100)
Digitaria eriantha	(Irene)	456	(167)	192	(70)	273	(100)
Eragrostis curvula	(Ermelo)	1473	(219)	981	(146)	674	(100)
Panicum antidotale	(SDT)	1081	(460)	718	(306)	235	(100)
P. coloratum	(Bambatsi)	1281	(203)	1129	(180)	632	(100)
	(Burnett)	977	(147)	848	(128)	664	(100)
	(Pollock)	1680	(198)	1203	(143)	850	(100)
	(Selection 75)	1261	(154)	1216	(148)	821	(100)
	(Verde)	948	(195)	815	(168)	485	(100)
P. maximum	(Centario)	3466	(147)	2340	(99)	2365	(100)
	(Gatton)	871	(364)	794	(332)	239	(100)
	(Vencedor)	3114	(219)	1815	(128)	1423	(100)
P. virgatum	(Alamo)	3037	(297)	1542	(151)	1023	(100)

TABLE 5.7 Ranking of vegetative and seeded grass species in terms of speed of establishment and productivity in first and second growing seasons, on a scale of 10 to 1

	Speed of establishment and Productivity 1994/95	Productivity 1995/96
Vegetative grasses	K 11 (9)	Bana (10)
	Bana (7)	P 66 (5)
	Torpedo (4)	K 11 (4)
	P 66 (3)	Beach (3)
	Beach (1)	Torpedo (2)
Seeded grasses	Vencedor (10)	Centario (10)
	Centario (10)	Vencedor (9)
	Pollock (5)	Alamo (9)
	Ermelo (5)	Pollock (6)
	Bambatsi (5)	Ermelo (5)
	SDT (4)	Bambatsi (4)
	Verde (4)	Selection 75 (4)
	Selection 75 (3)	SDT (4)
	Molopo (3)	Burnett (3)
	Burnett (3)	Verde (3)
	Alamo (3)	Gatton (3)
	Old World (2)	Molopo (2)
	Ironmaster < 1	Old World (2)
	Plains < 1	Irene (2)
	Spar < 1	Ironmaster (2)
	Gatton < 1	Spar (1)
	Irene < 1	Plains (1)

TABLE 5.8 Soil analyses at three depths along an irrigation gradient at the end of 1995/96 season

	pH(H^2O)	Ca $mgkg^{-1}$	SO_4	Mg	P Bray II	K
Non-irrigated						
0 - 20 cm	5.9	207	244	9	6.2	18.5
20 - 40 cm	4.9	61	152	4	2.1	14.6
40 - 60 cm	4.7	45	85	3	1.1	9.5
Mean	5.2	104	160	5	3.1	14.2
Medium irrigation						
0 - 20 cm	6.2	335	229	10	7.2	17.8
20 - 40 cm	5.5	193	220	4	2.0	9.4
40 - 60 cm	4.6	121	158	2	1.5	8.1
Mean	5.4	216	202	5	3.6	11.8
Well irrigated						
0 - 20 cm	6.8	627	266	17	28.3	18.8
20 - 40 cm	6.1	343	277	9	8.8	13.2
40 - 60 cm	5.1	197	212	4	2.1	14.8
Mean	6.0	389	252	10	13.1	15.6

TABLE 5.9 Yield of leguminous fodder trees/shrubs planted in the 1993/94 season (g DM plant^{-1})

Species	1994/95[1]	1995/96	
		Early season[2]	Late Season[3]
A. julibrissin	minimal	324	1205
C. palmensis	1152	836	2019
C. maderiensis	4247	509	2625
L. leucocephala	354	205*	2731
L. pulverulenta	74	141	1108
L. arborea	2011	-	-
M. arborescens	71	71	276
S. sesban	217	119*	3585
T. stenopetala	1073	482	1641

[1] Yields assessed in early winter after a late summer planting

[2] Yields assessed in November '95 after pruning in winter and replanting blanks of *L. leucocephala* and *S. sesban*. These* yields were thus obtained from seedlings, whereas the other species were already well established.

[3] These yields are the mean of yield assessments conducted in February and May 1996.

TABLE 5.10 Persistence of leguminous fodder trees/shrubs

Species	Originally planted 1994	Surviving May 1996	Subjective comments
A. julibrissin	(1)[1] 5	5	Excellent survival
C. palmensis	(2) 20	17	Very good
C. maderiensis	(4) 20	10	Couple of trees died each winter and summer
L. leucocephala	(3) 20	17	Winterkill a feature. Blanks planted each spring
L. pulverulenta	(2) 20	18	Very good survival
L. arborea	(5) 20	0	Very susceptible to disease in wet summers
M. arborescens	(4) 20	11	Couple of shrubs died each winter and summer
S. sesban	(5) 20	6	Severe winterkill. Treated as an annual
T. stenopetala	(2) 20	15	Good survival

[1] Persistence rated on a scale of (1) - (5)

TABLE 5.11 Proportion of total production of fodder trees/shrubs which is edible

Species	% Edible material				Mean
	May 1995	November 1995	February 1996	May 1996	
(D) *A. julibrissin*	negligible	43	66	5	38
(E) *C. palmensis*	50	44	66	56	54
(E) *C. maderiensis*	42	61	65	53	55
(D) *L. leucocephala*	48	69	30	58	51
(D) *L. pulverulenta*	60	64	62	53	60
(E) *L. arborea*	32	-	-	-	32
(E) *M. arborescens*	55	51	48	44	50
(D) *S. sesban*	36	53	81	47	54
(E) *T. stenopetala*	48	23	56	43	43

(D) Deciduous

(E) Evergreen

TABLE 5.12 Planting dates, seeding density, row spacing and dates of cut of annual crops

Crop	Planting date	Seeding density	Row spacing	Dates of cut
Maize	17-12-93	60000 seeds ha^{-1}	0.5 m	-
	04-10-94	55000 seeds ha^{-1}	0.8 m	-
	05-10-95	55000 seeds ha^{-1}	0.8 m	-
Soybean	17-12-93	300000 seeds ha^{-1}	0.5 m	-
	01-11-94	300000 seeds ha^{-1}	0.5 m	-
	09-11-95	300000 seeds ha^{-1}	0.5 m	-
Sorghum	17-12-93	20 kg ha^{-1}	0.5 m	19-04-94
	04-10-94	20 kg ha^{-1}	0.5 m	01-02-95
	05-10-95	20 kg ha^{-1}	0.5 m	31-01-95
Pearl millet	17-12-93	10 kg ha^{-1}	0.5 m	13-04-94
	04-10-94	10 kg ha^{-1}	0.5 m	01-02-95
	05-10-95	10 kg ha^{-1}	0.5 m	31-01-95
Cowpeas	17-12-93	80000 seeds ha^{-1}	0.5 m	-
	01-11-94	80000 seeds ha^{-1}	0.5 m	-
	09-11-95	80000 seeds ha^{-1}	0.5 m	-
Rye	21-04-94	40 kg ha^{-1}	0.3 m	-
	10-05-95	40 kg ha^{-1}	0.3 m	25-07-95 31-08-95
Oats	21-04-94	40 kg ha^{-1}	0.3 m	09-08-94 08-09-94
	10-05-95	40 kg ha^{-1}	0.3 m	31-08-95 05-10-95
Triticale	21-04-94	40 kg ha^{-1}	0.3 m	09-08-94
	10-05-95	40 kg ha^{-1}	0.3 m	31-08-95
Wheat	21-04-94	40 kg ha^{-1}	0.3 m	-
	25-04-95	40 kg ha^{-1}	0.3 m	25-07-95 31-08-95
Ryegrass	21-04-94	25 kg ha^{-1}	0.3 m	09-08-94 08-09-94 04-10-94
	25-04-95	25 kg ha^{-1}	Full area	05-10-95 07-11-95

TABLE 5.13 Planting dates, seeding density, row spacing and dates of cut of perennial species.

Crop	Planting date	Seeding density	Row spacing	Dates of cut
Lucerne	21-04-94	18 kg ha^{-1}	Full area	15-12-94; 01-02-95; 16-03-95; 18-04-95; 31-08-95; 05-10-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.
Fescue	21-04-94	25 kg ha^{-1}	Full area	15-12-94; 16-03-95; 18-04-95; 31-08-95; 05-10-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.
Crownvetch	01-02-95	vegetative material	Full area	15-12-95; 31-01-96; 12-03-96; 29-04-96.
Cocksfoot	21-04-94	25 kg ha^{-1}	Full area	15-12-94; 16-03-95; 18-04-95; 05-10-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.
Milkvetch	01-12-94	200000 seeds ha^{-1}	0.3 m	15-12-95; 31-01-96; 12-03-96; 29-04-96.
Weeping lovegrass	08-03-94	8 kg ha^{-1}	Full area	15-12-94; 01-02-95; 16-03-95; 18-04-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.
Smuts	08-03-94	10 kg ha^{-1}	Full area	15-12-94; 01-02-95; 16-03-95; 18-04-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.
Kikuyu	08-03-94	vegetative material	Full area	15-12-94; 01-02-95; 16-03-95; 18-04-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.
Panicum	05-10-95	12 kg ha^{-1}	Full area	31-01-96; 12-03-96; 29-04-96.
Rhodes	08-03-94	8 kg ha^{-1}	Full area	15-12-94; 01-02-95; 16-03-95; 18-04-95; 07-11-95; 15-12-95; 31-01-96; 12-03-96; 29-04-96.

TABLE 5.14 Fertilization treatments of subtropical annual crops during the 1993/94 season

Crop	Fertilization treatments
Maize	300 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K after emergence
Soybean	20 kg ha^{-1} P + 40 kg ha^{-1} K at planting; 100 kg ha^{-1} K after emergence
Sorghum	300 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K after emergence
Pearl millet	300 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K after emergence
Cowpeas	20 kg ha^{-1} P + 40 kg ha^{-1} K at planting; 100 kg ha^{-1} K after emergence

TABLE 5.15 Fertilization treatments of subtropical annual crops during the 1994/95 season

Crop	Fertilization treatments
Maize	300 kg ha^{-1} 2-3-4 (30) + Zn at planting; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 21-11-1994; 0.4 kg ha^{-1} Mo + 1.5 kg ha^{-1} B on 15-12-1994; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 01-02-1995
Soybean	20 kg ha^{-1} P + 40 kg ha^{-1} K at planting; 100 kg ha^{-1} K after emergence
Sorghum	300 kg ha^{-1} 2-3-4 (30) + Zn at planting; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 21-11-1994; 0.4 kg ha^{-1} Mo + 0.8 kg ha^{-1} B on 15-12-1994; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 01-02-1995
Pearl millet	300 kg ha^{-1} 2-3-4 (30) + Zn at planting; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 21-11-1994; 0.4 kg ha^{-1} Mo + 0.4 kg ha^{-1} B on 15-12-1994; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 01-02-1995
Cowpeas	20 kg ha^{-1} P + 40 kg ha^{-1} K at planting; 100 kg ha^{-1} K after emergence

TABLE 5.16 Fertilization treatments of subtropical annual crops during the 1995/96 season

Crop	Fertilization treatments
Maize	300 kg ha^{-1} 2-3-4 (30) at planting; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 22-11-1995; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 31-01-1996
Soybean	20 kg ha^{-1} P + 40 kg ha^{-1} K at planting; 100 kg ha^{-1} K after emergence
Sorghum	300 kg ha^{-1} 2-3-4 (30) at planting; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 22-11-1995; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 31-01-1996
Pearl millet	300 kg ha^{-1} 2-3-4 (30) at planting; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 22-11-1995; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 31-01-1996
Cowpeas	20 kg ha^{-1} P + 40 kg ha^{-1} K at planting; 100 kg ha^{-1} K after emergence

TABLE 5.17 Fertilization treatments of temperate annual crops during the 1994 season

Crop	Fertilization treatments
Rye	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 10-06-1994
Oats	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 10-06-1994; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 09-08-1994; 100 kg ha^{-1} N on 08-09-1994
Triticale	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 10-06-1994; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 09-08-1994
Wheat	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 10-06-1994
Ryegrass	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 10-06-1994; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 09-08-1994; 100 kg ha^{-1} N on 08-09-1994

TABLE 5.18 Fertilization treatments of temperate annual crops during the 1995 season

Crop	Fertilization treatments
Rye	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N on 31-08-1995
Oats	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N on 31-08-1995
Triticale	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N on 31-08-1995
Wheat	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N on 31-08-1995
Ryegrass	400 kg ha^{-1} 2-3-4 (30) at planting; 100 kg ha^{-1} N on 31-08-1995; 100 kg ha^{-1} N on 27-11-1995

TABLE 5.19 Fertilization treatments for pasture species during the 1995/96 season

Crop	Fertilization treatments
Lucerne	100 kg ha^{-1} K on 05-10-95, 04-12-95 and 07-02-96
Fescue	100 kg ha^{-1} N + 100 kg ha^{-1} K on 05-10-95; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 04-12-95 and 07-02-96
Crownvetch	75 kg ha^{-1} K on 05-10-95, 04-12-95 and 07-02-96
Cocksfoot	100 kg ha^{-1} N + 100 kg ha^{-1} K on 05-10-95; 50 kg ha^{-1} N + 50 kg ha^{-1} K on 04-12-95 and 07-02-96
Milkvetch	75 kg ha^{-1} K on 05-10-95, 04-12-95 and 07-02-96
Weeping lovegrass	20 kg ha^{-1} P + 100 kg ha^{-1} N + 100 kg ha^{-1} K on 05-10-95; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 04-12-95 and 07-02-96
Smuts	20 kg ha^{-1} P + 100 kg ha^{-1} N + 100 kg ha^{-1} K on 05-10-95; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 04-12-95 and 07-02-96
Kikuyu	20 kg ha^{-1} P + 100 kg ha^{-1} N + 100 kg ha^{-1} K on 05-10-95; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 04-12-95 and 07-02-96
Rhodes	20 kg ha^{-1} P + 100 kg ha^{-1} N + 100 kg ha^{-1} K on 05-10-95; 100 kg ha^{-1} N + 100 kg ha^{-1} K on 04-12-95 and 07-02-96

TABLE 5.20 Irrigation water chemical analyses (year 1994)

Parameter		Date				Mean
		20-01	25-02	10-03	15-03	
pH	Mean	6.5	6.8	5.3	5.5	6.0
	Std err	0.2	0.2	0.2	0.4	0.7
EC mSm^{-1}	Mean	200.7	143.0	149.0	132.0	156.2
	Std err	3.9	7.0	4.7	18.3	26.4
Ca $mg\ell^{-1}$	Mean	398.1	249.2	271.0	229.5	286.9
	Std err	0.7	1.4	7.0	30.0	65.8
Mg $mg\ell^{-1}$	Mean	22.7	18.1	14.1	20.6	18.9
	Std err	1.4	2.3	1.0	8.3	3.2
K $mg\ell^{-1}$	Mean	4.7	26.5	8.0	4.3	10.9
	Std err	0.1	30.3	2.8	0.9	9.1
Na $mg\ell^{-1}$	Mean	7.0	5.7	6.2	7.3	6.5
	Std err	0.5	0.4	0.4	3.3	0.6
CO_3 $mg\ell^{-1}$	Mean	0.0	0.0	0.0	0.0	0.0
	Std err	0.0	0.0	0.0	0.0	0.0
HCO_3 $mg\ell^{-1}$	Mean	12.1	12.1	7.9	8.5	10.1
	Std err	1.8	3.8	0.2	0.7	2.0
Cl $mg\ell^{-1}$	Mean	0.2	5.7	3.6	1.5	2.8
	Std err	0.3	7.8	2.1	1.4	2.1
SO_4 $mg\ell^{-1}$	Mean	1321.9	941.9	1010.4	716.1	997.6
	Std err	33.7	6.7	31.8	105.7	216.6

TABLE 5.21 **Top dry matter (TDM), dry matter of cobs (HDM) and water balance for three irrigation treatments of maize**

Season	Treatment	TDM $t ha^{-1}$	HDM $t ha^{-1}$	ET + D mm	I mm	P mm	ΔQ mm
1993/94	Wet	10.92	3.14	827	468	357	-2
	Medium	10.36	2.93	559	194	357	-8
	Dry	6.90	0.62	449	80	357	-12
1994/95	Wet	13.10	5.87	776	457	323	+4
	Medium	7.57	3.00	518	195	323	0
	Dry	5.90	1.12	421	90	323	-8
1995/96	Wet	16.52	6.52	1129	297	828	-4
	Medium	18.60	6.98	923	91	828	-4
	Dry	10.75	3.54	871	37	828	-6

TABLE 5.22 Top dry matter (TDM), dry matter of pods (HDM) and water balance for three irrigation treatments of soybean

Season	Treatment	TDM tha^{-1}	HDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1993/94	Wet	12.30	5.01	843	472	357	-14
	Medium	9.50	3.94	570	191	357	-22
	Dry	7.70	2.09	451	74	357	-20
1994/95	Wet	14.60	6.20	897	508	379	-10
	Medium	11.50	4.56	622	231	379	-12
	Dry	4.00	0.92	492	95	379	-18
1995/96	Wet	15.03	5.88	1070	290	782	-4
	Medium	14.26	4.96	947	161	782	-4
	Dry	11.39	3.92	826	34	782	-10

TABLE 5.23 Top dry matter (TDM) of sorghum and water balance for three irrigation treatments

Season	Treatment	TDM $t ha^{-1}$	ET + D mm	I mm	P mm	ΔQ mm
1993/94	Wet	9.95	718	357	357	-4
	Medium	7.59	520	155	357	-8
	Dry	6.65	431	62	357	-12
1994/95 (2 harvests)	Wet	18.47	943	560	379	-4
	Medium	11.80	667	284	379	-4
	Dry	7.27	496	105	379	-12
1995/96 (2 harvests)	Wet	13.55	1122	325	793	-4
	Medium	7.19	915	118	793	-4
	Dry	4.78	840	43	793	-4

TABLE 5.24 **Top dry matter (TDM) of pearl millet and water balance for three irrigation treatments**

Season	Treatment	TDM $t ha^{-1}$	ET + D mm	I mm	P mm	ΔQ mm
1993/94	Wet	20.60	682	323	357	-2
	Medium	19.50	491	126	357	-8
	Dry	18.30	420	51	357	-12
1994/95 (2 harvests)	Wet	29.20	1032	649	379	-4
	Medium	22.50	691	308	379	-4
	Dry	27.40	528	137	379	-12
1995/96 (2 harvests)	Wet	20.76	1138	343	793	-2
	Medium	12.44	933	136	793	-4
	Dry	9.24	835	38	793	-4

TABLE 5.25 **Top dry matter (TDM), dry matter of pods (HDM) and water balance for three irrigation treatments of cowpeas**

Season	Treatment	TDM tha^{-1}	HDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1993/94	Wet	9.11	3.28	858	497	357	-4
	Medium	7.94	2.61	587	218	357	-12
	Dry	4.87	1.53	425	54	357	-14
1994/95	Wet	9.70	-	907	522	379	-6
	Medium	7.80	-	620	231	379	-10
	Dry	5.00	-	443	50	379	-14
1995/96	Wet	9.57	-	1072	286	782	-4
	Medium	6.22	-	906	120	782	-4
	Dry	9.50	-	804	16	782	-6

TABLE 5.26 **Top dry matter (TDM), dry matter of ears (HDM) and water balance for three irrigation treatments of rye**

Season	Treatment	TDM tha^{-1}	HDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1994	Wet	8.00	2.81	499	471	24	-4
	Medium	4.60	1.50	324	288	24	-12
	Dry	3.10	0.95	127	85	24	-18
1995 (3 harvests)	Wet	4.61	-	360	284	72	-4
	Medium	3.25	-	256	176	72	-8
	Dry	3.54	-	232	144	72	-16

TABLE 5.27 **Top dry matter (TDM) of oats and water balance for three irrigation treatments**

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1994 (3 harvests)	Wet	14.82	653	572	75	-6
	Medium	9.05	357	274	75	-8
	Dry	5.68	224	143	75	-6
1995 (3 harvests)	Wet	5.29	629	347	276	-6
	Medium	3.88	454	172	276	-6
	Dry	2.09	420	134	276	-10

TABLE 5.28 **Top dry matter (TDM) of triticale and water balance for three irrigation treatments**

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1994 (2 harvests)	Wet	10.05	620	567	47	-6
	Medium	6.10	312	257	47	-8
	Dry	4.67	160	103	47	-10
1995 (2 harvests)	Wet	4.24	644	369	269	-6
	Medium	3.55	493	218	269	-6
	Dry	3.45	409	130	269	-10

TABLE 5.29 **Top dry matter (TDM), dry matter of ears (HDM) and water balance for three irrigation treatments of wheat**

Season	Treatment	TDM tha^{-1}	HDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1994	Wet	6.50	3.47	514	484	26	-4
	Medium	3.10	1.24	223	191	26	-6
	Dry	2.60	1.02	156	118	26	-12
1995 (3 harvests)	Wet	6.72	-	344	303	37	-4
	Medium	4.61	-	196	151	37	-8
	Dry	3.27	-	156	111	37	-8

TABLE 5.30 Top dry matter (TDM) of ryegrass and water balance for three irrigation treatments

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
1994 (4 harvests)	Wet	8.91	517	436	75	-6
	Medium	3.85	269	186	75	-8
	Dry	-	-	-	-	-
1995 (3 harvests)	Wet	5.59	779	422	351	-6
	Medium	3.63	523	166	351	-6
	Dry	1.96	389	30	351	-8

TABLE 5.31 Top dry matter (TDM) of lucerne and water balance for three irrigation treatments

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 05-10-1995 (6 harvests)	Wet	23.79	1426	1016	404	-6
	Medium	15.37	958	546	404	-8
	Dry	6.67	628	212	404	-12
from 05-10-1995 to 29-04-1996 (5 harvests)	Wet	16.90	1455	555	894	-6
	Medium	14.81	1232	332	894	-6
	Dry	8.74	1014	110	894	-10

TABLE 5.32 **Top dry matter (TDM) of fescue and water balance for three irrigation treatments**

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 05-10-1995 (5 harvests)	Wet	21.35	1326	916	404	-6
	Medium	15.11	911	501	404	-6
	Dry	5.25	608	194	404	-10
from 05-10-1995 to 29-04-1996 (5 harvests)	Wet	21.64	1403	505	894	-4
	Medium	23.62	1202	304	894	-4
	Dry	17.78	1001	101	894	-6

TABLE 5.33 **Top dry matter (TDM) of crownvetch and water balance for three irrigation treatments**

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 15-09-1995 to 29-04-1996 (4 harvests)	Wet	25.01	1416	515	897	-4
	Medium	15.63	1233	326	897	-10
	Dry	20.24	1043	134	897	-12

TABLE 5.34 **Top dry matter (TDM) of cocksfoot and water balance for three irrigation treatments**

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 05-10-1995 (4 harvests)	Wet	8.09	1330	920	404	-6
	Medium	5.46	906	496	404	-6
	Dry	3.14	607	189	404	-14
from 05-10-1995 to 29-04-1996 (5 harvests)	Wet	14.51	1401	503	894	-4
	Medium	13.46	1194	296	894	-4
	Dry	6.26	1015	111	894	-10

TABLE 5.35 **Top dry matter (TDM) of milkvetch and water balance for three irrigation treatments**

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 15-09-1995 to 29-04-1996 (4 harvests)	Wet	26.41	1427	526	897	-4
	Medium	13.35	1247	342	897	-8
	Dry	8.15	943	32	897	-14

TABLE 5.36 Top dry matter (TDM) of Eragrostis and water balance for three irrigation treatments

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 15-09-1995 (4 harvests)	Wet	14.99	1328	918	404	-6
	Medium	13.81	898	488	404	-6
	Dry	12.91	587	175	404	-8
from 15-09-1995 to 29-04-1996 (5 harvests)	Wet	33.71	1399	501	894	-4
	Medium	29.16	1210	312	894	-4
	Dry	27.55	1021	121	894	-6

TABLE 5.37 Top dry matter (TDM) of Smuts grass and water balance for three irrigation treatments

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 15-09-1995 (4 harvests)	Wet	21.37	1348	938	404	-6
	Medium	16.53	902	492	404	-6
	Dry	9.93	601	189	404	-8
from 15-09-1995 to 29-04-1996 (5 harvests)	Wet	36.51	1413	515	894	-4
	Medium	31.09	1224	326	894	-4
	Dry	24.65	1025	123	894	-8

TABLE 5.38 **Top dry matter (TDM) of Kikuyu and water balance for three irrigation treatments**

Season	Treatment	TDM $t ha^{-1}$	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 15-09-1995 (4 harvests)	Wet	18.47	1350	942	404	-4
	Medium	18.25	904	496	404	-4
	Dry	15.37	589	181	404	-4
from 15-09-1995 to 29-04-1996 (5 harvests)	Wet	31.99	1417	519	894	-4
	Medium	30.63	1220	322	894	-4
	Dry	22.11	1039	139	894	-6

TABLE 5.39 **Top dry matter (TDM) of Panicum and water balance for three irrigation treatments**

Season	Treatment	TDM $t ha^{-1}$	ET + D mm	I mm	P mm	ΔQ mm
from 05-10-1995 to 29-04-1996 (3 harvests)	Wet	13.19	1390	492	894	-4
	Medium	15.27	1202	300	894	-8
	Dry	8.36	1025	121	894	-10

TABLE 5.40 Top dry matter (TDM) of Rhodes grass and water balance for three irrigation treatments

Season	Treatment	TDM tha^{-1}	ET + D mm	I mm	P mm	ΔQ mm
from 13-09-1994 to 15-09-1995 (4 harvests)	Wet	17.42	1336	928	404	-4
	Medium	11.79	898	490	404	-4
	Dry	9.80	468	52	404	-12
from 15-09-1995 to 29-04-1996 (5 harvests)	Wet	34.16	1420	522	894	-4
	Medium	26.31	1228	328	894	-6
	Dry	17.28	924	18	894	-12

Table 5.41 pH and electrical resistance values measured in the soil profile of three treatments of subtropical annual crops at the end of the 1993/1994 season

Plot	Soil layer cm	Wet treatment		Medium treatment		Dry treatment	
		pH (H_2O)	Resistance ohm	pH (H_2O)	Resistance ohm	pH (H_2O)	Resistance ohm
Maize	0-20	4.88	1350	4.81	600	5.60	800
	20-40	4.60	1400	4.60	1200	4.96	900
	40-60	4.50	1400	4.51	2100	4.59	1300
	60-80	4.45	1500	4.66	1400	4.56	1500
	80-100	4.64	1100	4.72	1300	4.89	1100
Soybean	0-20	4.86	1300	4.87	540	5.11	500
	20-40	4.49	1050	4.78	650	4.80	1100
	40-60	4.70	1600	4.66	1600	4.56	1500
	60-80	5.04	1200	4.68	1800	4.49	1100
	80-100	4.91	1600	4.92	1500	4.90	1300
Sorghum	0-20	5.10	1100	5.05	900	4.73	1200
	20-40	4.57	1200	4.61	1500	4.55	1200
	40-60	4.55	1100	4.58	1400	4.46	1500
	60-80	4.64	1150	4.80	1300	4.39	1200
	80-100	4.93	1450	4.91	1200	4.81	1800
Babala	0-20	4.70	1250	4.70	1000	5.45	900
	20-40	4.50	1200	4.37	1550	4.73	1100
	40-60	4.48	1400	4.47	1800	4.59	1600
	60-80	4.64	1400	4.76	1500	4.83	1700
	80-100	4.83	1600	4.68	1600	4.67	4700
Cowpeas	0-20	4.54	1200	5.00	620	5.14	1100
	20-40	4.53	1400	4.60	850	4.75	1400
	40-60	4.42	1300	4.70	1400	4.35	1100
	60-80	4.65	1400	4.74	1750	4.51	1000
	80-100	4.82	1500	4.79	1700	4.76	2100

Table 5.42 **Soil chemical properties measured in the soil profile of subtropical annual crops (wet treatment) at the end of the 1993/1994 season**

