Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent

by

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ABSTRACT

A field trial was established in January 2002 under a centre pivot at Syferfontein (Sasol) open cast mine, close to Secunda in the Mpumalanga Province (Republic of South Africa). Field measurements of crop, soil, water and weather were taken up till May 2003. Growth analyses were undertaken during the growing period of the planted pastures. Crop growth parameters and input parameters for long term predictions with the SWB model were also determined. The determinations were made for five planted pastures to evaluate if they could be irrigated with Na_2SO_4 rich mine effluent, and to see if the SWB model could reliably simulate crop growth, as well as the salt and water balance. The results indicated that Fescue (cv. Iewag), Lucerne, and Fescue (cv. Demeter) could be grown successfully with satisfactory yield and quality. No leaf burn was observed for the irrigated pastures. The EC_e, pH and ESP of the soil increased slightly over the irrigation period, whereas the EC, pH and SAR of the soil solution fluctuated with rainfall. The model predicted the leaf area index (LAI), top dry matter (TDM), soil water deficit and salts reasonably well. In the long-term, 1420 mm year^{-1} of mine effluent can be used through irrigation. 93% of the salt added through irrigation was predicted to leach from the profile in a 20 year irrigation period which the rest precipitating in the 0.8 m deep soil profile in the form of gypsum. The Na_2SO_4 mine water can be utilized for pasture production provided that proper irrigation management and fertilization is done.

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AMD	Acid mine drainage
ARD	Acid rock drainage
BD	Bulk density (Mg m^{-3})
CDM	Canopy dry matter (kg m^{-2})
CDM_i	Canopy dry matter daily increment (kg m^{-2})
CEC	Cation exchange capacity
cv	Cultivar
DM	Dry matter production (kg m^{-2})
DM_i	Daily increment of total dry matter (kg m^{-2})
DWR	Vapour pressure deficit corrected dry matter-water ratio (Pa)
E_c	Radiation conversion efficiency (kg MJ^{-1})
EC	Electrical conductivity of the soil solution (mS m^{-1})
EC_e	Soil saturated electrical conductivity (mS m^{-1})
ESP	Exchangeable sodium percentage (%)
ET	Evapotranspiration (mm)
ET_o	FAO reference evapotranspiration (mm)
FC	Field capacity (m m^{-1})
FI	Fractional interception of radiation
FI_{evap}	Fractional interception of radiation by photosynthetically active and senesced leaves
FI_{transp}	Fractional interception of radiation by photosynthetically active leaves
f_l	Leaf partitioning factor
FLDD	Day degrees at end of vegetative growth

f_r	Fraction of dry matter partitioned to roots
GDD	Growing day degrees
GDD_i	Growing day degrees daily increment
Hc	Crop height (m)
HDM	Harvestable dry matter (kg m^{-2})
HDM_i	Harvestable dry matter daily increment (kg m^{-2})
K	Canopy radiation extinction coefficient
LAI	Leaf area index (m^2 m^{-2})
$LAIage_i$	Age of leaf area index generated on day "i"
LAI_i	Leaf area index daily increment
LDM	Leaf dry matter (kg m^{-2})
LDM_i	Leaf dry matter daily increment (kg m^{-2})
NWM	Neutron water meter
PAR	Photosynthetically active radiation (0.4-0.7 µm)
PART	Stem-leaf partitioning parameter (m^2 kg^{-1})
PWP	Permanent wilting point (m m^{-1})
RD	Root depth (m)
R_s	Incident solar radiation (MJ m^{-2} day^{-1})
RDM	Root dry matter (kg m^{-2})
RDM_i	Root dry matter daily increment (kg m^{-2})
RGR	Root growth rate (m^2 $kg^{-0.5}$)
r^2	Coefficient of determination
SAR	Sodium adsorption ratio (mmol $l^{-1})^{1/2}$
SDM	Stem dry matter (kg m^{-2})

SDM_i	Stem dry matter daily increment (kg m^{-2})
SI	Stress index
SLA	Specific leaf area (m^2 kg^{-1})
SWB	Soil Water Balance model
TDM	Top dry matter (kg m^{-2})
TDS	Total dissolved salts (mg l^{-1})
T_{avg}	Daily average air temperature (°C)
T	Transpiration (mm)
T_b	Base temperature (°C)
T_{cutoff}	Cutoff temperature (°C)
TDM	Top dry matter (kg m^{-2})
T_f	Temperature factor for light limited crop growth (°C)
T_{lo}	Temperature for optimum light-limited crop growth (°C)
T_{max}	Daily maximum air temperature (°C)
T_{min}	Daily minimum air temperature (°C)
T_p	Potential transpiration (mm)
TransDD	Day degrees of transition period from vegetative to reproductive growth
Transl	Factor determining translocation of dry matter from stem to grain
VPD	Vapour pressure deficit (Pa)
wsf	Water stress factor
yLAI	Leaf area index of senesced leaves
$yLAI_i$	Daily increment of leaf area index of senesced leaves

CHAPTER 1

INTRODUCTION

Mining continues to be a key foundation industry for the growth and development of the South African economy. However, a large amount of poor quality water is produced by these mining industries. As the mining technologies are developed to make it more profitable to mine more coal and gold, even more mine effluent will be generated in the future (Annandale *et al.*, 2002a). If this water is discharged freely into rivers, watercourses and aquifers, it is very likely to cause unacceptable pollution of the environment. The South African National Water Act of 1998 places emphasis on the protection of water resources for their sustainable utilization (Xu *et al.*, 2002). Thus, this trend requires the mining industry to adopt and consistently apply practices that minimize the environmental impacts of this wastewater.

Mine water treatment is a possible solution to prevent the pollution of water resources. However, it has become very expensive to treat the water to a condition acceptable for release into the streams. Interest has been growing in finding ways that can decrease the production of contaminated water and make its treatment less costly. According to the study conducted by Annandale *et al*. (1998), the use of gypsiferous minewater for irrigation of agricultural crops is a promising technology, which could alleviate a shortage of irrigation water and address the problem of disposal of mine effluent. Moreover, the high capital expense and operational cost of effluent treatment by mines could also be offset to some extent by farming income (Jovanovic *et al.*, 2002). Hence, appropriate irrigation management of this mine water with saline resistant plant species could be an alternative economical means of utilizing the mine water.

Depending on the geology of the mines and the minerals that water comes into contact with, different mines generate different qualities of mine water. At the Syferfontein coalmine, in the Province of Mpumalanga (Highveld region), where the research was carried out, Na_2SO_4 dominates the mine water and the type of soil is a black swelling clay (Arcadia, Soil Classification working group, 1991). As a result, perennial pastures were preferred to annual crops due to their suitability to the field conditions and the difficulty of cultivating the soil each year.

In broad terms, the ultimate objective of this research was to evaluate if planted pastures could be irrigated with a Na_2SO_4 rich mine effluent and whether the Soil Water Balance (SWB) model (Annandale *et al*., 1999) could simulate crop growth, as well as the field salt and water balance. Since SWB is a generic crop growth model, parameters specific for each crop have to be experimentally determined (Jovanovic and Annandale, 1999). In previous work, a database of crop specific growth parameters was generated for pasture species (Jovanovic, 1997). However, crop parameters for pastures irrigated with Na_2SO_4 rich mine effluent needed to be determined. In addition to this, the quality of the irrigated planted pastures had to be evaluated to see if the crude protein and nitrogen deviates from fresh water irrigated pastures.

In this study, unlike the gypsiferous water, the opportunity to precipitate gypsum in the profile could be insignificant. However, using $Ca(NO_3)_2$ as a nitrogen fertilizer will add some calcium to the system so that gypsum can be precipitated. For instance, 400kg N of $Ca(NO_3)_2$ applied as a fertilizer with irrigation water can precipitate 2.4 t ha^{-1} $year^{-1}$ gypsum. Salts are also expected to accumulate in the soil and influence the crop growth, and chemical properties of the soil. Salt movement to groundwater over time is also expected. Accordingly, it was necessary to consider the long-term impact (20-50 years) of these salts on the chemical properties of the soil.

The best way to evaluate the long-term impact of mine wastewater utilized in this way is through a well-designed field study. However, the setting up of long-term experiments and monitoring of slow processes is not very attractive, both for practical and financial reasons (Jovanovic, 1997). Therefore, computer models combined with a weather data generator are useful tools for predicting long-term environmental effects (Jovanovic, 1997).

Annandale *et al*. (1998) have developed a soil water and salt balance crop growth model, called Soil Water Balance (SWB) and a weather data generator called CLIMGEN (Campbell, 1990). In this study, SWB and CLIMGEN were used to run simulations for 20 years of irrigation, followed by 30 years of rain fed pasture production to assess the long-term impact of Na_2SO_4 rich mine effluent on soil chemical properties and the salt balance.

The specific objectives of this study were:

1. To determine crop specific model growth parameters of pasture species irrigated with Na_2SO_4 rich mine effluent;
2. To determine the effect of mine wastewater on the protein content of the selected pasture species;
3. To evaluate the reliability and accuracy of Soil Water Balance computer model, by collecting atmospheric, soil and crop data, and
4. To make long-term (20-50 year) predictions of the salt and water balance using the SWB computer model.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Crop production under irrigated agriculture in arid and semiarid areas is dependent on an adequate water supply of good quality. However, a shortage of good quality irrigation water has been pronounced in several countries under population pressure and the need to intensify production (Ayers and Westcott, 1994). Several irrigation management techniques are adopted world wide to address the shortage of irrigation water and maximize return and yield per unit of water (Tanji, 1990).

Currently, poor quality water is becoming the norm for irrigation, as an inevitable alternative water source in many arid and semiarid regions, to compensate for the rapidly increasing water demand. The availability of water resources of marginal quality in combination with skillful irrigation management could be a solution to the shortage of irrigation water to the farming community in several countries (Ayers and Westcott, 1994).

Irrigation with poor quality water has agronomic and economic benefits (Koegelenberg and van Niekerk, 2001), however, it can also have some negative aspects. Salinity is one concern that needs to be monitored so that the soil can be prevented from becoming too saline, which would consequently have adverse effects on crop yield. Heavy metals and trace elements occasionally have negative effects on crops, soil physical and chemical properties and on the environment. The level of sodium also needs to be monitored in order to prevent a reduction in soil permeability. As a result, the long-term effect of irrigation with poor quality water is very important in irrigation and crop management. Still, it is difficult to conduct a field study for a long period of time so as to see its effect on the crop growth, soil physical and chemical properties and groundwater pollution, because it is costly, time consuming, difficult to repeat and also to do on a large scale. When these data are not available, which is usually the case, another way must be found to simulate reality. Modelling plant-soil-water interactions for long periods of time is important for irrigation with poor quality water and crop management. The crucial question is how well the predictions of a model, or the data generated by it, conform to independently obtained observations of the real system (Hillel, 1977). Therefore, several sets of data are required so that model results can be compared to the real measurements.

In this literature survey, modelling the soil water balance and irrigation with mine effluent water is reviewed. Specifically, an emphasis is given to crop modelling, and soil and plant responses to poor quality irrigation water. The first part reviews approaches to modelling the soil water balance, modelling the soil water balance, modelling crop development, crop growth, radiation interception, and modelling crop growth parameters (with prominence given to the crop growth parameters of SWB). The second part of the review is limited to irrigation with mine wastewater, irrigation with gypsiferous water and irrigation with saline-sodic water. In addition, a general overview of model calibration, evaluation and sensitivity analysis is described.

2.2 Approaches to modelling the soil water balance

Soil water balance models are developed to achieve different goals and they are approached from different perspectives. There are several kinds of mathematical models available for calculating the soil water balance (Hillel, 1977). According to Ritchie and Johnson (1990), soil water balance models are categorized into deterministic, stochastic, mechanistic and functional models.

The deterministic models are developed to calculate a distinctive outcome for a given set of events. However, spatial variability of the soil and plant processes in some cases demands the involvement of uncertainty, which is related to the results. Thus, stochastic models are developed to measure the degree of uncertainty. Mechanistic models incorporate basic mechanisms of processes, whereas the functional models are based on capacity factors, and treat processes in a more simplified manner, reducing the amount of input required (Ritchie and Johnson, 1990).

According to Ritchie and Johnson (1990), mechanistic models are useful primarily as research tools for better understanding of integrated systems, and are usually not used by non-authors, due to their complexity. Though, Annandale *et al*. (1998) have bridged this gap by developing a mechanistic model with user-friendly interface, which can be used by non-authors. On the other hand, the functional models have more moderate input requirements making them useful for management purposes (Ritchie and Johnson, 1990).

2.2.1 The soil water balance

In modelling the soil water balance, information on its components is required (Campbell and Daiz, 1988). The objective is to obtain a balance between incoming and outgoing soil water so that adequate available water is maintained for the plant. Incoming soil water includes water in the form of rainfall and/or irrigation, whereas outgoing soil water is any water removal and losses that occur due to evapotranspiration (ET), drainage and runoff (Campbell and Daiz, 1988).

According to Campbell and Daiz (1988), estimates of water balance components must be based on models of soil water, since direct measurements in most cases, are not possible. The components of soil water balance are:

i) Water added to the soil profile through rainfall (RF) and/or irrigation (Ir),
ii) Water lost either as runoff (R) and drainage (D), or enhances soil water (PAW)
iii) Evaporation (E)- water lost from the soil surface, or from evaporation of water intercepted (I) by the canopy surface,
iv) Transpiration (T) from the crop depending upon its root penetration and leaf area index, and

Drainage from the bottom of the soil profile as determined by the retention and transmission properties of the soil. Runoff can be ignored if the lands are flat; the soils are coarse textured in nature and rainfall intensity is low.

Mathematically this is described as follows: $RF + Ir = E + T + R + D + I + \Delta PAW$

Δ PAW is plant available water.

2.3 Crop modelling

2.3.1 Background to crop modelling

The first attempt to generate comprehensive knowledge on plant physiological processes was made by the end of 1960, as computers evolved to enable a numerical description of the functioning of crops (Bouman *et al*., 1996).

Several crop growth soil salinity models have been published (Annandale *et al*., 1998). The models range from very simple to sophisticated, from crop specific to general, and from primarily crop based to soil based. Recently, there has been a radical increase in crop modelling (Tinker and Nye, 2000). In particular, the demand of models by agricultural and environmental funding agencies has initiated further the development and engagement of software for the applicability of modelling. Moreover, the reliability of well tested crop growth soil salinity models for long-term predictions of soil profile conditions, crop yield, and solute movement under various combinations of irrigation scheduling, water quality and soil salinity has contributed to the need of modelling (Cardon and Letey, 1992).

2.3.2 Growth analysis

According to Gardner *et al*. (1985) the analysis in which dry matter accumulation and plant development is quantified is referred to as growth analysis. Growth analysis is a fundamental concept in any crop modelling as it measures the changes in crop growth at different developmental stages. In growth analysis, three measurements are made at frequent intervals, leaf area, dry mass and rooting depth. From this, model parameters can be derived. Growth analysis is commonly done every 1-2 weeks on a relatively large number of plants. Both leaf area and dry mass give us the quantitative changes that occur in the plant over any particular time interval (Gardner *et al*., 1985).

Leaf area index (LAI)

Leaf area index is defined as the amount of leaf area in the canopy per unit area of land. Units for LAI are therefore m^2 (leaf) m^{-2} (ground area) and represent the value at a single point in time. In modelling, green leaf area is essential for photosynthetic carbon assimilation, and describes the growth potential of the crop. This is because the green area of the canopy is the major determinant of solar radiation absorption and photosynthesis (Penning de Vries and Van Laar, 1987). Under optimal water supply conditions, the radiation intensity and temperature are the main factors that influence the green leaf area expansion of the crop (Penning de Vries and Van Laar, 1987).

2.3.3 Crop modelling processes

Crop growth is affected by different factors such as the nature of the soil, nutrient availability, soil water, temperature and the amount of solar radiation. Specific plant species also have their own nutrient, water, soil, temperature and solar radiation requirements. Hence, experimental quantification of these growth factors is important to understand the requirement of the plant under different conditions.

To quantify the factors that affect crop growth, all the plant processes and mechanisms (such as photosynthesis, water uptake, and transpiration) need to be described in relation to the environmental factors such as radiation and temperature (Penning de Vries *et al*., 1987).

Crop growth models are therefore mathematical representations of the plant physiological processes, and constitute the interaction between plant organs (such as leaf, stem and root), processes (such as photosynthesis, respiration, water uptake and transpiration) with soil, water and weather. According to Penning de Vries *et al*. (1989), weather is the central driving variable for crop growth.

The interaction of plant organs (roots, stems and leaves) and processes with the individual environmental factors affects the overall physiological response of the crop, which results in the final yield of harvestable product. The complexity of these interactions has led crop physiologists to try to assess the effects of factors individually to understand the role of each factor in determining the physiology and yield (Salisbury and Ross, 1992).

Penning de Vries *et al*. (1989) explained further the factors that determine crop growth and are summarized for modelling purposes as follows:

- Solar radiation;
- Capacity to intercept solar radiation;
- Energy conversion efficiency of the plant;
- Soil water uptake and water use efficiency of the plant;
- Mobility of nitrogen within the plant tissue to build up new organs; and
- Rooting density of the plant (affects the uptake of phosphorus i.e., the higher the density the easier will be the uptake).

These factors in relation to the processes that characterize crop growth and development are required to be organized in a reasonable way to simulate crop growth. The processes that characterize crop growth and development are discussed below.

Modelling crop development

Crop development is the succession of a crop through defined stages from germination to death, in which the length depends on the development rate. The development rate of a crop is strongly affected by temperature (Campbell and Norman, 1998). Ritchie and NeSmith (1991) state that development rate is assumed to be directly proportional to temperature as temperature affects the photosynthesis. Accordingly, this linear relationship between temperature and development permits the use of the concept of thermal time.

Crop development is usually defined by growing day degrees (GDD) or thermal time. Since the day length may have an effect on the development of crop growth, it is important in some instances to take it into consideration. Thermal time is the timing of the important events in the phasic development of determinate or indeterminate crops such as germination, seedling emergence, leaf primordial appearance, leaf tip or ligule appearance and anthesis (flowering period of the plant from the opening of the flower bud) to maturity. Thus, the ability to predict the stage of crop development is important for management decisions, as timing of pesticide application, scheduling the orderly harvest of crops, or coordinating the flowering of cross-pollination crops for hybrid seed production (Ritchie and NeSmith, 1991).

Modelling crop development is easy for plants with a fixed pattern of development, i.e. when plants have almost a constant number of leaves, flowers and grains in its phenological stages (Goudriaan and van Laar, 1994). This helps to define the developmental stage of the plant with a definite margin. Though, some plants have a complex pattern of development, and therefore to model the development correctly, it is important to get appropriate assimilate distribution.

Modelling crop growth

Crop growth is defined as the accumulation of dry matter (Campbell and Norman, 1998). There are several approaches to crop growth modelling. One approach is to integrate leaf photosynthesis and solar radiation to model daily dry matter production. The carbohydrate fixed from this process is then distributed to different crop organs through a specific partitioning system of the plant (Donatelli & Stockle, 1999). Subsequently, maintenance and growth respiration is subtracted, unless photosynthesis is estimated as net photosynthesis. The simplest approaches to model daily biomass production are those which do not deal with photosynthesis and respiration. The second approach is to calculate biomass either as a function of transpiration or as a function of photosynthetically active radiation (PAR) intercepted (Donatelli & Stockle, 1999).

Modelling radiation interception

The integration of radiation interception and plant growth processes is an important method to simulate the productivity of a crop. The rate of biomass accumulation is principally influenced by the amount of light intercepted by plants over a wide range of temperatures (Ritchie and NeSmith, 1991). There are two reasons for the need to estimate the amount of incident radiation intercepted by the crop. The first is to calculate the amount of PAR that is used to create biomass and the second is to calculate the partitioning of the potential evapotranspiration into potential crop transpiration and potential soil evaporation (Donatelli & Stockle, 1999). In daily time step models, using three depths in the canopy can be a good approximation of canopy photosynthesis (Donatelli & Stockle, 1999). However, models which calculate photosynthesis from transpiration, need only a simple model of radiation interception (Donatelli & Stockle, 1999).

2.3.4 Crop growth model parameters

Crop growth is affected by several factors, as explained above. For successful crop growth modelling, understanding of the crop growth constraints is important. These constraints are the parameters that describe the growth and development of a crop. Throughout the literature, no standard forms of crop growth parameters are apparent for crop modelling. Hence, it is difficult to discuss the crop growth parameters of numerous crop growth models, as they all have varying ways of describing the parameters depending on the complexity and ultimate goal of the model. The most important thing in crop modelling is to include many of the factors involved in crop growth, essentially the most important factors, and to give reasonable estimates. Therefore, to achieve consistency in this literature some of the crop growth parameters used to run simulations in SWB are reviewed from Annandale *et al*. (1999). SWB is chosen, as it includes chemical equilibrium and used extensively in the field by farmers, irrigation officers and consultants for real time irrigation scheduling in South Africa.

A brief overview of the model and procedure for calculation of the parameters are included in the review. The crop growth model parameters are discussed inline with the procedures, to keep the flow of the idea simple and understandable.

Overview of the SWB model

Simulations with SWB can be run using two types of models, crop growth model or FAO model. The crop growth model is a mechanistic model that calculates crop growth and soil water balance components. The FAO type crop factor model is a simple, generic crop, irrigation-scheduling model that would not require time consuming and therefore expensive growth analysis data to determine model parameters (Jovanovic and Annandale, 1998).

In this study, the crop growth model part of SWB is used as it is mechanistic and has several advantages over the more empirical methods often used. Using the thermal time removes the need to use different crop factors to express crop development for different planting dates and regions. Splitting evaporation and transpiration solves the problem of taking irrigation frequency into account. Deficit irrigation strategies where water use is supply-limited can also be more accurately described (Annandale *et al*., 1999).

SWB performs the calculation of the water balance and crop growth using three units: weather, soil and crop unit. The weather unit calculates the Penman-Montheith grass reference daily evapotranspiration (ET_o) according to the recommendations of the Food and Agricultural Organization (FAO) of the United Nations (Annandale *et al*., 1999). The soil unit of SWB divides the potential evapotranspiration into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area. A detailed description of the model (weather and soil units) can be found in (Annandale *et al*., 1999).

The Crop unit of SWB describes phenological development, growth and yield formation for a crop from emergence until maturity, on the basis of crop growth factors and environmental conditions. It includes three procedures, initialization, planting and day step calculation. Crop initialization sets initial values of several crop parameters to zero. Crop height requires a starting value > 0 and this is set to 0.001m (Annandale *et al*., 1999). The procedure for crop planting is initiated once a valid planting date is identified. Top dry matter (TDM) is set to

TDM at emergence (crop specific model parameter). For most crops, TDM is estimated to be equivalent to seed mass density. Initial root dry matter (RDM) is then calculated as:

$$RDM = f_r \frac{TDM}{(1-f_r)}$$

$$f_r = \frac{RDM}{(TDM + RDM)}$$

f_r Fraction of dry matter partitioned to the roots (crop specific model parameter)

Initial modelled leaf area index (LAI) is calculated from specific leaf area multiplied by the mass of leaf dry matter (LDM) in kg m^{-2}.

$$LAI = SLA\ LDM$$

SLA Specific leaf area (m^2 kg^{-1}) (crop specific model parameter)

The crop day step procedure is performed on a daily basis, and includes the following calculations:

Growing day degrees

Growing day degrees (GDD) required for emergence of the crop starts to accumulate after crop planting (Jovanovic *et al*., 1998a) and is calculated using the expression:

$$GDD = GDD + GDD_i \quad \text{(Computer code, not algebra)}$$

Where GDD is growing day degrees of the first day after sowing and GDD_i is growing day degree increment.

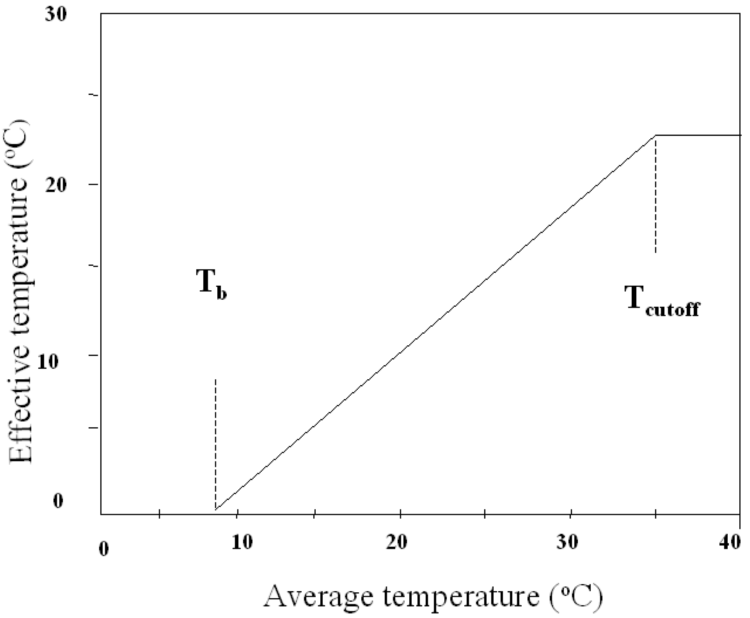


Figure 2.1 GDD (effective temperature) from sowing to emergence (Dewit, 1991)

The following relationship can be defined for the GDD (Figure 2.1):

$$
\begin{array}{lll}
\text{When} & T_{avg} \le T_b & GDD = 0 \\
 & T_b < T_{avg} < T_{cutoff} & GDD_i = T_{avg} - T_b \\
 & T_{avg} > T_{cutoff} & GDD_i = T_{cutoff} - T_b
\end{array}
$$

Where	GDD	GDD (effective daily temperature (^{o}C))
	T_{cutoff}	Maximum temperature beyond which phenological activity does not increase (^{o}C) (crop specific model parameter).
	T_b	Base temperature below which phenological development stops (^{o}C) (crop specific model parameter).
	T_{avg}	Daily average temperature (^{o}C)

Fractional interception of radiation

Fractional interception (FI) of radiation is used to determine the portion of radiation available for crop transpiration and evaporation from the soil surface. The basic equation describing transmission of a beam of solar radiation through the plant canopy is similar to Bouguer's law (Annandale *et al*., 1999). The two parameters calculated are:

$$FI_{transp} = 1 - e^{(-k\ LAI)}$$

$$FI_{evap} = 1 - e^{(-k\ (LAI + y\ LAI))}$$

Where k is canopy radiation extinction coefficient (crop specific model parameter) and yLAI is leaf area index of senesced (yellow) leaves. FI_{transp} is the amount of radiation intercepted by the canopy and used for photosynthesis and transpiration. 1 - FI_{evap} gives the amount of radiation penetrating the canopy and used for evaporation from the soil surface (Annandale *et al*., 1999).

The canopy radiation extinction coefficient (k) is a crop growth model parameter, which describes the beam of solar radiation that transmits through the plant canopy to the ground. It is calculated from field measurements of leaf area index (LAI) and fractional interception (FI) of PAR (Annandale *et al*., 1999). The FI is measured with a sunfleck ceptometer, while LAI is determined from growth analysis. Guidelines for determining k in the field are given by Jovanovic and Annandale (1998).

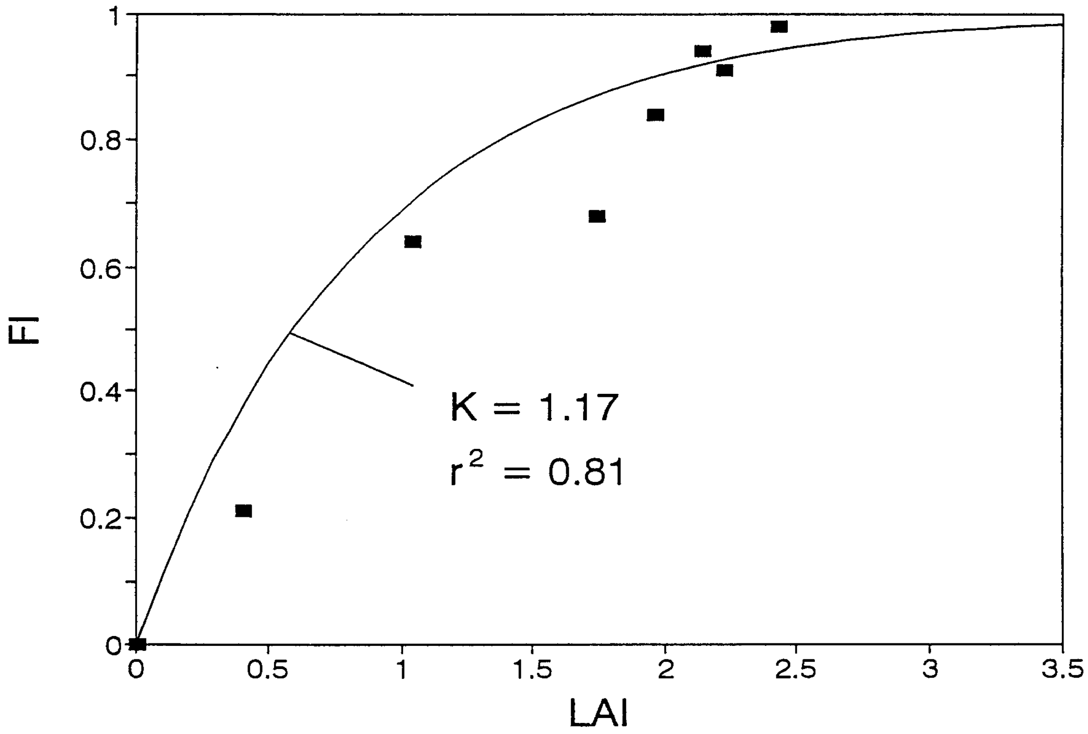


Figure 2.2 **Correlation between leaf area index (LAI) and fractional interception (FI) of radiation measured with the ceptometer for cabbage. Canopy extinction coefficient (k) and the coefficient of determination of the exponential regression function (r^2) (Jovanovic *et al.*, 1998a)**

Dry matter production increment

Dry matter (DM) accumulation is simulated as a function of temperature and crop characteristics as either water supply or radiation limited, between crop emergence and maturity, in a daily time step. Water supply limited DM_i (kg m^{-2}) is predicted using the relationship between dry matter accumulation and transpiration (Tanner and Sinclair, 1983):

$$DM_i = DWR\left(\frac{T}{VPD}\right)$$

DWR is dry matter-water ratio in Pa. VPD is vapour pressure deficit in Pa and *T* is crop transpiration in mm.

DWR is a crop specific parameter and used to determine the relationship between DM_i and T. To account for atmospheric conditions and make it more transferable-less site specific, DM is corrected with VPD (Jovanovic and Annandale, 1998). DM (kg m^{-2}) is harvests measured over a season, whilst VPD represents the seasonal average.

Under conditions of water limited crop growth, DM_i is calculated from radiation conversion efficiency of the plant using the equation recommended by Monteith (1977):

$$DM_i = E_c T_f FI_{transp} R_s$$

E_c - Radiation conversion efficiency (kg MJ^{-1})
T_f - Temperature factor for radiation-limited crop growth

where

$$T_f = \frac{T_{avg} - T_b}{T_{lo} - T_b}$$

T_{lo} is the optimal daily average air temperature for crop growth in °C. The upper limit of T_f is set at 1, when $T_{avg} > T_{lo}$.

Daily dry matter increment is chosen as the minimum of the water supply and radiation limited DM_i. According to Annandale *et al*. (1999), DM (kg m^{-2}) is calculated as a function of the daily cumulative product of the fractional interception (FI) of PAR used for photosynthesis and transpiration, and R_s (total incident solar radiation (M J m^{-2})). FI is measured with the sunfleck ceptometer and R_s with a pyranometer. E_c is the regression of DM vs. the cumulative FI and R_s.

Partitioning of dry matter into other plant organs

Partitioning factors, which are functions of phenology, are used to apportion the total daily biomass increment between the various plant organs. In the vegetative stage, top dry matter is partitioned in the following priorities:

1. Roots
2. Leaf

3. Stem

SWB assumes that DM_i is firstly partitioned into roots, then into leaves and finally into the stem. Daily dry matter increment for roots (RDM_i) is calculated as follows:

$$RDM_i = f_r\, DM_i$$

The top dry matter production is partitioned to leaves. Hence, canopy dry matter daily increment (CDM_i) is then calculated:

$$CDM_i = (1 - f_r) DM_i$$

Daily increment of leaf dry matter (LDM_i) is calculated as follows:

$$LDM_i = f_l\, CDM_i$$

f_l is fraction of top dry matter partitioned into leaves (crop specific model parameter)

f_l is calculated as a function of canopy dry matter (CDM):

$$f_l = \frac{1}{(1 + PART\, CDM)^2}$$

PART is the stem-leaf partitioning factor (crop specific model parameter).

The daily increment of stem dry matter (SDM_i) is then calculated as follows:

$$SDM_i = CDM_i - LDM_i$$

When the root depth reaches its maximum value, root dry matter partitioning stops and f_r is set to 0.

Therefore, top dry matter production will be partitioned to reproductive organs. On the day when flowering stage begins, initial harvestable dry matter (HDM) of the crop is calculated as follows:

$$HDM = Transl\ SDM$$

Transl	-	Factor determining translocation of dry matter from stem to grain (crop specific model parameter)
SDM	-	Stem dry matter (kg m^{-2})

During the flowering stage, the following equation is used to calculate the daily harvestable dry matter increment:

$$HDM_i = rpf\ DM_i$$

rpf - Reproductive partitioning fraction

Where

$$rpf = \frac{GDD - FLDD}{TransDD}$$

Where	FLDD	is flowering day degrees
	GDD	is growing day degrees
	TransDD	is transition day degrees between vegetative and reproductive stages

FLDD and TransDD are crop specific model parameters. The upper limit of rpf is set to 1 (all dry matter produced is partitioned to the reproductive portion). If the crop has not flowered, rpf is set to 0. Once the HDM calculation has been completed, SWB subtracts HDM_i from DM_i. HDM_i is finally added to CDM_i in order to include grain dry matter into CDM.

Partitioning of dry matter under conditions of water stress

The dry matter partitioning is affected by water stress. Water stress conditions are calculated from leaf age but speeded up somewhat when stress occurs (when the calculated daily water stress index is lower than the threshold, crop specific parameter). SI is calculated in the Soil unit as the ratio between actual and potential transpiration.

$$SI = \frac{T}{T_p}$$

T is actual transpiration

T_p is potential transpiration

Under conditions of water stress, a half of the daily leaf dry matter increment is partitioned into roots, the other half into the stem:

$$RDM_i = RDM_i + \frac{LDM_i}{2}$$

$$SDM_i = SDM_i + \frac{LDM_i}{2}$$

$$CDM_i = CDM_i - \frac{LDM_i}{2}$$

When the root system has already reached the maximum depth ($f_r = 0$), the daily leaf dry matter increment is fully partitioned into the stem:

$$SDM_i = SDM_i + LDM_i$$

and LDM_i becomes 0 and one stress day is accumulated.

Leaf area index

The daily leaf area increments (LAI_i) are calculated, once emergence has taken place. It is calculated using the following relationship:

$$LAI_i = LDM_i \, SLA$$

LAI	is leaf area index ($m^2\ m^{-2}$)
SLA	is specific leaf area ($m^2\ kg^{-1}$)
LDM	is leaf dry matter ($kg\ m^{-2}$)

LAI is then calculated by cumulating LAI_i values. It represents the "green leaf" or photosynthetically active canopy, which contributes to transpiration and dry matter production.

Leaf senescence is also accounted for in SWB. It is calculated from leaf age by tracking each individual day's LAI age ($LAIage_i$). The age (in d °C) of each day's leaf area increment is kept track of from the day it was generated. Once the LAI_i reaches a maximum age (crop specific parameter), it is classified as leaf area of "yellow/dead leaves" ($yLAI_i$) as it stops contributing to photosynthesis and dry matter production. The green LAI value is then reduced by $yLAI_i$. Leaf area index of senesced leaves (yLAI) is increased by $yLAI_i$, so as to estimate shading of the soil for the evaporation calculation (Soil unit).

Leaf senescence is speeded up when water stress occurs. A water stress factor (wsf) is used to simulate premature leaf senescence under water stress conditions. When SI is lower than the threshold value, wsf is calculated as follows:

$$wsf = \frac{1}{SI}$$

Therefore, multiplying the daily thermal time increment by wsf speeds up ageing of leaves:

$$LAIage_i = wsf\ GDD_i$$

The upper limit of wsf is set to 2, indicating that the ageing of leaves under water stress conditions can be at most twice as fast as that under well watered conditions.

Rooting depth

Rooting depth is calculated with the following equation:

$$RD = RGR\ RDM^{0.5}$$

RGR	Root growth rate ($m^2\ kg^{-0.5}$)

RGR is a crop specific parameter. RD is used in the calculation of transpiration (Soil unit).

2.4 Model calibration, evaluation and sensitivity analysis

Model calibration

Calibration is adjustment of a parameter such that one or more simulation output reach a predetermined level, usually that of an observation (Penning de Vries and Spitters, 1991). It is done to describe the system under study and to compare the model with the measured data. Calibration is only worthwhile when crop and environment are carefully monitored and observations appropriately recorded. For calibration a collection of benchmark experiments would be very helpful.

Model evaluation

To evaluate a model properly, it is necessary to obtain independent data (not the same data used for calibration). According to Donigian and Anthony (1983), input parameters can be obtained by appropriate measurement, by estimates based on correlations between parameters of crop and soil, by calibration, and from published values. Yusaf (1990) confirmed that the best way is to measure the required model parameters, but this is not always possible and estimates are often used.

Donigian and Anthony (1983) explained that the greatest need in model performance testing and evaluation is clearly the use of quantitative measures to describe comparisons of observed and predicted values. These authors stated further comparison of predicted and observed values for exact location in time and space is a rigorous test as timing differences can have a severe impact on statistical comparison.

Model sensitivity analysis

Sensitivity analysis tries to identify those key model parameters for which the greatest accuracy and precision are needed to reduce uncertainty in model predictions (Yusaf, 1990). According to Tanji (1990), for sensitivity analysis, one of the parameters is varied while simultaneously keeping other parameters constant. Model results are then compared. If outputs differ largely, the variable is sensitive. In accordance with this, Jovanovic (1997) states that it is difficult in general to carry out an analysis of sensitivity to assumptions in general terms, as the output depends heavily on a particular input data set.

2.5 Crop and soil response to poor quality irrigation water

2.5.1 Irrigation with mine wastewater

The excavation of coal and gold minerals is attained by digging holes in the ground. These opencast and underground mine workings extend down below the water table and non-stop dewatering facilities are required to allow mining to proceed (Chapman, 1998). The water pumped directly from the mines is known as mine water and its quality is often poor (highly mineralized), although this depends on the geology of the site. Mine water is only seen as a waste product if it is discharged to the environment via a point source. Mine water is therefore a major problem at several mines, and enormous quantities may have to be pumped continuously during operations. Hodgson *et al*. (1999), estimates 170 Ml d^{-1}.

Acid drainage is a potentially severe pollution hazard associated with mining (Jennifer *et al*., 2002). It occurs when pyrite and other sulphide minerals, upon exposure to oxygen and water, oxidize to create ferrous ions and sulphuric acid. This reaction is catalysed by bacteria. The ferrous ions react further with oxygen, producing hydrated iron oxide. This combination of hydrated iron oxide and sulphuric acid may contaminate surrounding soil, groundwater, and surface water, producing water with a low pH. When this reaction occurs within a mine it is called Acid Mine Drainage (AMD) or Acid Rock Drainage (ARD).

In the formation of AMD the water is first acidified to low pH levels, making it useless for irrigation and unacceptable for return to the environment. However, this problem can be overcome by neutralising the pH artificially or naturally. According to Korentajer (1992) mine drainage from both coal and gold mining in South Africa is often found to have low pH values and high concentrations of heavy metals, particularly iron, manganese and lead. A typical quality of three-mine waters used at Landau and Kleinkopje Collieries for irrigation is indicated in Table 2.1 (Annandale *et al*., 2002b)

Table 2.1. Typical qualities of three mine waters used for irrigation experiments (Landau and Kleinkopje Colliery, Witbank, South Africa) (Annandale *et al*., 2002b)

Analysis	Lime-treated AMD	Neutralized AMD	
	Kromdraai (Landau Colliery)	Jacuzzi (Kleinkopje Colliery)	Tweefontein (Kleinkopje Colliery)
pH	6.0	6.4	7.1
EC (mS m^{-1})	156	288	227
Ca^{2+} (mg l^{-1})	287	555	405
Mg^{2+} (mg l^{-1})	19	170	196
K^+ (mg l^{-1})	11	-	-
Na^+ (mg l^{-1})	7	46	47
HCO_3^- (mg l^{-1})	10	142	68
Cl^- (mg l^{-1})	3	19	32
SO_4^{2-} (mg l^{-1})	998	1986	1524

Irrigation with gypsiferous mine water

Disposal of such mine effluent to surface water or groundwater can cause serious impacts to the environment. A study has been done to establish the suitability of this water for agricultural production in the Republic of South Africa (Du Plessis, 1983). Jovanovic *et al*. (1998b) screened several crops to prove the feasibility of using this mine water for crop production. In the three-year screening trial conducted at Kromdraai, lime-treated AMD proved to be an additional resource in mining areas, particularly where prolonged drought periods are likely to occur (Jovanovic *et al*., 1998b).

With the rapid advances made in computer technology, the use of software to evaluate the mine water under different irrigation scenarios and its long-term impact on the environment has become possible. Annandale *et al*. (1998) recommend the use of gypsiferous mine water for irrigation of agricultural crops and point out that it is a promising technology that could solve problems related to both the shortage of irrigation water in certain areas and disposal of mine effluent.

In the study conducted by Annandale *et al*. (1998), a model was developed to assess the long-term impact of this water on soil and ground water pollution, and a simulation of 30 years of irrigations followed by 20 years of dry land cropping was undertaken. The soil appeared to act as an effective salt sink, with large quantities of calcium sulphate (340-440 Mg ha^{-1}) being precipitated in 30 years, and with negligible amounts of remobilization thereafter (Annandale *et al*., 1998). They concluded that year round, high frequency irrigation with a leaching fraction in winter should be an effective and economical means of utilizing a large quantity of water without causing irreparable damage to soil resources.

According to Jovanovic *et al*. (2002), several crops were successfully irrigated on a commercial scale with two gypsiferous mine waters of similar composition. In their studies, there were no yield reductions associated to irrigation with gypsiferous mine water. In addition, the saturated soil EC decreased after rainy periods and did not attain threshold values critical to yields of most crops. Monitoring of crop nutrient status and careful fertilisation management were recommended, as Ca^{2+} and Mg^{2+} dominate the soil-exchange complex with the risk of K^+ displacement and leaching (Jovanovic *et al*., 2002). Additionally, if rehabilitated mined land is to be used for crop production under irrigation, in the rehabilitation process the spoil material should be shaped to provide a gentle slope to allow lateral surface flow to prevent ponding that occurs in level areas (Jovanovic *et al*., 2002).

The risk of the gypsiferous mine water to groundwater was also evaluated by taking deep-soil sampling data, as well as groundwater quality from boreholes. The result indicated that most of the salts applied after three years of irrigation with gypsiferous mine water, were still trapped in the soil and vadose zone (Jovanovic *et al*., 2002).

Therefore, they concluded that for the purpose of lime-treated AMD utilisation, planting fast-growing species that use large volumes of water by maintaining as large as possible green transpiring canopy throughout the year were recommended. Nevertheless, for sandy soil they recommended that the cultivation and placement of lime and phosphorus should be deep enough in the soil (Jovanovic *et al*., 1998b).

Irrigation with saline-sodic water

The criteria required to achieve sustainable soil quality and crop production using saline- sodic water are salt tolerant plant species, cropping strategies that maintain a year-round ground cover to minimize the adverse impacts of rainfall, periodic application of nonsaline-sodic irrigation waters, routine monitoring of soil solution chemistry and irrigation water quality, and periodic application of chemical amendments to salt and sodium affected soils (Oster and Grattan, 2002).

According to Quirk (2001), disturbance of the soil surface by rainfall is likely to result in a rapid loss of permeability and structure. Seal formation is also another means of contributing to loss of soil hydraulic properties, which results from either physical disintegration of soil aggregates and soil compaction caused by the impact of water. Especially, water drops or chemical dispersion and movement of clay particles and blocking of conducting pores below the dispersed layer. Ayers and Westcott (1994) also reported that infiltration rates are particularly sensitive to SAR (sodium adsorption ratio) and EC (electrical conductivity). Oster and Grattan (2002) further pointed out that SAR and EC of the soil solution are closely linked to the SAR and EC of the irrigation water.

Rainfall, with less EC, on soils previously irrigated with saline-sodic water lowers the soil EC_e (soil saturated paste extract) at the soil surface to a greater extent than it lowers the SAR of the soil solution. This disproportionate lowering of the salinity likely upsets the balance between flocculation promoted by the salt concentration (EC_e) and dispersion promoted by sodicity (SAR) (Ayers and Westcott, 1994).

Many researchers correlated total dissolved salts (TDS) in mg l^{-1} with electrical conductivity (EC) (Hanson *et al.*, 1999; Bauder and Brock, 1992, Tanji, 1990) multiplying EC (mS m^{-1}) by a factor of 6.4. Thus, saline water is categorized as water with an EC > 300 mS m^{-1} while sodic water is categorized as water with an SAR > 12 $(mmoll^{-1})^{1/2}$ (Hanson *et al.*, 1999, Ayers and Westcott, 1994; Suarez, 1981). Although there is considerable debate over the absolute values for acceptable limits for SAR, there is consistent agreement that sodicity, as reflected in the SAR, is a source of significant impairment of many soils, particularly irrigated soils of montmorillonitic or 2:1 expanding lattice clay structure. The adverse impact of sodicity on dispersion of fine-textured soils is aggravated in environments where rainfall conditions seldom occur during the irrigation season (Tanji, 1990). In addition to the dispersive nature of sodium and soil-associated sodicity, sodium is also toxic to sodium sensitive plants at exchangeable sodium percentages (ESP) of the exchange complex >15% (Tanji, 1990, Ayers and Westcott, 1994). Similarly, salinity has the potential to have a significant impact on plant communities, plant community sustainability, and livestock and wildlife forage compatibility.

Sodium saturation and clay dispersion are frequently associated with salination. Soils leached with sodium salt solutions were found to have lower hydraulic conductivity and lesser porosity than the same soils when leached with soluble calcium salts (Waldron *et al*., 1970).

According to the study conducted by Quirk and Schofield (1955), when the salinity (EC) of the soil is maintained below a critical threshold level (though soil dependent), the hydraulic conductivity and permeability of the soil decreased as the ESP increased, i.e., increasing percentage of the soil exchange sites saturated with sodium without a simultaneous increase in EC of the soil solution results in dispersion and loss of large-diameter conductive porosity. McNeal and Coleman (1966) concluded that the decrease in hydraulic conductivity associated with high SAR low EC solutions was particularly pronounced for soils with high montmorillonitic clay content, while soils high in non-swelling kaolinite are insensitive to variations in solution composition with respect to loss of pore integrity (Bauder and Brock, 1992).

In Israel, a 16-year study was conducted on saline sodic water (EC = 460 mS m^{-1} and SAR = 26 $(mmol\ l^{-1})^{1/2}$ for irrigation of cotton during summer (450 mm), which resulted in ESP values 20 % to 26 % in the upper 0.6 m layer of the soil. According to Qadir and Oster (2003), there was no deterioration in soil hydraulic properties during the summer because salinity of the irrigation water was sufficient to counteract the deleterious effects of exchangeable Na^+. However, deterioration did occur during the rainy season because of the negligible salinity of rainwater. An annual application of phosphogypsum at 5 Mg ha^{-1}, prevented the formation of surface seals and crusts maintained adequate infiltration rate.

According to Bauder and Brock (1992) sustainability of irrigation with saline-sodic water was predicted on: 1) a nearly continuous supply of water and very short periods of soil drying, and 2) well-drained soils of predominantly sandy loam, fine sandy loam, or a silt loam. However, long-term irrigation resulted in accumulation of significant amounts of salt and sodium in the soils. Furthermore, equilibration of the soil solution saturation extract of the most coarse-textured soils with the irrigation water salinity/sodicity was observed. The salinity and sodicity of the finer-textured soils elevated to levels 1.5 to 2.0 times greater than the salinity or sodicity of the irrigation water over time.

Bauder and Brock (1992) also determined that these same soils, when irrigated for extended periods of time with water of elevated salinity and sodicity, exhibited decreased macro-porosity and reduced soil hydraulic conductivity. They were able to successfully reverse the trend in reduction in macro-porosity by the addition of calcium chloride, thereby increasing the EC of the soil solution and the available supply of calcium to displace sodium on the exchange complex. However, the net result was significant elevation of the sodium concentration of the soil solution that subsequently caused an elevation in sodium concentration of drainage water. Additional studies reported by Bauder and Brock (2001) substantiates the findings reported by Bauder and Brock (1992).

McNeal and Coleman (1966) proposed that water with salinities ranging from 60 to 200 mS m^{-1} and SARs ranging from 6 to 35 $(mmol\ l^{-1})^{1/2}$ can be used for irrigated forage production under appropriate soil and management conditions. Those conditions are irrigation of crops with tolerances to these salinity and sodicity levels and use of cropping and soil amendment strategies that prevent the development of adverse soil physical properties.

With respect to irrigation with saline-sodic water, as Oster and Grattan (2002) pointed out, it is possible to maintain soil permeability by choosing the appropriate salinity level in the irrigation water, even at excessively high sodicity levels. He further proposes irrigation water with high salinity (up to 200 mS m^{-1}) is more than adequate to maintain or enhance existing hydraulic conductivities. He cautions however that rainfall, or irrigation with nonsaline water poses a significant potential of leading to crusting, poor tilth, ponding, and poor aeration on lands previously irrigated with saline-sodic waters.

CHAPTER 3

MATERIALS AND METHODS

3.1. Experimental layout

The field trial was established in February 2002 at Syferfontein (Sasol) open cast mine (25° 48'S; 29° 05' E; altitude 1350m), close to Secunda in the Mpumalanga Province (Republic of South Africa). The treatments were five temperate and subtropical, annual and perennial pastures. The planted pastures are listed in Table 3.1 and the treatments are indicated in Table 3.2.

Table 3.1 The annual and perennial, temperate and subtropical pasture crops used in the field trial

Planted pastures (common name)	Scientific name	Classification
Fescue (cv. Iewag)	*Festcua arundinaceae*	Perennial Temperate species
Lucerne (cv. SA standard)	*Medicago sativa*	Perennial Temperate species
Fescue (cv. Demeter)	*Fescue arundinaceae*	Perennial Temperate species
Eragrostis	*Eragrostis curvula*	Perennial Subtropical species
Kikuyu	*Pennisetum clandestinum*	Perennial Subtropical species
Rye grass	*Lolium perenne*	Annual Temperate species

Table 3.2 Five treatments used in the field trial

Treatments
Fescue (cv. Iewag)
Mixture of Lucerne and Fescue (Demeter)
Fescue (cv. Demeter)
Mixture of Eragrostis and Ryegrass
Kikuyu

The mean monthly rainfall and evaporation of the area between 1963 and 1989 was 689 mm and 1526 mm respectively. The average summer temperature is in the range between 10 ^{o}C to 30 ^{o}C, with an average temperature of 20 ^{o}C, whilst the winter temperature varies between -3 ^{o}C and 21 ^{o}C. The summer vapour pressure deficit of the area is 1.2 kPa and the average for winter is 0.9 kPa. The average wind speed of the area was recorded to be 2.74 m s^{-1} during the growing season (January 2002-May 2003).

The type of soil was a heavy clay soil (55% Clay) with an average bulk density of 1.4 Mg m^{-3} and an average soil depth of 0.8 m. The average soil data prior to commencement of the experiment is given in Table 4.2 and the soil map is indicated in Figure 3.1.

Data for each treatment was collected on plots of 30 m X 50 m in size, replicating randomly three times within the plot. The total area of the irrigated field was 20 ha and irrigation was carried out with a centre pivot. Spillways were designed to facilitate drainage of excessive rainwater and/or irrigation. The layout of the field trial is shown in Figure 3.2. The mine rehabilitation manager was applying irrigations, whenever they had surplus of water.