Plot	Soil layer cm	SO_4 cmol, kg^{-1}	Ammonium acetate extractable cations (cmol, kg^{-1})	
			Ca	K
Maize	0-20	0.596	0.620	0.042
	20-40	0.598	0.586	0.041
	40-60	0.356	0.517	0.041
	60-80	0.523	0.567	0.048
	80-100	0.510	0.673	0.040
Soybean	0-20	0.691	0.841	0.045
	20-40	0.858	0.737	0.107
	40-60	0.879	0.808	0.061
	60-80	0.525	0.806	0.027
	80-100	0.446	0.779	0.030
Sorghum	0-20	0.437	1.071	0.054
	20-40	0.650	0.630	0.103
	40-60	0.831	0.577	0.110
	60-80	0.494	0.813	0.064
	80-100	0.535	0.777	0.032
Babala	0-20	0.579	0.590	0.051
	20-40	0.612	0.613	0.054
	40-60	0.621	0.639	0.057
	60-80	0.589	0.835	0.026
	80-100	0.508	0.716	0.022
Cowpeas	0-20	0.431	0.474	0.030
	20-40	0.442	0.486	0.034
	40-60	0.458	0.519	0.050
	60-80	0.514	0.714	0.060
	80-100	0.412	0.786	0.036

Table 5.43 Soil chemical properties on soybean plot at the end of the 1994/95 season

Plot	Soil layer cm	pH (H_2O)	EC_e mSm^{-1}	CO_3 $cmol_c\ kg^{-1}$	HCO_3 $cmol_c\ kg^{-1}$	Cl $cmol_c\ kg^{-1}$	SO_4 $cmol_c\ kg^{-1}$
Soybean Wet treatment	0-20	5.27	197	0	0.011	0.000	0.688
	20-40	4.62	138	0	0.009	0.001	0.506
	40-60	4.59	125	0	0.008	0.002	0.456
	60-80	4.59	132	0	0.007	0.001	0.464
	80-100	4.62	137	0	0.008	0.001	0.476
Soybean Dry treatment	0-20	5.18	119	0	0.009	0.000	0.470
	20-40	4.53	137	0	0.006	0.003	0.484
	40-60	4.54	145	0	0.006	0.002	0.516
	60-80	4.64	148	0	0.006	0.029	0.456
	80-100	4.74	176	0	0.005	0.024	0.362

Table 5.44 Soil chemical properties on soybean plot at the end of the 1994/95 season

Plot	Soluble cations cmol$_c$ kg^{-1}				Exchangeable cations cmol$_c$ kg^{-1}			
	Ca	Mg	K	Na	Ca	Mg	K	Na
Soybean Wet treatment	0.561	0.012	0.003	0.004	2.238	0.050	0.042	0.002
	0.332	0.018	0.003	0.005	1.117	0.035	0.051	0.015
	0.296	0.027	0.003	0.005	1.009	0.032	0.069	0.005
	0.307	0.027	0.004	0.006	1.121	0.050	0.073	0.012
	0.318	0.028	0.004	0.006	1.177	0.079	0.080	0.006
Soybean Dry treatment	0.312	0.030	0.003	0.005	1.432	0.039	0.078	0.014
	0.284	0.030	0.003	0.005	1.271	0.075	0.065	0.007
	0.288	0.027	0.003	0.005	0.974	0.108	0.063	0.007
	0.297	0.015	0.004	0.007	1.158	0.169	0.048	0.014
	0.262	0.006	0.005	0.008	1.619	0.129	0.033	0.013

Table 5.45 Soil chemical properties on soybean plot at the end of the 1995/1996 season

Plot	Soil layer cm	pH (H_2O)	EC_e mS m^{-1}	Bray I P mg kg^{-1}	SO_4 $cmol_c$ kg^{-1}
Soybean Wet treatment	0-20	7.56	115	111.1	0.279
	20-40	5.86	176	7.6	0.502
	40-60	4.74	140	5.6	0.393
	60-80	4.60	134	4.1	0.395
Soybean Medium treatment	0-20	6.81	115	160.0	0.300
	20-40	5.06	148	18.3	0.425
	40-60	4.58	204	7.3	0.590
	60-80	4.53	74	4.9	0.211
Soybean Dry treatment	0-20	7.27	61	97.4	0.166
	20-40	5.66	70	38.9	0.185
	40-60	4.82	86	14.3	0.163
	60-80	4.65	87	8.4	0.161

Table 5.46 Soil chemical properties on soybean plot at the end of the 1995/1996 season

Plot	Soil layer cm	Ammonium acetate extractable cations cmol$_c$ kg^{-1}				Exchangeable cations cmol$_c$ kg^{-1}			
		Ca	Mg	Na	K	Ca	Mg	Na	K
Soybean Wet treatment	0-20	4.068	0.146	0.103	0.034	3.854	0.139	0.058	0.020
	20-40	1.603	0.042	0.084	0.010	1.261	0.032	0.049	0.006
	40-60	1.044	0.039	0.090	0.028	0.779	0.022	0.052	0.017
	60-80	1.004	0.036	0.116	0.023	0.739	0.013	0.067	0.014
Soybean Medium treatment	0-20	3.280	0.137	0.113	0.027	3.052	0.125	0.065	0.016
	20-40	1.294	0.049	0.088	0.010	1.013	0.037	0.051	0.006
	40-60	1.244	0.053	0.122	0.033	0.849	0.02	0.071	0.020
	60-80	0.625	0.047	0.143	0.028	0.505	0.021	0.083	0.017
Soybean Dry treatment	0-20	2.841	0.158	0.203	0.030	2.716	0.142	0.118	0.018
	20-40	1.054	0.080	0.102	0.018	0.938	0.068	0.059	0.011
	40-60	0.635	0.076	0.099	0.016	0.545	0.060	0.021	-
	60-80	0.476	0.085	0.127	0.017	0.395	0.062	0.047	-

Table 5.47 **Soil chemical properties on wheat plot at the end of the 1994 season**

Plot	Soil layer cm	pH (H_2O)	Resis-tance ohm	Bray I P mg kg^{-1}	Cl^{-1} cmol$_c$ kg^{-1}	Ammonium acetate extractable cations cmol$_c$ kg^{-1}			
						Ca	Mg	K	Na
Wheat Wet treatment	0-20	4.4	420	31.2	0.0008	4.122	0.214	0.064	0.035
	20-40	4.4	750	53.2	0	2.236	0.148	0.056	0.030
	40-60	4.5	700	15.3	0	1.866	0.165	0.056	0.026
	60-80	4.7	800	5.3	0	1.657	0.156	0.049	0.026
	80-100	5.3	1000	2.5	0	1.517	0.132	0.059	0.030
Wheat Dry treatment	0-20	4.5	800	10.1	0.0031	1.667	0.189	0.054	0.026
	20-40	4.5	1100	3.3	0.0008	1.277	0.115	0.038	0.017
	40-60	4.3	2500	1.1	0	0.768	0.058	0.033	0.013
	60-80	4.5	1900	2.1	0	1.008	0.066	0.059	0.017
	80-100	4.4	2500	4.1	0	0.898	0.115	0.064	0.026

Table 5.48 Soil chemical properties on wheat plot at the end of the 1995 season

Plot	Soil layer cm	pH (H_2O)	EC_e mS m^{-1}	SO_4 $cmol_c$ kg^{-1}	Soluble cations $cmol_c$ kg^{-1}		Ammonium acetate extractable cations $cmol_c$ kg^{-1}	
					Ca	Mg	Ca	Mg
Wheat Wet Treatment	0-20	5.41	233	0.738	0.186	0.009	15.113	0.600
	20-40	4.46	233	0.692	0.179	0.016	8.334	0.783
	40-60	4.26	151	0.442	0.133	0.030	4.667	0.505
	60-80	4.15	143	0.347	0.142	0.026	4.484	0.493
	80-100	4.37	144	0.356	0.150	0.020	4.910	0.482
Wheat Dry treatment	0-20	4.82	228	0.813	0.187	0.015	10.322	0.833
	20-40	4.43	140	0.400	0.128	0.030	3.969	0.662
	40-60	4.19	128	0.345	0.137	0.033	3.596	0.691
	60-80	4.17	146	0.420	0.157	0.029	4.020	0.580
	80-100	4.44	144	0.364	0.152	0.044	2.143	1.363

Table 5.49 Soil chemical properties in the 0-20 cm layer at the beginning of the 1995/96 season

Plot	pH (H_2O)	Resistance ohm	Bray I P mg kg^{-1}	Ammonium acetate extractable cations cmol$_c$ kg^{-1}			
				Ca	Mg	K	Na
Maize	5.9	750	74.4	5.704	0.140	0.146	0.027
Soybean	6.0	800	59.0	4.511	0.107	0.110	0.031
Sorghum	6.0	1100	76.0	4.780	0.132	0.133	0.027
Babala	6.2	660	119.4	7.520	0.181	0.128	0.034
Cowpeas	6.0	600	63.4	5.359	0.140	0.118	0.023
Lucerne	6.8	550	157.2	9.880	0.247	0.046	0.040
Fescue	6.7	600	191.4	10.339	0.337	0.113	0.033
Crownvetch	6.2	660	251.9	6.737	0.214	0.166	0.018
Cocksfoot	7.0	760	208.2	8.877	0.280	0.115	0.020
Milkvetch	7.1	1000	138.9	6.916	0.230	0.146	0.023
Eragrostis	6.8	600	30.4	7.440	0.173	0.125	0.029
Smuts	6.2	550	21.6	8.777	0.247	0.089	0.038
Kikuyu	6.9	510	32.1	8.134	0.247	0.089	0.038
Rhodes	7.2	620	25.6	7.295	0.239	0.110	0.038

FIGURE 5.1 Experimental scheme

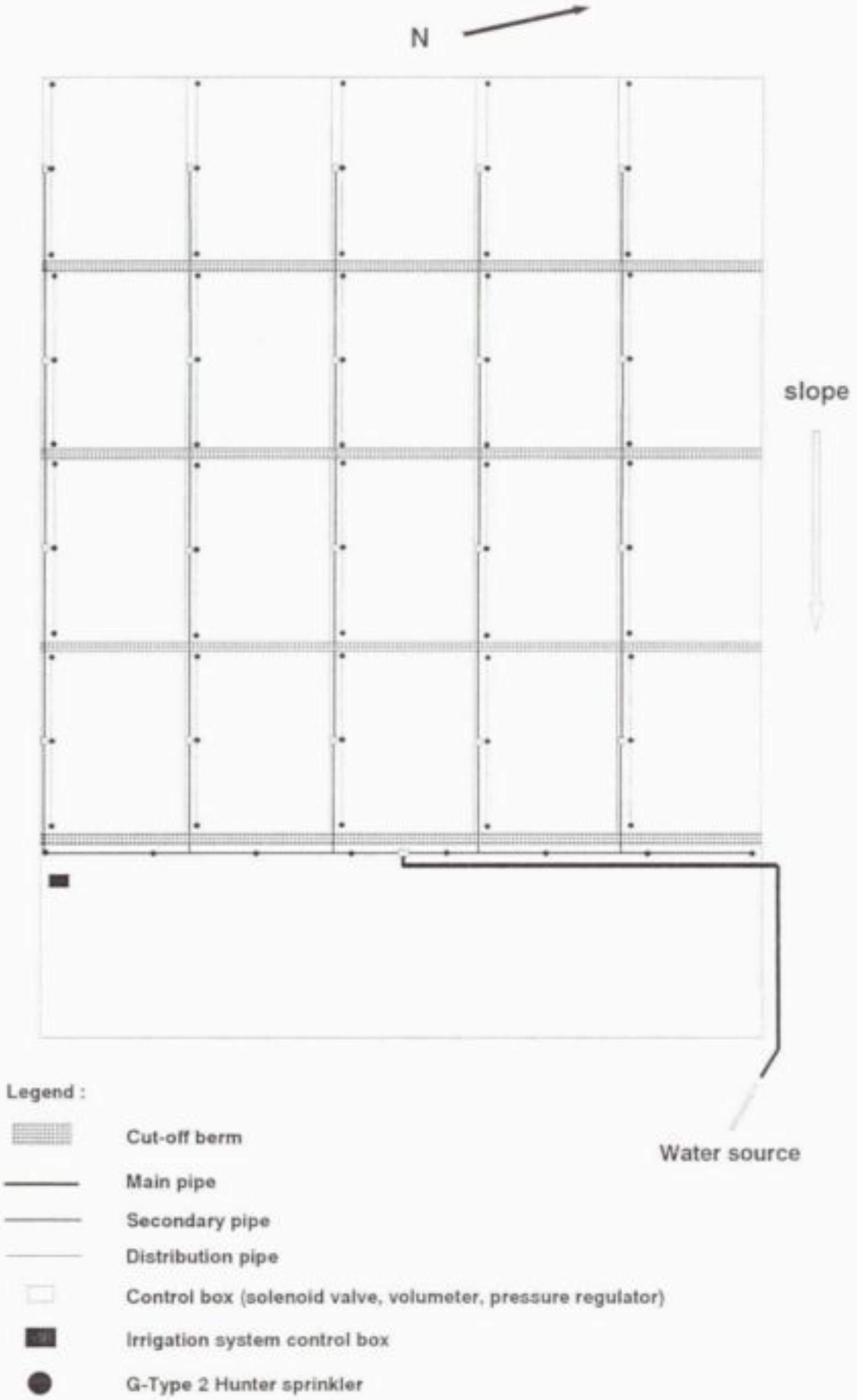


FIGURE 5.2 Experimental field irrigation scheme

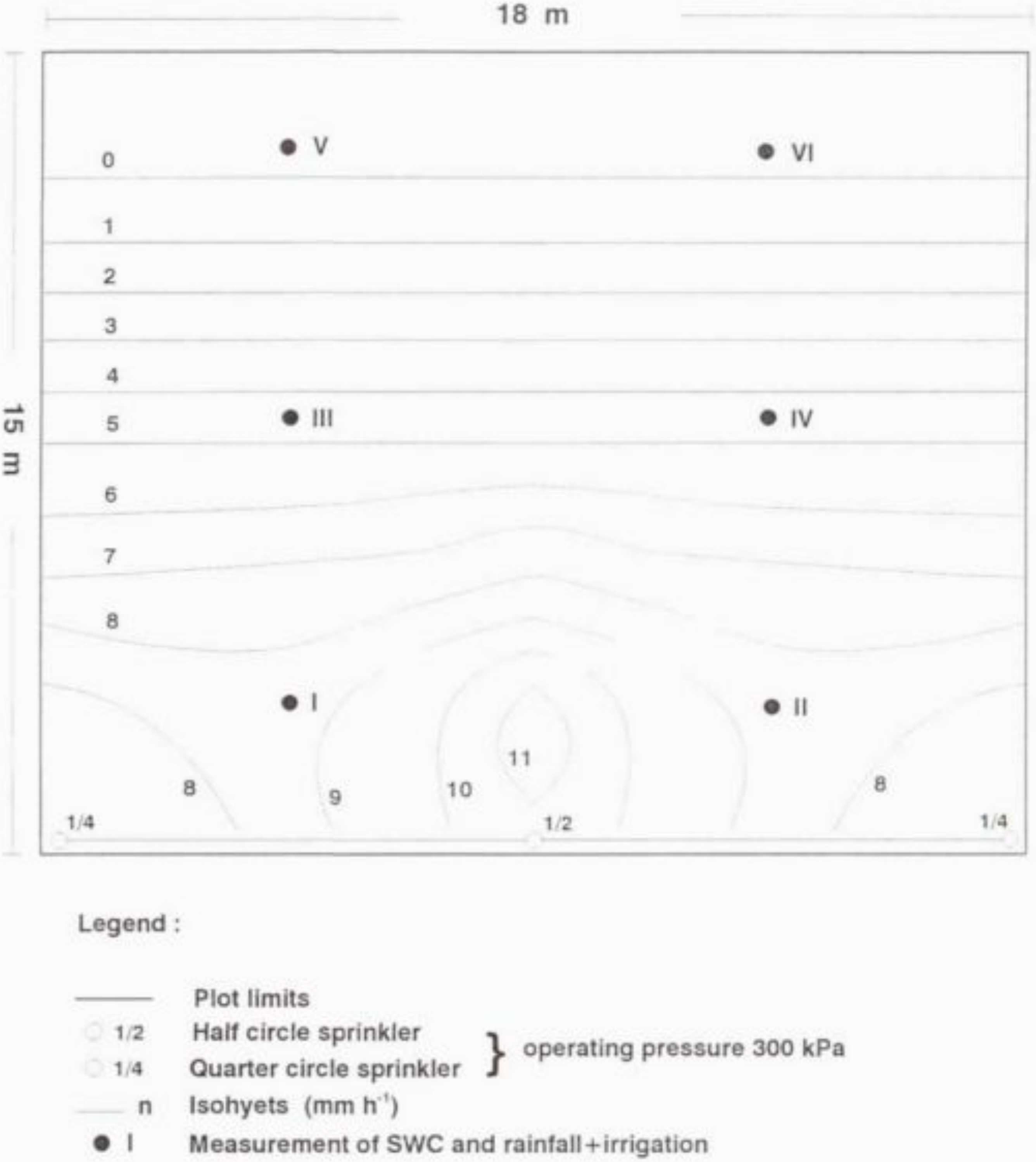


FIGURE 5.3 Water application rate pattern

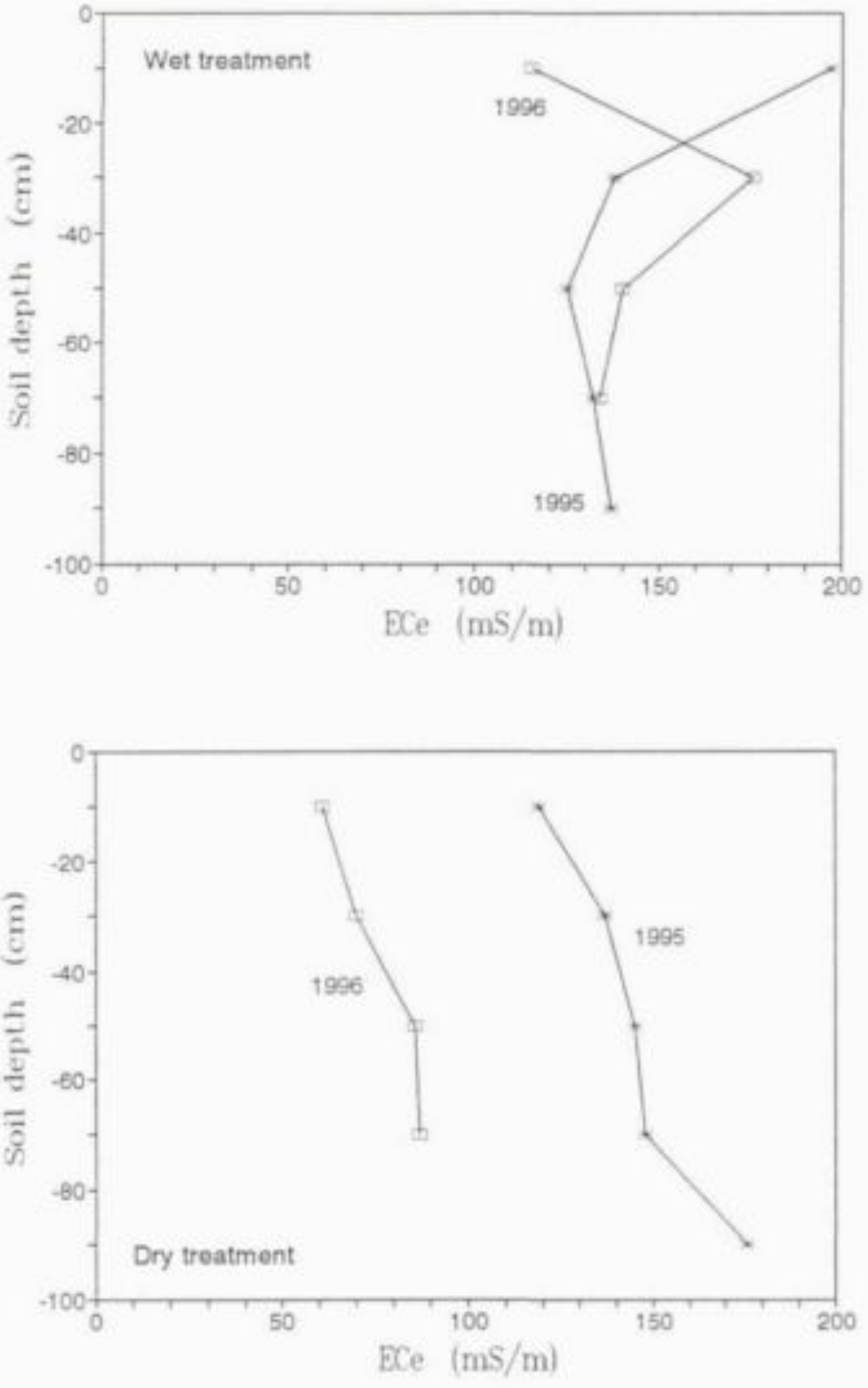
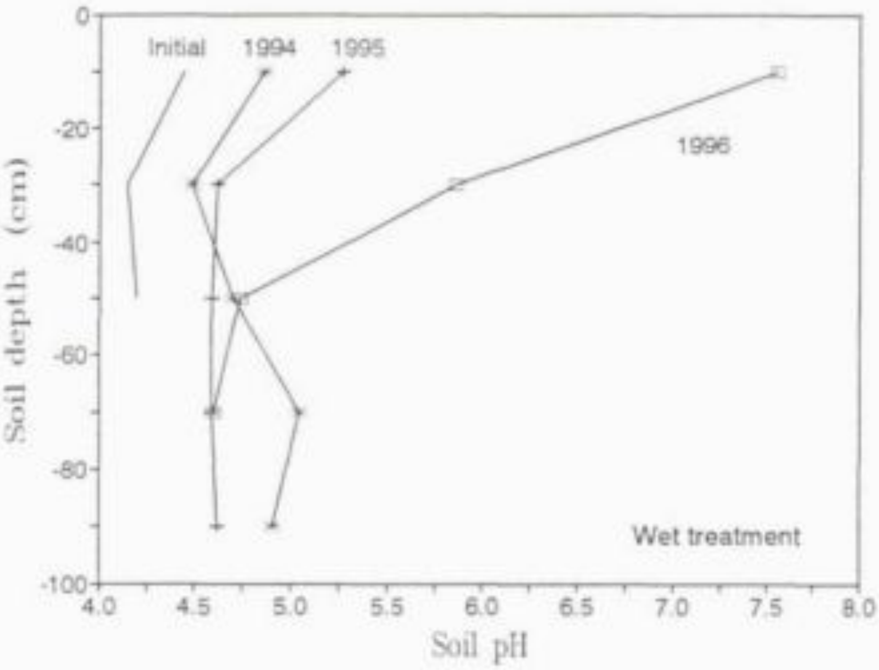


FIGURE 5.4 Measured values of electrical conductivity of saturated soil extract (EC_e) in the soil profile of soybean at the end of the 1994/95 and 1995/96 growing season



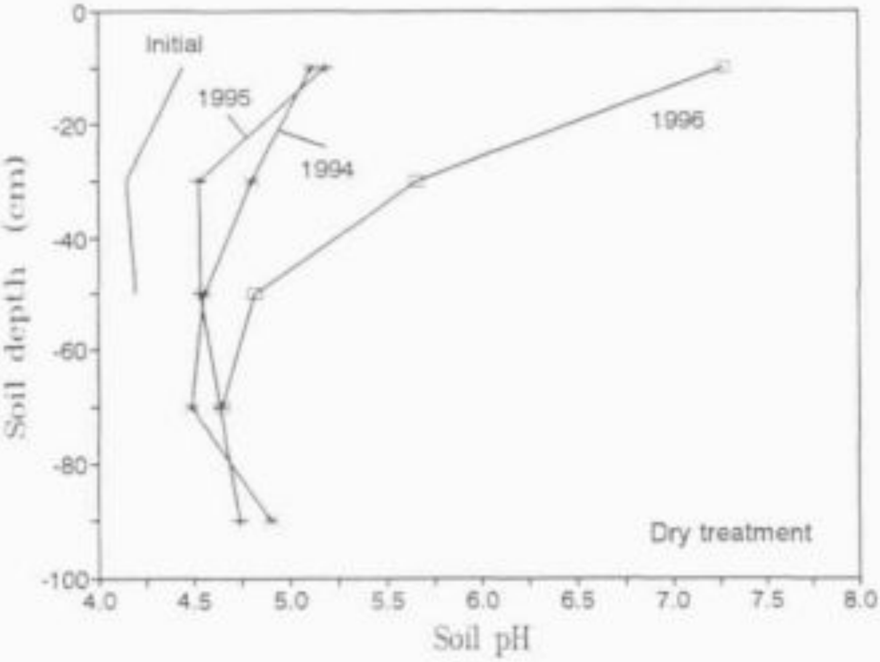


FIGURE 5.5 Measured values of soil pH (H_2O) in the soil profile of soybean

CHAPTER 6

CROP GROWTH AND WATER BALANCE - SOIL SALINITY MODEL

6.1 INTRODUCTION

Long-term changes in soil chemical properties can be experimentally measured, but the set-up of long-term experiments monitoring slow environmental processes is not attractive, both for practical and financial reasons. Computer models, combined with a weather data generator, are useful tools for predicting environmental effects.

Several crop production-salt movement models have already been published (Maas & Hoffman, 1977; Bresler, McNeal & Carter, 1982; Du Plessis, 1983b; Wagenet, 1984; Maas, 1986). In this study, a simple water movement-soil salinity model (SWB, Soil water balance) has been developed for management of irrigation with lime treated AMD.

The NEWSWB model of G.S. Campbell, Washington State University, an improved version of the published model (Campbell & Diaz, 1988), was used to simulate water movement in the soil profile as well as crop growth. This model has been expanded to include salt movement and precipitation of gypsum in the soil profile. The introduction of the soil chemistry subroutine allowed prediction of soil salinity parameters and crop growth while irrigating with lime treated AMD. Since NEWSWB is a mechanistic, generic crop growth model, parameters specific for each crop had to be determined using data from the field trial.

6.2 THEORETICAL OVERVIEW OF THE MODEL

The NEWSWB model was used as a basis from which to predict water movement in the soil profile as well as crop growth. Water movement in the soil profile can be simulated adopting either a cascading or a finite difference one-dimensional simulation. In this work, the cascading approach has been used. Movement of Ca, SO_4 and Mg in the soil profile by convection was simulated. Other ionic species were not considered as their concentration in lime treated AMD is negligible. Solute movement by molecular diffusion was neglected as it represents a minor component (Bresler *et al.*, 1982; Campbell, 1985). Ca, SO_4 and Mg activities in the soil solution were calculated in order to quantify precipitation/dissolution of gypsum. Soil water potential is updated on a daily basis taking into account water and salt redistribution in the profile and matric and osmotic potential fluctuations due to crop water uptake. Crop water consumption represents the driving force of the crop growth model. Potential evapotranspiration (PET) is calculated using a modified Priestley-Taylor equation, corrected for vapour pressure deficit. The two components of PET (potential evaporation and potential transpiration) are calculated according to canopy cover. Actual transpiration (T) is determined on a daily basis as either supply limited or demand limited water uptake. A stress index (SI), the ratio between actual and potential transpiration, is adopted as a limiting factor for crop growth.

A flow diagram of the simulation model is represented in Figure 6.1 (p. 267). The model is written in Turbo Pascal v. 7.0. An improved user friendly version, the SWB model, is available (Benadé, Annandale & van Zijl, 1995).

For the application of the model, the following parameters must be entered:

- Latitude;
- Starting day of year;
- Maximum rooting depth (m);
- Runoff curve number (mm);
- Planting day of year;
- Volumetric field capacity per layer;
- Volumetric permanent wilting point per layer;
- Initial volumetric soil water content per layer;
- Initial content of ionic species per unit area per layer (mol m^{-2});
- Bulk density per layer ($Mg\ m^{-3}$);
- Maximum daily temperature (°C);
- Minimum daily temperature (°C);

- Precipitation;
- Irrigation amounts; and
- Ca, Mg and SO_4 concentrations in irrigation water (mol l^{-1}).