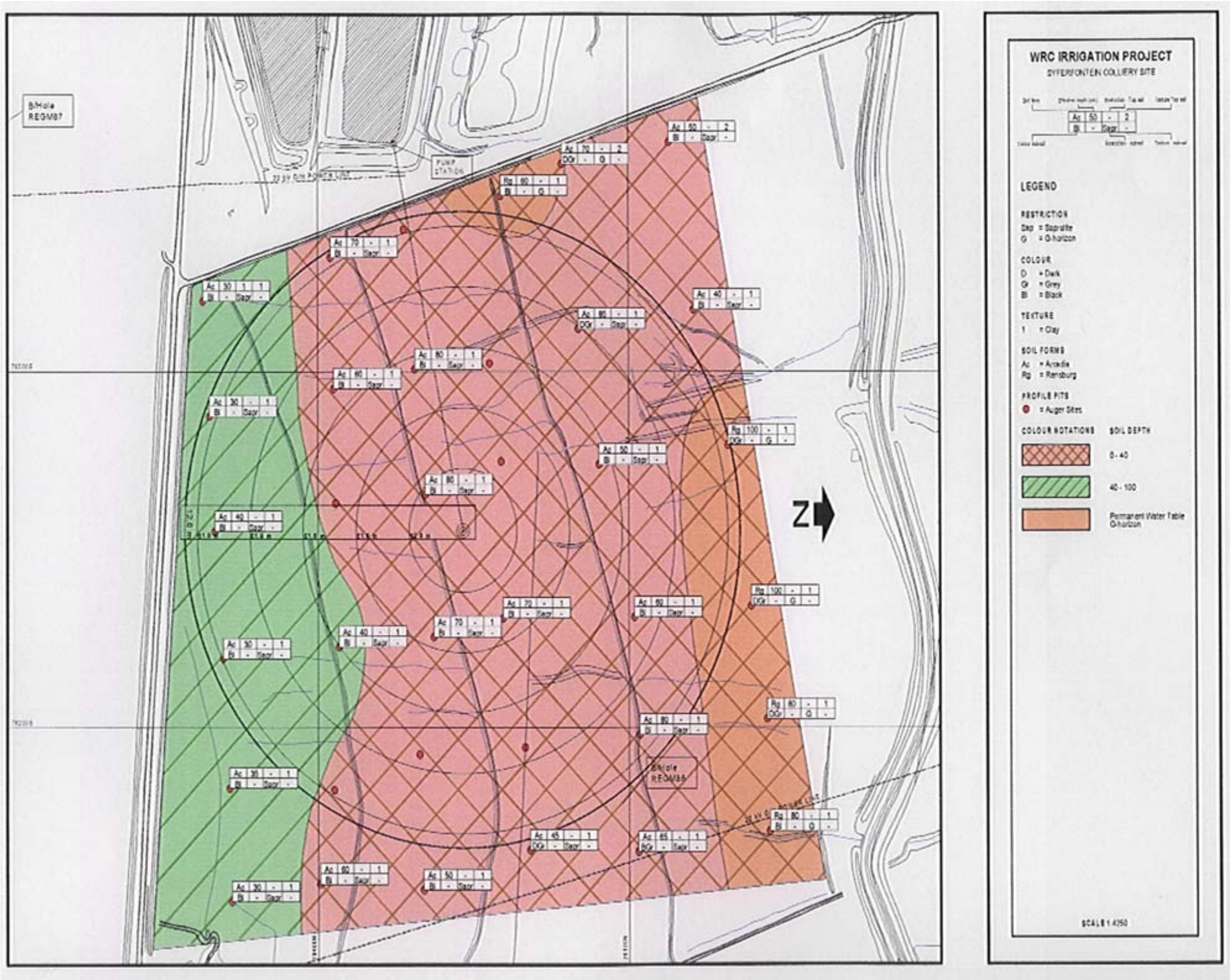
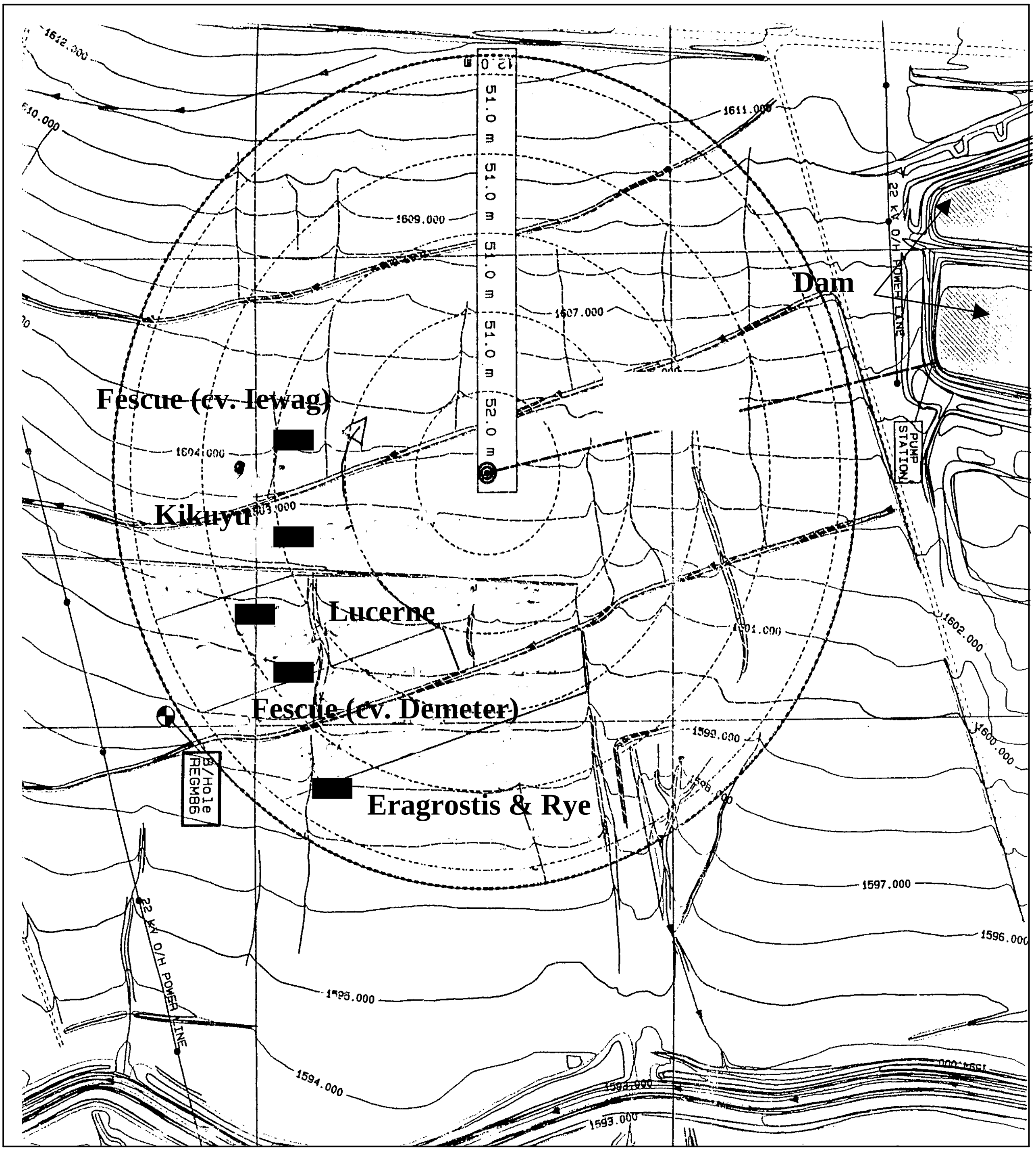


Figure 3.1 Soil map of the field trial



Key

……… Wheel tracks

▬ Plant and soil sampling plots

Figure 3.2 Lay out of the field trial

Agronomic techniques

Agronomic practices commonly used in the area were adopted; 300 kg ha^{-1} $Ca(NO_3)_2$ (51 kg N) and 200 kg ha^{-1} Urea (CH_4N_2O) (92 kg N) were applied in Oct/Dec 2001, 2002 and Jan 2003 to avoid nutrient deficiencies. Phosphorus (P) was not applied as it reduces the salt tolerance of the crop with the increase in salinity (Grattan and Grieve, 1994). Potassium (K) was also not applied, although it was present in relatively low concentration in the soil solution. As a high application of potassium is needed to correct the deficiency that occurred due to the adsorption onto the surface of the soil particles (Grattan and Grieve, 1994). The planted pastures were grown for forage and were harvested/grazed at the appropriate time before maturity.

3.2. Field measurements

Soil sampling and analysis

Soil samples were taken randomly from each plot four times during the growing period, i.e., after the layout of the experiment (initial conditions) in October 2001, and after harvest in October 2002, May 2003 and October 2003. Sampling was done at 0-0.2, 0.2-0.40, 0.40-0.60, 0.60-0.80, and 0.80-1.00 m depths and determinations were made for bulk density, pH, soil saturated electrical conductivity (EC_e), and ion concentrations (Ca^{2+}, Mg^{2+}, K^+, Na^+, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}). Exchangeable sodium percentage (ESP (%)) was calculated using concentrations of the cations Na^+ ($cmol_{(c)}$ kg^{-1}) and CEC ($cmol_{(c)}$ kg^{-1}) of the soil. The analysis was completed in the Soil Science laboratory of University of Pretoria. The complete result of the soil analysis is presented in Appendix E. A summary of the soil analysis results obtained from the field trial is given in Figures 4.21, 4.23, 4.25-4.29.

Soil water sampling and analysis

Two ceramic cup water samplers at depths of 0.30 and 0.60 m and an electronic wetting front detector at a depth of 0.40 m were installed in each plot. Water draining from the irrigated area after rain or irrigation, was sampled about every two weeks from the soil water samplers. The water samples from each plot were analysed for concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-} and electrical conductivity (EC) of the soil solution. Sodium adsorption ratio

(SAR) of the soil solution was calculated for each plot. During the growing period, no water could be collected from ceramic cups. This could be due to high suction force of the soil or low matric potential of the soil and cracking or swelling of the soil, which resulted in poor contact between soil and ceramic cups.

Soil water content

It was measured with a neutron water meter (NWM) Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). Two NWM access tubes to a depth of 0.80 m were installed, due to shallow depth of the soil, for each plot. There were five plots and 12 NWM access tubes. Soil water contents were measured at two depth increments of 0.2m every 10-14 days. The NWM was calibrated for the soil on the site.

TDR100 probes and heat dissipation sensors (HDS) at 5 depths (0-0.05, 0.05-0.15, 0.15-0.25, 0.25-0.35 and 0.35-0.45 m) were also attempted for intensive monitoring, but the probes could not record data due to the cracking and swelling character of the soil.

Rainfall and irrigation

Amounts and intensity of irrigation and rainfall were recorded with tipping bucket raingauges connected to a CR10X (Campbell Scientific, Utah, USA) data logger. Manual rainguages were also placed as a contingency in every site for each treatment. There were a total of 12 electronic raingauges and 12 manual raingauges in five plots.

Irrigation water analysis

The irrigation water quality at the beginning of the experiment was pH = 8.9,EC = 372 mS m^{-1}, Ca^{2+}= 0.8 mmol l^{-1}, Mg^{2+} = 3.65 mmol l^{-1}, Na^{+}= 34.6 mmol l^{-1}, Cl^{-} = 0.53 mmol l^{-1}, SO_4^{2-} = 17.16 mmol $l^{-1}$and SAR = 23.2 (mmol $l^{-1})^{1/2}$. It was monitored during the trial period and there was no change in water quality throughout the experimental period (January 2002-May 2003). The irrigation water quality is indicated in Table 4.1. This water was applied to satisfy crop evapotranspiration. The soil solution was also monitored at 0.4 m during the experimental period (Appendix E).

Growth analysis

During the experimental period, growth analysis was done at various stages of the treatments. This was carried out by taking plant samples from 1 m^2 areas at representative sites, with 3 replications every 10-14 days from each plot. Two essential measurements were made, leaf area index and above ground dry matter accumulation. Leaf area index (LAI) was calculated from leaf area determined with a leaf area meter (LI-3100, LiCor, Lincoln, Nebraska, USA) and dry matter of partitioned plant parts (leaf, stem, flower and seed) was determined after four to five days of oven drying at 60 ^{o}C. When plants reached the flowering stage, they were harvested and final yield determined.

Protein content (quality determination)

Nitrogen (N) content was determined on plant samples taken at harvest for each treatment. The samples were taken 7 cm above ground to represent the utilizable part of the plant. The N content was then multiplied by 6.25 to get crude protein content, which is a measure of forage quality.

Weather data

An automatic weather station was set up about 100 m from the irrigated field (outside the pivot) and the following meteorological data were recorded:

- Relative humidity and air temperature using a CS-500 Vaisala temperature and relative humidity probe
- Solar radiation using an LI –200 Pyranometer
- Rainfall amount and intensity, using a tipping bucket Texas Instrument Inc. rain gauge (Campbell Scientific, Inc, UT, USA)
- Wind speed using R.M.Young cup anemometer (Michigan, USA)

The data were recorded every 10 seconds and totaled or averaged hourly with a CR10X data logger.

3.3. Data processing and modelling

Crop growth

The experimental period of the treatments was from January 2002 to May 2003. Five harvests were made of each of the five treatments during this time. Crop specific growth parameters were determined for each crop according to the procedure developed by Jovanovic and Annandale (1999), using growth analysis, soil and weather data measurements for the experiment.

The specific leaf area and leaf stem partitioning parameters were calculated from the growth analysis data, while day degrees for emergence and flowering were calculated from weather data. The thermal time requirements of the pastures for emergence was calculated, though the crops were allowed initially to establish. The day degrees to maturity was not determined, since the crops regrew after harvesting. So, the HDM (harvestable dry matter) was eliminated by choosing very long day degrees for flowering (never reach of flowering), except for Lucerne as it regrew faster than the other grasses. The TDM at emergence was increased to enhance the DM produced in the growing cycle. The code was modified, asking permission of the developers of the model, so as to specify DM after harvest and harvest date. As, it was difficult to take TDM measurements after harvesting. The canopy radiation extinction coefficient (k) determined by Barnard *et al*. (1998) was used, as fractional interception was not measured due to technical problems. A canopy storage of water from rain and/or irrigation that is intercepted by the canopy and evaporates from it was estimated 1 mm (Annandale *et al*., 1999). Root fraction of the total dry matter was assumed as roots fully developed. Root growth rate was estimated, not calculated, due to the difficulty to dig out the roots from the soil and get an accurate measurement. SWB was then calibrated with the first cycle crop specific growth parameters and evaluated with the measured values of the other cycles. Thus, the January 2002 to May 2002 experimental period was selected as the model calibration period while, the model was evaluated using the results of the September 2002 to May 2003 trial period.

To run simulations, SWB provides two options. They are: long-term-pasture (LT-P) and not long-term (NLT). The NLT option was developed to run a single season simulation while the LT-P option runs several growing cycles harvested at a predetermined yield (when the planted pastures reached 3.5 t ha^{-1}). However, in this study the NLT option was used to run the simulations, as the pastures were not harvested at a predetermined yield during the growing cycle. Therefore, the dates of harvest had to be written in the code to harvest the pastures before they reached maturity stage.

During the June to August 2002 growing cycle, the plant growth was slow or plants in a dormancy phase due to winter frost, which would explain low water use due to low atmospheric demand. In order to avoid the winter season, as there was no growth and irrigation, the simulation was run separately for the growing periods of January to May 2002 and September 2002 to May 2003.

The predicted results of crop growth and water balance for SWB from the calibration data set (cycle 1) were compared with the independent data sets obtained from cycles 2, 3, 4 and 5. The values of the four statistical parameters recommended by De Jager (1994) were calculated to investigate the quality of the predicted results compared to measured values. The parameters are r^2, D, RMSE and MAE. The parameters RMSE and D were also used by Cardon and Letey (1992). The statistical indicators are at the right hand side of each graph. In all these graphs, the vertical bars indicate the standard deviation of the ± 1SE for replications of experimental values. The r^2 values represent the ratio between the scatter of the simulated and the measured values. The values of r^2 vary between one and zero, indicating one as excellent fit while zero is no agreement between the simulated and measured values. The RMSE statistics show how much the simulated values are overestimated or underestimated. The MAE gives the maximum absolute error. The Willmott's index of agreement (D) shows how well the predicted and observed deviations correspond to each other (Cardon and Letey 1992). It varies between one and zero with one representing perfect agreement and zero of many forms of disagreement. Therefore, RMSE and D quantify the agreement between simulated and observed results.

Salt simulation

The soil chemical properties and irrigation water qualities measured during the trial period (Appendix D, Table D1 and Table 4.1.), and rainwater quality suggested by Bolt (1979) were used as input values in the SWB database to run the salt simulations. According to Bolt (1979) the quality of the rainwater is: $Ca^{2+} = 2\ \mu mol\ l^{-1}$, $Mg^{2+} = 6\ \mu mol\ l^{-1}$, $SO4^{2-} = 12\ \mu mol\ l^{-1}$, $Na = 8\ \mu mol\ l^{-1}$, $K^{+} = 1\ \mu mol\ l^{-1}$, $Cl^{-1} = 1\ \mu mol\ l^{-1}$.

The salt simulations were run for all pastures for the growing period, January 2002 to May 2003. The salt concentrations calculated by the model were then tested with the data of irrigation and rainfall events over the treatments recorded with CR10X data loggers. This was to avoid the deviation that can occur as a result of irrigation or rainfall events that come about between the consecutive soil water sampling intervals. The model simulation results were then exported to a spreadsheet. The evaluation of the predicted vs. measured data was made by looking at the graphs and calculation of the four statistical parameters (RMSE, r^2, D and MAE). According to De Jager (1994) and, Cardon and Letey (1992), RMSE was calculated as:

$$RMSE = \left[\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{N-1} \right]^{1/2}$$

Where P_i and O_i are the *i*th predicted and observed values of the experimental data, respectively and *N* is the number of observed values. The value of RMSE is in the same unit as the corresponding data (mmol l^{-1}). The second statistical parameter D is expressed as:

$$D = 1 - \left[\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left[/ P_i' / + / O_i' / \right]^2} \right]$$

Where $P_i' = P_i - O_m, O_i' = O_i - O_m$ and O_m is the mean of the observed values.

$$r^2 = \left[\sum_{n=1}^{n=N} \frac{(Y^n{}_s - Y_{ams})(Y^n{}_m - Y_{amm})}{\sum (Y^n{}_s - Y_{ams})} \right]^2 (Y^n{}_m - Y_{amm})^2$$

$$MAE = 100 \sum_{n=1}^{n=N} \frac{(Y^n{}_s - Y_m)}{NY_{amm}}$$

Y_s	simulated values
Y_{ams}	arithematic mean of simulated values

Y_{amm}	arithmetic mean of measured values
Y_m	measured values
n	the n^{th} value in a data set totaling N values

The reliability criteria of the statistical parameters is as follows:

$r^2 > 0.8$,
$D > 0.8$,
and $MAE < 20\%$

Long-term simulations

Twenty years of historic daily weather data collected at Secunda meteorological station were used for the long-term simulation. Weather data were generated from the long-term data using CLIMGEN weather generator. CLIMGEN has two components CLIMPAR and CLIMGEN. CLIMPAR determines statistical parameters and CLIMGEN generates daily maximum and minimum air temperatures, and precipitation using the parameters determined in CLIMPAR. Fifty years of daily maximum and minimum temperatures and rainfall were generated to carry out the long-term crop growth, water and salt balance.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 General introduction

The results of the measurements taken for each treatment are tabulated and attached in Appendices A-E. The results include five growth cycles of the different pastures. The first and second cycle comprise four pastures: Fescue (cv. Iewag), Lucerne, Fescue (cv. Demeter) and Eragrostis. The third, fourth and fifth cycles also included Kikuyu. Each cycle consisted of records of leaf area index (LAI), dry matter (DM), plant analysis, volumetric water content measurements with neutron water meter (NWM), and soil solution chemical analysis results.

Irrigation water quality analysis results are expressed in Table 4.1. The average soil texture, field capacity, permanent wilting point and bulk density before commencing the field trial and during the trial period are shown in Table 4.2. The total yield and forage quality obtained from the pastures from January 2002 to May 2003 is summarized in Table 4.3. The crop growth parameters developed to simulate crop growth and soil water and salt balances are indicated in Table 4.4. The predicted TDM, LAI, deficit and salts are also presented in Figures 4.1-4.20 and the statistical indictors of the predicted vs. the measured values for the calibration and evaluation period are in Tables 4.5-4.11. Average soil chemical properties of the site at different depths over the trial period are in Figures 4.21, 4.23 and 4.25-4.29. The pH (H_2O), EC and SAR of the soil solution sampled from the irrigated field is illustrated in Figure 4.22, 4.24 and 4.30. Finally, predicted average annual soil water-salt-balance and root density weighted soil saturated EC of Lucerne irrigated with Na_2SO_4 rich mine effluent for 20 years using three different irrigation strategies is shown in Table 4.12, Table 4.13 and Figure 4.31.

Table 4.1 Irrigation water quality analysis results (Syferfontein Colliery, October 2001 to March 2003)

Date	pH	EC	Ions ($mmol\ l^{-1}$)					SAR
		$mS\ m^{-1}$	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	$(mmol\ l^{-1})^{1/2}$
Oct-2001	8.9	372	34.6	0.8	3.7	0.5	17.2	23.2
Jan-2002	9.4	314	33.6	0.4	2.8	0.7	12.1	18.9
Feb-2002	9.4	331	33.6	0.4	3	0.6	15.1	18.1
Mar-2002	9.1	281	21.7	0.5	2.3	0.6	10.7	12.9
Mar-2003	9.2	319	35.1	0.7	3.2	0.5	12.5	17.7
Mean	9.2	323.4	31.7	0.6	3	0.6	13.5	18.2
Std err	0.2	32.9	5.6	0.2	0.5	0.1	2.6	3.7

Table 4.2 Average soil texture, field capacity (FC), permanent wilting point (PWP) and bulk density of the soil (BD)

Textural fraction	Depth (cm)		
	0-20	20-40	40-60
Clay (%)	55	55	45
Silt (%)	25	25	30
Sand (%)	20	20	25
Field capacity $m\ m^{-1}$	0.44	0.40	0.38
Permanent wilting point $m\ m^{-1}$	0.28	0.20	0.15
Initial water content $m\ m^{-1}$	0.45	0.40	0.30
Bulk density ($Mg\ m^{-3}$)	1.4	1.6	1.5

4. 2 Crop growth

Commonly, the growth of grasses follows a sigmoidal curve from the time of establishment until death in annuals and a steady condition was reached in perennials (Tainton, 2000). As these planted pastures emerged from seed, they were observed to grow slowly and then accelerated their growth until they reached the flowering stage, after which growth slowed down again. A plateau was also observed during their growing periods, particularly in Lucerne.

The regrowth of the pasture crops after cutting should follow the same sigmoidal growth pattern as the previous cycle (Dovrat, 1993). However, after mechanical harvest and extended cutting interval, the recovery of Fescue (cv. Iewag), Fescue (cv. Demeter), Eragrostis and Kikuyu was slow. Cutting the grasses extremely short may have caused this slow regrowth. According to Dovrat (1993), small numbers of tillers may have remained after cutting that enabled the regrowth. It could also be due to the decrease in capacity to capture solar radiation. Accordingly, the plants depleted the stored carbohydrate reserves and slow regrowth was observed (Dovrat, 1993).

Since the pastures were harvested to the height of 3-7 cm above the ground, the apical meristem might have been removed, which could be another reason for the slow recovery of the grasses. While Lucerne, a perennial legume, unlike the grasses has a lignified stem, and has the capacity to develop secondary stems from the axillary buds of the lower leaves on the original primary stem (Tainton, 2000). Lateral tillering or branching becomes necessary before continuation of leaf production in grasses. Thus, the height of cutting changed the location of shoots that support regrowth (Dovrat, 1993).

The remaining TDM and leaf area after cutting are the most important factors in determining regrowth (Dovrat, 1993). Hence, in the following regrowth there was lower LAI and dry matter production than the previous cycle. Though, the regrowth of lucerne was faster than the other grasses. This might be due to the apex of grasses being higher from the ground while in legumes the apical meristem (terminal growing point) remains low to the ground during their vegetative growth (Tainton, 2000).

In this study, the idea was to grow a mixture of grasses but the tall growing grasses and legumes such as Eragrostis and Lucerne formed a canopy that covered the slow growing plants. So, after the first cut the taller plants crowded out the shorter plants, resulting in pure stands of Lucerne and Eragrostis. This could be due to the capturing of most of the solar radiation by the tall growing grasses, while the slow growing grasses remained shaded (Tainton, 2000).

A plant maximizes radiation absorption by accumulating leaves (Norman and Arkebauer, 1991). When the leaf area exposed to the sunrays equals the area of the ground on which plants are growing, the LAI is one. Fescue (cv. Iewag) and Lucerne were noted with an average LAI of 5.4 and 4.6 respectively, which is higher than the values for other grasses.

The average vapour pressure corrected dry matter water ratio of Lucerne was 2.8 Pa, which is higher than Kikuyu and Fescue (cv. Iewag) at 2.3 Pa (Table 4.4). Jovanovic *et al.* (1998b) also report that Lucerne can successfully utilize high acid mine water. This is because Lucerne does not exert stomatal control over water loss until soil water is depleted to -400 kPa (Dovrat, 1993). It could also be due to its ability to extend its roots deep into the soil profile.

The average yield and above ground dry matter of Fescue (cv. Iewag) was greater than that of Lucerne, Fescue (cv. Demeter), and Eragrostis (Table 4.3). This is because Fescue (cv. Iewag) is more tolerant to salinity than the other grasses. According to Tanji (1990), the EC_e threshold of Fescue is 390 mS m^{-1} while Kikuyu is 300 mS m^{-1}. In addition, Tanji (1990) also reported a salinity threshold of 200 mS m^{-1} for Lucerne and Eragrostis. The difference in yield between the two Fescue cultivars could be due to cultivar differences. However, the yields of all the planted pastures were lower than the yields that could be expected from irrigated pastures (Table 4.3). This could be due to climatic, soil, water and management differences.

Although the pastures were all harvested at the same time, the regrowth of Lucerne was observed to be much faster and with higher N and CP content than the other grasses (Table 4.3). The basal cover of Fescue (cv. Iewag), Fescue (cv. Demeter) and Kikuyu was outstanding. In the growth cycles, there was no any observation of leaf burn due to the mine effluent. The leaves of Lucerne were small in size, which could be due to the EC of the irrigation water and periodic water logging, as lucerne is adapted to well drained soils. The soil was water logged dueto in appropriate irrigation management.