The following crop parameters have been determined using the field trial data:

- Average daily radiant transmission coefficient;
- Corrected dry matter water ratio (Pa);
- Radiation conversion efficiency (kg MJ^{-1});
- Emergence day degrees;
- Day degrees at the end of vegetative growth;
- Maturity day degrees;
- Transition period from vegetative to reproductive growth;
- Day degrees for leaf senescence;
- Base temperature (°C);
- Temperature for optimum light limited crop growth (°C);
- Cutoff temperature (°C);
- Fraction of stem dry matter translocated to heads during grain fill;
- Leaf water potential at maximum transpiration (J kg^{-1});
- Maximum possible transpiration rate (mm day^{-1});
- Specific leaf area (m^2 kg^{-1});
- Stem-leaf partition parameter;
- Canopy dry matter at emergence (kg m^{-2});
- Fraction of dry matter partitioned to roots;
- Potential grain production as fraction of stem dry matter at anthesis;
- Root growth rate (m^2 $kg^{-0.5}$ day^{-1}); and
- Stress index.

The desired output of the model can be easily modified in the _IRUN.PAS file of the package.

The different components of the model are discussed under the following headings: the atmospheric environment, the soil environment, and the crop growth.

6.2.1 The atmospheric environment

The aim of this section is to calculate PET from available meteorological input data.

6.2.1.1 Radiation

Net radiation provides most of the energy which drives the evapotranspiration process. As net radiation was not measured directly, it had to be estimated from available environmental measurements.

Potential solar radiation S_o is calculated as a function of day of year (DOY) as follows:

$$S_o = 117.5\,(\omega_s \sin(\mathrm{Lat}) \sin(\mathrm{Dec}) + \cos(\mathrm{Lat}) \cos(\mathrm{Dec}) \sin(\omega_s))/\pi$$

(Duffie & Beckman, 1980; Bristow & Campbell, 1984)

S_o - Incoming solar radiation on a horizontal surface outside the earth's atmosphere (MJ m^{-2} day^{-1})
ω_s - Sunset hour angle (rad)
Lat - Latitude (rad)
Dec - Solar declination (rad)

where

$$\sin(\mathrm{Dec}) = 0.39785 \quad \sin(4.869+0.0172 \quad \mathrm{DOY}+0.03345 \sin(6.224+0.0172\ \mathrm{DOY}))$$

(Swift, 1976)

The coefficient 117.5 accounts for the solar constant G_{sc} (118.08 MJ m^{-2} day^{-1}) and the relative distance of the earth from the sun.

Daily incoming solar radiation S_t is defined as:

$$S_t = S_o\,T_t$$

T_t - Daily atmospheric transmission coefficient

Bristow & Campbell (1984) suggested an expression for the calculation of T_t as a function of daily maximum and minimum air temperature difference:

$$T_t = 0.7\ (1\text{-}\exp(-0.329\ \Delta T_a^2/S_{o30}))$$

where

$$\Delta T_a = T_{max} - T_{min}$$

T_{max} - Daily maximum air temperature (°C)
T_{min} - Daily minimum air temperature (°C)
S_{o30} - Extraterrestrial solar radiation 30 days previous to the simulation day (MJ m^{-2} day^{-1})

The factor 0.7 represents the maximum clear sky T_t of any given area. It varies with elevation and pollution content of the air. Small ΔT_a values imply cloudy conditions. Under clear sky conditions, large ΔT_a values are likely to occur. The emissivity of the atmosphere is strongly affected by water vapour. Brutsaert (1975) expressed clear sky emissivity ε_a as:

$$\varepsilon_a = 0.768\ e_a^{1/7}$$

e_a - atmospheric vapour pressure (kPa)

Unsworth and Monteith (1975) derived a correction to clear sky emissivity to account for cloudiness ε_{ac} , and this was modified by G.S. Campbell (Annandale, 1991) as follows:

$$\varepsilon_{ac} = \varepsilon_a + (1\text{-}\varepsilon_a)/(1+0.048\ \exp(7.1T_t))$$

Isothermal net radiation (Rni) in W m^{-2} is calculated after Monteith (1975) as:

$$Rni = (1-\alpha)\ S_t + (\varepsilon_{ac} - \varepsilon_s)\ \sigma\ T_a^4$$

σ - Stefan-Boltzmann constant ($5.67\ 10^{-8}$ W m^{-2} K^{-4})
ε_s - Emissivity of the surface (0.98) (Davies and Idso, 1979)
α - Albedo (0.2) (Davies and Idso, 1979)
T_a - Air temperature (K)

The isothermal net radiation is used to calculate the Priestley-Taylor potential evapotranspiration.

6.2.1.2 Vapour pressure deficit

Vapour pressure deficit (VPD) was needed in order to determine potential evapotranspiration and for the calculation of dry matter accumulation.

Daily average VPD is calculated as a function of maximum and minimum daily temperature after Campbell & Diaz (1988):

$$VPD = 0.7\ s\ \Delta T_a$$

s - Slope of the saturation vapour pressure curve (Pa °C^{-1})

where

$$s = ((0.00223\ T_{avg} + 0.0549)\ T_{avg} + 2.97)\ T_{avg} + 45.3$$

T_{avg} - Daily average air temperature (°C)

where

$$T_{avg} = (T_{max} + T_{min})/2$$

6.2.1.3 Potential evapotranspiration

The resistance form of the Penman combination equation (Penman, 1948) gave unrealistically high values for PET, especially on windy days when the crop was tall (0.55 m). This is to be expected as aerodynamic resistance is negligible under these conditions and actual transpiration is controlled by canopy resistance, a term which does not appear in the Penman equation. The Penman-Monteith equation (Monteith, 1965) does have a canopy resistance term in it, but estimating canopy resistance is difficult and the equation is not applicable to early season conditions before canopy closure is complete. Priestley and Taylor (1972) multiplied the radiative portion of the combination equation by a constant (α) and dropped the aerodynamic term:

$$\lambda E_p = \alpha\ (s/(s+\gamma))\ (Rn - G)$$

λ - Latent heat of vaporization (MJ kg^{-1})

$$\lambda = 10^6\ (2.5 - 2.361\ 10^{-3}\ T_a)$$

with T_a in °C (Allen, Jensen, Wright & Burman, 1989).

E_p - Potential evaporation (kg m^{-2} s^{-1})
γ - Psychrometer constant (kPa $°C^{-1}$) [$\gamma = (C_p\ P_a)/(\varepsilon\ \lambda)$]
C_p - Specific heat of moist air at constant pressure ($1.01\ 10^3$ J kg^{-1} $°C^{-1}$)
ε - Ratio of the molecular masses of air to water (0.622)
P_a - Atmospheric pressure at a given altitude (kPa)

$$P_a = P_0\ (T_0 - \alpha\ (Alt - Alt_0))^{g/(\alpha R)}/T_0$$

Alt - Altitude (m)
Alt_0 - Altitude at sea level (0 m)
T_0 - Standard temperature at sea level (288 K)
P_0 - Standard atmospheric pressure at sea level (101.3 kPa)

g - Gravitational acceleration (9.8 m s^{-2})
R - Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})
α - Adiabatic lapse rate (K m^{-1})

The adiabatic lapse rate is 0.01 K m^{-1} for dry air and 0.0065 K m^{-1} for saturated air, but it does not influence P_a for altitudes up to 7000 m.

Rn - Net radiation (W m^{-2})
G - Soil heat flux (W m^{-2})

Soil heat flux is assumed to be 10% of net radiation.

The Priestley-Taylor equation works well because high radiation environments are also usually dry environments. Jury & Tanner (1975) accounted for VPD in the Priestley-Taylor equation by introducing a variable α rather than using a constant value. Steiner, Howell & Schreider (1991) compared measured lysimeter evapotranspiration to predictions with the Priestley-Taylor equation and concluded that local calibration of the Jury and Tanner type adjustment to α was not necessary. The variable parameter used in this work (α_v) is expressed as:

$$\alpha_v = 1 + (\alpha - 1)\ \mathrm{VPD}$$

where $\alpha = 1.26$ and VPD is in kPa.

6.2.2 The soil environment

The aim of this section was to simulate the dynamics of water movement in the soil profile in order to determine soil water availability for the crop. The mechanistic solution of water movement in the soil-plant-atmosphere continuum makes the NEWSWB model applicable to any climatic condition. The model assumes that water is taken from soil layers with highest root densities when soil water potential is uniform. Reduction in soil water potential closes stomata and decreases transpiration and dry matter production.

6.2.2.1 The soil profile

Water movement is simulated with a cascading model. This divides the soil profile into a number of layers. Each layer has its own physical properties (Figure 6.2, p. 268):

- Soil matric potential Ψ_m (J kg^{-1});
- Volumetric soil water content Θ;
- Volumetric soil water content at field capacity Θ_{fc};
- Volumetric soil water content at permanent wilting point Θ_{pwp}; and
- Campbell's a and b parameters of the log-log water retention function;

Field capacity and permanent wilting point water content values used in this work are based on field measurements. Initial water content values were inserted and actual water content was calculated on a daily basis balancing water sources (precipitation, irrigation) and sinks (evaporation, transpiration, drainage, runoff) in the soil profile.

Soil matric potential is calculated using the moisture release relationship suggested by Campbell (1985):

$$\Psi_m = a\ \Theta^{-b}$$

By plotting Ψ_m and Θ on a log-log scale and fitting a straight line to the data, it is possible to derive a and b as the intercept and the slope of the relation. In the model, a and b are computed using the following relations:

$$b = \ln(\Psi_{pwp}/\Psi_{fc})/\ln(\Theta_{fc}/\Theta_{pwp})$$

Ψ_{pwp} - Soil matric potential at permanent wilting point

Ψ_{fc} - Soil matric potential at field capacity

$$a = -\Psi_{pwp} + \Theta_{pwp}^{b}$$

Hillel (1982) suggested values of -1500 J kg^{-1} for Ψ_{pwp} and -10 J kg^{-1} for Ψ_{fc}.

6.2.2.2 Infiltration

Rainfall (P) and irrigation (I) are inputs in the weather file. Runoff (R_o) is assumed to be zero if

$$P + I \leq 0.2\ S$$

S - Runoff curve number (mm)

If

$$P + I > 0.2\ S\ ,$$

runoff is calculated according to the following relation:

$$R_o = (P + I - 0.2\ S)^2/(P + I + 0.8\ S)$$

(Stewart, Woolhiser, Wischmeier, Caro & Frere, 1976)

The model distributes water from precipitation and irrigation by filling soil layers starting from the top of the soil profile towards the bottom. Drainage (D) is calculated when the sum of P and I exceeds the water deficit in the soil profile. D is assumed instantaneous.

6.2.2.3 Evaporation and transpiration

The actual partitioning between evaporation (E) and transpiration (T) depends on the available energy reaching crop canopy and soil surface and the resistance to water transport (Norman & Campbell, 1983). In this model, the ratio of potential transpiration to potential evapotranspiration is assumed to be the same as the ratio of radiation intercepted by the crop to total incident radiation, called radiation fractional interception FI (Ritchie, 1972). The FI calculation is presented in the following section on crop growth. The expression for evaporation from the top soil layer is given by:

$$E_p = (1 - FI)\ PET$$

(Reddy, 1983)

If water content decreases in the top soil layer below permanent wilting point water content:

$$E_p = PET\ (1 - FI)\ ((\Theta - \Theta_{ad})/(\Theta_{pwp} - \Theta_{ad}))^2$$

Θ_{ad} - Air dry volumetric soil water content

$$\Theta_{ad} = 0.3\ \Theta_{pwp}$$

Water loss by transpiration is computed for each layer in the soil profile adopting the following equation:

$$T = (FI\ Tr_{max}\ f\ (\Psi_x - \Psi_m)/(0.67\ \Psi_{lmin}))/(d_w\ dz)$$

(Campbell & Stockle, 1993)

Tr_{max} - Maximum possible transpiration rate (mm day^{-1})
f - Factor for weighted root distribution in the soil layer
Ψ_x - Xylem water potential (J kg^{-1})
Ψ_{lmin} - Leaf water potential at maximum transpiration rate (J kg^{-1})
ρ_w - Water density (1000 kg m^{-3})
dz - Soil layer thickness (m)

Tr_{max} was assumed to be 9 mm day^{-1}. Ψ_{lmin} was assumed to be -1250 J kg^{-1}. Soil layers of 20 cm were considered. The factor "f" is computed according to the following expression:

$$f = dz\,(2\,(RD-z) + dz)/RD^2$$

(Campbell & Diaz, 1988)

RD - Root depth (m)
z - Soil depth (m)

Ψ_x is calculated using the expression:

$$\Psi_x = \Psi_{lmin}\,(\Psi_{avg}^{\,*} + 0.67\ T^*)$$

where

$$\Psi_{avg}^{\,*} = \Psi^* / \Psi_{lmin}$$

Ψ^* - Root weighted average soil matric potential (J kg^{-1})

$$\Psi^* = f\ \Psi_m$$

T^* - Dimensionless actual water uptake

T^* is chosen as the minimum between dimensionless root uptake rate (rootU)

$$\text{rootU} = 1 - 0.67\ \Psi_{avg}^{\,*}$$

and maximum dimensionless loss rate (evapD)

$$\text{evapD} = \text{PET}/\text{Tr}_{max}$$

The factor "0.67" takes into account the resistances which water flow encounters in the path from the soil toward the leaf. The major resistances are in the endodermis, where water enters the root steele and in the leaf, at the bundle sheath. For typical plants growing in moist soil, the potential drop across the endodermis is 60-70% of the total (Campbell, 1985). In this model, root resistance is assumed to be 67%. Xylem resistance is assumed to be negligible as water flows in cell walls and xylem vessels without crossing membranes. Soil resistance is also considered negligible. Water uptake is calculated only when

$$\Psi_{avg}^{*} = \Psi^{*} / \Psi_{lmin} < 1.5$$

If the ratio between root weighted average soil matric potential and leaf water potential at maximum transpiration rate exceeds 1.5, water loss by transpiration is assumed to be 0. Under this condition, the actual leaf water potential is equal to the root weighted mean soil matric potential ($\Psi_x = \Psi^*$). Finally, water losses by transpiration are cumulated for each layer in order to determine daily T in mm.

6.2.2.4 Soil salinity

The soil salinity subroutine was added to the original NEWSWB model of G.S. Campbell. The objective was to describe the effects of osmotic potential on root water uptake and crop growth and changes in soil properties while using saline water for irrigation.

The redistribution of the main ionic species present in lime treated AMD (Ca^{2+}, SO_4^{2-}, Mg^{2+}) is simulated according to the scheme in Figure 6.3 (p. 269). The following soil chemical properties are determined for each layer in the soil profile:

- Molar ionic concentration C_i (mol l^{-1});
- Mass of ionic species per unit area M_i (g m^{-2});
- Total dissolved salts TDS (mol l^{-1});
- Osmotic potential Ψ_o (J kg^{-1});
- Electrical conductivity EC (mS m^{-1});
- Ionic activity a_i (mol l^{-1}); and
- Ionic strength of the soil solution I_s (mol l^{-1}).

Initial soil solution chemical properties are needed as input. Irrigation and rain water chemical characteristics need to be known in order to determine the quantity of salts added to the soil profile.

The following assumptions are made:

- Instantaneous redistribution;
- Complete mixing of soil solution with irrigation or rainfall water;
- No dissolution from weathering soil minerals;
- No input of fertilizers and chemical amendments;
- No salt removed by crop;
- No decrease in root permeability due to soil salinity; and
- Movement of salts only by convection.

Movement of salts by molecular diffusion is not considered as it is assumed to be negligible under conditions of high average water flow velocity typical for a sandy soil (Olsen & Kemper, 1968).

The following basic salt balance relationship has been adopted:

$$\Delta S = V_{dw} C_{dw} - V_{iw} C_{iw}$$

(Wilcox & Resch, 1963)

ΔS - Salt balance (mg m^{-2})
V_{dw} - Volume of drainage water (kg m^{-2})
V_{iw} - Volume of irrigation water (kg m^{-2})
C_{dw} - Concentration of drainage water (mg kg^{-1})
C_{iw} - Concentration of irrigation water (mg kg^{-1})

C_{iw} and V_{iw} are inputs. V_{dw} is calculated for each soil layer as:

$$V_{dw} = V_{iw} - ((\Theta_{fc} - \Theta) \, dz \, \rho_w)$$

C_{dw} is a critical term as it depends on the quantity of drainage water, the quality of receiving water (Rhoades, Ingvalson, Tucker & Clark, 1973; Rhoades, Oster, Ingvalson, Tucker & Clark, 1974), the weathering of soil minerals (Carter & Robbins, 1978) and the properties of the soil and underlying material (Skogerboe & Walker, 1974). Chemical amendments, fertilizers and salts removed by growing crops were reported to have a very limited influence on drainage water quality (Bresler *et al.*, 1982). Under steady state conditions (assuming $\Delta S=0$), C_{dw} is calculated as:

$$C_{dw} = (C_{iw}\ V_{iw})\ /\ V_{dw}$$

(Rhoades, 1974)

This equation determines the concentration of water reaching deeper layers (Tanji, Doneen & Paul, 1967). The molar mass of each ionic species (M_i) present in each soil layer per unit area after redistribution of irrigation or rainfall water is calculated:

$$M_i = C_i\ (\Theta\ \rho_w\ dz)$$

C_i - Concentration of ionic species (mol l^{-1})

EXAMPLE:

Irrigation amount (input): $I = 20$ mm

Ca concentration in irrigation water (input): $C_{Ca} = 0.01$ mol l^{-1}

Volumetric water content of top soil layer (initial input value): $\Theta_{20} = 0.15$

Field capacity water content of top soil layer (constant input): $\Theta_{fc20} = 0.20$

Soil layer thickness (constant input): $dz = 0.2$ m

Water density (constant): $\rho_w = 1000$ kg m^{-3}

Mass of Ca per unit area in the top soil layer (initial input value):

$M_{20} = 0.04$ mol m^{-2}

The mass of incoming Ca diluted in irrigation water (M_{Ca}) is:

$$M_{Ca} = I \times C_{Ca} = 20 \text{ l m}^{-2} \times 0.01 \text{ mol l}^{-1} = 0.2 \text{ mol m}^{-2}$$

Assuming complete mixing of water present in the top soil layer with the incoming irrigation water, the new concentration of soluble Ca in the top soil layer (C_{20}) is:

$$C_{20} = (M_{Ca} + M_{20}) / (I + \Theta_{20} \, dz \, \rho_w) =$$

$$= (0.2 \text{ mol m}^{-2} + 0.04 \text{ mol m}^{-2}) / (20 \text{ l m}^{-2} + 0.15 \times 0.2 \text{ m} \times 1000 \text{ l m}^{-3}) = 0.0048 \text{ mol l}^{-1}$$

At the same time, C_{20} is assumed to be the concentration of water penetrating the deeper soil layer. The quantity of water penetrating the deeper soil layer ($I_{20\text{-}40}$) is equal to the amount of irrigation water reduced by the amount of water required to fill the top layer up to field capacity:

$$I_{20\text{-}40} = I - (\Theta_{fc20} - \Theta_{20}) \, dz \, \rho_w = 20 \text{ l m}^{-2} - (0.20 - 0.15) \times 0.2 \text{ m} \times 1000 \text{ l m}^{-3} = 10 \text{ l m}^{-2}$$

The new mass of Ca per unit area in the top soil layer is calculated as:

$$M_{20} = C_{20} \, \Theta_{fc20} \, dz \, \rho_w = 0.0048 \text{ mol l}^{-1} \times 0.20 \times 0.2 \text{ m} \times 1000 \text{ l m}^{-3} = 0.192 \text{ mol m}^{-2}$$

The same procedure is repeated for each soil layer and for Mg and SO_4.

Due to soil water consumption by evapotranspiration (ET), and assuming no plant uptake of solute, the ionic concentration in each soil layer is updated on a daily basis after crop water uptake has been calculated, as follows:

$$C_i = M_i / (\Theta \, \rho_w \, dz)$$

Total dissolved salts are calculated as the sum of Ca, SO_4 and Mg concentrations:

$$TDS = [Ca^{2+}] + [SO_4^{2-}] + [Mg^{2+}]$$

Robbins, Wagenet & Jurinak (1980) found that, when either the soil or irrigation water contains gypsum, the salt concentration in the soil solution is controlled by gypsum solubility. The solubility product of gypsum (K_{sp}) is the product of the ionic activities of Ca^{2+} and SO_4^{2-} in equilibrium with a solid phase:

$$K_{sp} = (Ca^{2+})\,(SO_4^{2-}) = 2.4 \times 10^{-5}\ mol^2\ l^{-2}$$

(Latimer, 1952; Dutt, Shaffer & Moore, 1972;
Sposito & Traina, 1987)

The activities of Ca^{2+} and SO_4^{2-} are calculated according to Bohn, McNeal & O'Connor (1985):

$$(Ca^{2+}) = \gamma_{Ca}\,[Ca^{2+}]$$
$$(SO_4^{2-}) = \gamma_{SO4}\,[SO_4^{2-}]$$

where γ_i is the ionic activity coefficient calculated after Arslan & Dutt (1993):

$$\log \gamma_i = (-A\, z_i^2\, I_s^{0.5}) \,/\, (1 + \alpha_d\, \beta\, I_s^{0.5})$$

The activity coefficients are therefore equal for Ca^{2+} and SO_4^{2-}. Parameters A and β are associated with absolute temperature and dielectric constant of the solvent, while parameter α_d is a function of ion diameter. According to Corsaro (1962), A is a constant 0.511 at 298 K. The product of α_d and β was assumed to be 1.3 at 298 K, after Glasstone (1947).

z_i - Charge of the ionic species

The ionic strength of the solution is calculated as:

$$I_s = 0.5 \, \Sigma \, C_i \, z_i^2$$

The product $(Ca^{2+})\,(SO_4^{2-})$, under equilibrium conditions, should be equal to the solubility product of gypsum (K_{sp}):

$$K_{sp} = (Ca^{2+})\,(SO_4^{2-}) = 2.4 \times 10^{-5}\ mol^2\ l^{-2}$$

If $(Ca^{2+})\,(SO_4^{2-}) > K_{sp}$, the model reduces iteratively the activity of both Ca^{2+} and SO_4^{2-} by the same amount in mol l^{-1}, so that their product equals 2.4×10^{-5} $mol^2\ l^{-2}$. The concentrations of Ca and SO_4 are reduced by the same amount in mol l^{-1}. The amount of precipitated $CaSO_4$ in g is therefore increased. If $(Ca^{2+})\,(SO_4^{2-}) < K_{sp}$, and enough gypsum is available to dissolve, the model increases the activity of both Ca and SO_4 by the same amount in mol l^{-1}, so that their product equals 2.4×10^{-5} $mol^2\ l^{-2}$. The concentrations of Ca and SO_4 are increased by the same amount in mol l^{-1}. The amount of precipitated $CaSO_4$ in g is therefore reduced. Activity coefficients, activities of Ca^{2+} and SO_4^{2-}, and ionic strength of the soil solution are recalculated for each iteration. The procedure is repeated until:

$$K_{sp} - (Ca^{2+})\,(SO_4^{2-}) = 10^{-10}$$

The activity of the $CaSO_4^0$ ion pair is calculated as:

$$(CaSO_4^0) = (Ca^{2+})\,(SO_4^{2-}) \times 10^{2.31}$$

where $10^{2.31}$ represents the formation constant of the $CaSO_4^0$ ion pair (Bolt & Bruggenwert, 1978). The amount of precipitated gypsum is reduced by $(CaSO_4^0)$ as a portion of Ca and SO_4 remains in the soil solution in the form of $CaSO_4^0$. The concentrations of Ca^{2+} and SO_4^{2-} in the soil solution are therefore increased by $(CaSO_4^0)$.

TDS is finally corrected for the quantity of salts precipitated/dissolved (Tanji, Dutt, Paul & Doneen, 1967). Precipitation/dissolution of gypsum is simulated at the end of each day, after water and salt redistribution and root water uptake occurred.

In the absence of specific-ion effects, crop growth reduction due to salinity is generally related to the osmotic potential of the soil solution in the root-zone (Maas & Hoffman, 1977; Bernstein, 1975). Total osmotic potential is the sum of the contributions from ionic components, as interaction between species is small (Campbell, 1985). Osmotic potential Ψ_o (J kg^{-1}) is calculated as:

$$\Psi_o = - \nu \Sigma C_s \chi R_g T_s$$

ν - Number of ions per molecule of ionising solute (2 for $CaSO_4$ solution)
C_s - Concentration of solute (mol kg^{-1})
χ - Osmotic coefficient
R_g - Gas constant (8.314 J K^{-1} mol^{-1})
T_s - Temperature of solution (K)

The osmotic coefficient is a function of solution concentration and solute species. Osmotic coefficients for common solutes are given by Robinson & Stokes (1965). In this work, χ was assumed to be 1. Decreasing Ψ_o has the net effect of reducing the availability of water to plants. Osmotic potential and gravitational potential (Ψ_g) are therefore added to soil matric potential in order to determine total water potential for each layer in the soil profile.

Soil solution EC is calculated according to the following empirical equation valid in the range 300-3000 mS m^{-1}:

$$\Psi_o = - 0.36 \text{ EC}$$

(U.S. Salinity Laboratory Staff, 1954)

where Ψ_o is in J kg^{-1} and EC in mS m^{-1}.

6.2.3 Crop growth

The aim of this section was to verify the effects of soil salinity on crop growth. A second objective was to verify crop parameters by comparing simulations to field data.

Crop development is simulated using thermal time, an approach suggested by Monteith (1977). Growing degree days (GDD) are accumulated daily using the following expression:

$$GDD = T_{avg} - T_b$$

T_b - Base temperature (°C)

Thermal time accumulation is limited by a maximum temperature (T_{cutoff}).

Yield is predicted using the relationship between dry matter accumulation and transpiration (Tanner & Sinclair, 1983):

$$TDM = DMWR \, (T/VPD)$$

DMWR - Dry matter water ratio (Pa)
TDM - Total dry matter (kg m^{-2})

Under conditions of light-limited crop growth:

$$TDM = T_f \, E_c \, FI \, S_i$$

T_f - Temperature factor for light-limited crop growth

where

$$T_f = (T_{avg} - T_b) \, / \, (T_{lo} - T_b)$$

T_{lo} - Temperature of optimum light-limited growth (°C)
E_c - Radiation conversion efficiency (kg MJ^{-1})

The succession of phenological stages is simulated from day degree requirements for emergence, completion of vegetative growth, maturity and transition period between vegetative and reproductive growth.

During the vegetative stage, TDM is partitioned to roots, leaves and stems according to the following expressions:

$$RDM = f_r \, TDM$$

RDM - Root dry matter (kg m^{-2})
f_r - Fraction of total dry matter partitioned to roots

$$LDM = (1 - f_r) \, f_l \, TDM$$

LDM - Dry matter partitioned to leaves (kg m^{-2})
f_l - Leaf partitioning factor

$$f_l = 1 \, / \, (1 + PART \, TDM)^2$$

PART - Stem-leaf partition parameter

$$SDM = (1 - f_r) \, (1 - f_l) \, TDM$$

SDM - Stem dry matter (kg m^{-2})

Root depth is calculated according to the expression:

$$RD = RGR \, RDM^{0.5}$$

RGR - Root growth rate (m^2 $kg^{-0.5}$)

Root dry matter accumulation is terminated once root depth reaches a maximum value. Maximum rooting depth was measured in the field and is used as an input in the model.

Partitioning of TDM to reproductive organs is calculated as follows:

$$HDM = GPF \, TDM$$

HDM - Harvestable dry matter (kg m^{-2})
GPF - Grain partition fraction

$$GPF = (GDD\text{-}FLDD) / GPDD$$

FLDD - Day degrees at end of vegetative growth
GPDD - Day degrees of transition period from vegetative to reproductive growth

FLDD and GPDD are input values. Once GPF equals 1, the crop is fully reproductive and the daily TDM increment is fully partitioned into reproductive organs.