Table 4.3 A comparison of the total yield and forage quality of five planted pastures irrigated with Na_2SO_4 rich mine effluent and typical values for fresh water irrigated pastures (Tainton, 2000)

Planted Pastures	Growing period	Mine water irrigated pastures			Fresh water irrigated pastures		
		Total Yield $(t\ ha^{-1})$	Forage quality		Total Yield $(t\ ha^{-1})$	Forage quality	
			N $(g\ kg^{-1})$	% CP		N $(g\ kg^{-1})$	% CP
Fescue (cv. Iewag)	Jan 02 - May 03	15.1	18.5	11.5	16-18	18-24	12-15
	Std err	± 0.4			-	-	-
Lucerne	Jan 02 - May 03	10.7	26.9	16.8	18-20	22-28	14-18
	Std err	± 0.05			-	-	-
Fescue (cv. Demeter)	Jan 02 - May 03	11.3	17.7	11.08	16-18	18-24	12-15
	Std err	± 0.04			-	-	-
Eragrostis	Jan 02 - May 02	10.2	16.6	10.4	16-18	18-20	12-13
	Std err	± 0.12			-	-	-
Kikuyu	Sep 02- Dec 02	11.4	–	–	20-24	35-38	20-24
	Std err	± 3.5			-	-	-

4.3 Forage quality

The N and CP contents of the pasture were determined from the plant analysis results for 2002 and 2003. These were compared with the quality of pastures grown under fresh water irrigated conditions. The quality for Fescue and Lucerne was in the range that can be expected from the species grown under fresh water irrigation (Table 4.3). As a result, the effect of the quality of the Na_2SO_4 rich irrigation water on forage quality of the planted pastures (Fescue and Lucerne) was negligible for the growing period. Eragrostis and Kikuyu showed low quality as compared to the fresh water irrigated pastures. This could possibly be due to the uptake of considerable Na^+ from the soil solution that inhibited the enzymatic process of the plant (Tester and Davenport, 2003).

Table 4.4 Crop specific parameters of five planted pastures for the growing period determined from growth analysis of cycle one

Crop parameters	Planted pastures				
	Fescue (cv. Iewag) (C_3)	Lucerne (C_3)	Fescue (cv. Demeter) (C_3)	Eragrostis (C_4)	Kikuyu (C_4)
Canopy radiation extinction coefficient **	0.8	0.6	0.8	0.9	0.9
Dry matter water ratio (DWR (Pa)) *	2.3	2.8	2	2	2.34
Radiation use efficiency (kg (M J)$^{-1}$)**	0.0015	0.0015	0.0015	0.0037	0.002
Base temperature (^{o}C)***	6	8	6	10	14
Temperature for optimum crop growth (^{o}C)**	15	15	15	15	20
Cut off temperature (^{o}C)**	30	25	30	25	30
Day degrees to emergence*	84	112	84	100	140
Maximum crop height (m)*	0.5	0.6	0.5	0.5	0.4
Maximum root depth (m)*	0.6	0.8	0.6	0.6	0.8
Stem to grain translocation**	0.01	0.01	0.05	0.005	0.005

Canopy storage (mm)**	1	1	1	1	1
Minimum leaf water potential (k Pa)**	-1250	-1250	-1250	-1250	-1250
Maximum transpiration (mm day^{-1})**	9	9	9	9	9
SLA (m^2 kg^{-1})*	11.6	18.4	10.3	8.2	17
P (m^2 kg^{-1})*	0.2	0.14	0.3	0.3	1.3
TDM at emergence (kg m^{-2})**	0.05	0.05	0.05	0.05	0.05
Root fraction**	0.9	0.9	0.9	0.9	0.9
Root growth rate $(m^2\,kg^{-0.5})$ **	15	15	15	15	15
Stress index*	0.95	0.95	0.95	0.95	0.95

* Measured values

** Estimated

*** Personal communication (Prof. NFG Rethman, Department of Plant Production and Soil Science, University of Pretoria)

4.4 Model simulations

a. Crop growth and water balance

Graphical plots of the time variation of the soil water balance (a summary graph), root depth (RD), crop growth variables (LAI and TDM), and soil water deficit to field capacity are shown for each pasture (Figures 4.1-4.16). Root depth, leaf area index, top dry matter and soil water deficit graphs include simulated (solid line) and measured (symbols) data points (Figures 4.2, 4.4, 4.6, 4.8, 4.10, 4.12, 4.14 and 4.16). The soil water deficit graph shows the prediction of the average water content with time for two depths that range from 0-0.4 m.

The histograms in the soil water balance (SWB) summary graph are the irrigation and rainfall input data for the growing period (Figures 4.1, 4.3, 4.5, 4.7, 4.9, 4.11 and 4.15). The blue line in the bottom part of the summary graph is the simulated water deficit, whereas the horizontal line is the field capacity level of the soil. The output summary below the graph also shows the planting date, irrigation system, and seasonal soil water balance components.

For all pastures, the measured values of LAI, TDM and deficit were distributed both above and below the simulated line (Figures 4.2, 4.4, 4.6, 4.8, 4.10, 4.12, 4.14 and 4.16). This occurred because the pastures were experiencing some water stress between irrigations. When plants are stressed the salt concentration of the soil solution increases and as an effect the leaf water potential and transpiration rate decreases (McCree and Richardson *et al.*, 1987). This causes a decline in leaf growth with declining soil water and increasing water stress (Meyer and Green *et al.*, 1980). Thus, the rate of leaf area expansion declined when there was stress, or increased when plants were supplied with sufficient water and rainfall diluted the soil solution.

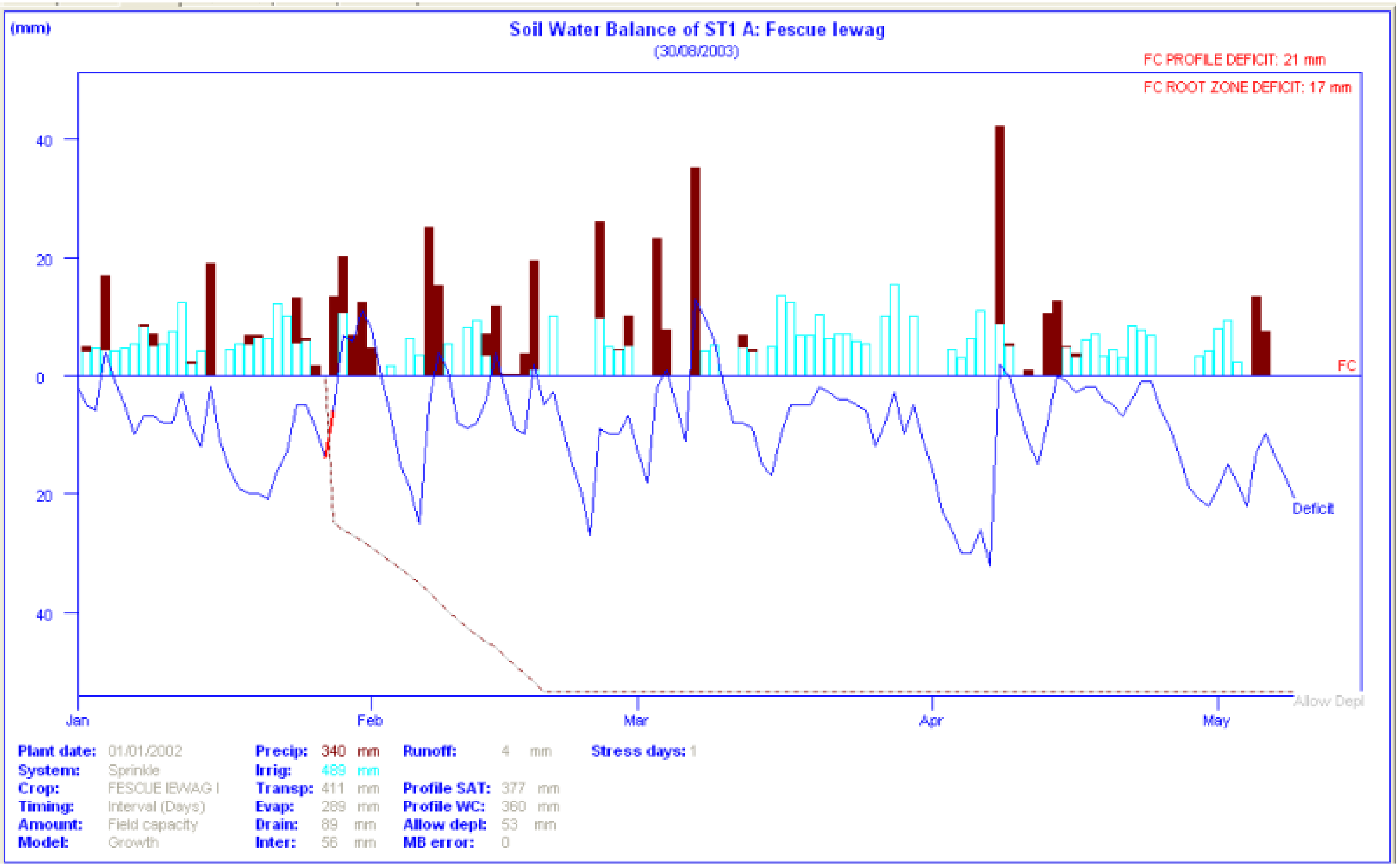
The measured water content of all the plots were between saturation and field capacity at some time of the study period. Whereas, in the other times the model predicted too much water use (the soil was too dry) compared to measurements with the NWM for that period. This might have been occurred due to the clayey nature of the soil (low hydraulic conductivity) that slowed down infiltration, and resulted in the high SAR of the irrigation water (Table 4.1) that probably deflocculated the soil. In addition to that, the increase in ESP of the top layer of the profile and cracking and swelling character of the soil may have caused the NWM to under or over estimate the water content.

For Lucerne, predicted LAI (Figures 4.8) showed a plateau. This may have been caused due to the growth of new leaves, approximately equaled to the senescence of old leaves. The statistical output parameters of LAI, TDM and deficit indicated that predictions were satisfactory (Figures 4.2, 4.4, 4.6, 4.8 and Tables 4.5-4.10).

Similarly for Fescue (cv. Demeter), the model simulated well by not consistently over or under estimating (Figures 4.10 and 4.12). Statistically the results indicated that the model predicted adequately the LAI, TDM and deficit.

For Eragrostis, the measured LAI values lie below the simulated line, and it indicates that the model consistently overestimated the FI (Figure 4.14). This could be for the grasses were stunted after the first growing cycle. The grasses were stunted probably due to the high salinity of the soil solution that resulted from the irrigation water or by the uptake of Na^+ from the soil solution. The threshold salinity for Eragrostis is 200 mS m^{-1} (Tanji, 1990), while in this field trial, EC of the soil solution during the growing period fluctuated between 200 and 500 mS m^{-1} (Figure 4.24). Besides this, SWB does not simulate the effect of waterlogging on the crop, and therefore may have overestimated the total above ground dry matter production (Annandale *et al*., 1999).

The simulated soil water content values were similar to measured data. The model generally gave satisfactory prediction of soil water deficits. However, the growth variables (LAI and TDM) were predicted better than the water content. The model also predicted the deficit with satisfactory r^2 and D values, while RMSE and MAE were not satisfactory in all the pastures (Tables 4.9 and 4.10).



Plant date: 01/01/2002
System: Sprinkle
Crop: FESCUE IEWAG I
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 340 mm
Irrig: 489 mm
Transp: 411 mm
Evap: 289 mm
Drain: 89 mm
Inter: 56 mm

Runoff: 4 mm
Profile SAT: 377 mm
Profile WC: 360 mm
Allow depl: 53 mm
MB error: 0

Stress days: 1

Figure 4.1 Soil water balance summary graph Fescue (cv. Iewag), January 2002 - May 2002

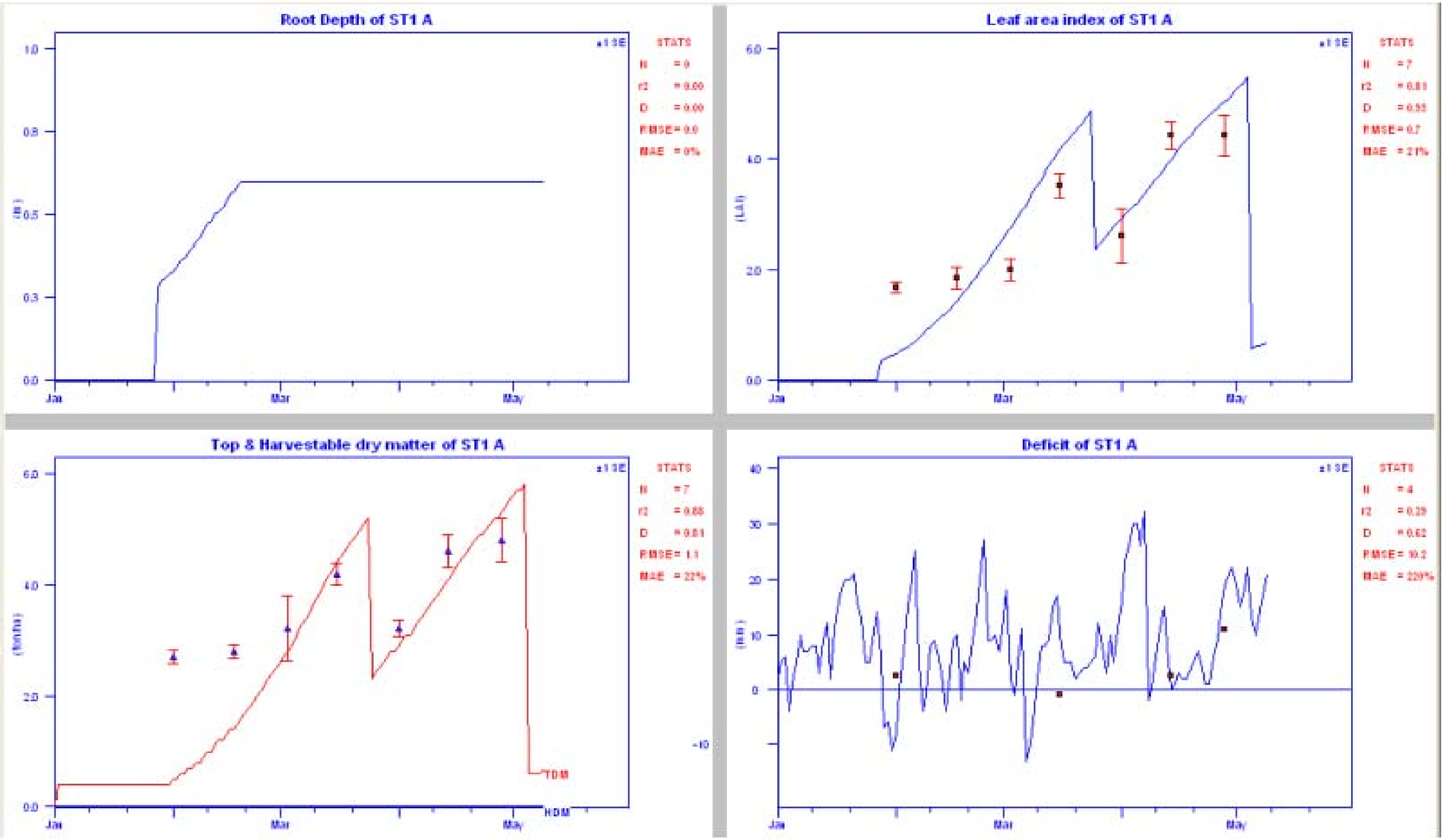
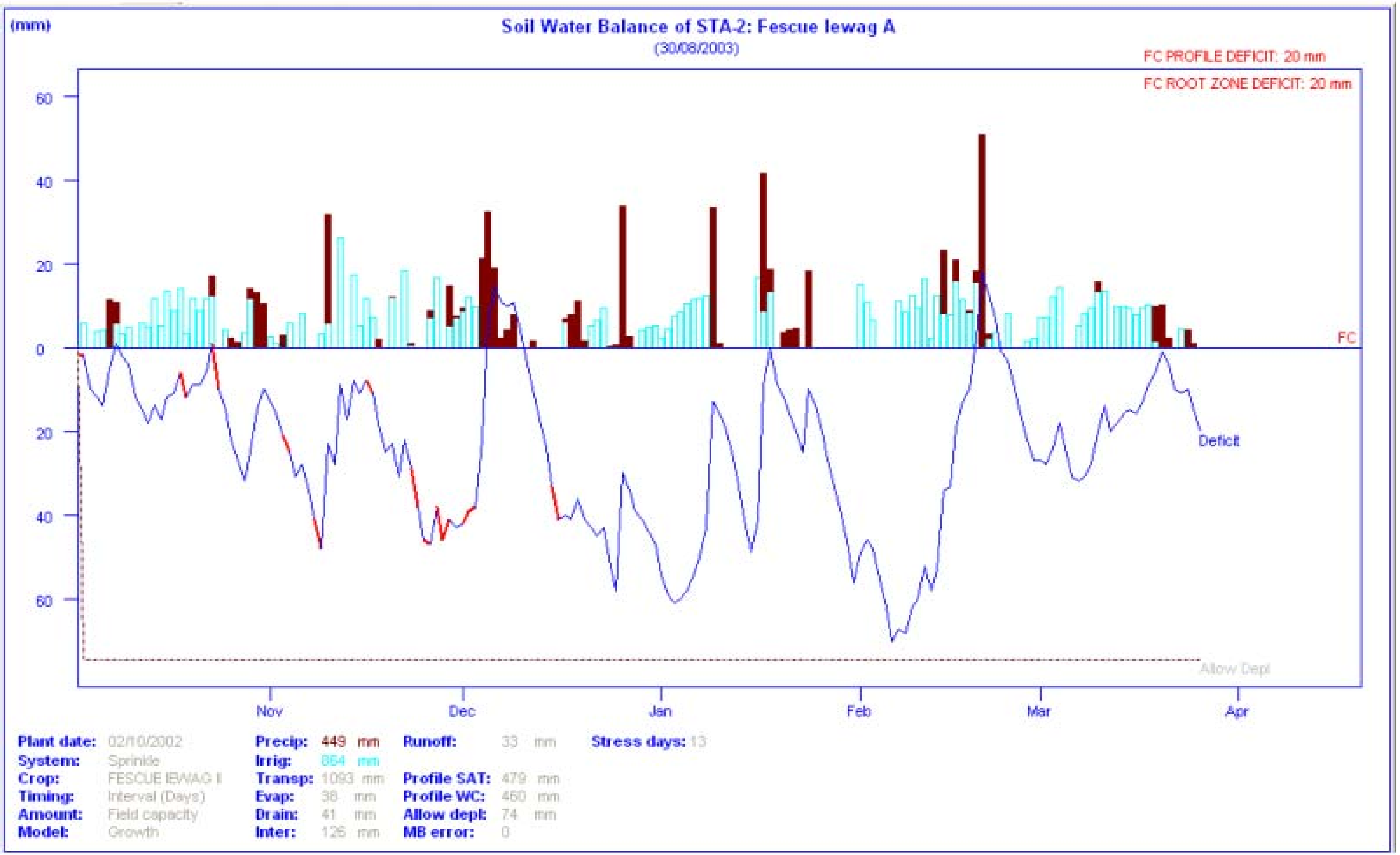


Figure 4.2 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Fescue (cv. Iewag), January 2002 - May 2002



Plant date: 02/10/2002
System: Sprinkle
Crop: FESCUE IEWAG II
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 449 mm
Irrig: 864 mm
Transp: 1093 mm
Evap: 38 mm
Drain: 41 mm
Inter: 126 mm

Runoff: 33 mm
Profile SAT: 479 mm
Profile WC: 460 mm
Allow depl: 74 mm
MB error: 0

Stress days: 13

Figure 4.3 Soil water balance summary graph Fescue (cv. Iewag), September 2002 - May 2003

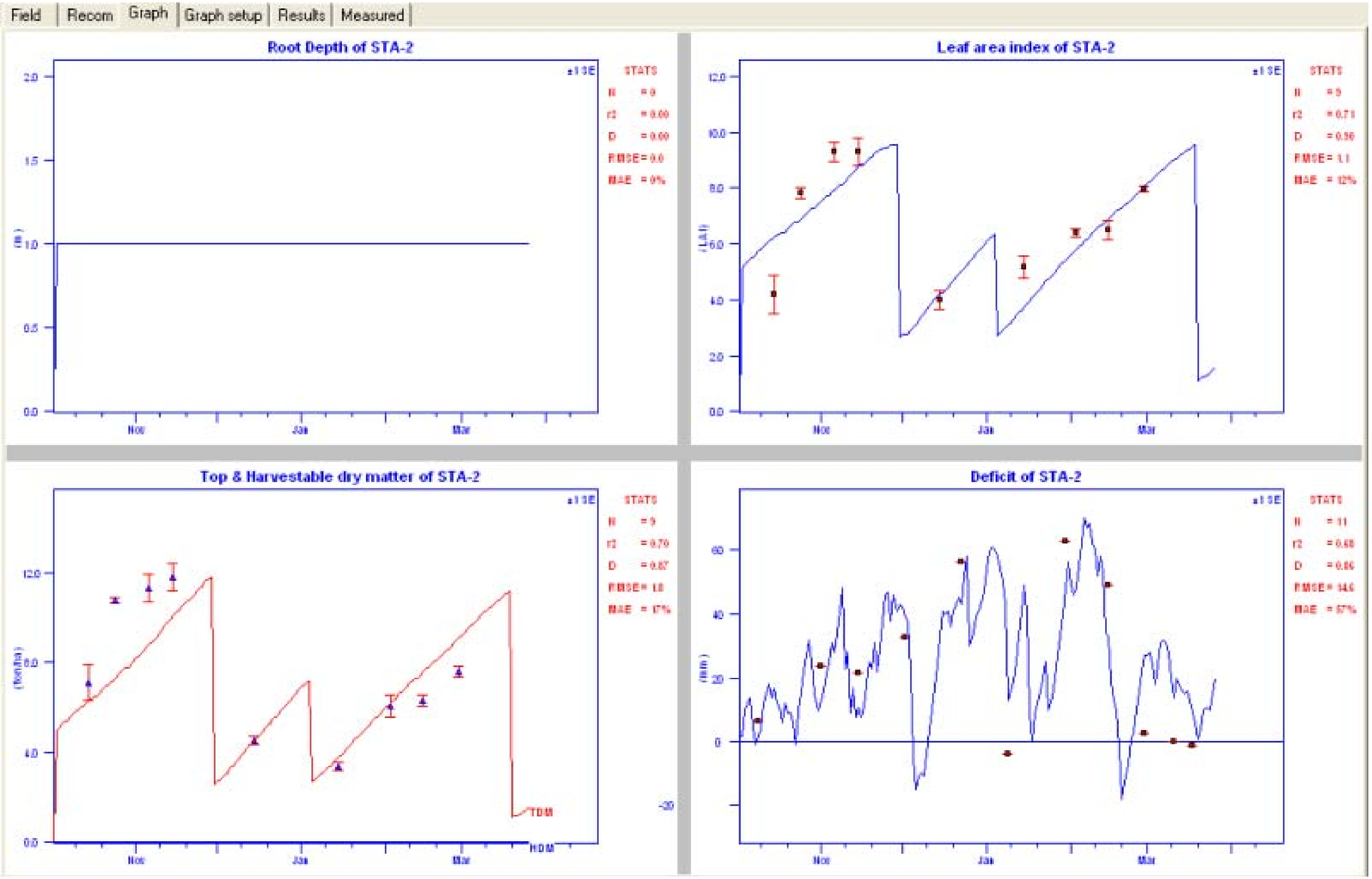
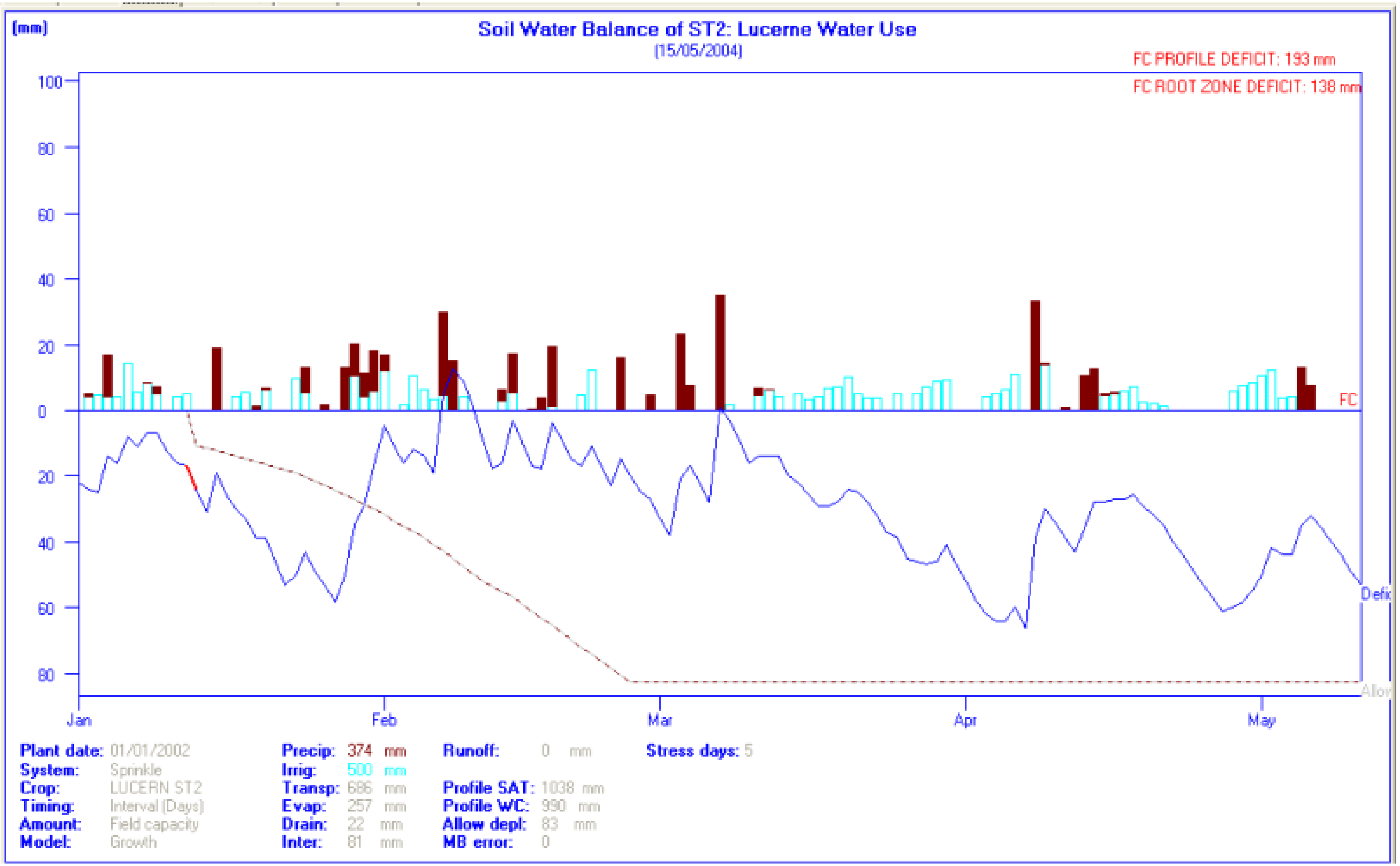