LAI is calculated from the specific leaf area SLA (m^2 kg^{-1}), an input parameter which describes the morphology of a specific crop:

$$LAI = SLA\ LDM$$

LAI is limited by an input factor representing the maximum leaf age. A non-dimensional stress index is also calculated to take into account limitations in crop growth due to water stress:

$$SI = T / (FI\ PET)$$

Estimated SI threshold values were used as input in the model. Premature leaf senescence is simulated to occur when calculated SI values are lower than the threshold value.

Canopy radiation fractional interception is calculated as a function of LAI:

$$FI = 1 - e^{-KC\ LAI}$$

KC - Canopy radiation extinction coefficient for net radiation

where KC is an input. FI is estimated by the model in order to determine the portion of net radiation available for crop transpiration.

6.3 RESULTS AND DISCUSSION

6.3.1 Crop growth parameters

NEWSWB is a generic model for predicting crop growth. The values of crop specific parameters suggested as model inputs are summarized in Tables 6.1-6.4 (pp. 259 to 262). Crop parameters have been measured or estimated using data from the field trial.

Specific leaf area was measured in the field and seasonal average values used as input in the model. Emergence day degrees and day degrees at the end of vegetative growth have been determined from average daily air temperatures and monitoring phenological stages of each crop. Day degrees for leaf senescence and transition period day degrees from vegetative to reproductive stage have been estimated using field data. Crops grown for forage never reached the flowering stage as they were harvested during the growing season. Stress index was estimated to be 0.95 for all species. Very low values of fraction of TDM translocated to roots were estimated because of the shallow rooting depths. Maximum root depths of most crops hardly reached depths below 50 cm possibly due to high soil acidity, soil compaction and P deficiency in deeper layers. Base temperature was assumed to be 4 °C for temperate and 10 °C for subtropical species. Temperature for optimum light-limited crop growth was assumed to be 25 °C for subtropical annuals, 20 °C for subtropical pastures and 15 °C for temperate species.

In the following sections, the calculation of dry matter water ratio, canopy radiation extinction coefficient and radiation conversion efficiency of each crop will be presented in detail.

6.3.1.1 Dry matter water ratio

Figure 6.4 (p. 270) represents top dry matter production of soybean as a function of the evapotranspiration-vapour pressure deficit ratio for two growing seasons. TDM was measured at harvest and does not include root dry matter. ET was calculated adopting the following water balance equation:

$$ET = P + I - D - R_o - \Delta Q$$

where D was estimated and R_o neglected.

Average VPD during the cropping season was calculated as a function of maximum and minimum daily air temperature and the slope of the saturation vapour pressure curve (Campbell & Diaz, 1988; see section 6.2.1.2 (p. 225).

The slope of the linear regression was calculated in order to obtain the dry matter water ratio value, as follows:

$$DMWR = (TDM\ VPD) / ET$$

The same procedure was applied in the calculation of DMWR values for the other 19 species.

Data from the 1995/96 season were not included in the correlation as it was very difficult to estimate water losses by drainage due to frequent and heavy rains.

Evapotranspiration was considered instead of transpiration as it was impossible to separately measure E and T in the field. Evaporation from soil surface should not be included in the calculation of DMWR as it does not contribute to the building of dry material. The portion of soil water lost by evaporation could become substantial in row crops, particularly at the beginning of the season when canopy covering is partial. DMWR values had therefore to be corrected. Model simulations of crop growth have been used to separately calculate E and T and correct DMWR values. Corrected dry matter water ratios for each crop (Tables 6.1-6.4, pp. 259 to 262) were then used as model input.

Among the subtropical species, **pearl millet**, **soybean** and **sorghum** had a higher water use efficiency than **maize** and **cowpeas**. **Oats** showed the highest water use efficiency among the temperate crops. DMWR values of perennial pastures were generally lower compared to annual crops.

Lower DMWR values of **maize**, **sorghum** and **pearl millet** were calculated compared to those reported by Monteith (1988). Nutritional problems due to shallow rooting depth, experienced in particular for **maize** and **sorghum**, could have been a reason for lower water use efficiency. No nutritional constraints were observed for **soybean** and **wheat**. The calculated DMWR values for these two crops were in the range of those reported by Monteith (1988).

6.3.1.2 Canopy radiation extinction coefficient

Canopy radiation extinction coefficients have been calculated for 20 species using field measurements of leaf area index and radiation fractional interception.

LAI direct measurements with the LI 3100 were used as a reference in order to test the reliability of data provided by the LAI 2000.

Figure 6.5a (p. 271) represents the correlation between LAI of **soybean** measured directly and indirectly. The linear function is very close to the 1:1 line indicating that LAI of soybean can be non-destructively estimated in the field with the LAI 2000, avoiding in this way the tedious direct measurement with the LI 3100.

The plant canopy analyzer overestimated LAI values of **cowpeas** at LAI > 3 (Figure 6.5b, p. 271), due to the specific canopy structure of the crop. It is very likely that leaves or other organs of this creeping species could have covered the sensor while measurements were taken below the canopy. Under these conditions, both radiation fractional interception and leaf area index measured with the LAI 2000 were overestimated.

LAI of **ryegrass** measured with the plant canopy analyzer was heavily underestimated compared to the directly measured LAI (Figure 6.5c, p. 271). The sensor does not view below its 3 cm thick base and large portions of grass canopies cannot be recorded. A rough estimation of LAI in ryegrass is, however, possible using the correlation coefficients reported in Table 6.5 (p. 263).

Table 6.5 (p. 263) summarizes linear regression coefficients and squared correlation coefficients of LI 3100 - LAI 2000 functions for 18 crop and pasture species. Measurements in crownvetch and Panicum canopies were not made due to the late establishment of these two grasses.

The LAI 2000 proved to be suitable to measure LAI of sorghum and pearl millet, but several replications are recommended in order to overcome canopy heterogeneity.

The plant canopy analyzer overestimated LAI values of maize. It should be taken into account that the LAI 2000 sensor detects the canopy in an angular band of 74° about the zenith point. For this reason, the area sampled with the LAI 2000 in maize is much larger than the area of 1 m^2 sampled for the direct measurement, particularly when plants are tall. The maize canopy was poorly and unevenly developed due to nutritional problems experienced by the crop on a highly acid soil. The effect of gaps viewed by the sensor on LAI estimation is major as LAI is calculated as a function of the logarithms of measured gap fractions. The presence of irregular gaps in the maize canopy could have been a reason of the disagreement between LAI data obtained with the LAI 2000 and those obtained with the LI 3100. The use of appropriate restriction caps providing a narrow view of the sensor is therefore recommended in order to hide large gaps in maize canopies. More than six readings below the canopy and a few replications are recommended while measuring LAI in maize.

Temperate crops were harvested several times during the season and LAI values > 1 were seldom measured. LAI of rye, oats and wheat could be measured with the plant canopy analyzer. However, more data in the range of LAI > 1 are necessary in order to be able to draw definite conclusions.

LAI values obtained with the plant canopy analyzer were overestimated for triticale. This was probably due to the specific canopy structure of the crop. A large portion of the incoming radiation was intercepted by stem and grain which are bigger in triticale than in other cereals. Furthermore, older leaves of triticale are very close to the ground and out of the view range of the LAI 2000 sensor.

The LAI 2000 overestimated LAI of lucerne. It is likely that leaves of lucerne covered the sensor while measurements were taken below the canopy.

Low squared correlation coefficients were obtained from the linear regression between LI 3100 and LAI 2000 readings for temperate and subtropical perennial grasses. For this reason, LAI of these species can only be roughly estimated using the LAI 2000 and the correlation factors suggested in Table 6.5 (p. 263).

Values of canopy radiation extinction coefficient have been calculated in three different ways:

1) FI measured with the ceptometer, LAI measured directly;
2) FI measured with the LAI 2000, LAI measured directly; and
3) both FI and LAI measured with the LAI 2000.

Figure 6.6 (p. 272) represents radiation fractional interception values as a function of LAI of soybean. FI and LAI data concern all irrigation treatments. Squared correlation coefficients of the exponential function as well as KC values obtained with three methods are reported in the Figure. The intention was to determine the most suitable method for calculating KC. No further statistical analysis was carried out.

Slight differences in spacing between rows and sampling during different periods of the day caused oscillations in below canopy radiation values measured with the ceptometer. This resulted in FI - LAI 3100 function having a low squared correlation coefficient. FI values measured with the ceptometer are highly dependent on solar orientation and a whole-day measurement is recommended in order to get a reliable estimation.

More reliable estimations of FI were provided by the LAI 2000 as the fisheye sensor makes the measurement independent of solar orientation. Another advantage of using the plant canopy analyzer for estimating FI and LAI is that output data concern the same sampling area for both parameters. The function obtained measuring LAI indirectly with the LAI 2000, is very close to that obtained measuring LAI directly.

KC is a model input used to calculate FI as a function of LAI, where LAI is previously calculated as a function of dry matter production, stem-leaf dry matter partition parameter and specific leaf area. KC values obtained with the LAI 2000 refer to diffuse radiation in the range below 0.49 μm (portion of photosynthetically active radiation, PAR). As the solar spectrum varies little with time of day and atmospheric conditions (only a few percent according to Stanhill & Fuchs, 1977), it can be assumed that FI measured with the LAI 2000 is the actual fraction of PAR (0.4-0.7 μm wavelength) used by the crop for photosynthesis.

The model uses the input value of FI to quantify the dry matter daily increment as a function of intercepted solar radiation (S_i). For this reason, KC values calculated using measurements of FI and LAI with the plant canopy analyzer had to be converted into values referring to solar radiation. The procedure suggested by Campbell & van Evert (1994) was used in order to convert KC for PAR into KC for S_i.

A canopy extinction coefficient referred to black leaves and diffuse radiation (K_{bd}) was calculated as follows:

$$K_{bd} = KC\ a_p^{0.5}$$

a_p - Leaf absorptance in the range of photosynthetically active radiation

The canopy extinction coefficient for solar radiation (K_s) was therefore calculated as:

$$K_s = K_{bd} \left((a_p \; a_n)^{0.5} \right)^{0.5}$$

a_n - Leaf absorptance in the near infrared range of solar radiation

Leaf absorptance represents the portion of intercepted radiation which is absorbed by the canopy and used to produce dry matter. Goudriaan (1977) reported that typical values of leaf absorptance are 0.8 in the PAR range and 0.2 in the near infrared (NIR, 0.7-3 μm wavelength). The square root of the product of a_p and a_n represents the geometric mean of the absorptances in the two wavebands.

K_s values obtained from measurements of FI and LAI with the plant canopy analyzer were used as model input (Tables 6.1-6.4, pp. 259 to 262). K_s values for grass species covering almost completely the soil surface after full establishment, were estimated to be 0.8 (fescue, cocksfoot, and Smuts) and 0.9 (weeping lovegrass, Kikuyu and Rhodes). As canopy structure of crownvetch and Panicum was not measured, K_s values obtained for milkvetch and Smuts were used.

6.3.1.3 Radiation conversion efficiency

Radiation conversion efficiency is a crop specific input parameter which is used in the model to calculate dry matter production under conditions of light-limited crop growth. It is calculated as follows:

$$E_s = TDM \,/\, \Sigma \left(T_f \; FI \; S_i \right)$$

where TDM, T_f, FI and S_i were determined using data from field measurements.

Figure 6.7 (p. 273) represents TDM values of soybean as a function of the term Σ (T_f FI S_i). The slope of the regression line represents the radiation conversion efficiency. Data refer to the growing period until flowering (1994/95 season), as leaf senescence reduces the amount of absorbed energy at later phenological stages.

E_c is a relatively constant and predictable parameter, particularly under conditions of good water supply. In this work, low squared correlation coefficients of TDM - Σ (T_f FI S_i) functions were obtained in the case of some annual crops as data referring to three treatments of water supply were used.

Calculated E_c values (Tables 6.1-6.4, pp. 259 to 262) were generally in the range of those reported by Monteith (1988).

6.3.2 Verification of the model

The model was tested using data from field measurements as reference. Soil analyses were carried out to test the prediction of soil salinity parameters, whilst the soil water balance components and crop growth parameters were measured in the field in order to verify the reliability of the soil water balance-crop growth part of the model.

On the basis of irrigation water analyses, model simulations were carried out using the following irrigation water parameters as input:

- $[Ca^{2+}]$: 0.011 mol l^{-1}
- $[SO_4^{2-}]$: 0.013 mol l^{-1}
- $[Mg^{2+}]$: 0.002 mol l^{-1}

The presence of other ions in the irrigation water was neglected as their concentrations were very low. However, the effect of any other ionic species on ionic strength can easily be included in the model.

The following rain water characteristics suggested by Bolt (1979) have been used as input:

- $[Ca^{2+}]$: 2 μmol l^{-1}
- $[SO_4^{2-}]$: 6 μmol l^{-1}
- $[Mg^{2+}]$: 12 μmol l^{-1}

Table 6.6 (p. 264) represents measured values of nutrient content in maize plants at the end of the 1993/94 growing season. Considering that the final yield of maize was 1.092 kg m^{-2}, the amount of Ca and S used by the crop in the well irrigated treatment was:

$$Ca = 1.092 \text{ kg m}^{-2} \times 0.0032 = 0.00349 \text{ kg m}^{-2}$$
$$S = 1.092 \text{ kg m}^{-2} \times 0.00194 = 0.00212 \text{ kg m}^{-2}$$

The amount of Ca and S in the form of SO_4 applied to the soil through irrigation water was:

$Ca = 468 \text{ l m}^{-2} \times 0.011 \text{ mol l}^{-1} \times 40.08 \text{ g mol}^{-1}$ (atomic mass Ca) / 1000
$= 0.20633 \text{ kg m}^{-2}$
$S = 468 \text{ l m}^{-2} \times 0.013 \text{ mol l}^{-1} \times 32.06 \text{ g mol}^{-1}$ (atomic mass S) / 1000
$= 0.19505 \text{ kg m}^{-2}$

It was therefore calculated that 1.69 % of the total amount of Ca and 1.09% of the total amount of S applied through irrigation water was absorbed by the crop. No crop salt uptake subroutine was included in the model simulations.

6.3.2.1 Soil salinity parameters

Figure 6.8 (p. 274) reports simulated and measured values of electrical conductivity of saturated soil extract at five depths in the soil profile of soybean (end of the 1994/95 season). Samples were taken in the well irrigated and dry treatments in order to point out possible differences in salt build-up while irrigating with lime treated AMD. Measured values represent the average of three samples for each treatment. Horizontal bars represent standard errors of the measurement. Simulated values of EC_e have been calculated for each soil layer as follows:

$$EC_e = EC\ \Theta/(1-\rho_b/2.65)$$

ρ_b - Bulk density (Mg m^{-3})

The factor "2.65" represents the density of solid particles in Mg m^{-3}, so $1-\rho_b/2.65$ is equivalent to the soil water content at saturation.

The agreement between measured and simulated values of EC_e was fairly good. Slight differences could have been caused by several reasons:

- Soil heterogeneity and sampling error,
- Preferential paths of water and salt movement through the soil profile were not modelled,
- No molecular diffusion was assumed in modelling salt movement,
- No dissolution from weathering soil minerals was assumed in the model, and
- Fertilizer input and salts removed by the crop were not considered in the model.

The introduction of a cation exchange subroutine would probably make the model more reliable, but more inputs would be required. In this work, it was assumed that Ca^{2+} would quickly saturate the soil adsorptive complex while irrigating with lime treated AMD, particularly on a sandy soil with low cation exchange capacity. Soil solution-solid phase interactions were not therefore expected to significantly affect parameters which determine crop water consumption (Ψ_o) and soil salinity (TDS and amount of $CaSO_4$ precipitated in the soil profile).

Soil samples were also collected in the soil profiles of other crops at the end of the growing season. Similar observations could be made concerning measured and predicted values of EC_e as in the case of soybean.

6.3.2.2 Soil water balance and crop growth

Field data were used to validate the soil water balance-crop growth part of the model. The validation concerned all crops and treatments.

Simulated and measured data of top dry matter production, harvestable dry matter, root depth, LAI and cumulative ET + D are represented in Figures 6.9-6.13 (pp. 275 to 279) for three water treatments of soybean. Data refer to the 1993/94 season. The effect of osmotic potential on root water uptake was included in the crop growth simulations.

Good agreement between predicted values and measured data was observed for all treatments. It was observed in the field that plants in the dry treatment lost leaves due to water stress conditions, particularly after flowering. For this reason, the simulated value of top dry matter was higher than the measured value at the end of the growing season.

The agreement between simulated and measured values was particularly encouraging for cumulative evapotranspiration and drainage, as the SWB is being specifically developed for irrigation scheduling.

Good agreement between simulated values and measured data was observed for soybean grown both under good water supply and dry conditions. Similar results were obtained for other crops.

6.3.3 Model sensitivity analysis

In this section, model output sensitivity to input parameters is discussed. It was very difficult to carry out an analysis of sensitivity to assumptions in general terms as the output depends heavily on the particular input data set. Two input data sets have been chosen, one for soybean (wet treatment, 1993/94 season, Kromdraai), and the other for wheat (wet treatment, 1994 season, Kromdraai). In this way, two model output sensitivity analyses have been performed for two different conditions of water supply. The wheat crop, grown during the dry winter period, was almost entirely supplied with water through irrigation, whilst soybean, cropped during the rainy summer season, was partially supplied by rainfall.

A few key output variables were looked at: top dry matter production, evaporation from the soil surface and crop transpiration for the soil water balance-crop growth part of the model, whilst root density weighted seasonal average electrical conductivity, amount of salts leached from the soil profile and amount of $CaSO_4$ precipitated in the 1.2 m top soil layer were considered for the soil salinity part of the model. Seasonal average root density weighted EC values were obtained by multiplying the soil solution EC in each layer by the factor "f" for weighted root distribution (see section 6.2.2.3, p. 229). Other output variables were not considered as they are generally a direct function of those mentioned.

On the other hand, some key input parameters were considered: DMWR, KC, E_c, top soil layer thickness (dz_1), soil available water content (AWC) and concentration of Ca, SO_4 and Mg in irrigation water.

Values of each input parameter were decreased by 10%, simulations performed and the percentage change of each output parameter recorded. The results are presented in Table 6.7 (p. 265) for soybean and Table 6.8 (p. 265) for wheat. Output values of the standard setting are reported in the bottom row of each Table.

DMWR and E_c are crop specific coefficients determining daily dry matter increments. Decreasing DMWR by 10%, lowers calculated T and TDM, whilst E output values are increased. Model output for wheat was more sensitive to the decrease in DMWR than to E_c. This indicates that, under the specific environmental conditions, crop growth was more limited by available soil water than by radiation. TDM of soybean was less sensitive to DMWR variations than wheat. A smaller amount of irrigation water rich in salts was applied to the soil profile of soybean compared to wheat. Less concentrated soil solutions therefore occurred in the root zone of soybean, particularly after a portion of soil water was depleted. Ψ_o values and soil water availability were therefore higher throughout the season. A decrease in soil water consumption of soybean caused more salts to be leached by rain and less $CaSO_4$ to precipitate in the soil profile. In the absence of rain, a decrease in crop growth of wheat caused a smaller canopy and increase in E, resulting in more $CaSO_4$ precipitating in the top soil layer (Table 6.8, p. 265).

KC is a crop specific parameter describing the canopy structure and determining the partitioning of PET into E and T. Lowering KC, causes more solar energy to penetrate the canopy resulting in more water evaporating from the soil surface. This results in a decrease in soil water available for crop uptake and therefore lower T and TDM. Output sensitivity was higher in soybean, which develops a bigger canopy than wheat. Soil salinity output parameters, even if not directly dependent on canopy structure, are moderately sensitive to changes in KC input values as they depend on water and salt redistribution patterns in the soil profile.

Water loss by soil evaporation is modelled to occur only from the top soil layer. The input value of dz_1 was decreased by 10%. The growth of soybean, which has a more closed canopy than wheat, was less affected by the variation in the depth of the top soil layer.

AWC represents the difference between volumetric soil water content at field capacity (Θ_{fc}) and volumetric soil water content at permanent wilting point (Θ_{pwp}). For the purpose of output sensitivity analysis, volumetric water content at permanent wilting point was increased in each soil layer by 10% in order to narrow the Θ_{fc}-Θ_{pwp} difference. Output parameters, in particular the amount of leached salts, were affected by the change in AWC input value.

Irrigation water quality input parameters, namely [Ca^{2+}], [SO_4^{2-}] and [Mg^{2+}], are of basic importance for predicting both crop growth and soil salinity parameters. A 10% decrease in [Ca^{2+}] and [SO_4^{2-}] in irrigation water caused a slightly weaker osmotic effect and increase in TDM output values. Very large variations in soil salinity output parameters were observed according to the new water balance and salt redistribution conditions. [Mg^{2+}] in lime treated AMD is very low and this parameter did not play a major role in the calculation of salt redistribution and osmotic potential.

Model sensitivity to soil solution osmotic potential will be presented in the following section, while discussing crop growth under soil salinity conditions. Additional sensitivity analysis is required in order to test the performance of the model.

6.3.4 Crop salt tolerance

The effect of soil salinity on crop growth was modelled by adding osmotic potential to soil matric and gravitational potential.

Top dry matter of soybean was calculated with differing osmotic potential levels in the soil profile. Osmotic potential was kept constant during the season in each simulation. No decrease in emergence rate due to soil salinity was assumed.

Relative yield of aerial plant organs (Y_{rel}) was calculated as the ratio between the simulated yield obtained using differing Ψ_o levels and the simulated yield with no osmotic effect included. Calculated relative yield was plotted against values of seasonal average root density weighted EC_e obtained in each simulation (Figure 6.14, p. 280). Only points in the Y_{rel} range between 5 and 95% have been considered in the linear regression. The obtained function was compared with the function reported by Maas (1986).

Assuming the Maas function as reference, the model overestimated relative yield at high soil salinity levels. Increase in root resistance at higher osmotic potential levels could be a reason for such disagreement. Root resistance is believed to increase due to changes in sterol ratios occurring in the root cell membranes under soil salinity conditions (Shannon M., personal communication).

Majeed, Stockle & King (1994) modelled the increase in root resistance under salinity conditions adding a root resistance factor in the calculation of root water uptake:

$$R_c = RRES\ \Psi_o$$

R_c - Root resistance factor (J kg^{-1})
RRES - Crop specific root resistance increase coefficient

R_c was calculated as a function of osmotic potential and added to the total soil water potential. Simulations of relative yield and root zone EC_e were repeated with differing Ψ_o levels in the soil profile and including the root resistance factor. The objective was to improve the agreement between simulated and Maas function. The Y_{rel}-EC_e function including R_c is reported in the graph (Figure 6.14, p. 280). Points in the Y_{rel} range between 5 and 95% have been considered in the linear regression. RRES of soybean was estimated to be 0.75.

The same procedure was adopted for the other crops and the results are summarized in Table 6.9 (p. 266). Simulated threshold values and slope of the crop salt tolerance functions, obtained excluding the effect of root resistance increase, are reported in the Table. Estimated RRES values are also reported. Majeed *et al.* (1994) suggested RRES values of 0.84 for sorghum and 0.5 for wheat. Besides processing experimental data in order to get crop salt tolerance functions, Maas (1986) also gave a general description rating species as moderately sensitive, moderately tolerant or tolerant to soil salinity.

Salinity threshold values depend to a great extent on the atmospheric demand of the atmosphere, particularly on air temperature and relative humidity (American Society of Civil Engineers, 1990). The day by day calculation of water movement in the soil-plant-atmosphere continuum makes the SWB a useful tool for predicting yield depressions under conditions of irrigation with gypsiferous water. However, a critical study would be needed in order to validate the model and apply it in practice.

6.4 CONCLUSIONS

SWB proved to be a useful tool for crop growth simulations and irrigation scheduling. Simulations using the calculated crop growth coefficients fitted measured data of water balance and crop growth parameters fairly well. The mechanistic solution of the model worked well both under good water supply and crop water stress conditions. It should, however, be tested using independent sets of data.

SWB should give a good first approximation of the movement of water in well drained fairly uniform profiles. One should, however, be aware of the limitations of such soil water balance models. Textural discontinuities and impermeable layers have marked effects on water movement and this can only be reasonably described by a finite-difference model which moves water according to Darcy's law (i.e. using water potential and hydraulic conductivity). Another disadvantage of the cascading model is that upward flow of water and salts is not simulated. This could be important especially if a high or perched water table is present.

The water balance-soil salinity model presented in this work, was specifically developed to solve problems concerning the use of lime treated AMD for irrigation. The predictions of soil solution EC_e were in good agreement with observed data. SWB, combined with a weather data generator, could be a useful tool for predicting the long-term environmental impact due to irrigation with lime treated AMD.

The model could also be used to determine crop salt tolerance. The major advantage of estimating crop salt tolerance with a mechanistic crop growth model is that yield depressions can be calculated under specific conditions of soil water supply and evaporative demand of the atmosphere.

SWB could be further developed introducing sub-routines describing, for example, the redistribution of other ionic species, cation exchange processes, the calculation of soil pH and aluminium hydroxide interactions in the soil solution.

Output values of top dry matter production and evapotranspiration were particularly sensitive to input values of DMWR, KC, SLA and available water capacity of the soil. Soil salinity parameters are mainly dependent on the irrigation water quality input data. It is imperative to use the correct value of the above mentioned parameters in order to get reliable simulations. The model output was generally less sensitive to input variations when the crop was partially supplied by water through rainfall. Additional sensitivity analysis is required for testing the performance of the model.

The LAI 2000 plant canopy analyzer could be used in order to get reliable and quick estimates of FI and LAI in annual crop canopies. The measurement of FI with the LAI 2000 is independent of solar orientation as the sensor views the canopy in all directions. The Decagon sunfleck ceptometer is cheaper, but it requires whole-day measurements as its output depends on solar orientation.

Non-destructive and time saving measurement of LAI with the plant canopy analyzer is recommended in soybean, sorghum, pearl millet, rye, oats and wheat canopies, provided that proper measurement techniques are applied. At least six readings along diagonal transects in the row beneath the canopy are recommended, along with the use of a 180° view restriction cap. LAI values obtained with the plant canopy analyzer for the other crops should be corrected using the LAI 2000-LAI 3100 functions suggested in this study.

The LAI 2000 proved to be very useful for the estimation of canopy radiation extinction coefficients as it instantaneously provides data of both FI and LAI for the same sampling area. Disadvantages are that the LAI 2000 is expensive and it requires measurements to be made at dawn, at sunset or under uniform cloudy conditions, since light scattering from sunlit foliage increases errors in output.