Figure 4.4 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Fescue (cv. Iewag), September 2002 - May 2003



Plant date: 01/01/2002
System: Sprinkle
Crop: LUCERN ST2
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 374 mm
Irrig: 500 mm
Transp: 686 mm
Evap: 257 mm
Drain: 22 mm
Inter: 81 mm

Runoff: 0 mm

Profile SAT: 1038 mm
Profile WC: 990 mm
Allow depl: 83 mm
MB error: 0

Stress days: 5

Figure 4.5 Soil water balance summary graph Lucerne, January 2002 - May 2002

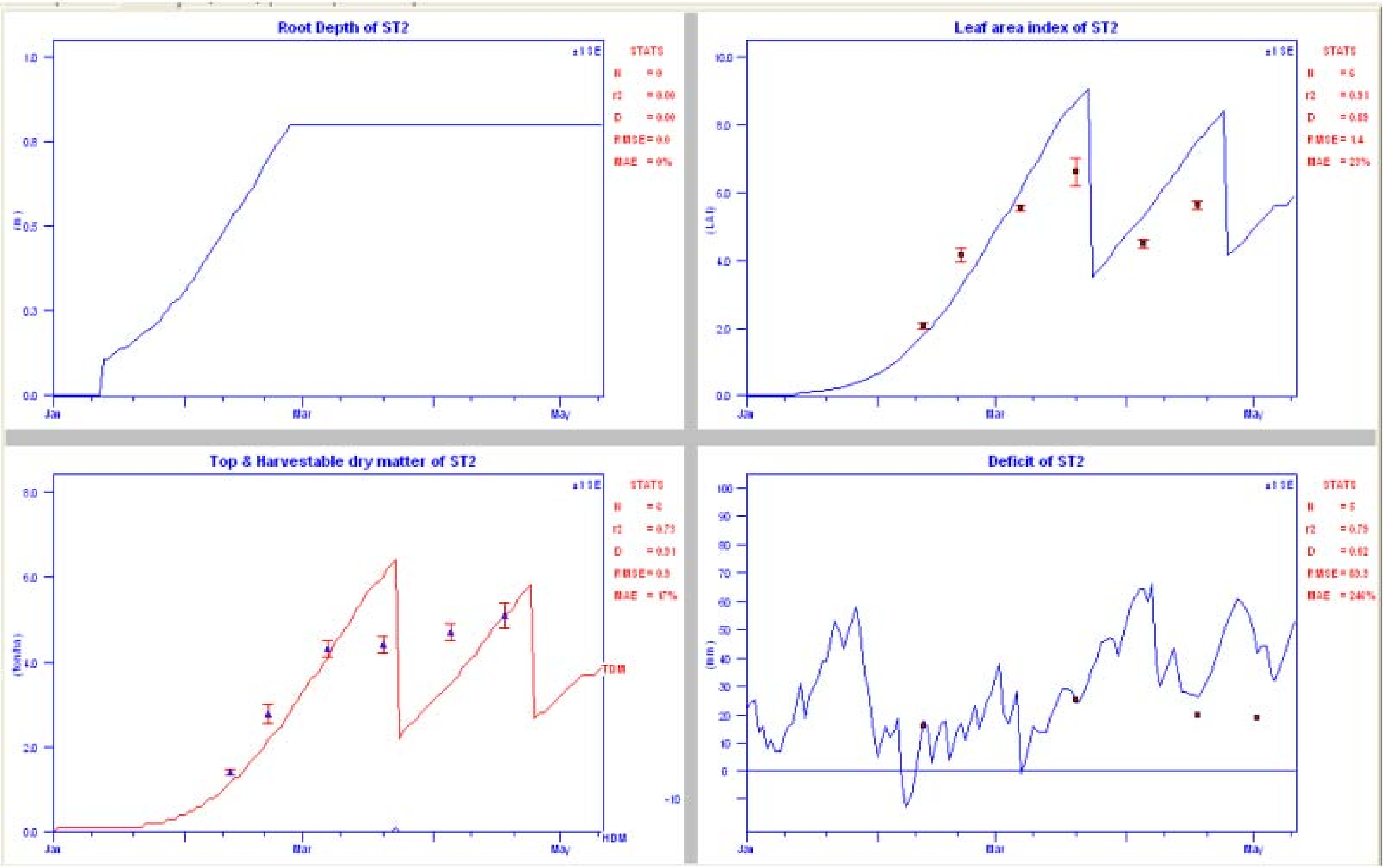
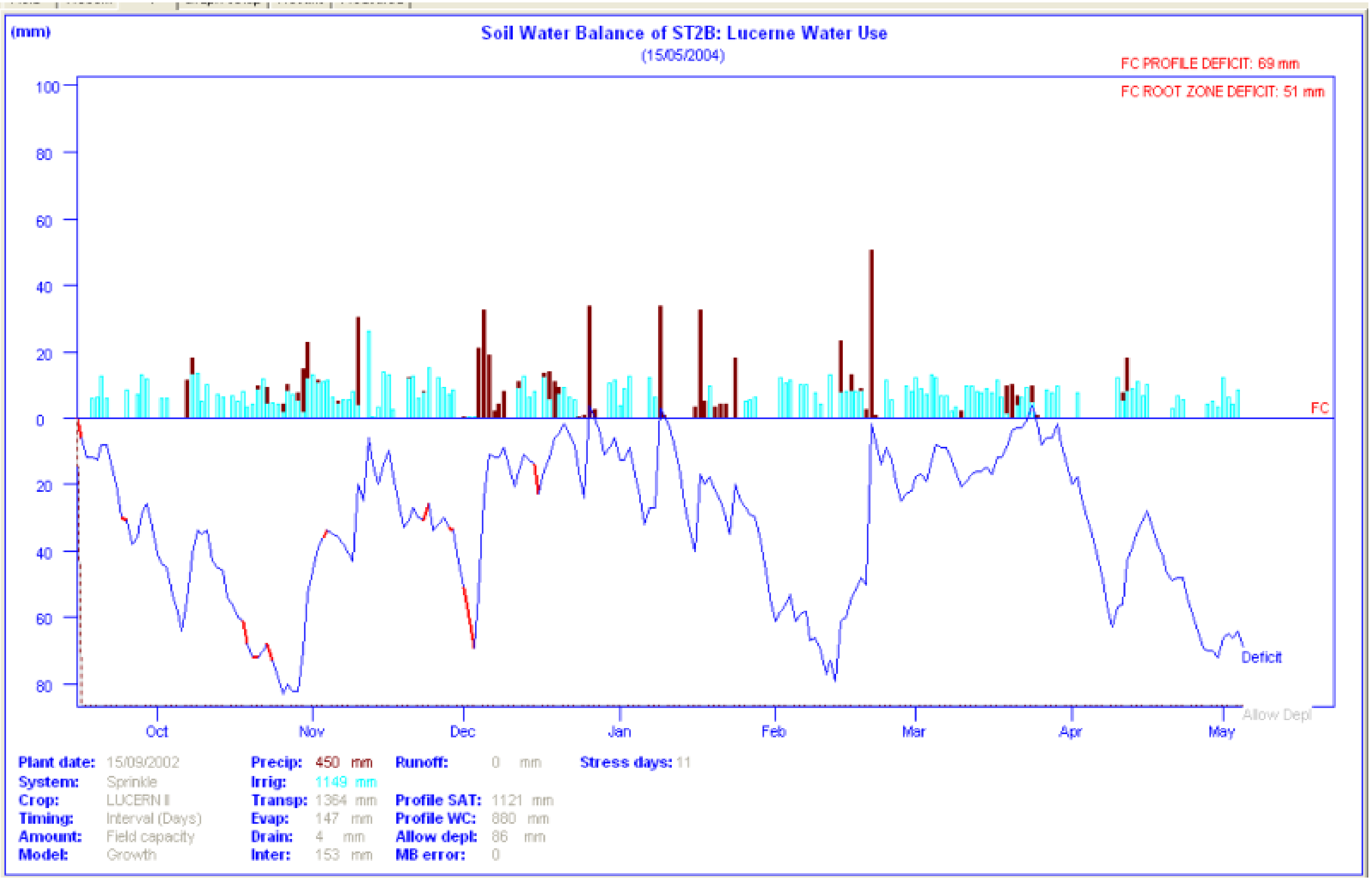


Figure 4.6 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Lucerne, January 2002 - May 2002



Plant date: 15/09/2002
System: Sprinkle
Crop: LUCERN II
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 450 mm
Irrig: 1149 mm
Transp: 1364 mm
Evap: 147 mm
Drain: 4 mm
Inter: 153 mm

Runoff: 0 mm
Profile SAT: 1121 mm
Profile WC: 880 mm
Allow depl: 86 mm
MB error: 0

Stress days: 11

Figure 4.7 Soil water balance summary graph Lucerne, September 2002 - May 2003

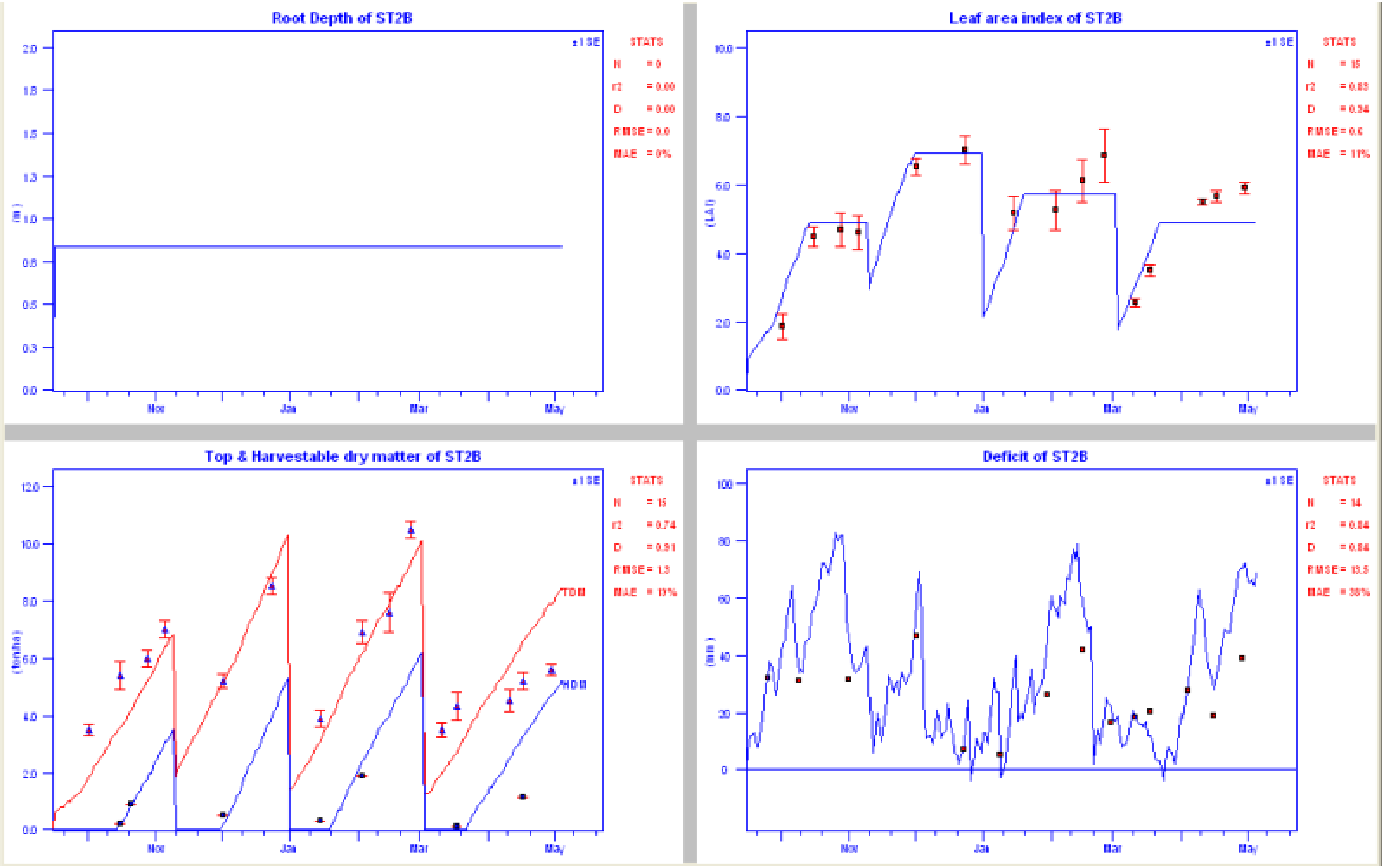
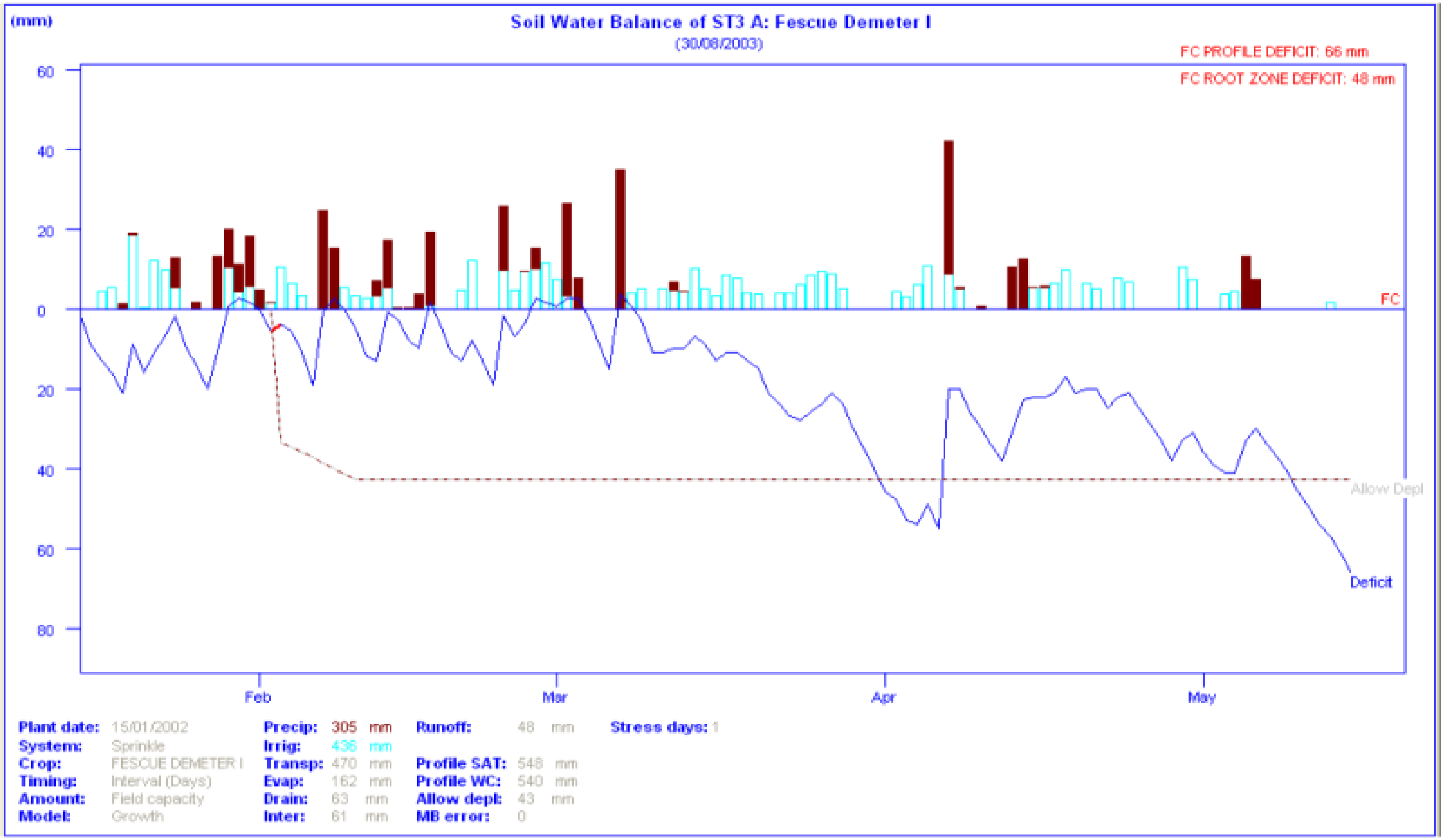


Figure 4.8 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Lucerne, September 2002 - May 2003



Plant date: 15/01/2002
System: Sprinkle
Crop: FESCUE DEMETER I
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 305 mm
Irrig: 436 mm
Transp: 470 mm
Evap: 162 mm
Drain: 63 mm
Inter: 61 mm

Runoff: 48 mm
Profile SAT: 548 mm
Profile WC: 540 mm
Allow depl: 43 mm
MB error: 0

Stress days: 1

Figure 4.9 Soil water balance summary graph Fescue (cv. Demeter), January 2002 - May 2002

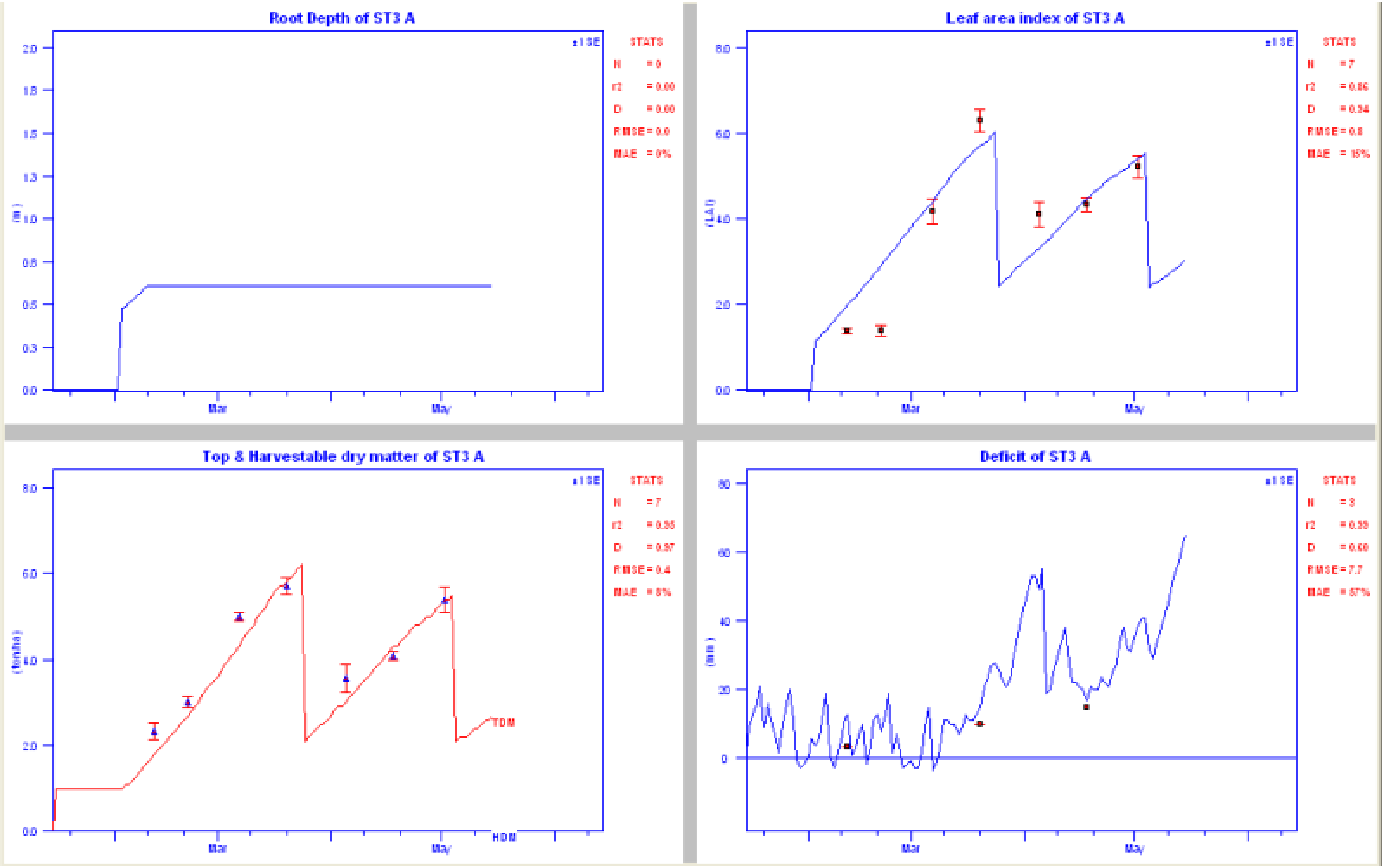
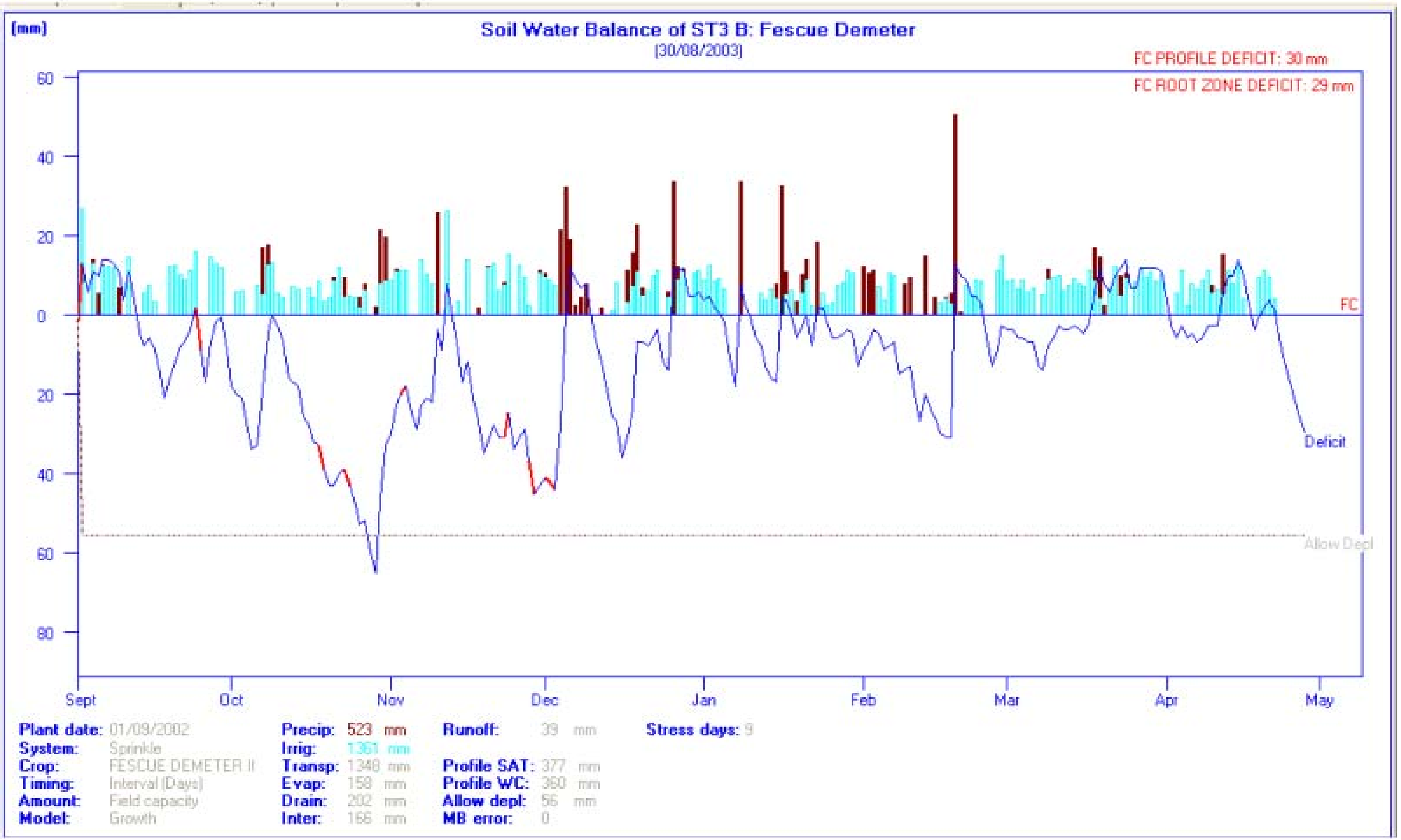


Figure 4.10 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI),top dry matter (TDM) and deficit to field capacity Fescue (cv. Demeter), January 2002 - May 2002



Plant date: 01/09/2002
System: Sprinkle
Crop: FESCUE DEMETER II
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 523 mm
Irrig: 1361 mm
Transp: 1348 mm
Evap: 158 mm
Drain: 202 mm
Inter: 166 mm

Runoff: 39 mm
Profile SAT: 377 mm
Profile WC: 360 mm
Allow depl: 56 mm
MB error: 0

Stress days: 9

Figure 4.11 Soil water balance summary graph Fescue (cv. Demeter), September 2002 - May 2003

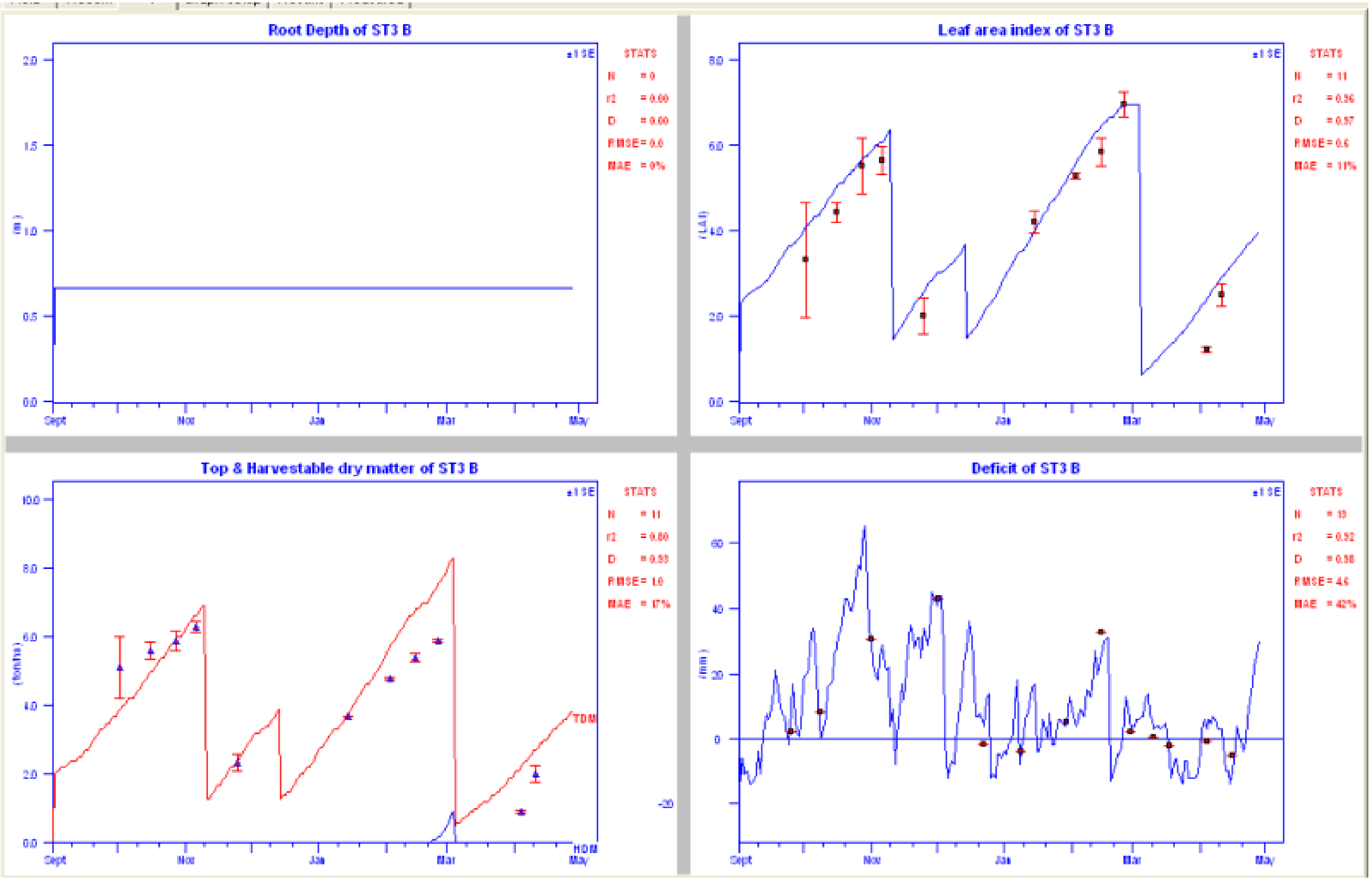
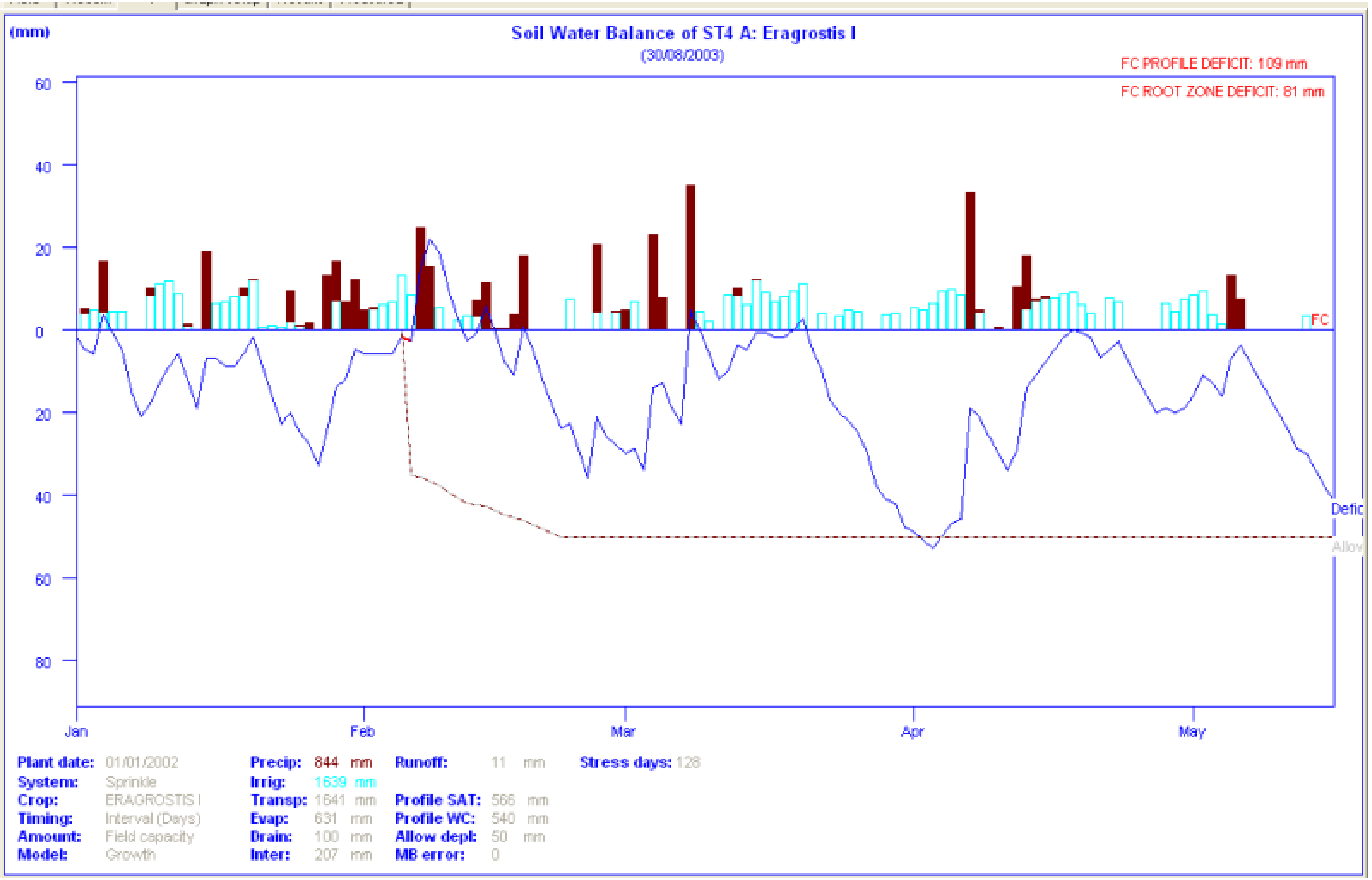


Figure 4.12 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Fescue (cv. Demeter), September 2002 - May 2003



Plant date:	01/01/2002	**Precip:**	844	mm	**Runoff:**	11	mm	**Stress days:**	128
System:	Sprinkle	**Irrig:**	1639	mm					
Crop:	ERAGROSTIS I	**Transp:**	1641	mm	**Profile SAT:**	566	mm		
Timing:	Interval (Days)	**Evap:**	631	mm	**Profile WC:**	540	mm		
Amount:	Field capacity	**Drain:**	100	mm	**Allow depl:**	50	mm		
Model:	Growth	**Inter:**	207	mm	**MB error:**	0			

Figure 4.13 Soil water balance summary graph Eragrostis, January 2002 - May 2002

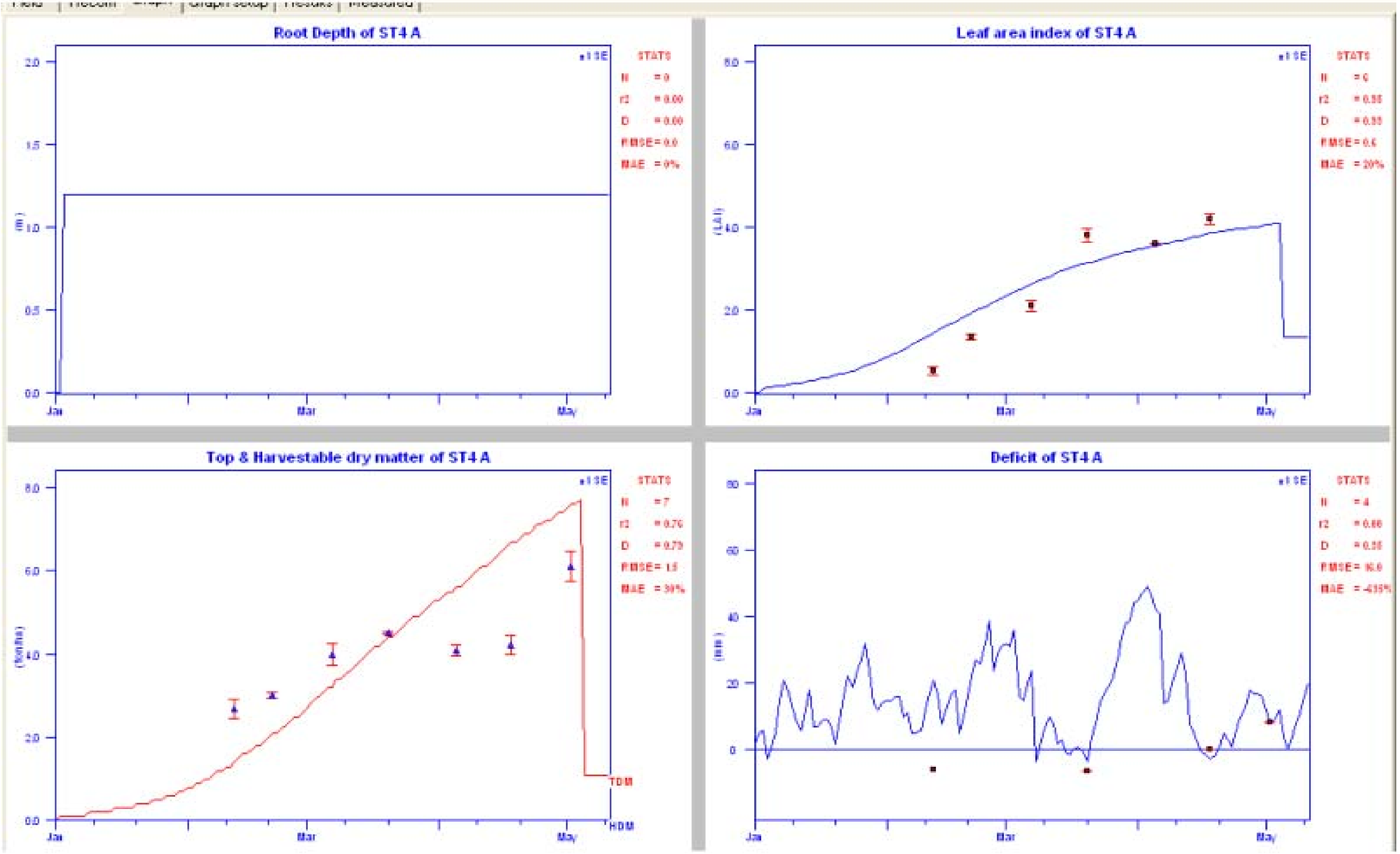
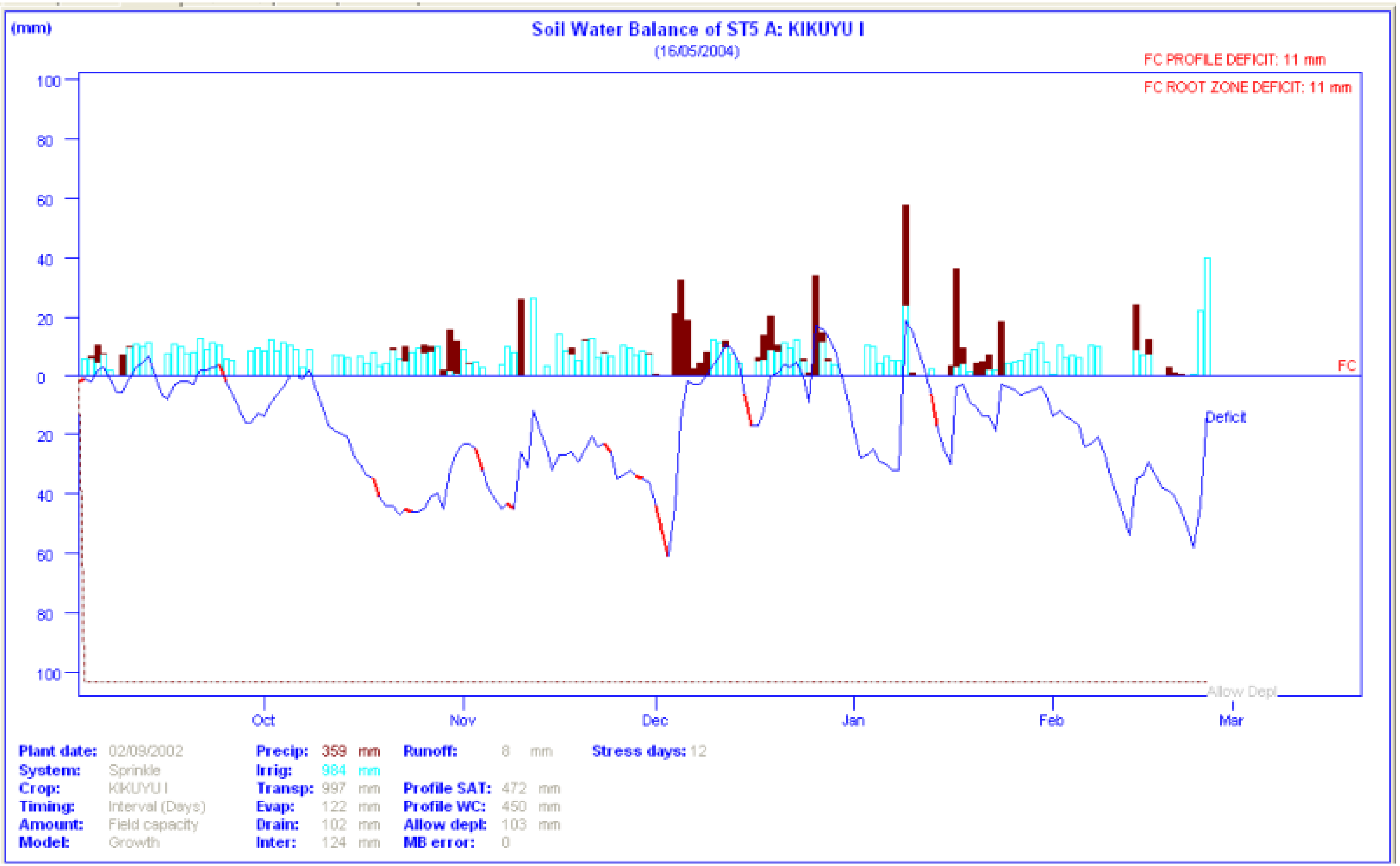


Figure 4.14 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Eragrostis, January 2002 - May 2002



Plant date: 02/09/2002
System: Sprinkle
Crop: KIKUYU I
Timing: Interval (Days)
Amount: Field capacity
Model: Growth

Precip: 359 mm
Irrig: 984 mm
Transp: 997 mm
Evap: 122 mm
Drain: 102 mm
Inter: 124 mm

Runoff: 8 mm
Profile SAT: 472 mm
Profile WC: 450 mm
Allow depl: 103 mm
MB error: 0

Stress days: 12

Figure 4.15 Soil water balance summary graph Kikuyu, September 2002 - March 2003

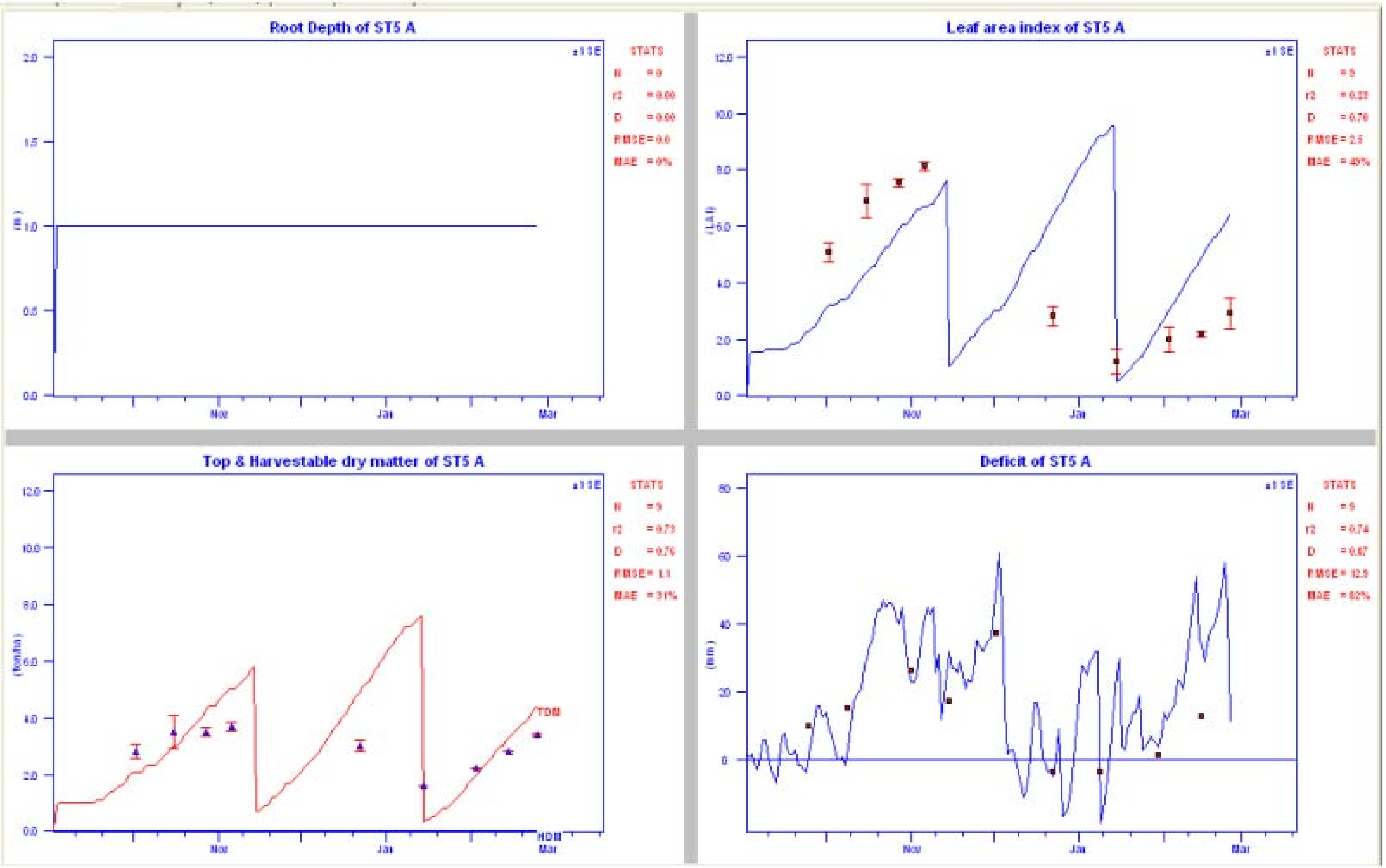


Figure 4.16 Simulated (solid lines) and measured values (symbols) of root depth (RD), leaf area index (LAI), top dry matter (TDM) and deficit to field capacity Kikuyu, September 2002 - March 2003

Table 4.5 Statistical results of the simulated vs. measured values for LAI period January - May 2002, calibration period

Treatments	LAI				
	N	r^2	D	RMSE ($m^2\ m^{-2}$)	MAE
Fescue (cv. Iewag)	7	0.89	0.93	0.7	21%
Lucerne	6	0.91	0.89	1.4	23%
Fescue (cv. Demeter)	7	0.86	0.94	0.8	15%
Eragrostis	7	0.95	0.93	0.6	20%

Table 4.6 Statistical results of the simulated vs. measured values for LAI September 2002 - May 2003, evaluation period (independent data)

Treatments	LAI				
	N	r^2	D	RMSE ($m^2\ m^{-2}$)	MAE
Fescue (cv. Iewag)	10	0.71	0.90	1.1	12%
Lucerne	15	0.83	0.94	0.6	17%
Fescue (cv. Demeter)	11	0.96	0.97	0.6	11%
Kikuyu	9	0.81	0.93	1.2	25%

The parameters of the statistical analysis are:

N	Number of observations;
r^2	Coefficient of determination;
D	Wilmott's index of agreement;
RMSE	Root mean square error ($m^2\ m^{-2}$); and
MAE	Mean absolute error.

Table 4.7 Statistical results of the simulated vs. measured values for TDM January - May 2002, calibration period

Treatments	**TDM**				
	N	**r^2**	**D**	**RMSE (kg m^{-2})**	**MAE**
Fescue (cv. Iewag)	10	0.88	0.81	1.1	22%
Lucerne	15	0.73	0.91	0.9	17%
Fescue (cv. Demeter)	11	0.95	0.97	0.4	8%
Kikuyu	9	0.76	0.79	1.5	30%

Table 4.8 Statistical results of the simulated vs. measured values for TDM September 2002 - May 2003, evaluation period (independent data)

Treatments	**TDM**				
	N	**r^2**	**D**	**RMSE (kg m^{-2})**	**MAE**
Fescue (cv. Iewag)	7	0.79	0.80	1.8	17%
Lucerne	6	0.74	0.91	1.3	18%
Fescue (cv. Demeter)	7	0.80	0.93	1	17%
Eragrostis	7	0.75	0.76	1.2	31%

The parameters of the statistical analysis are:

N	Number of observations;
r^2	Coefficient of determination;
D	Wilmott’s index of agreement;
RMSE	Root mean square error (kg m^{-2}); and
MAE	Mean absolute error.

Table 4.9 Statistical results of the simulated vs. measured values for deficit January - May 2002, calibration period

Treatments	Deficit				
	N	r^2	D	RMSE (mm)	MAE
Fescue (cv. Iewag)	4	0.29	0.62	10.2	220%
Lucerne	4	0.79	0.82	89.3	240%
Fescue (cv. Demeter)	3	0.99	0.6	7.7	57%
Eragrostis	4	0.70	0.8	6.7	-43%

Table 4.10 Statistical results of the simulated vs. measured values for deficit September 2002 - May 2003, evaluation period (independent data)

Treatments	Deficit				
	N	r^2	D	RMSE (mm)	MAE
Fescue (cv. Iewag)	13	0.68	0.86	14.6	57%
Lucerne	14	0.84	0.84	19.5	38%
Fescue (cv. Demeter)	13	0.92	0.98	4.6	42%
Kikuyu	9	0.74	0.82	16.3	82%

The parameters of the statistical analysis are:

N	Number of observations;
r^2	Coefficient of determination;
D	Wilmott’s index of agreement;
RMSE	Root mean square error (mm); and
MAE	Mean absolute error.

b. Salts

The statistical parameters and graphs for salts are summarized in Table 4.11 and Figures 4.17-4.20. The graphic comparisons of the salt simulation of the treatments show fairly good agreement with the measured data. However, for Fescue (cv. Iewag), Lucerne and Eragrostis the model overestimated the predicted SO_4^{2-} in the soil solution. The deviation might have taken place for some SO_4^{2-} was precipitated as $CaSO_4$ in the soil. For Fescue (cv. Iewag), although there was a good trend between the simulated and measured values, Cl^- was predicted with a higher deviation (D) (lower D value) from the mean observed value. Similarly, for Lucerne the trend of the simulated and measured values of Ca^{2+}, Na^+ and K^+ were outstanding.

For Fescue (cv. Iewag) some simulated values of Ca^{2+}, Na^+, K^+ and SO_4^{2-} were overestimated. Perhaps the profile was too wet and runoff was underestimated. For Eragrostis, the agreement between simulated and measured values was satisfactory. The simulation was not run, for Kikuyu, as the number of soil water samples taken were too few.

Some simulated ions were underestimated. This could be as the measurements were taken while irrigation was in progress, before the soil reached equilibrium. Generally, in all the treatments, the predicted values were satisfactory for the experimental period.

Table 4.11 Statistical results of salts predicted with SWB vs. measured values (calibration and evaluation period)

Treatments	Parameters	Ca^{2+}	Mg^{2+}	Na^{+}	Cl^{-}	K^{+}	SO_4^{2-}
Fescue (cv. Iewag)	RMSE	1.56	1.26	18.1	0.04	0.86	11.8
	D	0.71	0.88	0.82	0.44	0.61	0.57
	r^2	0.24	0.8	0.66	0.41	0.42	0.42
	MAE	29%	12%	35%	12%	35%	42%
Lucerne	RMSE	1.5	2.28	28.8	0.11	0.72	6.52
	D	0.42	0.66	0.64	0.41	0.85	0.56
	r^2	0.69	0.26	0.6	0.2	0.63	0.25
	MAE	21%	33%	27%	38%	23%	42%
Fescue (cv. Demeter)	RMSE	3.35	3.75	14.1	0.11	0.75	6.13
	D	0.65	0.42	0.81	0.48	0.76	0.53
	r^2	0.43	0.42	0.23	0.5	0.57	0.65
	MAE	31%	37%	48%	23%	16%	13%
Eragrostis	RMSE	1.86	1.13	4.64	0.69	0.07	5.31
	D	0.54	0.87	0.95	0.68	0.62	0.55
	r^2	0.45	0.62	0.52	0.87	0.33	0.87
	MAE	68%	16%	41%	10%	21%	12%

The parameters of the statistical analyses are:

D	Wilmot's index of agreement;
RMSE	Root mean square error (mmol l^{-1});
r^2	Coefficient of determination; and
MAE	Mean absolute error.