TABLE 6.1 Crop parameters of subtropical annual species

Crop Parameters	Maize	Soybean	Sorghum	Pearl millet	Cowpeas
Dry Matter Water Ratio[1] (Pa)	4.0	5.0	4.5	7.0	3.5
Canopy Radiation Extinction Coefficient[1]	0.56	0.58	0.54	0.55	0.59
Specific Leaf Area[1] (m^2 kg^{-1})	15	14	18	17	18
Stem-Leaf Partition Parameter[1]	0.8	1.5	0.5	1.3	1
Stress Index[2]	0.95	0.95	0.95	0.95	0.95
Max Root Depth[1] (cm)	40	50	40	60	30
Emergence Day Degrees[1]	50	50	50	50	50
Day Degrees at End of Vegetative Growth[1]	900	1100	1000	1000	900
Day Degrees for Leaf Senescence[2]	900	1100	450	1100	700
Day Degrees for Maturity[2]	1700	1700	1500	1650	1700
Transition Period Day Degrees[2]	10	10	100	10	200
Fraction of TDM Translocated to Roots[2]	0.01	0.01	0.01	0.05	0.01
Fraction of TDM Translocated to Heads[2]	0.05	0.05	0.05	0.05	0.05
Canopy storage[2] (mm)	0	0	0	0	0
Base Temperature[2] (°C)	10	10	10	10	10
Temperature for Optimum Crop Growth[2] (°C)	25	25	25	25	25
Cutoff Temperature[2] (°C)	30	30	30	30	30
Leaf Water Potential at Max T Rate[2] (J kg^{-1})	-1250	-1250	-1250	-1250	-1250
Max Transpiration[2] (mm day^{-1})	9	9	9	9	9
Radiation Conversion Efficiency[1] (kg MJ^{-1})	0.0012	0.0012	0.0012	0.0015	0.0009
Root Growth Rate[2] (m^2 $kg^{-0.5}$ day^{-1})	4	4	4	4	4
Canopy Dry Matter at Emergence[2] (kg m^{-2})	0.0019	0.0019	0.0019	0.0019	0.0019

[1] Measured [2] Estimated

TABLE 6.2 Crop parameters of temperate annual species

Crop Parameters	Rye	Oats	Triticale	Wheat	Ryegrass
Dry Matter Water Ratio[1] (Pa)	4.0	4.5	4.0	4.0	4.0
Canopy Radiation Extinction Coefficient[1]	0.54	0.54	0.55	0.55	0.53
Specific Leaf Area[1] ($m^2\ kg^{-1}$)	15	12	10	12	10
Stem-Leaf Partition Parameter[1]	2	1.8	0.5	1.2	0.8
Stress Index[2]	0.95	0.95	0.95	0.95	0.95
Max Root Depth[1] (cm)	40	70	60	50	40
Emergence Day Degrees[1]	50	50	50	50	50
Day Degrees at End of Vegetative Growth[1]	700	-	-	750	-
Day Degrees for Leaf Senescence[2]	900	-	-	900	-
Day Degrees for Maturity[1]	1800	-	-	1500	-
Transition Period Day Degrees[2]	900	-	-	400	-
Fraction of TDM Translocated to Roots[2]	0.02	0.05	0.01	0.02	0.01
Fraction of TDM Translocated to Heads[2]	0.05	0.05	0.05	0.05	0.05
Canopy storage[2] (mm)	0	0	0	0	0
Base Temperature[2] (°C)	4	4	4	4	4
Temperature for Optimum Crop Growth[2] (°C)	15	15	15	15	15
Cutoff Temperature[2] (°C)	25	25	25	25	25
Leaf Water Potential at Max T Rate[2] ($J\ kg^{-1}$)	-1250	-1250	-1250	-1250	-1250
Max Transpiration[2] ($mm\ day^{-1}$)	9	9	9	9	9
Radiation Conversion Efficiency[1] ($kg\ MJ^{-1}$)	0.0015	0.0019	0.0013	0.0017	0.0013
Root Growth Rate[2] ($m^2\ kg^{-0.5}\ day^{-1}$)	4	4	4	4	4
Canopy Dry Matter at Emergence[2] ($kg\ m^{-2}$)	0.0019	0.0019	0.0019	0.0019	0.0019

[1] Measured [2] Estimated

TABLE 6.3 Crop parameters of temperate perennial species

Crop Parameters	Lucerne	Fescue	Crownvetch	Cocksfoot	Milkvetch
Dry Matter Water Ratio[1] (Pa)	2.2	2.3	4.4	2.0	2.5
Canopy Radiation Extinction Coefficient[1]	0.57	0.8	0.57	0.8	0.57
Specific Leaf Area[1] ($m^2\ kg^{-1}$)	15	9	15	9	15
Stem-Leaf Partition Parameter[1]	0.6	0.1	0.5	0.1	0.5
Stress Index[2]	0.95	0.95	0.95	0.95	0.95
Max Root Depth[1] (cm)	80	60	80	60	80
Emergence Day Degrees[1]	0	0	0	0	0
Day Degrees at End of Vegetative Growth[1]	-	-	-	-	-
Day Degrees for Leaf Senescence[2]	-	-	-	-	-
Day Degrees for Maturity[2]	-	-	-	-	-
Transition Period Day Degrees[2]	-	-	-	-	-
Fraction of TDM Translocated to Roots[2]	0.01	0.01	0.01	0.01	0.01
Fraction of TDM Translocated to Heads[2]	0.05	0.05	0.05	0.05	0.05
Canopy storage[2] (mm)	0	0	0	0	0
Base Temperature[2] (°C)	4	4	4	4	4
Temperature for Optimum Crop Growth[2] (°C)	15	15	15	15	15
Cutoff Temperature[2] (°C)	30	25	30	25	30
Leaf Water Potential at Max T Rate[2] ($J\ kg^{-1}$)	-1250	-1250	-1250	-1250	-1250
Max Transpiration[2] ($mm\ day^{-1}$)	9	9	9	9	9
Radiation Conversion Efficiency[1] ($kg\ MJ^{-1}$)	0.0015	0.0015	0.0015	0.0015	0.0015
Root Growth Rate[2] ($m^2\ kg^{-1}\ day^{-1}$)	25	25	25	25	25
Canopy Dry Matter at Emergence[2] ($kg\ m^{-2}$)	0.05	0.05	0.05	0.05	0.05

[1] Measured [2] Estimated

TABLE 6.4 Crop parameters of subtropical perennial species

Crop Parameters	Weeping Love-grass	Smuts	Kikuyu	Panicum	Rhodes
Dry Matter Water Ratio[1] (Pa)	4.0	4.0	3.5	4.0	3.5
Canopy Radiation Extinction Coefficient[1]	0.9	0.8	0.9	0.8	0.9
Specific Leaf Area[1] (m^2 kg^{-1})	8	7	10	7	15
Stem-Leaf Partition Parameter[2]	0.1	0.2	0.3	0.2	0.9
Stress Index[2]	0.95	0.95	0.95	0.95	0.95
Max Root Depth[1] (cm)	140	140	140	140	40
Emergence Day Degrees[1]	0	0	0	0	0
Day Degrees at End of Vegetative Growth[1]	-	-	-	-	-
Day Degrees for Leaf Senescence[2]	-	-	-	-	-
Day Degrees for Maturity[1]	-	-	-	-	-
Transition Period Day Degrees[2]	-	-	-	-	-
Fraction of TDM Translocated to Roots[2]	0.05	0.05	0.05	0.05	0.01
Fraction of TDM Translocated to Heads[2]	0.005	0.005	0.005	0.005	0.005
Canopy storage[2] (mm)	0	0	0	0	0
Base Temperature[2] (°C)	10	10	10	10	10
Temperature for Optimum Crop Growth[2] (°C)	20	20	20	20	20
Cutoff Temperature[2] (°C)	30	30	30	30	30
Leaf Water Potential at Max T Rate[2] (J kg^{-1})	-1250	-1250	-1250	-1250	-1250
Max Transpiration[2] (mm day^{-1})	9	9	9	9	9
Radiation Conversion Efficiency[1] (kg MJ^{-1})	0.0015	0.0015	0.0015	0.0015	0.0015
Root Growth Rate[2] (m^2 $kg^{-0.5}$ day^{-1})	4	4	4	4	4
Canopy Dry Matter at Emergence[2] (kg m^{-2})	0.05	0.05	0.05	0.05	0.05

[1] Measured [2] Estimated

TABLE 6.5 Linear regression coefficients and squared correlation coefficients of the LI 3100 - LAI 2000 functions for 20 annual and perennial species

Crop	LAI 2000 = a LI 3100 + b		
	a	b	r^2
Maize	0.75	0.71	0.75
Soybean	1.10	-0.33	0.93
Sorghum	0.65	0.59	0.64
Pearl millet	0.81	0.26	0.77
Cowpeas	1.31	0.25	0.80
Rye	0.45	0.37	0.20
Oats	0.72	0.21	0.48
Triticale	0.95	0.32	0.66
Wheat	0.66	0.22	0.61
Ryegrass	0.58	-0.04	0.79
Lucerne	1.52	-0.06	0.73
Fescue	0.37	0.19	0.62
Cocksfoot	0.55	-0.04	0.56
Milkvetch	0.69	0.13	0.75
Weeping lovegrass	0.72	0.15	0.35
Smuts	0.33	0.18	0.44
Kikuyu	0.52	-0.39	0.50
Rhodes	0.58	-0.20	0.72

TABLE 6.6 Chemical analysis of maize dry material at the end of the 1993/1994 season

Treatment	N	P	K	Ca	Mg	Na	S	Fe	Mn	Cu	Zn
	%							mg kg^{-1}			
Wet treatment	0.42	0.13	0.79	0.32	0.11	0.007	0.194	580.5	97.5	4.5	16.5
Medium treatment	1.02	0.17	0.79	0.20	0.10	0.007	0.201	588.0	91.5	3.0	25.5
Dry treatment	1.35	0.15	1.18	0.21	0.09	0.006	0.228	874.5	97.5	3.0	21.0

TABLE 6.7 Output sensitivity to 10% decrease in crop, soil and irrigation water quality input parameters (soybean, 1993/94 season, Kromdraai)

Input Parameter	Top dry matter	Evaporation	Transpi-ration	EC in root zone	Leached salts	$CaSO_4$ precipi-tated
	%					
Dry Matter Water Ratio	13.0	-6.7	9.1	0.6	-4.3	4.1
Radiation Conversion Efficiency	13.7	-6.1	7.8	0.4	-3.4	3.4
Canopy Radiation Extinction Coefficient	10.5	-16.7	10.5	1.2	0.3	0.7
Top Soil Layer Thickness	0.0	3.3	-0.0	0.7	-0.1	-0.1
Available Water Capacity of the Soil	8.4	1.1	9.5	0.4	-10.8	7.2
Ca Concentration in Irrigation Water	-0.1	0.0	-0.0	9.3	8.2	4.5
SO_4 Concentration in Irrigation Water	0.0	0.0	0.1	-25.6	-7.2	14.7
Mg Concentration in Irrigation Water	0.0	0.0	-0.0	1.6	0.7	-0.2
STANDARD SETTING	1.23 ($kg\ m^{-2}$)	161 (mm)	343 (mm)	321 ($mS\ m^{-1}$)	9.373 ($mol\ m^{-2}$)	2.869 ($mol\ m^{-2}$)

TABLE 6.8 Output sensitivity to 10% decrease in crop, soil and irrigation water quality input parameters (wheat, 1994 season, Kromdraai)

Input Parameter	Top dry matter	Evaporation	Transpi-ration	EC in root zone	Leached salts	$CaSO_4$ precipi-tated
	%					
Dry Matter Water Ratio	17.9	-5.5	7.7	0.1	5.4	-0.6
Radiation Conversion Efficiency	-0.6	-0.5	-0.4	0.9	3.3	-0.8
Canopy Radiation Extinction Coefficient	10.8	-6.6	9.9	0.9	4.9	-1.2
Top Soil Layer Thickness	-3.7	4.7	-3.5	0.7	-16.3	1.5
Available Water Capacity of the Soil	4.8	0.9	4.9	2.0	-19.0	0.2
Ca Concentration in Irrigation Water	-0.2	-0.0	-0.1	6.7	1.6	10.6
SO_4 Concentration in Irrigation Water	-1.3	-0.0	-1.2	-15.6	5.6	0.8
Mg Concentration in Irrigation Water	0.0	-0.0	-0.0	3.3	0.4	0.0
STANDARD SETTING	0.65 ($kg\ m^{-2}$)	264 (mm)	150 (mm)	384 ($mS\ m^{-1}$)	5.109 ($mol\ m^{-2}$)	7.455 ($mol\ m^{-2}$)

TABLE 6.9 Soil salinity threshold values and slope of the relative yield (Y_{rel}) - electrical conductivity at saturation (EC_e) function for 20 crop and grass species

Crop	Simulated			Maas (1986)		
	Threshold mSm^{-1}	Slope % per 100 mSm^{-1}	RRES	Threshold mSm^{-1}	Slope % per 100 mSm^{-1}	Rating
Maize	446	14.2	-	180	7.4	Ms[1]
Soybean	954	15.0	0.75	500	20	Mt[2]
Sorghum	476	14.4	0.84[4]	680	16	Mt
Pearl millet	516	12.2	-	-	-	-
Cowpea	961	16.0	0.75	250	11	Ms
Rye	326	5.5	-	-	-	Ms
Oats	410	9.4	-	-	-	Ms
Triticale	523	10.0	-	-	-	T[3]
Wheat	678	10.7	0.5[4]	450	2.6	Mt
Ryegrass	571	10.5	-	-	-	Mt
Lucerne	461	6.7	0.3	200	7.3	Ms
Fescue	493	6.7	-	-	-	-
Crownvetch	484	6.9	-	-	-	-
Cocksfoot	498	6.7	0.3	150	6.2	Ms
Milkvetch	509	7.2	-	-	-	Ms
Weeping Love-grass	268	6.8	0.25	200	8.4	Ms
Smuts	148	5.5	-	-	-	-
Kikuyu	286	5.9	-	-	-	-
Panicum	148	5.5	-	-	-	-
Rhodes	612	6.1	-	-	-	MT

[1] Moderately sensitive

[2] Moderately tolerant

[3] Tolerant

[4] Majeed *et al.* (1994)

FIGURE 6.1 Flow diagram of the model

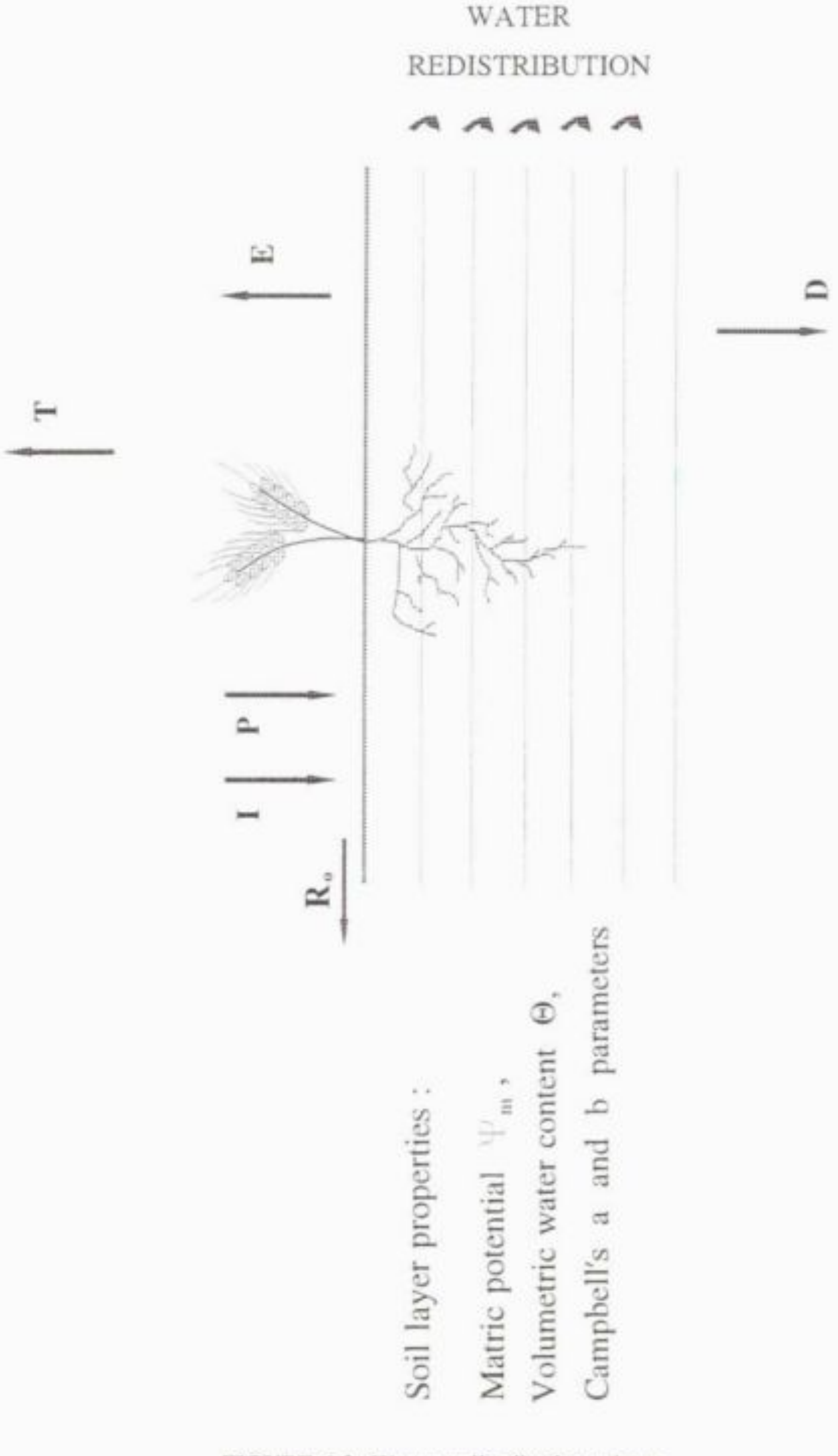


FIGURE 6.2 Water redistribution scheme

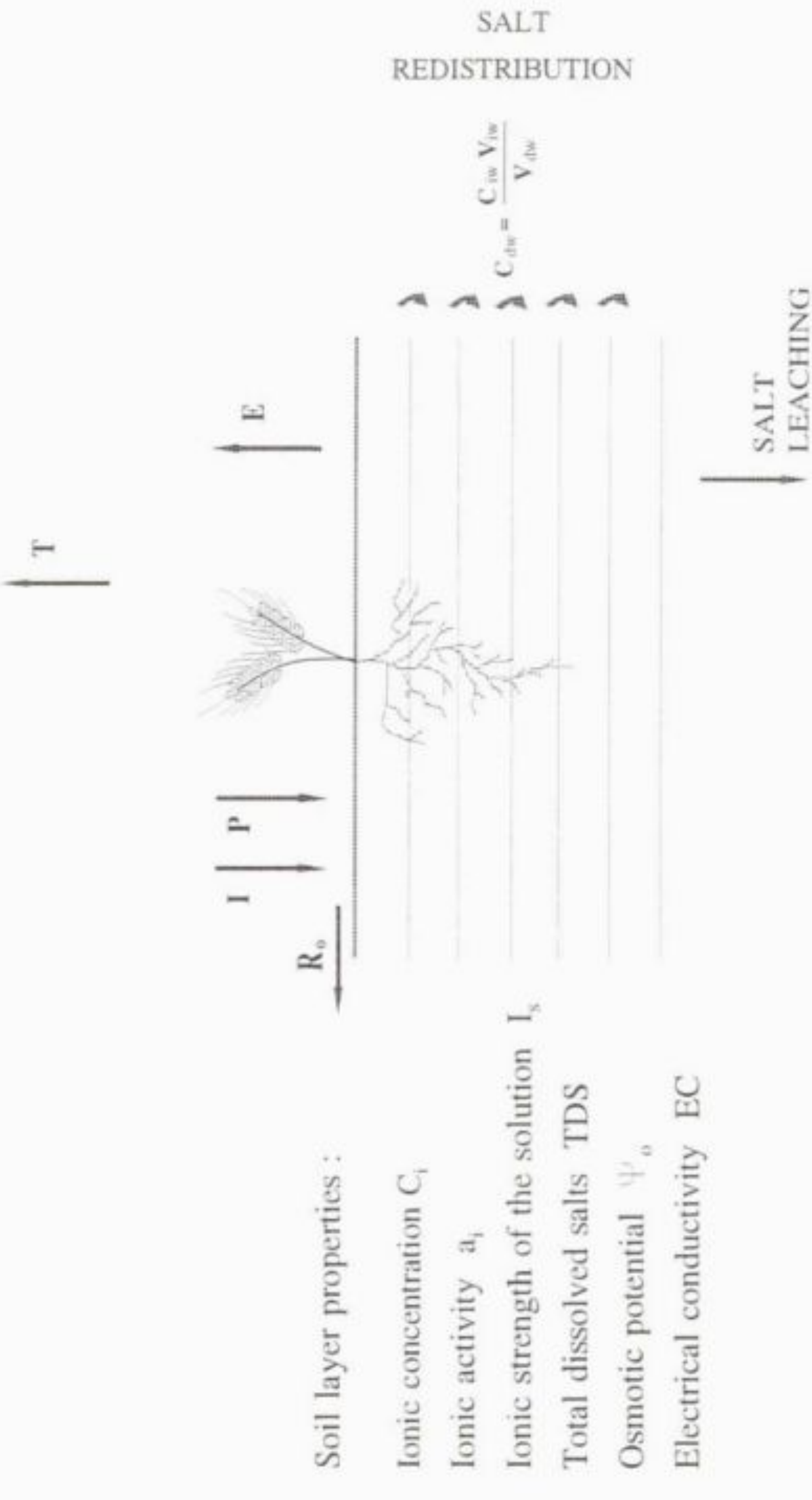


FIGURE 6.3 Salt redistribution scheme

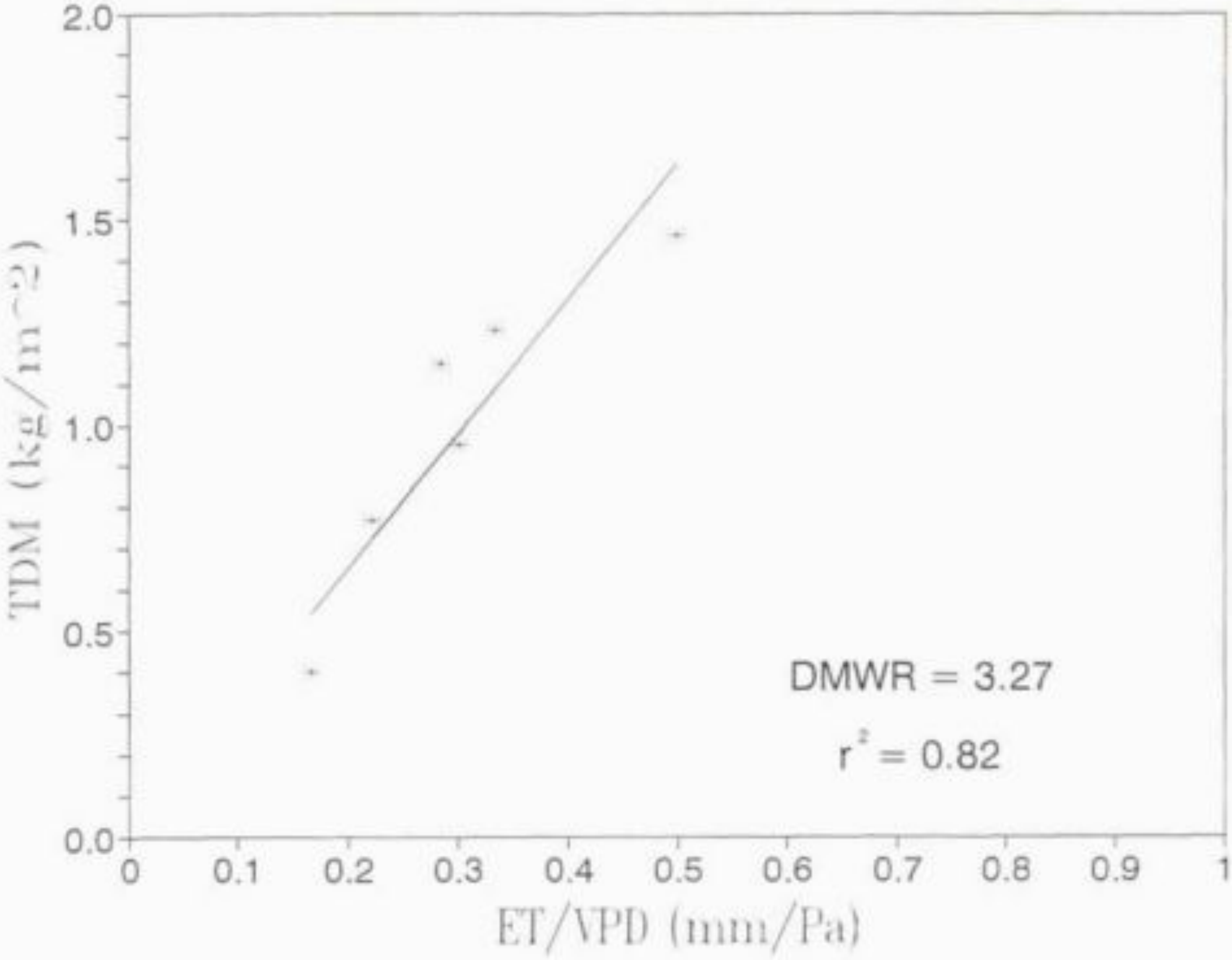


FIGURE 6.4 **Correlation between evapotranspiration-vapour pressure deficit ratio (ET/VPD) and total dry matter production (TDM) of SOYBEAN; dry matter water ratio value (DMWR) is reported (data concern two seasons)**

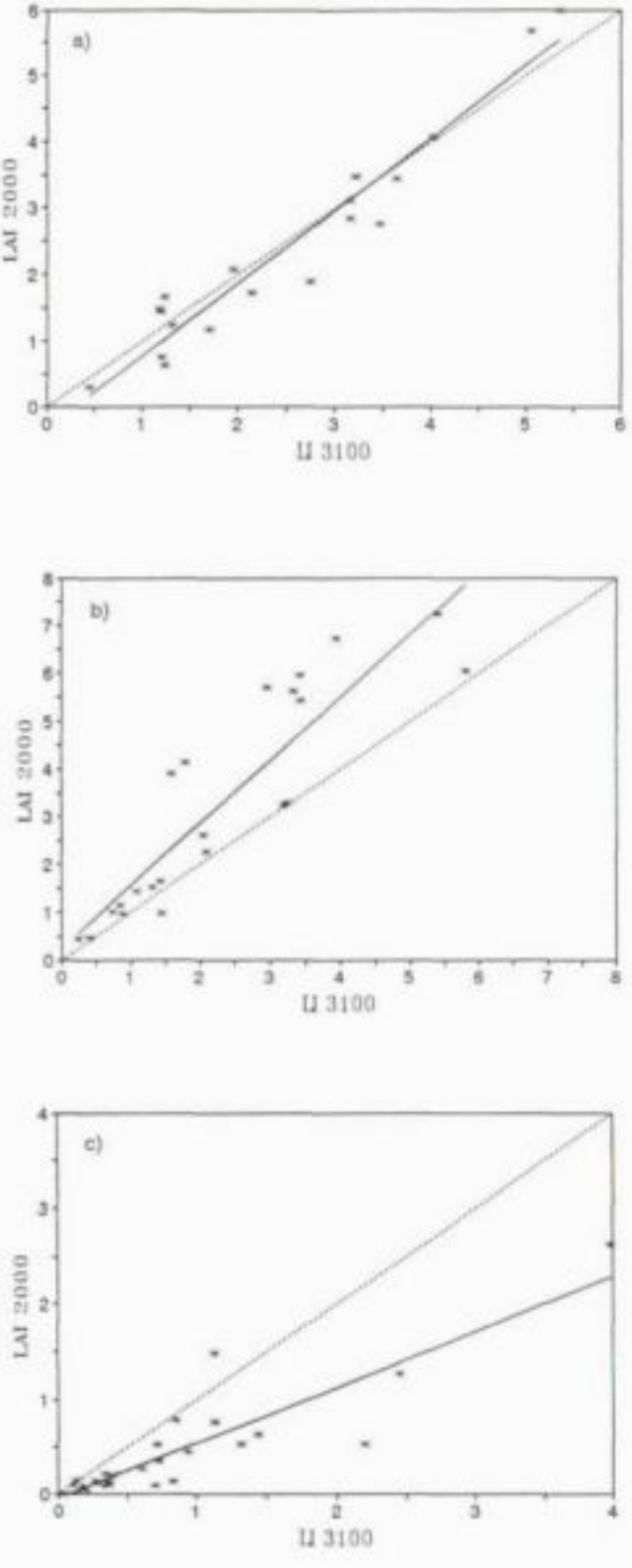
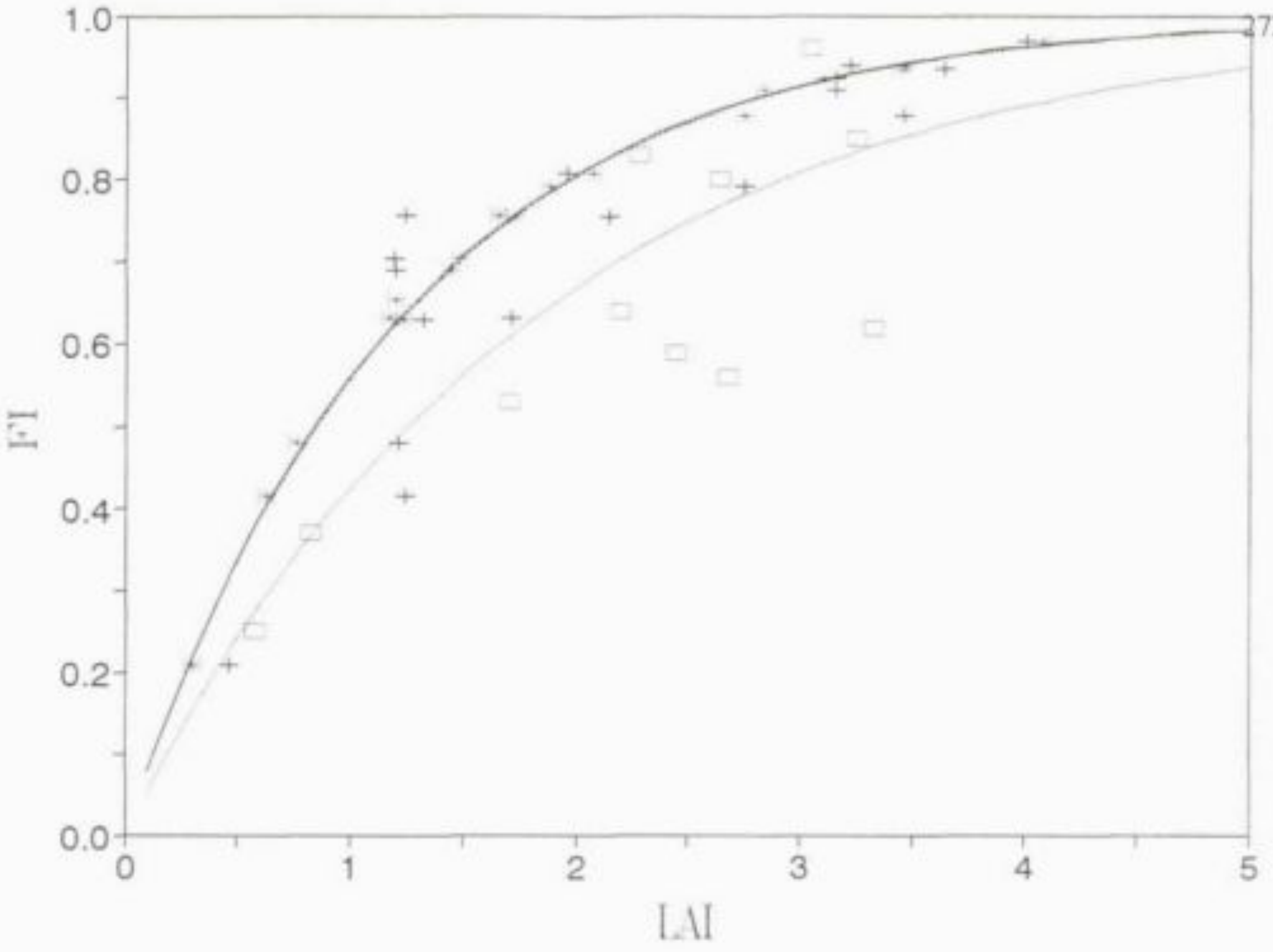


FIGURE 6.5 Correlation between leaf area index of SOYBEAN (a), COWPEAS (b) and RYEGRASS (c), measured directly with the LI 3100 leaf area meter (LI 3100) and indirectly with the LAI 2000 plant canopy analyzer (LAI-2000)



$$FI = 1 - e^{-KC\ LAI}$$

□ ···	LAI measured directly, FI measured with the ceptometer.	KC = 0.55	$r^2 = 0.40$
+ ---	LAI measured directly, FI measured with the LAI 2000.	KC = 0.82	$r^2 = 0.91$
* —	LAI and FI measured with the LAI 2000.	KC = 0.82	$r^2 = 0.99$

FIGURE 6.6 Correlation between leaf area index (LAI) and radiation fractional interception (FI) of SOYBEAN; values of canopy radiation extinction coefficient (KC) are reported

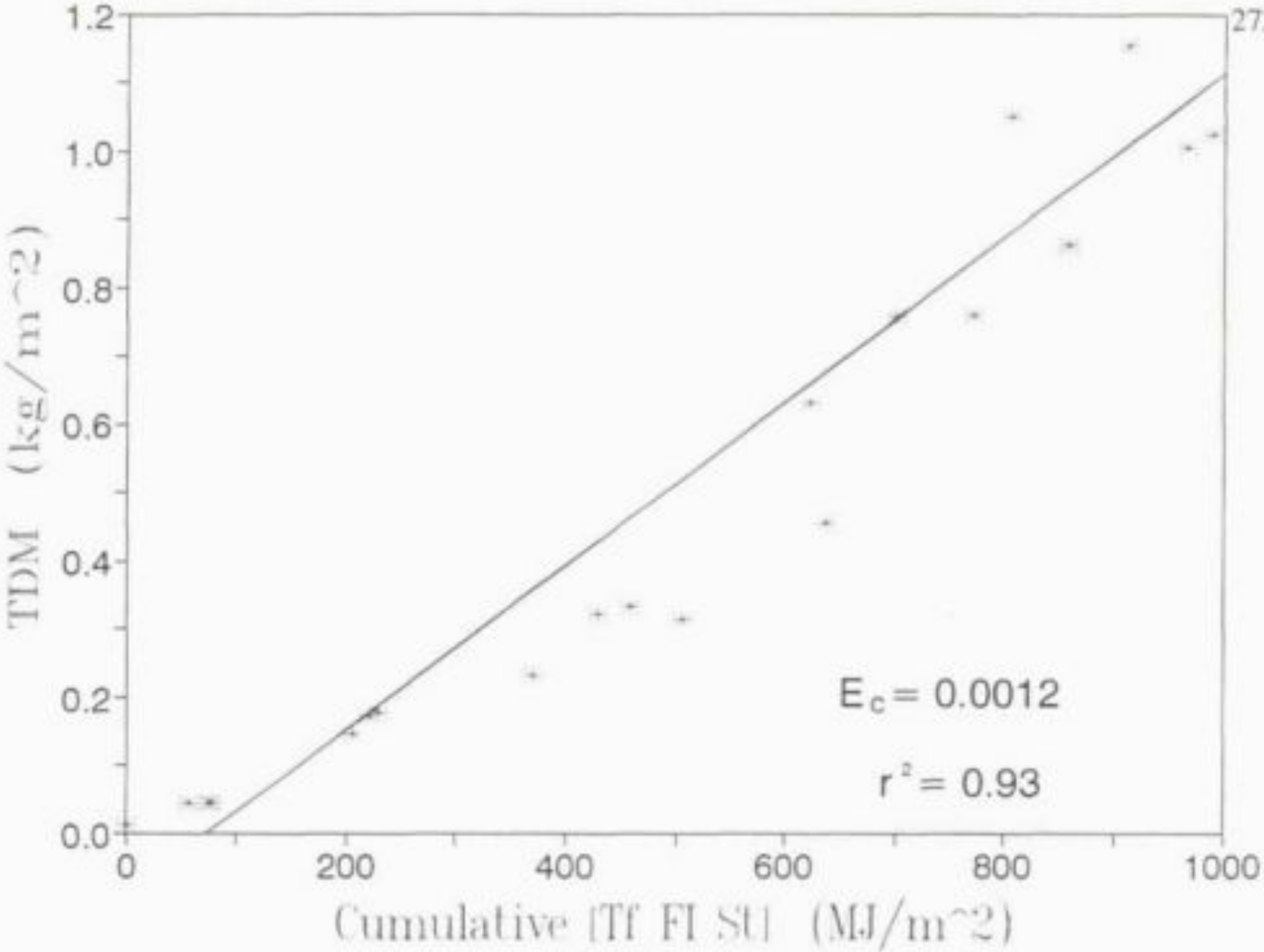


FIGURE 6.7 Top dry matter production (TDM) of SOYBEAN as a function of the cumulative product of temperature factor for crop growth, radiation fractional interception and total incoming solar radiation (Σ T_f FI S_t); value of radiation conversion efficiency (E_c) is reported

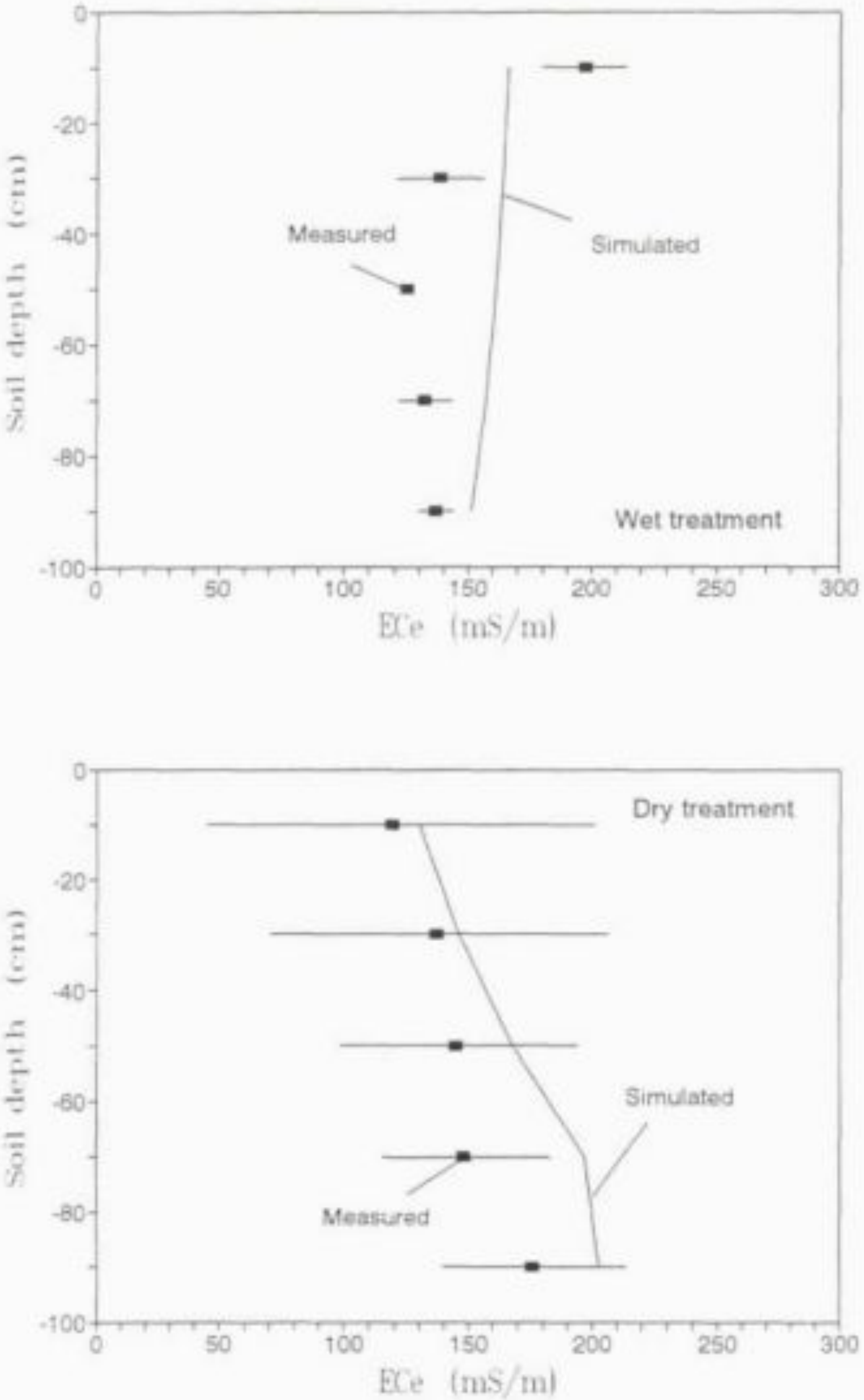


FIGURE 6.8 Measured and simulated values of electrical conductivity at saturation (EC_e) at five depths in the soil profile of SOYBEAN at the end of the 1994/95 season

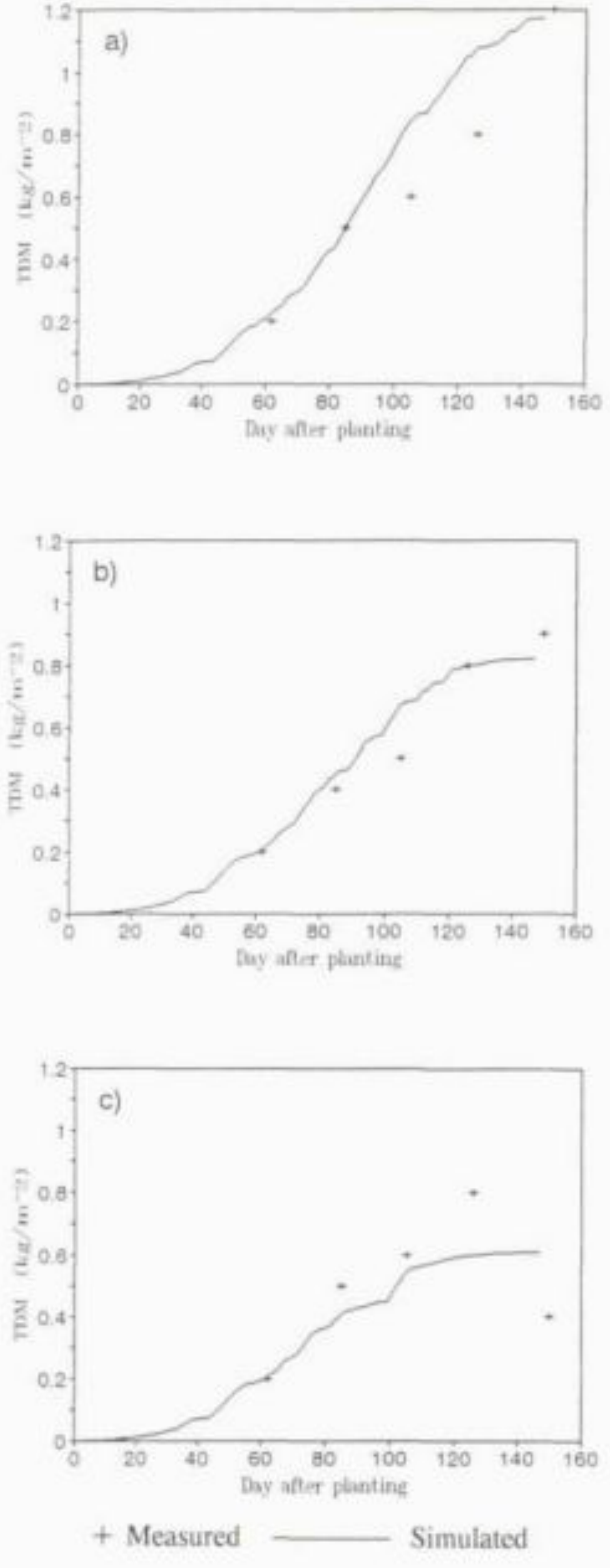


FIGURE 6.9 **Measured and simulated values of top dry matter production (TDM) of soybean in kg m^{-2}. Data refer to: a) well irrigated treatment, b) medium irrigated treatment, and c) dry treatment**

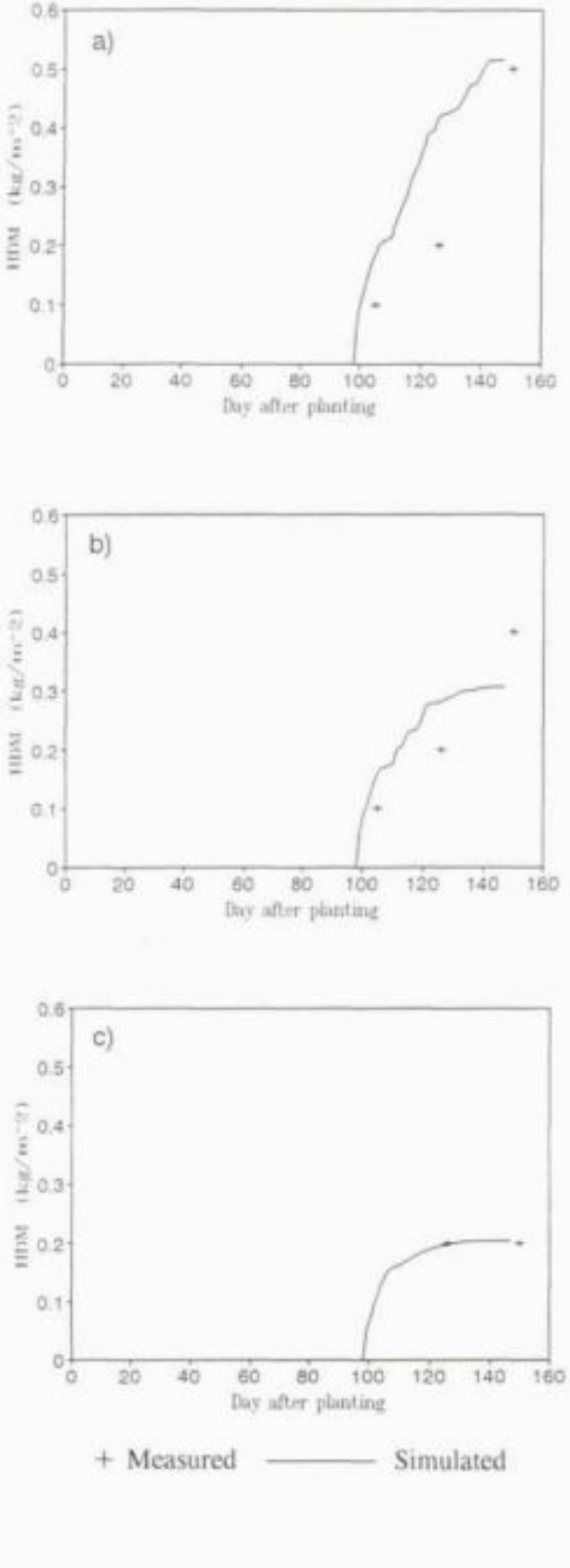


FIGURE 6.10 **Measured and simulated values of harvestable dry matter (HDM) of soybean in kg m^{-2}. Data refer to: a) well irrigated treatment, b) medium irrigated treatment, and c) dry treatment**

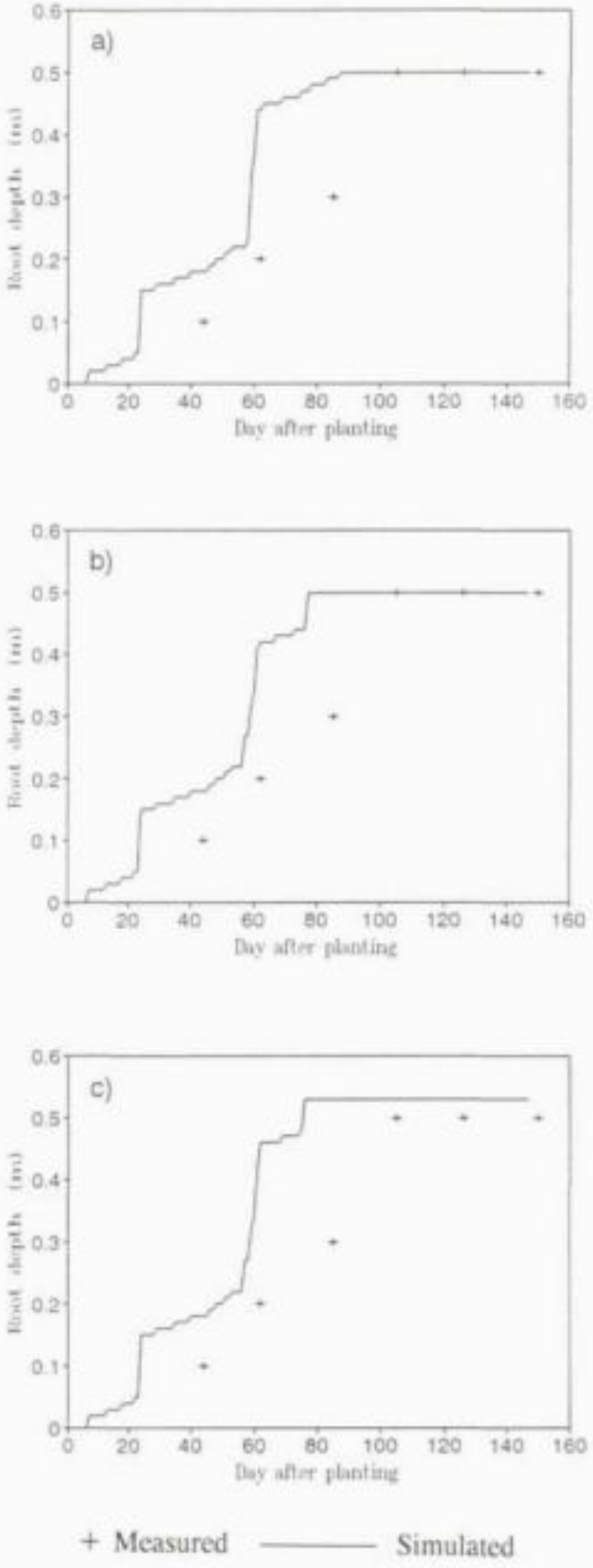


FIGURE 6.11 Measured and simulated values of root depth (RD) of soybean in m. Data refer to: a) well irrigated treatment, b) medium irrigated treatment, and c) dry treatment

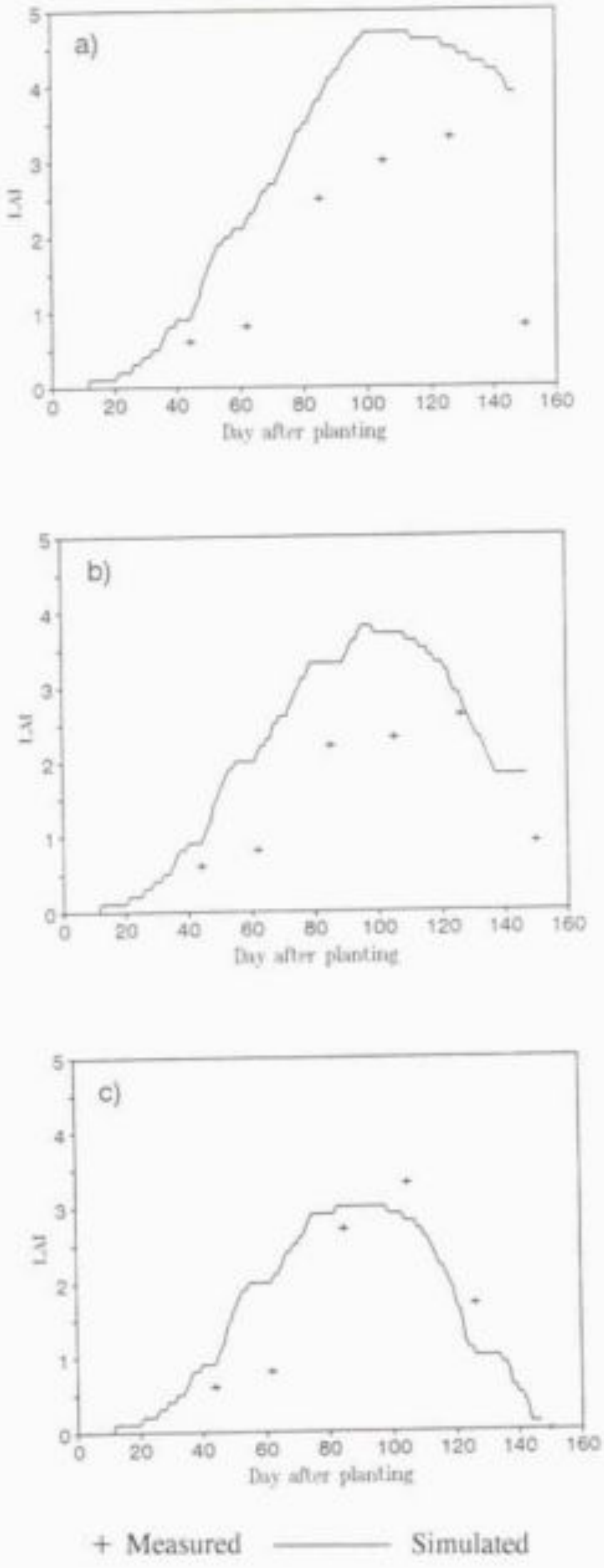


FIGURE 6.12 Measured and simulated values of leaf area index (LAI) of soybean. Data refer to: a) well irrigated treatment, b) medium irrigated treatment, and c) dry treatment

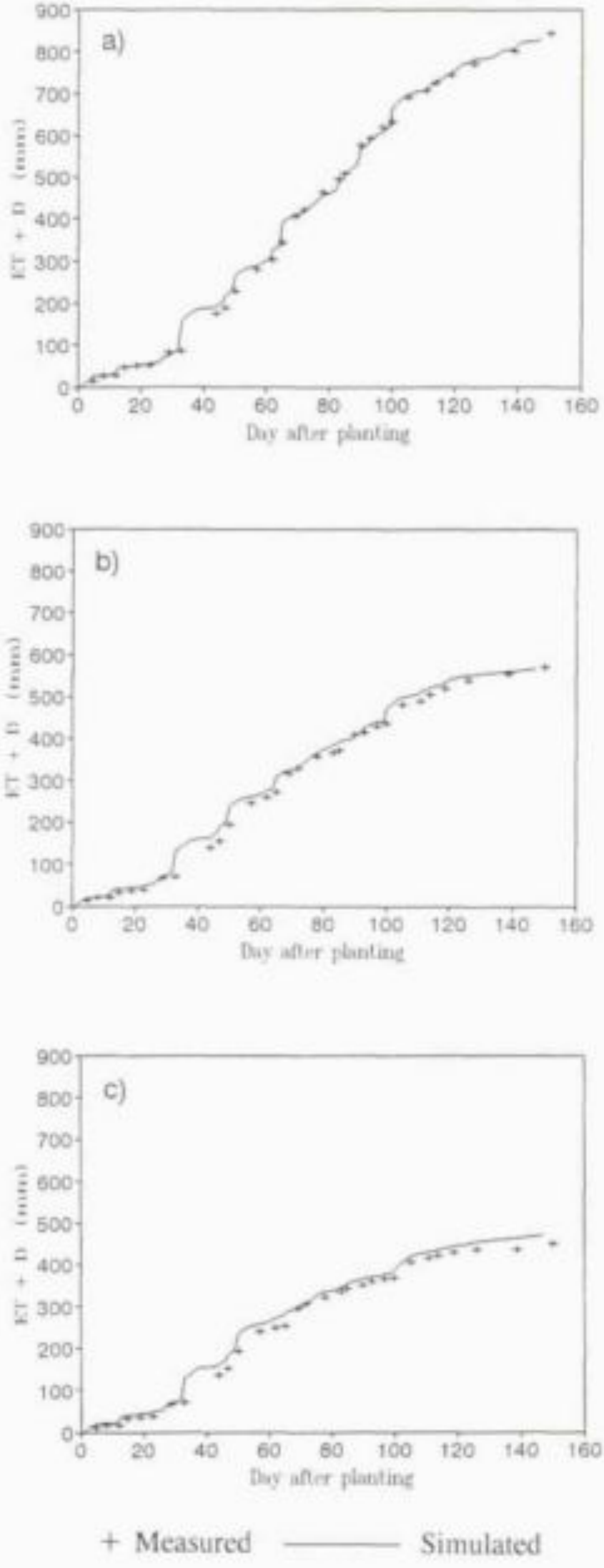
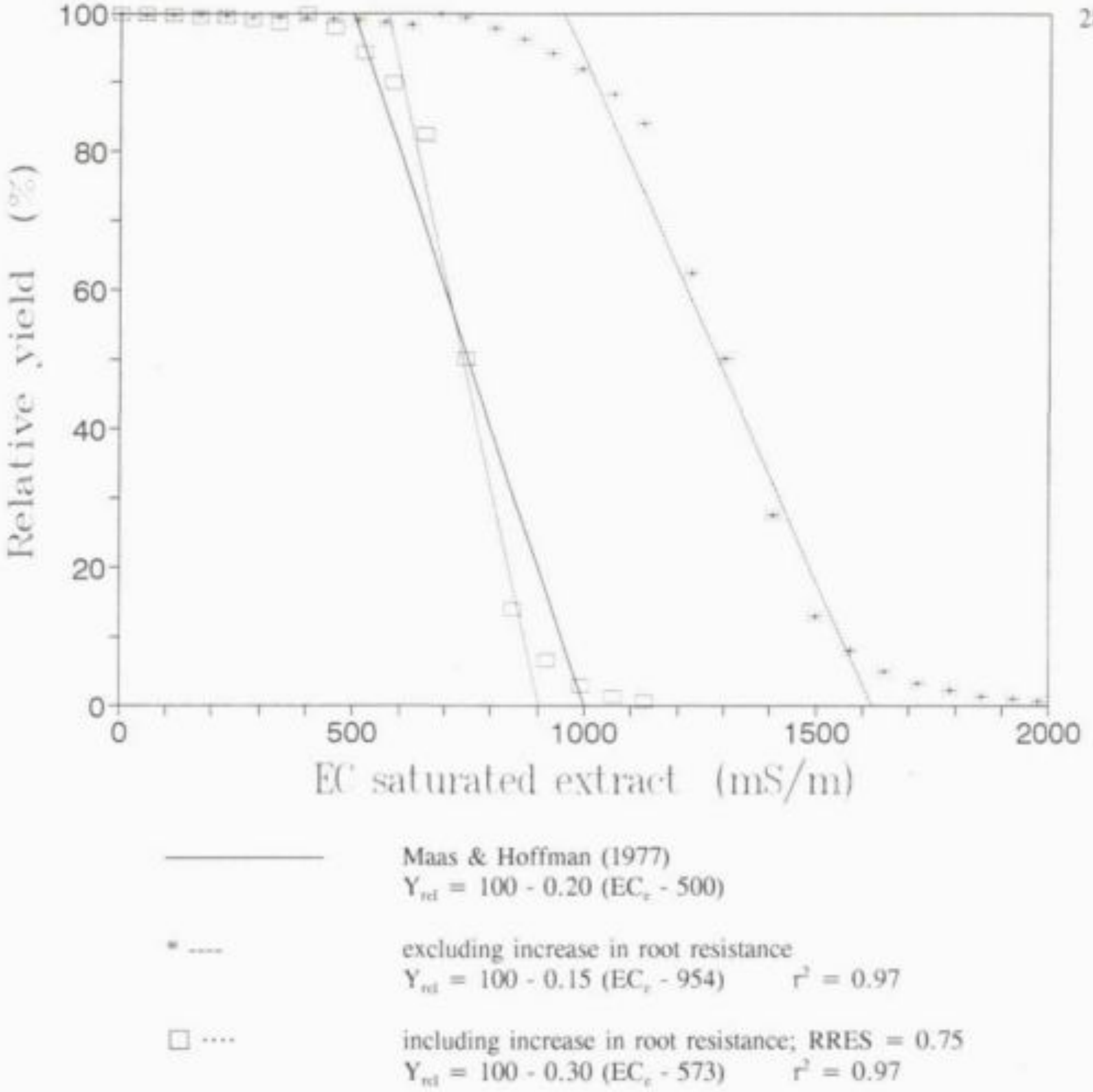