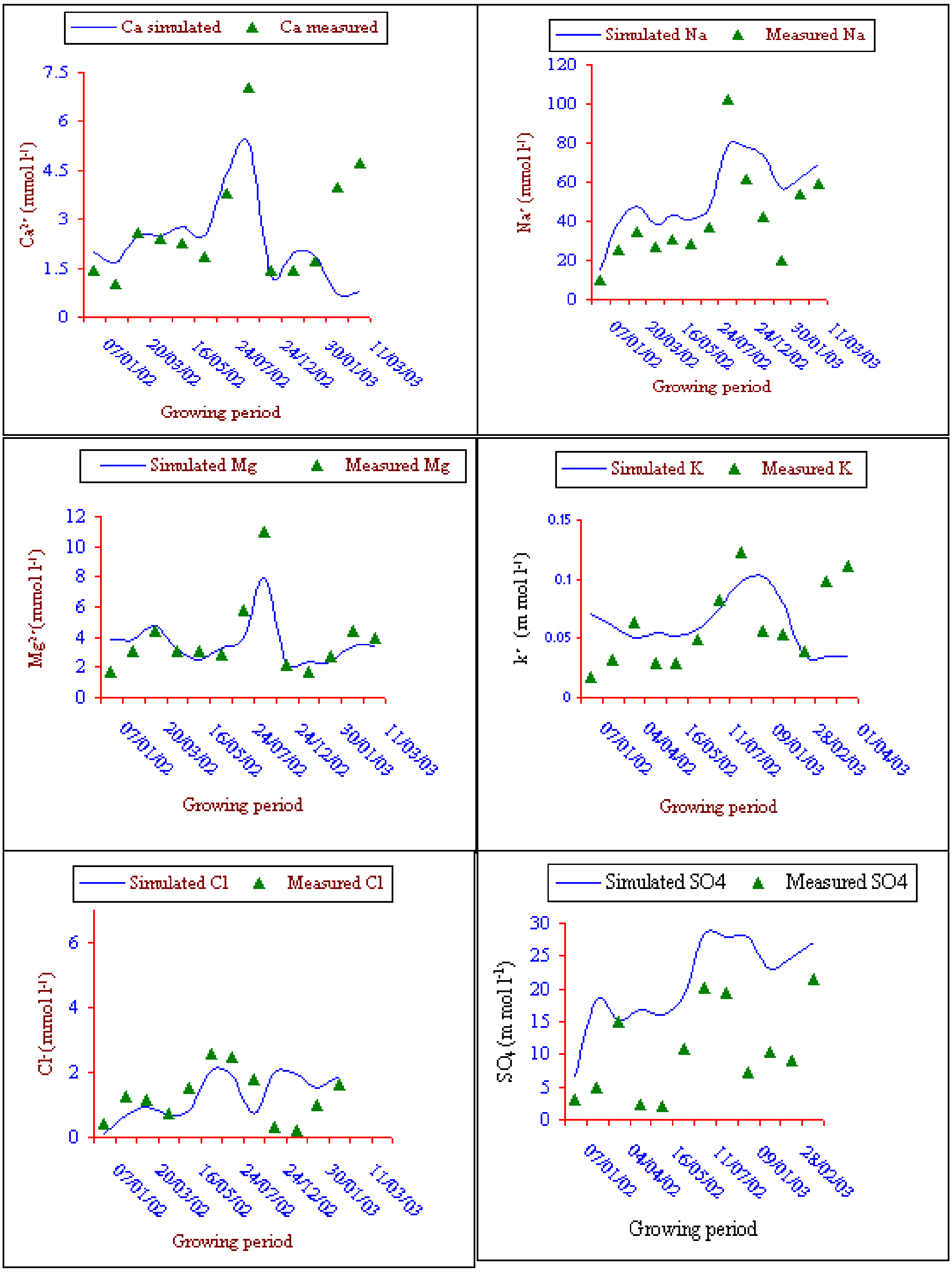


Figure 4.17 **Simulated (solid lines) and measured values (symbols) for concentration of Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-} and SO_4^{2-} in the soil solution at a depth of 0.4 m in the Fescue (cv. Iewag) field January 2002 - March 2003**

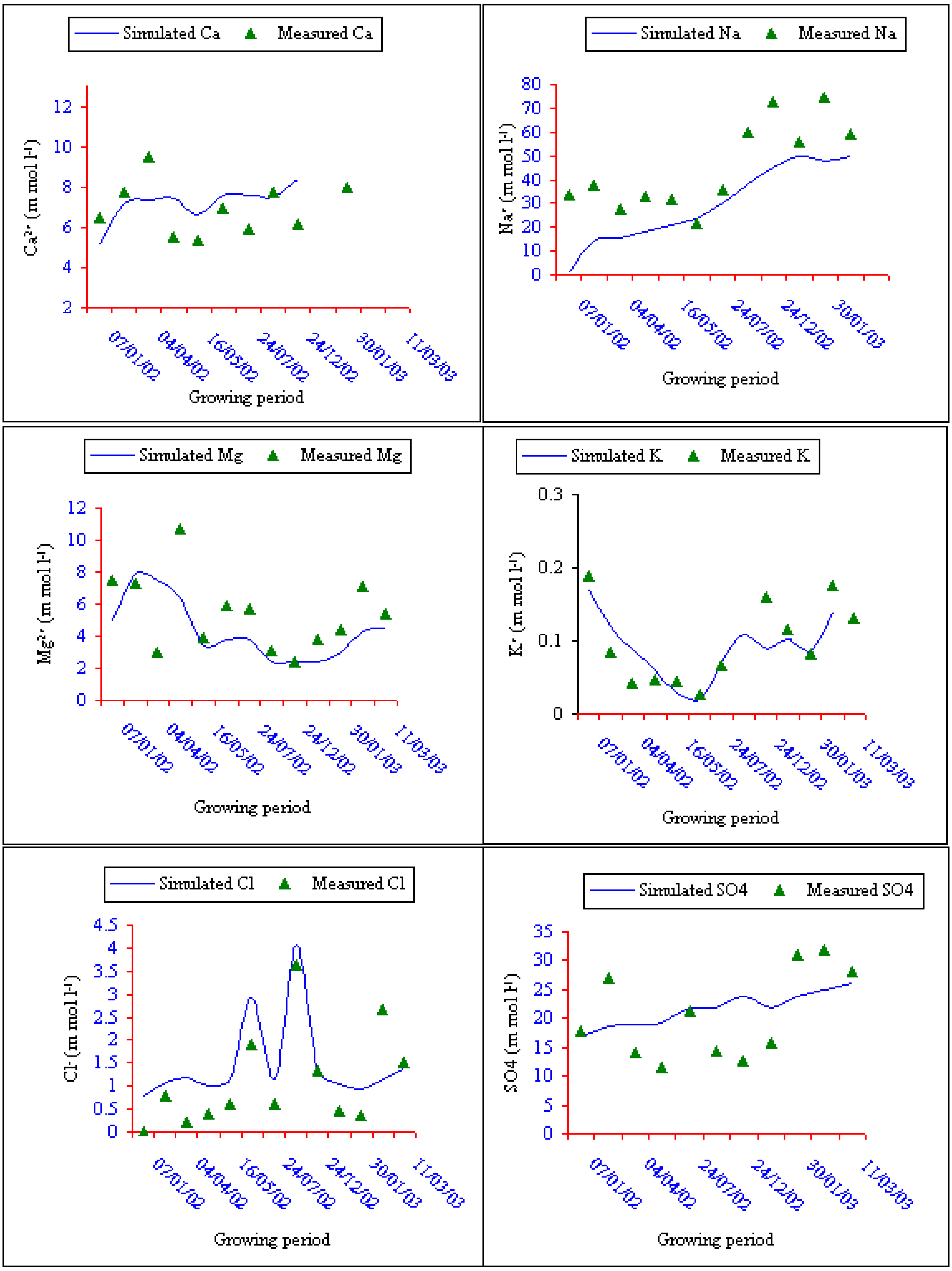


Figure 4.18 **Simulated (solid lines) and measured values (symbols) for concentration of Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-} and SO_4^{2-} in the soil solution at a depth of 0.4 m in the Lucerne field January 2002 - March 2003**

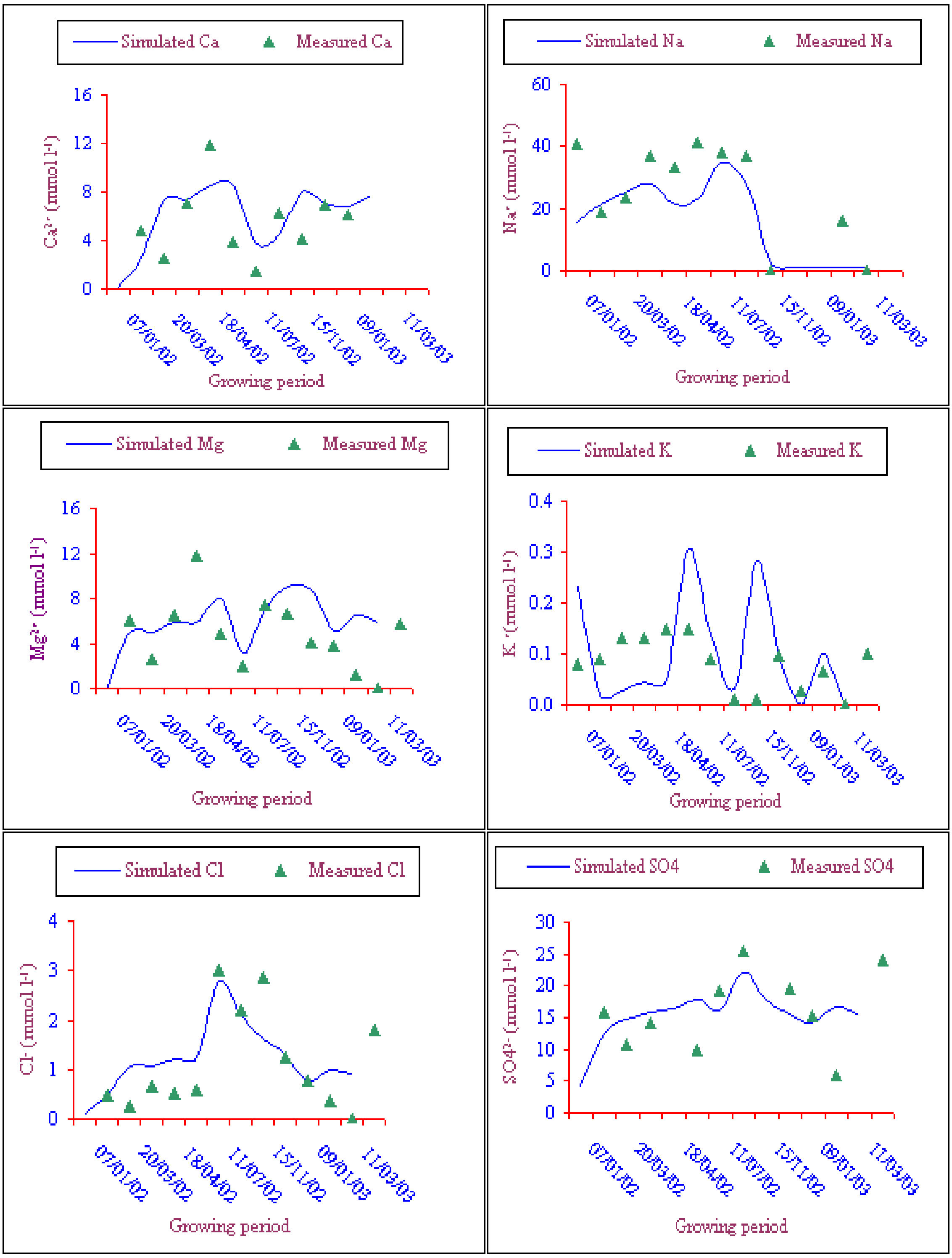


Figure 4.19 **Simulated (solid lines) and measured values (symbols) for concentration of Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-} and SO_4^{2-} in the soil solution at a depth of 0.4 m in the Fescue (cv. Demeter) field January 2002 - March 2003**

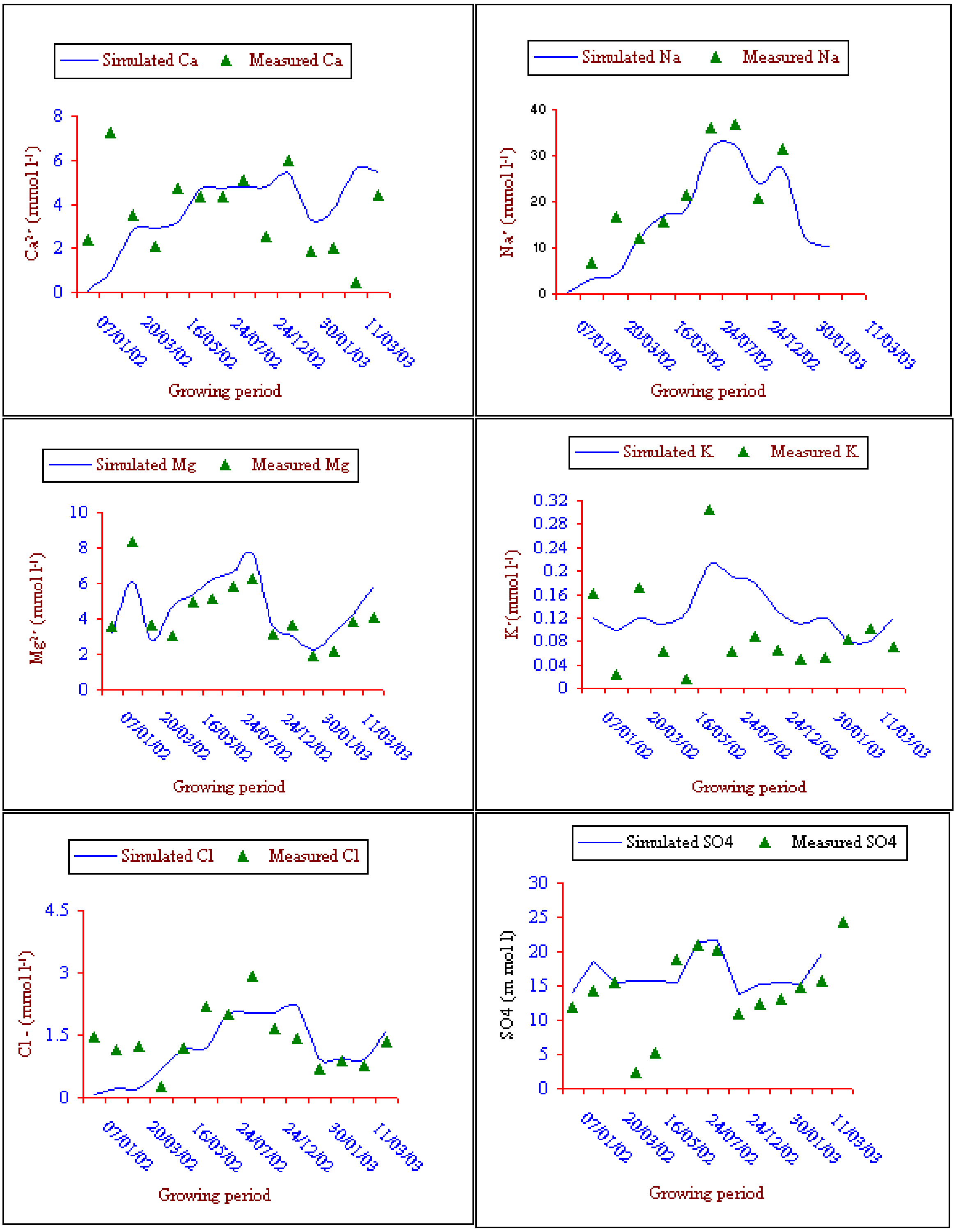


Figure 4.20 Simulated (solid lines) and measured values (symbols) for concentration of Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-} and SO_4^{2-} in the soil solution at a depth of 0.4 m in the Eragrostis field January 2002 - March 2003

4.5 Soil chemical properties

The soil analysis results show an increase in pH and, fluctuation in EC_e and salt concentration over the trial period (Figures 4.21, 4.23, and 4.25-4.29), as compared to the non-irrigated soil. However, average EC_e and pH was not above the threshold level that could restrict crop growth (Ayers and Westcott, 1994).

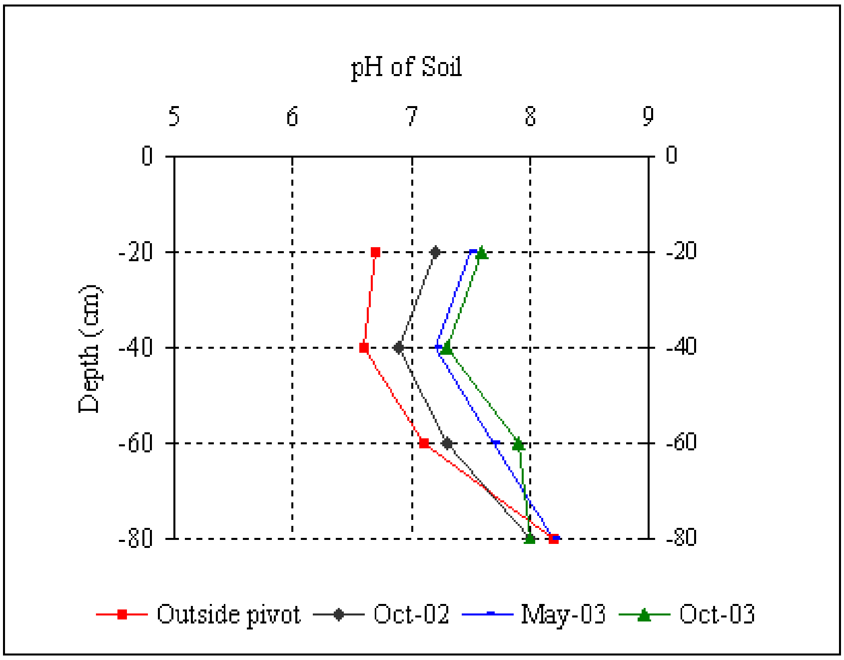


Figure 4.21 Average pH of the non-irrigated soil outside the pivot and the irrigated soil during the trial period

The pH of the soil did not change considerably during a period of one-year of irrigation (Figure 4.21). A noticeable increase in pH overtime was measured in 20, 40 and 60 cm depths. It was also insignificant in the upper most layer of the soil profile compared to deeper down the profile. The pH (H_2O) of soil solution also fluctuated within a range of 6 to 8 during the trial period of January 2002 - May 2003 (Figure 4.22), which could probably be attributable to the rainfall pattern (Jovanovic *et al*., 2002).

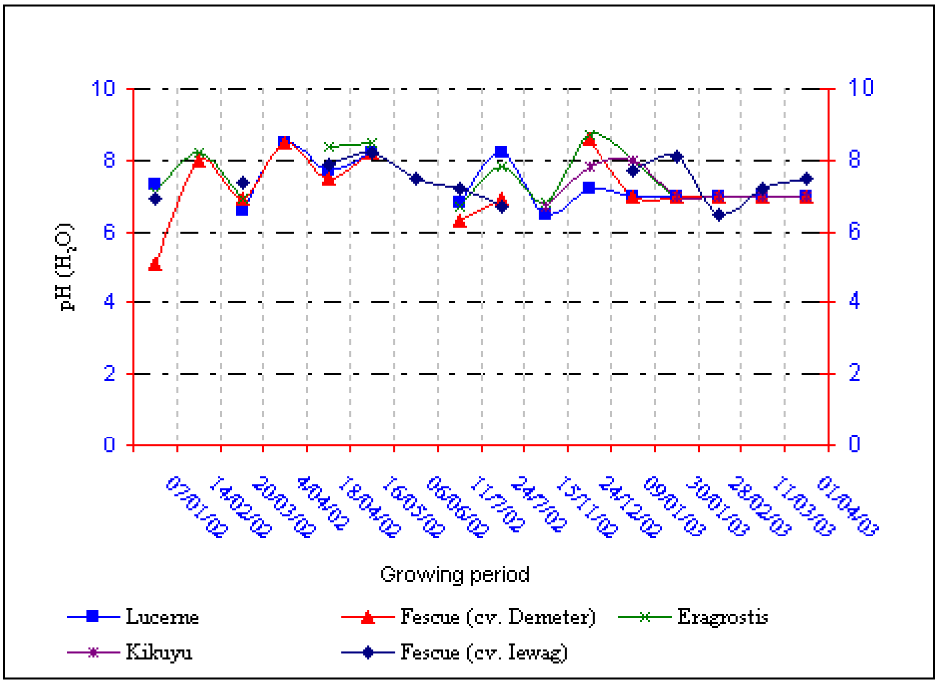


Figure 4.22 pH (H_2O) of the soil solution from a field of five planted pastures during the experimental period

EC_e measured from the non-irrigated soil outside pivot was compared with the EC_e of the irrigated soil in October 2002, May 2003 and October 2003. EC_e measured in May 2003 was observed to be lower than October 2002 (Figure 4.23). This could be due to the high seasonal rainfall during the period October 2002 to May 2003, which could have diluted the soil solution. The variation in EC of the soil solution, for each planted pasture grown soil, during the growing period is graphically plotted in Figure 4.24.

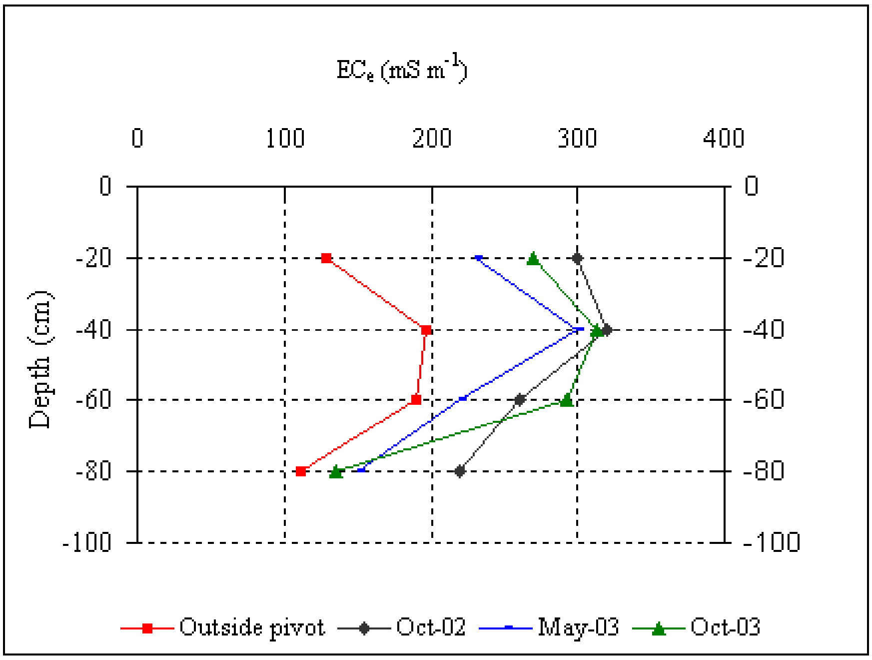


Figure 4.23 **Average EC_e (mS m^{-1}) of the non-irrigated soil outside the pivot and the irrigated soil during the trial period**

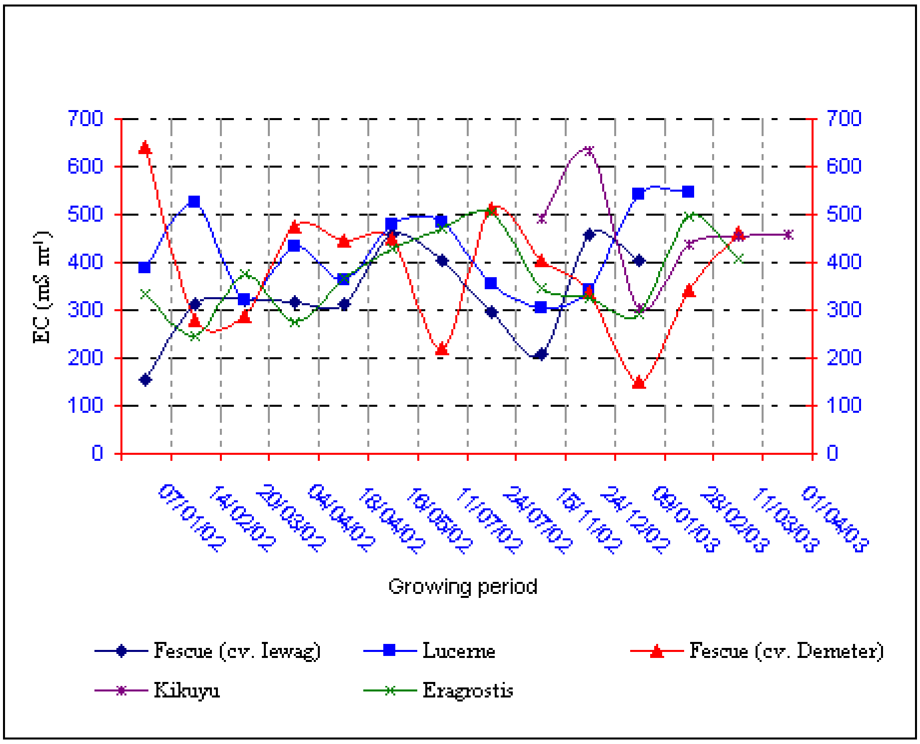


Figure 4.24 **EC (mS m^{-1}) of the soil solution from the field of five planted pastures during the trial period**

ESP of the soil was observed to fluctuate between different periods (Figure 4.25). According to Ayers and Westcott (1994), irrigation with sodium containing water causes high ESP, primarily in the upper few centimeters of the soil. Similarly, in May 2003 ESP of the soil with in the top 0-0.2 m was higher than deeper down the profile. ESP increased in May 2003 with irrigations, then droped again in October 2003 due to $Ca(NO_3)_2$ application (Figure 4.25). This shows that the soil did not attain a sodicity threshold level (Ayers and Westcott, 1994).

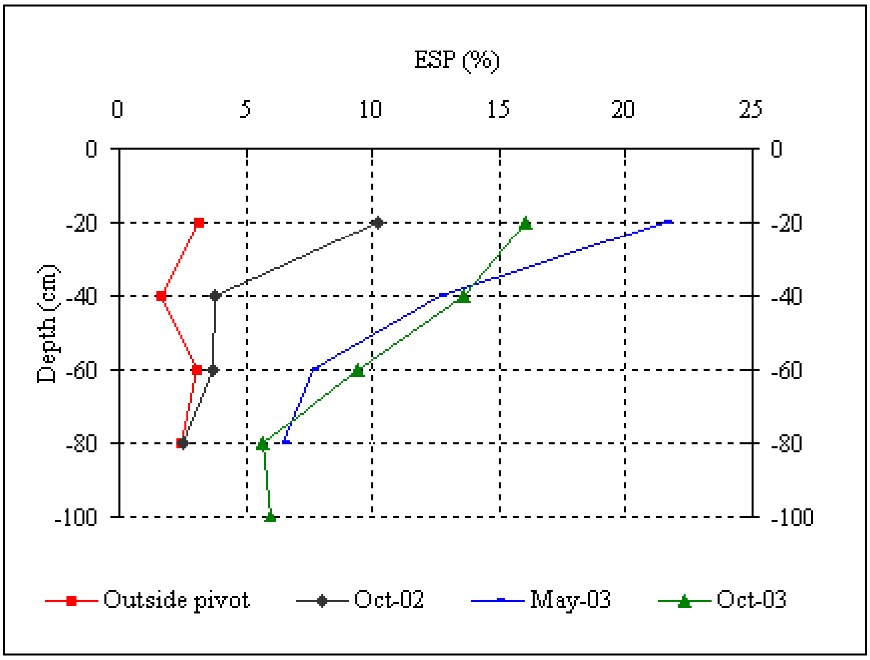


Figure 4.25 Average ESP (%) of the non-irrigated soil outside the pivot and the irrigated soil during the trial period

A general increase in exchangeable Ca^{2+} was measured in the irrigated plots as the depths increased, whilst the exchangeable Ca^{2+} decreases outside the pivot as depth increases (Figure 4.26). A slight increase in exchangeable Mg^{2+} was observed in the pivot as depth increases. Also, a very low Mg^{2+} with no depth trend was measured outside the pivot (Figure 4.27). On the contrary, the exchangeable Na^{+} was higher in the top layer than the exchangeable Ca^{2+} and Mg^{2+} (Figure 4.28). This could be for the reason that Na^{+} replaced the cations (Ayers and Westcott, 1994). However, the trend of exchangeable and soluble Na^{+} was generally inferior down the profile (Figure 4.28). K^{+} decreased in quantity during the trial period, probably it is replaced by Ca^{2+} and Mg^{2+} (Figure 4.29).