FIGURE 6.13 **Measured and simulated values of cumulative evapotranspiration and drainage (ETD) of soybean in mm. Data refer to: a) well irrigated treatment, b) medium irrigated treatment, and c) dry treatment**



Maas & Hoffman (1977)
$Y_{rel} = 100 - 0.20\ (EC_e - 500)$

* ---- excluding increase in root resistance
$Y_{rel} = 100 - 0.15\ (EC_e - 954)$ $r^2 = 0.97$

□ ···· including increase in root resistance; RRES = 0.75
$Y_{rel} = 100 - 0.30\ (EC_e - 573)$ $r^2 = 0.97$

FIGURE 6.14 Relative yield (Y_{rel}) as a function of seasonal average electrical conductivity at saturation (EC_e) in the root zone of SOYBEAN at different osmotic potential levels; value of root resistance increase coefficient (RRES) is reported

CHAPTER 7

IDENTIFICATION OF PROMISING WETLAND SPECIES

7.1 INTRODUCTION

While the major emphasis in this project has been placed on assessing the response of annual and perennial crops, which offer promise as potential irrigation crops, it is also recognized that such waters make their way via a network of waterways and wetlands to the river systems supplying downstream users. Dependent on the characteristics of such "mine" water, wetland areas may be severely impacted **or** they may play an invaluable role in "polishing" or improving water quality. A healthy, functioning wetland is dependent on healthy plant growth. In the past when wetland species have been discussed virtually the only species receiving mention were *Phragmites* and *Typha*.

It was the objective of this facet of the project to demonstrate that there are probably a wide range of indigenous wetland species occuring in Mpumalanga, ranging from species growing on the margins of wetlands to species adapted to "sponge" areas, to species adapted to periodic or prolonged inundation, to species growing in permanently inundated conditions, which could be used in wetland development programmes. The aforementioned species (*Phragmites* and *Typha*) would appear to be restricted to a large extent to the latter two categories.

Observations on the adaptation of *Paspalum vaginatum* (syn. *P. distichum*) on mineseeps in the Witbank and Newcastle areas and the promising performance of *Panicum repens* on some mine reclamation sites on the Highveld, led to the inclusion of these two species into a screening trial evaluating perennial summer growing species irrigated with lime-treated acid mine drainage (Chapter 5). As with other summer grasses there was a marked positive response to such irrigation compared with dryland, or rainfed, conditons indicating, at least in the short term, a tolerance of such saline waters.

7.2 METHODOLOGY

These observations were followed up by two other pilot trials. The **first** of these consisted of a comparison of the botanical composition of wetland areas - the one pristine and the one impacted by mine water. This approach was first used in the Appalachion coalfields of the eastern USA where favourable results were obtained. The **second** trial consisted of a comparison of six species grown in a replicated greenhouse trial. Once well established these plants received four different quality waters, namely: untreated AMD from Kromdraai Colliery; lime-treated AMD from Kromdraai; gypsiferous water from Kleinkopje Colliery and Control deionized water. Their relative performance was then monitored over a 100 day period. The six species were *Typha* and *Phragmites* for inundated conditions and *Paspalum vaginatum*, *P. notatum*, *Panicum repens* and *Echinochloa haploclada*.

7.3 RESULTS

The water quality in pristine and impacted wetlands, which were surveyed, was characterized by large differences (Table 7.1, p. 284). It was, therefore, surprizing that in the impacted wetlands a greater diversity of species (33% more species) was registered. Although limited in scope these results indicate that a wide range of indigenous species (see Table 7.2, p. 284) are able to survive such impacted conditions and that this aspect warrants more detailed examination. Certain species (e.g. *Sphagnum*) might even have the potential for commercial exploitation.

The quality of water used in the pot trial with six species varied from the acidic Kromdraai water (A), to the moderately saline lime treated Kromdraai water (B) (Table 7.3, p. 285), to Kleinkopje mine water (C) (Table 7.3), which tended to be even more saline, to deionized water (D). All plants were grown in soil to which standard corrective N-P-K fertilizer had been applied. While *Typha* and *Phragmites* were kept inundated, the other species were kept saturated but did not have standing water on the soil surface.

Plant heights (in the case of stoloniferous species such as *P. vaginatum* and *P. repens*, lengths) did not provide a good measure (Table 7.4, p. 285) of plant productivity. Although there were obvious genotypical differences with plants varying from 57 to 198 cm, there did not appear to be marked differences between the mean heights recorded with different qualities of water.

When, however, plants were harvested and dry matter yield recorded, (Table 7.5, p. 285) it appears that there were minimimal differences between the two waters from Kromdraai, while the more highly saline Kleinkopje water gave the best results (15-19% better than Kromdraai water) and the Control was intermediate. It would, therefore, appear that in the short term mine waters such as these do not have a drastic effect on the wetland species evaluated. This would obviously exclude extremely acid water or water with very high NaCl content, which would be more detrimental.

7.4 CONCLUSIONS AND RECOMMENDATIONS

Within the limits of these preliminary studies it would appear that there is a wide range of species adapted to, or tolerant to, moderate deviations from neutrality and reasonably high salt loads provided that such salinity be characterized by high calcium and sulphate. This might, to some extent, be explained by the fact that plants adapted to the Mpumalanga Highveld would often be growing in acid soils. In such agro-ecological areas the highest "salt" concentrations would also be commonly found in the bottomland sites, which are often the sink for leachate from the surrounding landscapes.

The fact is that in developing and using wetland areas as part of water treatment programmes there are possibilities of enriching bio-diversity using indigenous species. In some cases there might even be the possibility of using forage species (such as *Panicum*, *Paspalum* and *Echinochloa*) or a genus such as *Sphagnum* for commercial purposes. It is strongly recommended that such dual purpose uses (for polishing polluted water and commercial production) be actively followed up.

TABLE 7.1 Water quality in pristine and impacted wetlands on Mpumulanga Highveld

Wetland	pH	Acidity	EC	TDS	Ca	Mg	K	Na	Fe	Mn	Al	SO_4
		mg $CaCO_3$ ℓ^{-1}	mSm^{-1}	$mg\ell^{-1}$								
Pristine	5.5	41	5	53	4	1	2	6	0.1	0.4	0.7	13
Impacted	3.9	748	197	1643	358	34	6	14	2.1	6.8	19.6	1168

TABLE 7.2 Botanical composition of pristine and impacted wetland areas in the Kromdraai area

Species	Pristine	Impacted
	%	%
Andropogon distachyos	28.14	12.40
A. huillensis	-	2.90
Centello sp.	-	1.29
Chenolea sp.	-	4.92
Indigofera sp.	2.51	-
Juncus exertus	-	5.16
Jungermannia sp.	-	1.13
Mariscus congestus	14.07	45.50
Marchantia sp.	-	2.24
Paspalum urvillei	-	2.32
Phragmites sp.	24.12	-
Polygonium lapatifolium	3.00	-
Scheonoplectus carymbosus	-	1.29
Senecio glandulose-pilosus	5.53	-
Setaria sphacelata	0.03	-
Sphagnum sp.	-	13.88
Typha sp.	17.59	4.60
Verbena brasilliensis	0.5	-

TABLE 7.3 **Typical analysis of lime treated AMD from Kromdraai Colliery compared with Kleinkopje water**

Mine water	pH	EC mSm^{-1}	Ca	Mg	K	Na	SO_4
			$mg\ell^{-1}$				
Kromdraai	6,5	201	398	23	5	7	1322
Kleinkopje	7,0	335	425	217	12	48	2248

TABLE 7.4 **Height and length (m) of six wetland species grown with four different water qualities**

Species	Water				Mean
	A	B	C	D	
Typha	1.90	1.90	1.93	1.73	1.87
Phragmites	1.63	1.55	1.53	1.58	1.57
Paspalum vaginatum	1.33	1.25	1.43	1.43	1.36
Panicum repens	1.15	1.08	1.23	1.15	1.15
Echinochloa haploclada	2.23	1.80	1.85	2.05	1.98
Paspalum notatum	0.63	0.58	0.53	0.53	0.57
Mean	1.48	1.36	1.42	1.41	

TABLE 7.5 **Dry matter yield of six wetland species grown with four different water qualities (g DM/pot)**

Species	Water				Mean
	A	B	C	D	
Typha	68.74	61.29	80.09	78.09	72.05
Phragmites	36.32	40.77	43.80	43.04	40.98
Paspalum vaginatum	53.99	50.23	62.33	48.30	53.61
Panicum repens	61.31	56.65	65.99	60.97	61.23
Echinochloa haploclada	110.42	105.65	124.53	122.23	115.71
Paspalum notatum	29.20	33.19	36.05	35.36	33.45
Mean	60.00	57.96	68.80	64.67	

CHAPTER 8

SOIL INVESTIGATION : COLUMN STUDY

8.1 INTRODUCTION

In order to investigate the effect that treated acid mine drainage would have on soil properties, it was decided to initiate a leaching study on soil packed into artificial columns. It was also decided to include a few other alternatively treated soils/waters, to obtain indications of other possibilities for handling acid mine drainage in practice.

8.2 MATERIALS AND METHODS

Two soils were used for the investigation: a reddish brown loam (Hutton form) from the University Experimental Farm, Pretoria, and the soil used in the field trial at Kromdraai (Hutton form).

Bulk samples were collected from the top approximately 600 mm at both sites.

Chemical properties of these soils are given in Table 8.3 (p. 295).

PVC pipes (110 mm diameter x 700 mm long) were cut vertically down the middle, rejoined with PVC tape and supported in suitably-sized vegetation vessels with washed quartz sand. At the base of each column, 80% shade net was affixed, to provide for drainage.

Careful packing of the columns with sand was obtained by first filling the lower 45 mm with soil and vibrating it carefully to ensure adequate compaction. The top 150 mm was mixed with the necessary fertilizers/ameliorants and treated in similar fashion. A depth of 100 mm at the top of the column was kept free to accommodate water additions.

Additional P and K was applied in all cases, at the equivalent of 20 $mgkg^{-1}$ as KH_2PO_4. Certain treatments received calcite or dolomite as well.

The volume of water required to bring each soil to field capacity was determined in separate columns. After planting, this volume was added.

Subsequent water applications were made every second day, at the rate of 25 mm per application. A total of 1 000 mm of water was applied, before the suspension of water applications.

The test crop was wheat Inia.

Additional nitrogen as ammonium nitrate was added on two occasions during the growing season, at the rate of 50 kg N ha^{-1} 150 mm each time.

Where the acid mine drainage was treated with neutralizing agents, this was predetermined with small volumes and then conducted on a batch basis. Where soil additions were made, a blanket application of 10 t ha^{-1} 150 mm was given.

The following treatments were applied, with a view to evaluating different management options/approaches:

- Control, deionized water
- Acid mine water as obtained, untreated
- Acid mine water as obtained after treatment, and used in other experiments
- Acid mine water neutralized to pH 5 with calcite
- Acid mine water neutralized to pH 5 with dolomite
- Acid mine water, untreated, applied to soil treated with calcite
- Acid mine water, untreated, applied to soil treated with dolomite

There were three replications of each treatment.

At the termination of the initial water applications, one replicate of each of the treatments was allowed to dry out, whereafter the column was carefully removed, placed horizontally and opened after removing the PVC tape. It was then sampled in 150 mm increments, prior to analysis for the normal exchangeable and soluble constituents according to standard techniques. The two additional replicates were subsequently sampled in the same way.

The statistical analysis was executed with the computer package SAS (Statistical Analyses System) using the GLM (General Linear Models) procedure.

8.3 DISCUSSION OF RESULTS

8.3.1 Growth of Wheat

The total dry mass of plants at maturity is given in Table 8.1 (p. 294), while that of grain yield only is given in Table 8.2 (p. 294).

The following comments are pertinent:

(a) Application of the acid mine water as such to both soils was catastrophic on growth. This is an interesting observation, as the application of 1 000 mm of this water (at the end of the period) did not have a marked effect on soil chemical properties as such. The extremely low pH, however, (soil pH (H_2O) 3,44 & 3,53) obviously resulted in dramatic nutrient imbalances. This aspect could fruitfully be followed up.

(b) There were very little differences between growth with mine water treated in different ways.

(c) Soil application of neutralizing agents, followed by use of acid mine water, appeared to be a satisfactory alternative, although growth was perhaps slightly lower. Use of dolomitic lime for this purpose on the Kromdraai soil, which was low in native Mg, gave the best results on that soil.

8.3.2 Chemical analyses of soils

The soil analyses at completion of the experiment are given in Tables 8.4 to 8.5 (pp. 295 & 296).

8.3.2.1 General effects on soil properties for both soils

pH

Direct soil application of acid mine drainage caused a dramatic drop in pH, to around 4. All treatments tended to result in some decline in pH, not always statistically significant. The lime-treated AMD tended to give the highest values, whereas dolomitic lime, both mixed into the water and incorporated into the soil, was virtually as effective. This is an interesting result, as dolomitic lime is normally regarded as slower acting than calcitic lime.

Electrical conductivity

The conductivity, as a measure of soluble salts, was the lowest in the control and with the AMD *per se*, and the highest with dolomite added to the soil. Other treatments were intermediate.

Calcium

Calcium was highest for the mine treated AMD, which of course contained the highest Ca. The other water and soil treatments didn't really differ much from each other. The Ca in the controls was considerably lower, but the AMD *per se* did not deplete it statistically.

Magnesium

All the Ca-treatments tended to lower the soil Mg levels significantly on the Pretoria soil, although this was not evident on the Kromdraai soil. Dolomitic lime treatments, especially to the soil, resulted in significantly higher Mg levels.

Potassium and sodium

None of the treatments had any effect on the potassium or sodium levels in both soils.

8.3.2.2 Treatment effects with depth

pH

As a general effect the pH was the highest in the top (0-20 cm) layer, although there were not large differences.

Electrical conductivity

This was highest in the top layer and lower deeper down. Some accumulation of salts in the 60-80 cm layer, relative to the other subsurface layers, was noted on the Pretoria soil.

Calcium

This was highest in the top 20 cm, and did not differ significantly below this.

Magnesium

This was highest in the top 20 cm, and tended to be lowest in the next 20 cm, increasing thereafter.

Potassium

Potassium tended to increase with depth, especially on the Pretoria soil. The levels were considerably higher than in the Kromdraai soil, however.

Sodium

There was no significant pattern for sodium distribution in the profiles of both soils.

Careful study of the individual treatments with depth did not reveal any specific patterns that would affect the general conclusions discussed above.

8.3.2.3 Comparison of mine treated AMD with other treatments

The treatment of AMD to near neutrality is the standard procedure currently adopted. Alternatives, with neutralization to lower levels or liming of soils and direct application of AMD were other possibilities considered.

Neutralization with calcite to pH 5

This treatment did not appear to be particularly effective, as the pH of the topsoil was in the order of 4 for both soils. It seems probable that the neutralization of the AMD in the laboratory was not as successful as originally thought. The amount of Ca added to the soil was much lower than in the case of the mine treated AMD, however.

Neutralization with dolomite to pH 5

This treatment appeared relatively successful, probably because effective neutralization at least to the envisaged level was attained. The advantage of adding Mg with the Ca makes this type of treatment attractive.

Addition of calcite to soil

Should it prove feasible, "treatment" of AMD in the soil *per se* would have advantages. Although it initially appeared satisfactory, soil analyses indicated potential problems. The pH of the top three layers of the Kromdraai soil, and of the lower layers on the Pretoria soil, were extremely low, in the order of $pH(H_2O)$ of 4. The Ca values in the subsoil were also low, even slightly lower than in the control, indicating that reaction with the incorporated lime had not taken place to any marked degree. This tends to emphasize the complex nature of acidity and its amelioration in soil.

Addition of dolomite to soil

This treatment proved relatively satisfactory, with neutralization of the lower layers taking place on the Kromdraai, but not on the Pretoria, soil. Ca values were not particularly high, but Mg values were satisfactory in all layers. Further investigation of this type of treatment is warranted.

Direct application of AMD

The effect that this treatment had on the soil to which it was applied shows how dangerous this material actually is. The devastating effect that it had on plant growth has been noted, and the chemical effects are also apparent: extremely low pH that would tend to dissolve clay minerals; lowering of Ca, Mg and K that would result in severe deficiencies, and probably other complications not immediately apparent. It is obviously not a treatment that could be considered in practice, but it is a phenomenon that is occurring at many unguarded sites.

8.3.2.4 Soluble salts

Analyses of representative samples for soluble cations and anions (data not given) did not reveal any patterns of significance relating to accumulation of salts in any specific layers.

8.4 CONCLUSIONS

In this preliminary column study of two soils, the mine treated AMD, adequately neutralized, proved to be satisfactory for soil application.

Lower levels of neutralization investigated gave inconclusive results, with dolomitic lime tending to be superior. Efficiency of neutralization needs to receive adequate attention, however. Soil application of relatively large amounts of calcitic or dolomitic lime prior to direct application of AMD also proved questionable, with dolomitic lime again appearing superior. The efficiency of neutralization under these conditions warrants further investigation.

The extremely negative effect of direct application of AMD illustrates the problems that are currently occurring wherever this material comes into contact with soil.

This investigation covered only the application of 1000 mm of water, and was of necessity fairly preliminary. Even so, quite dramatic effects of application of different materials were apparent. It is obviously not possible to say what the effect of prolonged treatment would be.

The method could be used to estimate the effect of longer term treatment, although drying of the soil as occurs over time in practice would be difficult to accelerate.

From this study the application of the mine treated AMD appears perfectly safe, at least in the short term.

TABLE 8.1 Total dry mass of wheat from different treatments

Treatment	Total top growth g/column	
	Pretoria	Kromdraai
1. Control (Deionized water)	12.50 a	9.73 ab
2. Acid mine water	1.13 b	0.16 c
3. AMD after treatment at mine	13.00 a	9.26 ab
4. AMD neutralized with calcite	13.46 a	9.81 ab
5. AMD neutralized with dolomite	13.17 a	9.43 ab
6. AMD + soil treated with calcite	11.94 a	8.64 b
7. AMD + soil treated with dolomite	12.64 a	10.58 a
c.v. %	9.59	8.14
LSD$_T$ (5%)	2.97	1.86

TABLE 8.2 Grain mass of wheat from different treatments

Treatment	Grain Mass g/column	
	Pretoria	Kromdraai
1. Control (Deionized water)	4.95 a	4.43 ab
2. Acid mine water	0.02 b	0.00 c
3. AMD after treatment at mine	4.45 a	4.59 a
4. AMD neutralized with calcite	4.83 a	4.44 ab
5. AMD neutralized with dolomite	5.06 a	4.21 ab
6. AMD + soil treated with calcite	4.40 a	3.68 b
7. AMD + soil treated with dolomite	4.91 a	4.73 a
c.v. %	9.07	7.76
LSD$_T$ (5%)	0.65	0.80

TABLE 8.3 Chemical properties of soils used in column study

Description	pH (H_2O)	Bray I P mgkg^{-1}	Ammonium acetate extractable cations			
			Ca mgkg^{-1}	Mg mgkg^{-1}	K mgkg^{-1}	Na mgkg^{-1}
Experimental farm, Pretoria	5.10	4.00	303	87.50	119.50	9.80
Kromdraai soil	5.36	14.04	211	10.00	13.00	3.40

TABLE 8.4 Soil analyses at completion of leading experiment, for Pretoria soil

Soil	Treatment	pH (H_2O)	EC mSm^{-1}	Ammonium acetate extractable cmol kg^{-1}			
				Ca	Mg	K	Na
Pretoria 1	Control Deionized water	4.9 a	52.09 f	1.47 d	0.98 bc	0.28 a	0.03 a
2	Acid mine water	3.95 d	214.16 e	1.09 d	0.52 d	0.25 a	1.27 a
3	AMD after treatment at mine	4.66 b	268.83 c	4.61 a	0.54 d	0.25 a	0.1 a
4	AMD neutralized with calcite	4.41 c	271.83 c	2.82 bc	0.64 cd	0.25 a	0.06 a
5	AMD neutralized with dolomite	4.65 b	293.41 b	2.95 b	1.09 b	0.26 a	0.04 a
6	AMD neutralized treated with calcite	4.37 c	229.66 d	2.79 bc	0.61 d	0.26 a	0.04 a
7	AMD + soil treated with dolomite	4.77 ab	359.41 a	2.3 c	2.19 a	0.27 a	0.4 a
c.v. %		5.42	4.71	16.46	31.12	11.75	44.81
LSD$_T$ (5%)		0.13	14.19	0.53	0.36	0.03	0.08

	DEPTH						
Pretoria	0 - 20 cm	4.8 a	304.87 a	4.69 a	1.28 a	0.18 d	0.51 a
	20 - 40 cm	4.43 b	201.35 c	2.04 b	0.69 c	0.24 c	0.24 a
	40 - 60 cm	4.46 b	199.65 c	1.75 b	0.82 bc	0.29 b	0.03 a
	60 - 80 cm	4.44 b	259.5 b	1.83 b	0.96 b	0.32 a	0.34 a
LSD$_T$ (5%)		0.08	10.09	0.34	0.24	0.02	1.03

TABLE 8.5 Soil analyses at completion of leading experiment, for Kromdraai soil

Soil	Treatment	pH	EC mSm^{-1}	Ammonium acetate extractable cmol, kg^{-1}			
				Ca	Mg	K	Na
Kromdraai 1	Control Deionized water	5.71 a	20 d	1.32 c	0.31 b	0.03 a	0.03 a
2	Acid mine water	4 c	168.5 d	0.79 c	0.28 b	0.03 a	0.03 a
3	AMD after treatment at mine	5.47 a	235.5 b	3.8 a	0.34 b	0.03 a	0.02 a
4	AMD neutralized with calcite	4.81 b	227.75 bc	2.58 b	0.32 b	0.03 a	0.02 a
5	AMD neutralized with dolomite	5.45 a	226.58 bc	2.78 b	0.48 b	0.03 a	0.02 a
6	AMD + soil treated with calcite	4.86 b	224.41 c	2.8 b	0.33 b	0.03 a	0.02 a
7	AMD + soil treated with dolomite	5.55 a	264 a	2.42 b	1.15 a	0.03 a	0.01 a
c.v. %		5.42	3.96	0.89	46.61	31.47	70.42
LSD$_T$ (5%)		0.34	9.00	0.77	0.27	0.01	0.02

	DEPTH						
Kromdraai	0 - 20 cm	5.13 ab	246.27 a	3.73 a	0.64 a	0.03 b	0.02 a
	20 - 40 cm	4.98 b	180.46 b	1.75 b	0.33 b	0.03 b	0.02 a
	40 - 60 cm	5.06 b	182.11 b	1.96 b	0.39 b	0.03 ab	0.02 a
	60 - 80 cm	5.31 a	172.42 c	2 b	0.48 ab	0.04 a	0.02 a
LSD$_T$ (5%)		0.22	10.06	0.5	0.17	0.009	0.01

CHAPTER 9

CONCLUSIONS

The main thrust of the study was the screening of plants for their tolerance to treated AMD. Sodic-saline and an untreated neutral high sulphate mine water were included in container studies. During the course of the investigation it became apparent that other aspects required attention as well. These were especially related to the potential effect of such waters on soil and this was evaluated both in a preliminary column study and by means of modelling. The main findings and recommendations of the study were the following:

1. Generally germination of most cultivars of both the subtropical and temperate annual crops was not influenced by either the high sulphate or sodic-saline mine water. There were, however, exceptions where germination of the odd cultivar of sorghum and pearl millet was suppressed with the sulphate salinity, while the same was true for lucerne with the sodic-saline water.

   Germination should not be a problem if these crops are irrigated with comparable waters; where it was suppressed, it ranged from 5 to 16%, which could easily be compensated for by sowing more densely.

2. Seedling growth on the actual 'worst case' mine waters showed that the subtropical cereal crops exhibited more cultivar differences and sensitivity to the neutral high sulphate water than did the legumes. Soybean and drybean grew exceptionally well on the sulphate-saline water. Generally the seedling growth of the annual temperate crops was more tolerant to the sulphate water than that of the subtropicals. Wheat seedling growth was, however, apparently less sensitive to the sulphate water when N was partly supplied as NH_4. Lucerne cultivars were generally sensitive to the sulphate mine water, with the relative seedling growth of different cultivars ranging from 55% to 76%.

   On the sodic-saline 'worst case', actual, mine water the seedling growth of the annual cereal crops was suppressed; again the subtropicals were influenced to a greater extent than the temperate annuals. All lucerne cultivars were very sensitive, however. The relative growth of soybean, dry bean and cowpea seedlings was generally less suppressed than that of the subtropical cereals, with some cultivar differences.

There is a relatively wide choice of cultivars that should successfully bridge the sensitive seedling stage by irrigation with sulphate-saline waters originating from coal mines in the Mpumalanga Highveld region. The choice of cultivars to be grown under irrigation with the sodic-saline mine waters is more limited.

3. With increasing sulphate concentrations of a simulated sulphate mine water there was a general tendency for seedling growth to be increasingly suppressed to a point usually in the vicinity of 2000 to 3000 $\text{mg}\ell^{-1}$ sulphate. In the treatments where the gypsum was either not dissolved or started precipitating, the seedling growth either increased or did not decrease any further. Where salinity was, however, due to increasing sodium sulphate content, seedling growth generally decreased further.

4. The vegetative growth of both the subtropical and temperate annuals was mostly not significantly influenced by the lime treated AMD and sodic-saline mine waters. The vegetative growth of bermuda grass cultivars, a subtropical perennial species, was tolerant to the lime treated AMD water, but cultivars differed significantly with the sodic-saline water.

   Vegetative growth of the temperate perennial forage crops was tolerant to the lime treated AMD water; lucerne grew exceptionally well. The vegetative growth of lucerne, tall fescue and cocksfoot was also tolerant to the sodic-saline water evaluated, but crown vetch and white clover were very sensitive.

5. When extrapolating these results to field conditions it must be remembered that salt tolerance varies for different growth stages and is dependent on a multitude of soil, climatic and other factors. Tolerance found in the seedling and vegetative stages is not always a reliable guide for predicting seed or grain yields. When comparing results, the electrical conductivity of the growth medium can be equated to the mean seasonal EC of the soil water in the rooting zone. Furthermore it must also be remembered that the apparently more sensitive, subtropical crops are produced during the rainy summer growing season. In an area that receives 600-700 mm of summer

rainfall, this 'clean' water can have a diluting effect and reduce the need for supplementary irrigation except for periodic drought conditions, thus inferring that one can go much further with relatively poor quality irrigation water.

6. The screening field trial determined which species are the most suitable for the specific environmental conditions. From a potential production point of view, legumes (soybean and cowpeas) among the subtropical and triticale among the temperate crops proved to be the most suitable.

7. Shallow rooting depth was observed for all crops, due to high soil acidity. High frequency irrigation and application of fertilizers several times during the growing season in smaller amounts are recommended. In particular, potassium and magnesium fertilization are critical due to the low content of these elements in the soil and the added problem of displacement with the high gypsum content of the treated AMD.

8. For the purpose of lime treated AMD disposal, fast growing species that use a lot of water are recommended (pearl millet in combination with a winter cereal, or a lucerne/fescue mixed pasture). It is important to have as large a transpiring canopy as possible throughout the year.

9. Sub-tropical and perennial grass species which are well adapted to local soil and climatic conditions responded well to irrigation with gypsiferous water. From the range of species and cultivars evaluated it is evident that reclamationists can incorporate several hitherto unused grasses into seeding mixtures, which will benefit both biodiversity and productivity. Future work should, however, place the emphasis on the long term implications for the whole eco-system including plant, soil and leachate.

10. The preliminary screening work with leguminous woody species found large differences with respect to climatic adaptation, disease resistance, productivity, leaf retention and persistence and several species warrant further investigation. The lack of response to an irrigation gradient was surprizing and may be linked to the high variability in a relatively small population and/or the strong limit on root development in all but the upper horizon of the experimental soil.

11. Within the limits of preliminary studies on wetland species it would appear that there is a wide range of species adapted to, or tolerant of, moderate deviations from neutrality and reasonably high salt loads, provided that such salinity be characterized by high calcium and sulphate. This might, to some extent, be explained by the fact that plants adapted to edaphic factors of the Mpumalanga Highveld would be adapted to growing in soils which are often very acid.

    The fact is that in developing and using wetland areas as part of water treatment programmes there are possibilities of enriching bio-diversity using indigenous species. In some cases there might even be the possibility of using forage species (such as *Panicum*, *Paspalum* and *Echinchloa*) or a genus such as *Sphagnum* for commercial purposes.

12. Although the main thrust of the investigation was the screening of plants for utilization with treated AMD, several other related aspects also received attention, including crop growth modelling and soil related aspects.

    The water movement - soil salinity model (SWB - "SOIL WATER BALANCE" MODEL), developed for management of irrigation with lime treated AMD, proved a useful tool for crop growth simulations and irrigation scheduling.

    Simulations using the calculated crop growth coefficients fitted measured data of water balance and crop growth parameters fairly well. The mechanistic solution of the model worked well both under good water supply and crop water stress conditions. It needs, however, to be tested using independent data sets.

13. The SWB model was specifically developed to solve problems concerning the use of lime treated AMD. The predictions of soil solution electrical conductivity were in good agreement with observed data. Combined with a weather data generator, this model could be a useful tool for predicting the long-term environmental impact due to irrigation with lime treated AMD.

14. The model could also be used to determine crop salt tolerance. The advantage of doing this with a mechanistic crop growth model is that yield depression can be calculated under specific conditions of soil water supply and evaporative demand of the atmosphere.

It could be developed further by introducing sub-routines describing other aspects of the possible chemical reactions in the rooting zone. The necessary sensitivity analyses would have to be included.

15. In a preliminary column study carried out on two soils, in an attempt to evaluate the suitability of different treatments of AMD for soil applications, adequate neutralization proved necessary.

16. Lower levels of neutralization investigated gave inconclusive results, with dolomitic lime tending to be superior. Efficiency of neutralization needs to receive adequate attention, however. Soil application of relatively large amounts of calcitic or dolomitic lime prior to direct application of AMD also proved questionable, with dolomitic lime again appearing superior. The efficiency of neutralization under these conditions warrants further investigation.

17. The extremely negative effect of direct application of AMD illustrates the problems that are currently occurring wherever this material comes into contact with soil.

18. This investigation covered only the application of 1000 mm of water, and was of necessity fairly preliminary. Even so, quite dramatic effects of application of different materials were apparent. It is obviously not possible to say what the effect of prolonged treatment would be.

    The method could be used to estimate the effect of longer term treatment, although drying of the soil as occurs over time in practice would be difficult to accelerate.

    Application of the lime treated AMD appears perfectly safe, at least in the short term, from this study.

    It is clear that with adequate neutralization of AMD, it should be possible to irrigate a large spectrum of agronomic and pasture species. At the same time soil conditions should not change unfavourably.

19. It is recommended that these observations, based on laboratory, growth chamber, glasshouse and a preliminary field trial, but also on modelling, be further tested under

practical field conditions. Careful monitoring of plant growth, soil conditions both chemical and plant nutritional and drainage water would be required. Other aspects relating to treated AMD, such as wetland dynamics, could also be followed up.

20. With the necessary knowledge and management it is likely that treated AMD could play an important role in at least augmenting irrigation water, of which both the supply and quality are steadily decreasing in the RSA, in an environmentally acceptable manner to the ultimate advantage of all the inhabitants of the RSA.

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APPENDIX A

PLANT MATERIALS USED IN GLASSHOUSE AND LABORATORY SCREENING

APPENDIX A

PLANT MATERIALS USED IN GLASSHOUSE AND LABORATORY SCREENING

A1 SUBTROPICAL ANNUAL CROPS

Maize

1.	SNK 2042	Yellow; excellent performance with stress: drought resistant; also used with irrigation; medium growth length; planting early to medium.
2.	SNK 2888	Yellow; good performance with stress; good drought resistance; good with irrigation; good acid tolerance (Al); medium growth length.
3.	SNK 2266	Yellow; performs well on acid soil.
4.	SNK 2151	White; performs well over a wide range of environments - dryland and irrigation; very good acid tolerance; medium growth length.
5.	SNK 2665	White; performs with stress (dryland) and irrigation; very good acid tolerance (also Al); medium-tall growth length; suitable for most planting times.
6.	PAN 6480	Yellow; outstanding agronomic balance; very good resistance to grey leaf spot; medium growing season.
7.	PAN 6364	Yellow; exceptionally high yield potential; proved under drought stress; medium-short growing season.
8.	PAN 6552	Yellow; high potential; quick grain fill with particularly good standability; medium growing season.
9.	PAN 6363	White; quick, recommended for late plantings.
10.	PAN 6549	White; outstanding performance under widely varying conditions; known for good standability and grain quality.

11.	PAN 6479	White; good performance under widely varying conditions including stress; outstanding resistance to grey leaf spot.
12.	CRN 3816	Yellow
13.	CRN 3414	Yellow
14.	CRN 3818	Yellow
15.	CRN 3631	White
16.	CRN 4403	White
17.	CRN 4523	White
18.	SNK 2340	Yellow; performs particularly well in eastern Highveld; good with centre pivot irrigation and dryland conditions; for early planting; medium growth length. SNK 2340 was also used in the vegetative evaluation and in the field trials.

Sorghum

1.	SNK 3860	Grain; birdproof; very high hay production; used in Middelburg/Stofberg area.
2.	SNK 3939	Grain; sweet malt (GM); excellent (outstanding) production; any planting date; medium growth length.
3.	SENFOR	Forage; very high forage production; regrowth very fast; high protein; very palatable.
4.	SENTOP	Forage; very high forage production; regrowth very good; high protein; low hydrocyanic acid.
5.	SNK 3000	Grain for ensiling; high biomass and grain; medium growth length; good drought resistance.
6.	PAN 8494	
7.	PAN 8501	Grain; good livestock feed (sweet type); medium to long growing season; stands exceptionally until harvest; strong "stay-green" characteristic; short even plant with thick stalk.

8.	PAN 8522	
9.	PAN 8564	Grain; reliable medium to long growing season; good yield potential; good malting and feed characteristics.
10.	PAN 8591	Grain; medium to long growing season; good yield potential; medium plant height; wide area adaptability; GM malt class.
11.	NK 283	Industrial standard (PANNAR); most popular sorghum hybrid; high yield potential, long growing period.
12.	PAN 888	Leafy forage hybrid; performs well on marginal soils; also used in the vegetative evaluation and field trials.
13.	CRN 766W	
14.	CRN 7686	

Pearl Millet (Babala)

1.	PAN 911	Hybrid forage millet; outstanding summer grazing; recovers quickly after drought; can be planted as soon as soil temperatures are suitable (early October); also for haymaking and ensiling. Seed variable.
2.	Common	The same seed that was used in the vegetative evaluation and field trials. Seed variable.

Soybean

1.	Bakgat (Sensako)	Short growing season; planting time 15 November to 15 December; short growth length; used for irrigation.
2.	Ibis (Sensako)	Strongly recommended for warmer areas. Also used in sand culture pot trials and in the field trial.
3.	PAN 494	Top performance; excellent standability; intermediate growth habit; good protein and oil content.

4.	PAN 577G	Short to medium growing season; recommended for coal production areas; recommended for later plantings in warm areas; very good standability; stable above average yield potential; fairly branched upright determinate growth habit.
5.	PRIMA (Pannar)	Most widely planted in Highveld; medium-short growing period; excellent yield potential; widely recommended particularly for temperate regions.
6.	HUTCHESON (Pannar)	
7.	A 2233 (Carnia)	
8.	A 5409 (Carnia)	
9.	A 7119 (Carnia)	

Dry bean (for furrow irrigation)

1.	PAN 122	small white canning bean
2.	PAN 127	speckled sugar bean
3.	MKUSI	very aluminium tolerant; does well in marginal conditions; responds very well to fertiliser; seed type carioca not popular; soil temperature critical - must be at least 11-12°.
4.	NANDI	genetically similar to MKUSI with the same characteristics.

Cowpea

1.	Dr Saunders	used in field trial - generally produces better under hot, dry conditions; generally not well adapted to cooler areas.

Sunflower

1.	SNK 43	Medium-long growing period; increased resistance to disease.
2.	SNK 34	Short growing period; early-late and late planting; drought resistance good; short growth length.
3.	SNK 37	Medium-long growing period; early and first in later planting, drought resistance good; used with irrigation on Highveld.
4.	PAN 7392	Medium growing period; top performer in National trials.
5.	PAN 7411	
6.	PAN 7369	Medium growing period; high potential; very adaptable; best yield reliability of all cultivars in the one to two ton category.
7.	CRN 1445	
8.	CRN 543	
9.	A 1006 9 (CARNIA)	

Potato

The following cultivars were recommended for Highveld conditions: Buffelspoort, BP1 and Up-to-date. (Information of cultivars obtained from the Potato Board by A.F. Visser and J.L. Schoeman of the Vegetable and Ornamental Research Institute.)

1.	BP1	Medium growth period (50 to 110 days from emergence to haulm die-back); high yield; tubers: predominantly medium sized, very regular shape, little malformation even under heat and moisture stress. Tuber dormancy short (60 to 90 days at room temperature). Dormancy shorter (60 days) when hot dry conditions are experienced during growth. Very susceptible to common scab. Firm when boiled.

2.	Buffelspoort	Medium-short growth period (80 to 90 days); high yield. Very suitable for plantings under high temperature growing conditions and irrigation. Tubers: medium and large, regular tuber shape, hardly any malformation, even under unfavourable growing conditions; tuber dormancy short (60 to 90 days at room temperature). Susceptible to freezing temperatures. Susceptible to common scab. Non-floury boiling type and firm.
3.	Up-to-date	Medium growth period (90 to 120 days); high yield. Tubers: medium and large, but inclined to form a high % of small tubers with heat and moisture stress during tuber development; malformation, with heat and moisture stress during tuber development. Tuber dormancy short (60 to 90 days at room temperature). Dormant period shortened by hot, dry conditions during growth. Very susceptible to freezing temperatures. Fairly susceptible to common scab. Floury when boiled.
4.	Herta	A cultivar from Holland; used for potato chips.

A2 SUBTROPICAL PERENNIALS

1. Cynodon hybrid Coast Cross 2 K11 (vegetative material from University of Pretoria experimental farm)
2. *Cynodon dactylon* (bermuda grass) Primavera
3. *Cynodon dactylon* Tierra Verde
4. *Cynodon dactylon* Sahara
5. *Sporobolus airoides* (alkali sacaton)

A3 TEMPERATE ANNUAL CROPS

Oats

1.	SSH 421 (SENSAKO)	Plant height - tall; medium growing season; fast grower can be cut every 3 weeks.
2.	SSH 423 (SENSAKO)	Plant height - tall; medium/late growing season
3.	Witteberg (Small Grain Centre)	
4.	Perdeberg (Small Grain Centre)	
5.	Echidna (Small Grain Centre)	
6.	Overberg	Probably developed for winter rainfall area; the same seed that was used in the vegetative evaluation and in the field trial

Barley

1. Stirling (Small Grain Centre)

Canola

1. CRN 045 (CARNIA)

Triticale

1.	Kiewiet (Small Grain Centre)	
2.	SShR1 (Small Grain Centre)	
3.	Rex (Small Grain Centre)	
4.	PAN 299	
5.	SSKR 626 (SENSAKO)	Tall; fast grower; very late
6.	SSKR 628 (SENSAKO)	Tall; slow grower; very late; used for winter pasture

7.	Cloc 1	Same seed as used in the vegetative evaluation and field trial

Wheat (all cultivars recommended for irrigation as in cooler eastern Highveld areas)

1.	SST 822 (replaces SST 86)	Short growth period; best response to increasing N-fertilisation; sensitive to drought stess; needs efficient irrigation management; good resistance to sprouting; good Al tolerance.
2.	SST 825	Medium growth period.
3.	Palmiet	Medium growth period; poor Al tolerance (?); good resistance to sprouting.
4.	Marico	Longer growth period; poor Al tolerance.
5.	Kariega	Longer growth period; poor Al tolerance.
6.	Inia	..... growth period; for later planting; also popular for warmer Transvaal irrigation regions, e.g. Springbok flats; poor Al tolerance; used in vegetative evaluation and field trial.
7.	Wheat cultivar bred for use as a nursecrop on mine spoils from USA.	

Rye

1.	SSR 727	Same qualities as SSR 1 but resistant to aphids.
2.	SSR 729	Drought resistant
3.	SSR 1	Uses moisture efficiently; also used in vegetative evaluation and field trial
4.	Henoch	

Ryegrass

1.	Macho	

2.	Dargle	
3.	Apollo 64	
4.	Midmar	Used in vegetative evaluation and field trial

A4 TEMPERATE PERENNIAL CROPS

Lucerne (used for seedling trials)

1.	PAN 4860	Good for Highveld; Feb/March planting; synthetic composite - some genetic variation; also used for vegetative evaluation and in field trial.
2.	PAN 4581	Good for Highveld; Feb/March planting. Synthetic composite - some genetic variation.
3.	Baronet	
4.	Topaz	Used with irrigation; high biomass.
5.	Diamond	

The following crops were used for a **vegetative evaluation** in water culture:

1. Lucerne (*Medicago sativa*) PAN 4860
2. Tall Fescue (*Festuca elatior*) Au Triumph
3. Crown Vetch (*Coronilla varia*) Penngift
4. Cocksfoot (*Dactylis glomerata*) Hera
5. White Clover (*Trifolium repens*) Dusi

APPENDIX B

ANALYSES OF LIME TREATED WATER FROM THE KROMDRAAI LIMING PLANT FOR THE PERIOD JANUARY 1994 TO AUGUST 1996

ANALYSES OF LIME TREATED WATER FROM THE KROMDRAAI LIMING PLANT FOR THE PERIOD JANUARY 1994 TO AUGUST 1996[1]

Date[2]	SO_4 mg/ℓ	pH	EC mS/m	Al	Ca	Fe	Mg	Cl	Mn	K	Na	TDS	F
				mg/ℓ									
01/94	993	4,5	148	0,3	365,6	1,6	16,2	6	8,1	0,5	28,8	1420	
03/94	776	5,4	127	0,6	292,2	0,2	18,1	4	9,4	4,4	8,9	1128	0,1
04/94	939	4,4	136	0,01	325,1	0,01	14,6	4	1,8	0,9	34,8	1320	
06/94	935	7,3	137	0,01	387,4	0,1	24,3	4	3,6	4,4	9,4	1377	0,3
07/94	1298	5,6	161	0,01	458,7	0,01	10,7	4	2,5	4	4,9	1793	0,2
08/94	1101	7,1	147	0,01	392,7	0,1	10,6	8	2,4	5,9	6,6	1536	0,3
10/94	1198	5	193	0,01	449,8	0,9	38,5	10	7,6	7,1	16,7	1739	0,2
12/94	881	7,5	184	4,9	382	0,03	5,1	8	0,3	4,2	8	1304	
04/95	1171	6,2	206		447,4	0,01	14,8	4	0,01	1,9	9,8	1659	
05/95	1965	5,3	257									1973	
06/95	1748	5,3	269		577,5	0,2	17,1	6	3,6	2,3	10,7	2375	
07/95	1165	7,1	181		590,4	0,33	17,9	12	5,4	0,4	11,4	1833	
08/95	1415	5	226									1425	
10/95	2156	6,4	286	0,01	700,6	1,13	19,66	8	0,36	3,4	7,3	2896	
11/95	1915	5,2	230		574,9	0,82	58,64	14	2,52	2,7	7	2576	0,1
11/95	2179	6,2	280	0,65	510,36	0,16	14,8	16	0,2	3,8	8,4	2743	
12/95	1991	5,2	252	0,5	474,2	0,2	15	12	0,2	3,3	8,3	2515	
01/96	1341	7	217	19,14	417,75	0,01	9,23	10	1,39	1,1	3,9	1811	
04/96	782	9	144	0,24	289,5	0,28	3,05	6	0,25		4,1	1151	
05/96	766	5,6	128	0,18	289,6	0,31	28	6	2,97	0,1	4,5	1124	
05/96	802	7,7	129	0,24	293,1	1,52	32,24	6	2,04	1	8,4	1167	
07/96	759	10,1	130	5,71	278,3	0,56	1,87	6	0,25	2	6,3	1144	
07/96	1176	5,8	194	19,82	398,3	0,01	33,23	8	1,76	2,5	26	1684	
08/96	1509	6,6	237	0,01	560,7	0,45	51,45	8	1,61	3	3,9	2156	
minimum	759	4,4	127	0,01	278,3	0,01	1,87	4	0,01	0,1	3,9	1124	0,1
average	1290	6,3	192	2,91	430,3	0,41	20,69	8	2,65	2,8	10,8	1744	0,2
maximum	2179	10,1	286	19,82	700,6	1,60	58,64	16	9,40	7,1	34,8	2896	0,3

1. Analyses by Amcoal Colliery and Industrial Operations Ltd., South African Coal Estates Division, Landau Colliery.
2. 1994 and 1996 were years with a high summer rainfall, whereas 1995 was a "dry" year. This corresponds to some extent with the quality of the water, which is, however, also dependent on specific locations being mined.

APPENDIX C

ANALYSES OF FINAL SAMPLES OF MINES A, B & C WATER MAINLY FOR TRACE METALS

APPENDIX C

ANALYSES OF FINAL SAMPLES OF MINES A, B & C WATER MAINLY FOR TRACE METALS[1]

MINE A		
DETERMINAND	UNIT	RESULT
Major inorganic determinands		
pH		6.6
NH_4-N	mg/ℓ	3.10
$NO_3 + NO_2$-N	mg/ℓ	1.42
F	mg/ℓ	0.5
TAL AS $CaCo_3$	mg/ℓ	10
Na	mg/ℓ	4
Mg	mg/ℓ	20
Si	mg/ℓ	< 0.4
PO_4-P	mg/ℓ	0.028
SO_4	mg/ℓ	1386
Cl	mg/ℓ	4
K	mg/ℓ	2.7
Ca	mg/ℓ	552
EC	mS/m	219.0
TDS	mg/ℓ	1991
Trace metals		
Be	mg/ℓ	< 0.001
Be-ACID SOL	mg/ℓ	< 0.001
B	mg/ℓ	< 0.002
B-ACID SOL	mg/ℓ	< 0.002
Al	mg/ℓ	0.673
Al-ACID SOL	mg/ℓ	0.741
Ti	mg/ℓ	< 0,001

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[1] Department of Water Affairs and Forestry, Institute for Water Quality Studies, Private Bag X313, Roodeplaat Dam, Pretoria.

DETERMINAND	UNIT	RESULT
Ti-ACID SOL	mg/ℓ	< 0.001
V	mg/ℓ	0.028
V-ACID SOL	mg/ℓ	0.052
Cr	mg/ℓ	0.063
Cr-ACID SOL	mg/ℓ	0.068
Mn	mg/ℓ	2.159
Mn-ACID SOL	mg/ℓ	2.128
Fe	mg/ℓ	< 0.003
Fe-ACID SOL	mg/ℓ	0.114
Co	mg/ℓ	< 0.005
Co-ACID SOL	mg/ℓ	0.012
Ni	mg/ℓ	0.068
Ni-ACID SOL	mg/ℓ	0.075
Cu	mg/ℓ	< 0.004
Cu-ACID SOL	mg/ℓ	0.103
Zn	mg/ℓ	< 0.003
Zn-ACID SOL	mg/ℓ	< 0.003
Sr	mg/ℓ	0.312
Sr-ACID SOL	mg/ℓ	0.256
Zr	mg/ℓ	< 0.001
Zr-ACID SOL	mg/ℓ	< 0.001
Mo	mg/ℓ	< 0.006
Mo-ACID SOL	mg/ℓ	< 0.006
Cd	mg/ℓ	< 0.001
Cd-ACID SOL	mg/ℓ	< 0.001
Ba	mg/ℓ	0.015
Ba-ACID SOL	mg/ℓ	0.018
Pb	mg/ℓ	< 0.020
Pb-ACID SOL	mg/ℓ	< 0.020

MINE B

DETERMINAND	UNIT	RESULT
Major inorganic determinands		
pH		8.5
NH_4-N	mg/ℓ	1.18
$NO_3 + NO_2$-N	mg/ℓ	< 0.04
F	mg/ℓ	3.7
TAL AS $CaCo_3$	mg/ℓ	299
Na	mg/ℓ	1252
Mg	mg/ℓ	48
Si	mg/ℓ	4.1
PO_4-P	mg/ℓ	0.029
SO_4	mg/ℓ	1384
Cl	mg/ℓ	871
K	mg/ℓ	10.3
Ca	mg/ℓ	49
EC	mS/m	570.0
TDS	mg/ℓ	3984
Trace metals		
Be	mg/ℓ	< 0.001
Be-ACID SOL	mg/ℓ	< 0.001
B	mg/ℓ	< 0.002
B-ACID SOL	mg/ℓ	< 0.002
Al	mg/ℓ	0.269
Al-ACID SOL	mg/ℓ	0,406
Ti	mg/ℓ	< 0.001
Ti-ACID SOL	mg/ℓ	< 0.001
V	mg/ℓ	0.050
V-ACID SOL	mg/ℓ	0.053
Cr	mg/ℓ	< 0.003
Cr-ACID SOL	mg/ℓ	0.014
Mn	mg/ℓ	< 0.001

DETERMINAND	**UNIT**	**RESULT**
Mn-ACID SOL	mg/ℓ	< 0.001
Fe	mg/ℓ	< 0.003
Fe-ACID SOL	mg/ℓ	< 0.003
Co	mg/ℓ	0.023
Co-ACID SOL	mg/ℓ	0.030
Ni	mg/ℓ	0.147
Ni-ACID SOL	mg/ℓ	0.152
Cu	mg/ℓ	< 0.004
Cu-ACID SOL	mg/ℓ	0.039
Zn	mg/ℓ	< 0.003
Zn-ACID SOL	mg/ℓ	< 0.003
Sr	mg/ℓ	4.006
Sr-ACID SOL	mg/ℓ	3.547
Zr	mg/ℓ	< 0.001
Zr-ACID SOL	mg/ℓ	< 0.001
Mo	mg/ℓ	< 0.006
Mo-ACID SOL	mg/ℓ	< 0.006
Cd	mg/ℓ	< 0.001
Cd-ACID SOL	mg/ℓ	< 0.001
Ba	mg/ℓ	0.077
Ba-ACID SOL	mg/ℓ	0.073
Pb	mg/ℓ	< 0.020
Pb-ACID SOL	mg/ℓ	< 0.020

MINE C		
DETERMINAND	UNIT	RESULT
Major inorganic determinands		
pH		8.3
NH_4-N	mg/ℓ	0.18
$NO_3 + NO_2$-N	mg/ℓ	0.29
F	mg/ℓ	0.4
TAL AS $CaCo_3$	mg/ℓ	94
Na	mg/ℓ	56
Mg	mg/ℓ	191
Si	mg/ℓ	6.4
PO_4-P	mg/ℓ	0.029
SO_4	mg/ℓ	2065
Cl	mg/ℓ	19
K	mg/ℓ	10.9
Ca	mg/ℓ	537
EC	mS/m	318.0
TDS	mg/ℓ	2996
Trace metals		
Be	mg/ℓ	< 0.001
Be-ACID SOL	mg/ℓ	< 0.001
B	mg/ℓ	< 0.002
B-ACID SOL	mg/ℓ	< 0.002
Al	mg/ℓ	0.615
Al-ACID SOL	mg/ℓ	0.647
Ti	mg/ℓ	< 0.001
Ti-ACID SOL	mg/ℓ	< 0.001
V	mg/ℓ	0.050

DETERMINAND	UNIT	RESULT
V-ACID SOL	mg/ℓ	0.059
Cr	mg/ℓ	< 0.003
Cr-ACID SOL	mg/ℓ	< 0.003
Mn	mg/ℓ	5.508
Mn-ACID SOL	mg/ℓ	6.920
Fe	mg/ℓ	< 0.003
Fe-ACID SOL	mg/ℓ	< 0.003
Co	mg/ℓ	0.047
Co-ACID SOL	mg/ℓ	0.051
Ni	mg/ℓ	0.131
Ni-ACID SOL	mg/ℓ	0.148
Cu	mg/ℓ	0.039
Cu-ACID SOL	mg/ℓ	0.086
Zn	mg/ℓ	< 0.003
Zn-ACID SOL	mg/ℓ	< 0.003
Sr	mg/ℓ	2.745
Sr-ACID SOL	mg/ℓ	2.602
Zr	mg/ℓ	< 0.001
Zr-ACID SOL	mg/ℓ	< 0.001
Mo	mg/ℓ	< 0.006
Mo-ACID SOL	mg/ℓ	< 0.006
Cd	mg/ℓ	< 0.001
Cd-ACID SOL	mg/ℓ	< 0.001
Ba	mg/ℓ	0.027
Ba-ACID SOL	mg/ℓ	0.027
Pb	mg/ℓ	< 0.020
Pb-ACID SOL	mg/ℓ	< 0.020

Hg, As, Se: There were traces of Hg in all three mine waters but no As or Se.