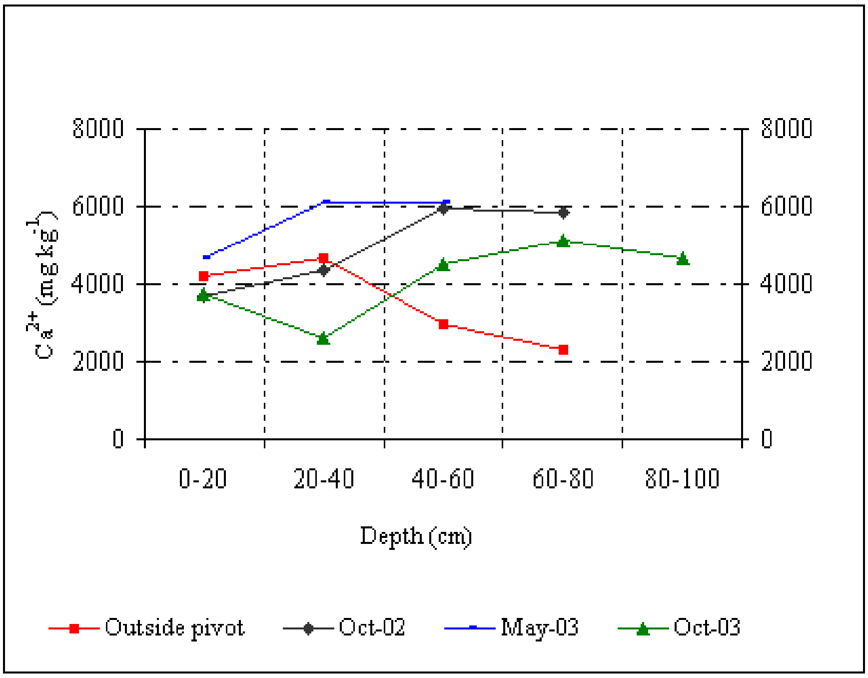


Figure 4.26 Average exchangeable Ca^{2+} (mg kg^{-1}) of the non-irrigated soil outside the pivot and the irrigated soil (October 2002, May 2003 and October 2003)

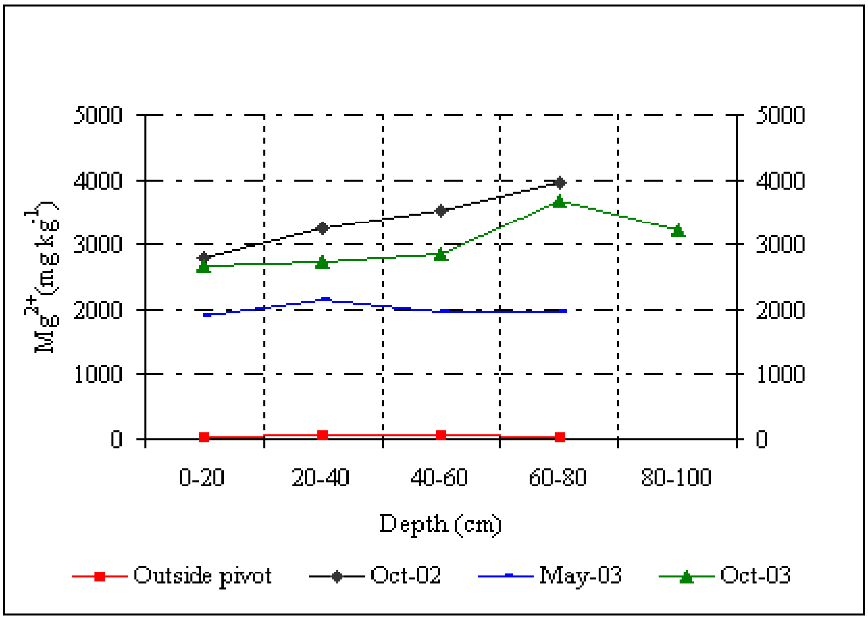


Figure 4.27 Average exchangeable Mg^{2+} (mg kg^{-1}) of the non-irrigated soil outside the pivot and the irrigated soil (October 2002, May 2003 and October 2003)

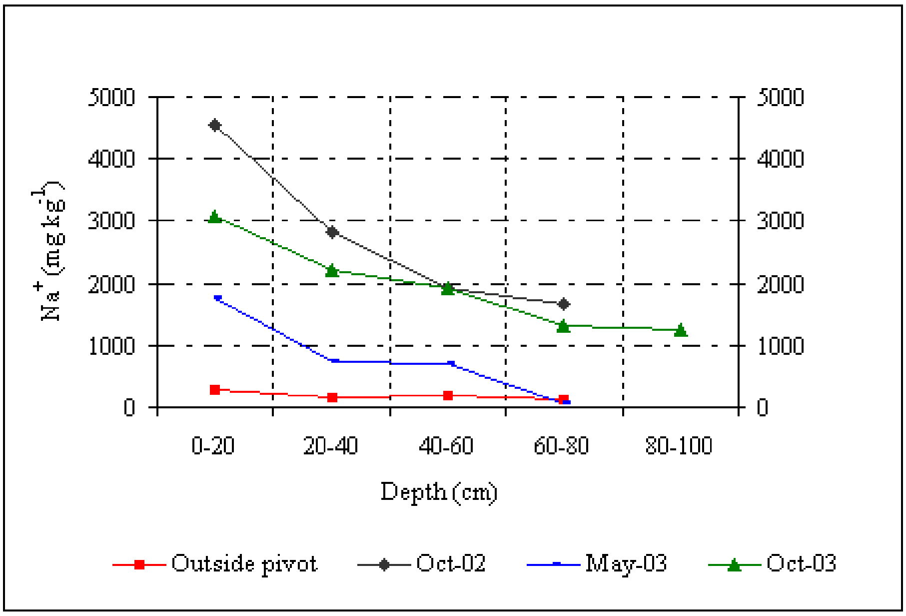


Figure 4.28 Average exchangeable Na^+ (mg kg^{-1}) of the non-irrigated soil outside the pivot and the irrigated soil (October 2002, May 2003 and October 2003)

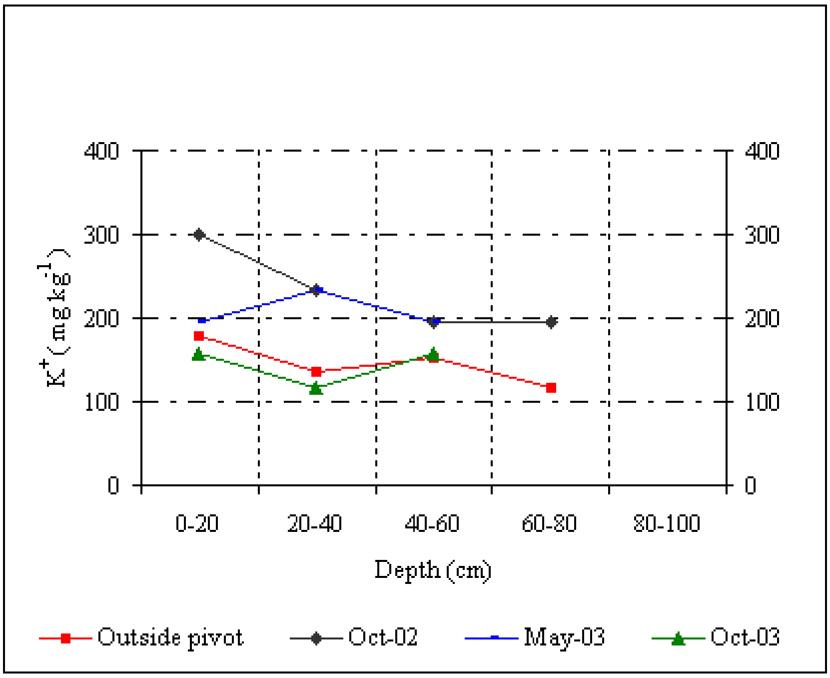


Figure 4.29 Average exchangeable K^+ (mg kg^{-1}) of the non-irrigated soil outside the pivot and the irrigated soil (October 2002, May 2003 and October 2003)

At the beginning of the field trial the average SAR of the soil solution was 3.3 (mmol $l^{-1})^{1/2}$ where Na^+, Ca^{2+} and Mg^{2+} were measured in mmol l^{-1}. After irrigating the soil for a year, the average SAR increased to 16.1, 13.1,12.5, 15.5, and 13.9 (mmol $l^{-1})^{1/2}$ for Fescue (cv. Iewag), Lucerne, Fescue (cv. Demeter), Eragrostis and Kikuyu respectively. Nevertheless, SAR of the soil solution was fluctuating during the growing period with the irrigation and rainfall pattern (Figure 4.30).

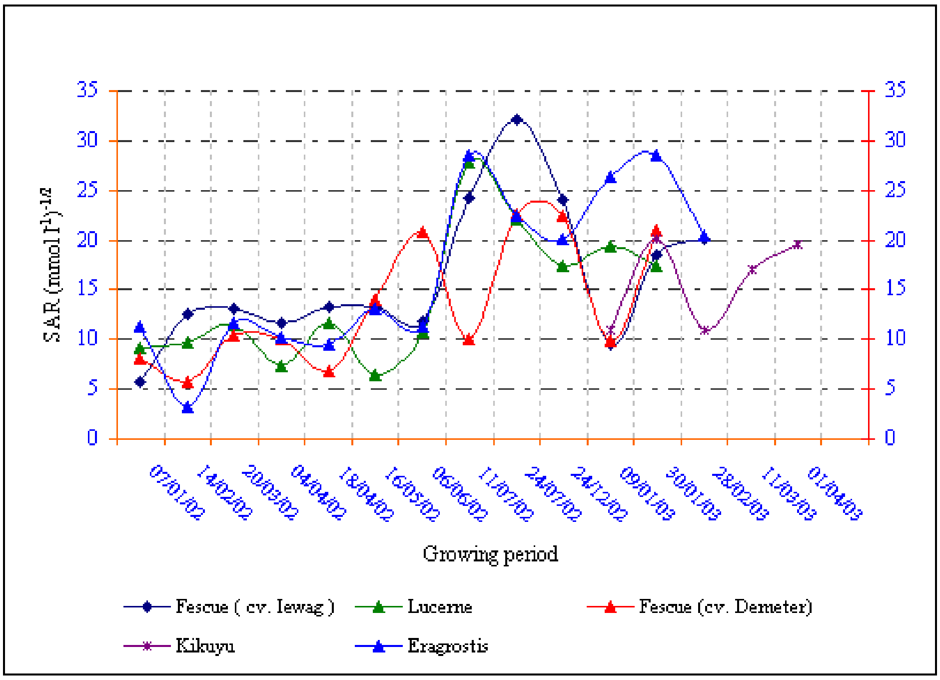


Figure 4.30 SAR (mmol $l^{-1})^{1/2}$ of the soil solution from the field of five planted pastures during the trial period

In the soil analysis results (Figure 4.23), the salts are accumulated within the 0.4-0.6 m soil depth due to the heavy textural character (negative charge) of the soil. This indicates that salts are leached to there and do not drain away easily.

In this study, Eragrostis and Kikuyu died in February 2003. This could be due to accumulation of salt in the crop root zone was higher than the tolerance threshold level of the two crops that reduced water availability to the crop. It could also probably be for the plants absorbed high amounts of Na^+ that disrupted the various enzymatic processes in the cytoplasm of the cells of the plant (Tester and Davenport, 2003). Fescue (cv. Iewag), Lucerne and Fescue (cv. Demeter) were in a superior condition with a realistic cumulative yield as illustrated in (Table 4.3).

4.6 Long-term simulations

Twenty years of irrigation with Na_2SO_4 rich mine effluent were simulated, followed by 30 years of dry land (rain fed) pasture production. The idea was to evaluate the possibility of salt accumulation, gypsum precipitation and leaching of salts in the 20 years of irrigation and thereafter. Also, three irrigation strategies were evaluated to see the most suitable irrigation management option for sustainable utilization of this water in the long-term. Automatic irrigation up to field capacity were simulated when the water deficit was calculated to be equal to, or greater than, 30 mm by the model. Besides, irrigations were simulated at leaching requirement of 20% and when soil water deficit to field capacity (0.9 FC) is 90%.

The highest irrigation amount and drainage was predicted for the leaching fraction strategy Table 4.13. The least drainage was predicted for the 0.9 FC irrigation strategy, leaving a room for rain to replenish the soil. Large quantities of salt were added and leached by the leaching fraction during the 20 years irrigation period. Small quantity of salt was leached by the deficit irrigation strategy. The deficit strategy showed maximum soil saturated EC (root density weighted soil saturated EC) during the 20 years irrigation period Table 4.13. This was compared with the EC_e threshold level pointed out by Maas and Hoffman (1977) for the crops. The EC_e predicted for Fescue, and Lucerne was higher than the threshold level indicated by Maas and Hoffman (1977). Nevertheless, Maas and Hoffman (1977) specified that the EC_e tolerance of the plants could be twice as high as the predicted values when there was some gypsum precipitation.

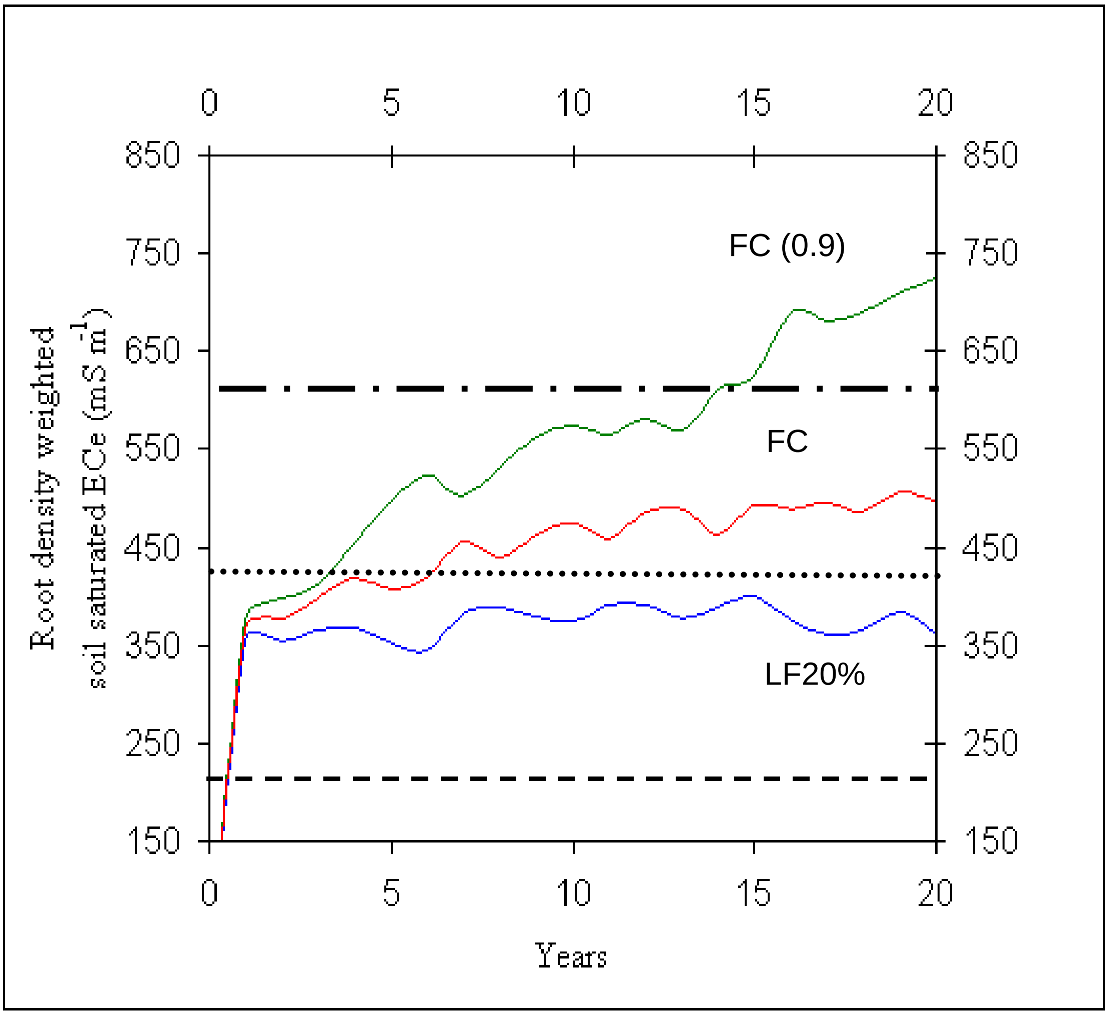
The results indicated that an average of 1420 mm yr^{-1} mine effluent could be utilized. Lucerne was found out to utilize the highest volume of water as compared to Fescue. Considerable quantities of salts were predicted to leach out below 0.8m deep soil profiles. Also, gypsum was predicted to precipitate in the top 20-60 soil layers with small quantity during the 20 years irrigation period. The application of $Ca(NO_3)_2$ as nitrogen fertilizer with the irrigation water contributed in trapping SO_4^{2-} from the soil solution. After 20 years of irrigation, a decrease in quantity of salts for the profile was predicted as washing out of the salts by the rainfall was high.

Table 4.12 Predicted average annual soil water balance for 20 years of irrigation with Na_2SO_4 rich mine effluent for Fescue and Lucerne

Soil-water balance	Fescue			Lucerne		
	FC	LF 20%	FC 0.9	FC	LF 20%	FC 0.9
Rainfall (mm yr^{-1})	563	563	563	563	563	563
Irrigation (mm yr^{-1})	1270	1891	1255	1580	2100	1570
Runoff (mm yr^{-1})	275	78	103	125	95	119
Canopy interception	17	21	17	19	23	19
Drainage (mm yr^{-1})	116	660	99	125	685	112
Evapotranspiration (mm yr^{-1})	1587	1590	1610	1610	1619	1625

Table 4.13 Predicted average annual salt-water balance for 20 years of irrigation with Na_2SO_4 rich mine effluent

Salt balance	**Fescue**			**Lucerne**		
	FC	**LF 20%**	**FC 0.9**	**FC**	**LF 20%**	**FC 0.9**
Salt added (Mg ha^{-1} yr^{-1})	31	47	30	40	53	39
Salt leached (Mg ha^{-1} yr^{-1})	29.2	44.8	28.5	37	49	36
Salt precipitated (Mg ha^{-1} yr^{-1})	1.9	2.2	1.48	2.8	3.6	2.4
Salt runoff (Mg ha^{-1} yr^{-1})	0	0.01	0	0	0.08	0
Soluble salt storage (Mg ha^{-1} yr^{-1})	0	0	0.02	0.2	0.32	0.42
Maximum root density weighted soil saturated EC (mS m^{-1})	460	345	648	495	360	725



Key:

- .... ECₑ threshold for Lucerne and Eragrostis (Maas and Hoffman, 1977)
- .... ECₑ threshold for Fescue and Kikuyu (Maas and Hoffman, 1977)
- — · · — ECₑ threshold for Ryegrass (Maas and Hoffman, 1977)

Figure 4.31 Root density weighted soil saturated EC_e of Lucerne irrigated with Na_2SO_4 rich mine effluent for 20 years using three different irrigation strategies

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Planted pastures were evaluated to see if they could grow when irrigated with Na_2SO_4 rich mine effluent. Fescue (cv. Iewag), Lucerne, and Fescue (cv. Demeter) were grown successfully with satisfactory yield and forage quality. Also, Lucerne and Fescue (cv. Iewag) were found to have higher dry matter water ratios than the other pastures.

Eragrostis and Kikuyu died probably due to the uptake of high amounts of sodium that disrupted the enzymatic processes of the plants. On the contrary, Fescue and Lucerne performed well, which could probably be because of the plants ability to take up less Na^+ and maintain higher K^+ levels in the shoot. Hence, it was concluded that the Na_2SO_4 rich mine effluent water is sustainable for pasture production. Especially, if summer rainfall is sufficient enough to dilute the salts and if proper fertilization with KNO_3 and $Ca(NO_3)_2$ is applied to reduce the Na : K and Na : Ca ratio in the soil solution. Also, to remove SO_4^{2-} from the water system so that a higher mass of gypsum can be precipitated.

The effect of Na_2SO_4 rich mine effluent water on the soil chemical properties was evaluated during the field trial. The salts accumulated at the 0.4-0.6 m depth, which indicates the salts are leached and battling to drain away. An increase of salts was generally observed in the soil during the growing period although it fluctuated with rainfall and dry spells. However, further study is needed to observe possible salt accumulation in the soil profile.

The ESP of the soil was also observed to fluctuate during the trial period. However, the determination of the hydraulic conductivity of the soil is very important to notice the effect of the water on the infiltration rate of the soil.

SWB was proved to work well for the short term. The model predicted LAI, TDM and deficit reasonably well with average r^2 values of 85%, 83.2% and 85% respectively. The average RMSE values for LAI, TDM and deficit were 0.99 $m^2\ m^{-2}$, 1.1 t ha^{-1} and 10.3 mm respectively, which were quite low. This indicates that the average deviation of the simulated from the measured values was relatively small. The model showed some disparity in the water content simulation. This may be improved by adding a subroutine that enables the model to consider waterlogging which can occur due to the heavy texture of the soil. The pastures were harvested at pre determined intervals (not at flowering) and the grasses remained after cut was then estimated. This contributed to the discrepancy between modelled and observed values. However, model performance was generally realistic for the irrigated planted pastures.

The long-term simulations for Fescue and Lucerne indicated that an average of 1420 mm year $^{-1}$ of mine effluent could be used through irrigation. From the point of view of mine water utilization and salt precipitation, Lucerne was found the most suitable crop. Furthermore, Fescue (cv. Iewag) and Fescue (cv. Demeter) can utilize an average of 4 mm day^{-1}. For the deficit irrigation, 93% of the total amount of salts added through irrigation were predicted to leach out of the soil after the 20 years irrigation period. Besides, 7 % of the salts added precipitated as gypsum in the profile. The choice of heavy clay soil for irrigation with this mine effluent together with the application of $Ca(NO_3)_2$ can be advantageous in profile gypsum precipitation and slow release of sulphates. The time for salts to be leached out from the profile will reach the ground water will be hopefully delayed by the negative charge of the soil. In the long-term, for sustainable pasture production, a net downward flow of water through the root zone is needed to a suitable depth. Hence, the mine needs 37 ha to utilize 1 Ml day^{-1} Na_2SO_4 mine effluent water with a leaching fraction of 20%.

Appendix A

Growth analysis

Table 1 A. LAI ($m^2\ m^{-2}$) of four planted pastures during the growing period of January 2002 - May 2002

Date	Fescue (cv. Iewag) ($m^2\ m^{-2}$)	Lucerne ($m^2\ m^{-2}$)	Fescue (cv. Demeter) ($m^2\ m^{-2}$)	Eragrostis ($m^2\ m^{-2}$)
12/02/2002	1.67	2.08	1.38	0.55
21/02/2002	1.85	4.14	1.40	1.35
07/03/2002	2.01	5.55	4.18	2.11
20/03/2002	3.51	6.59	6.3	4.11
05/04/2002	2.62	4.48	4.33	4.14
18/04/2002	6.63	5.61	4.09	4.8
02/05/2002	4.42		5.2	8.42

Table 2 A. Top dry matter (kg m^{-2}) of four planted pastures during the growing period of February 2002 - May 2002

Date	Fescue (cv. Iewag) (kg m^{-2})	Lucerne (kg m^{-2})	Fescue (cv. Demeter) (kg m^{-2})	Eragrostis (kg m^{-2})
12/02/2002	0.28	0.14	0.23	0.27
21/02/2002	0.28	0.28	0.30	0.30
07/03/2002	0.32	0.43	0.5	0.41
20/03/2002	0.43	0.43	0.57	0.45
05/04/2002	0.32	0.48	0.36	0.41
18/04/2002	0.47	0.51	0.42	0.42
02/05/2002	0.47		0.54	0.61

Table 3 A. Leaf area index ($m^2 m^{-2}$) of 5 planted pastures during the growing period of September - December 2002

Date	Fescue (cv. Iewag) ($m^2 m^{-2}$)	Lucerne ($m^2 m^{-2}$)	Fescue (cv. Demeter) ($m^2 m^{-2}$)	Eragrostis ($m^2 m^{-2}$)	Kikuyu ($m^2 m^{-2}$)
02/10/02	4.2	3.9	3.3	1.9	5.1
16/10/02	9.3	4.7	5.5	4.4	6.9
28/10/02	9.3	4.7	5.7	5.9	7.5
06/11/02	7.8	4.5	4.4	4.5	8.1

Table 4 A. Dry matter (kg m^{-2}) of 5 planted pastures during the growing period of September - December 2002

Date	Fescue (cv. Iewag) (kg m^{-2})	Lucerne (kg m^{-2})	Fescue (cv. Demeter) (kg m^{-2})	Eragrostis (kg m^{-2})	Kikuyu (kg m^{-2})
02/10/02	0.7	0.06	0.51	0.47	0.9
16/10/02	1.1	0.07	0.56	0.63	1.19
28/10/02	1.2	0.06	0.63	0.69	1.15
06/11/02	1.1	0.06	0.59	0.6	1.14

Table 5 A. Fresh yield (FY) and dry matter (DM) in (kg m^{-2}) for the growing period of September - December 2002

Pasture Crops	FY (kg m^{-2})	DM (kg m^{-2})
Fescue (cv. Iewag)	3.16	1.04
Lucerne	1.5	0.57
Fescue (cv. Demeter)	1.64	0.59
Eragrostis	1.72	0.6
Kikuyu	3.81	1.14

Table 6 A. Leaf area index ($m^2 m^{-2}$) of four planted pastures during the growing period of December 2002 - February 2003

Date	Fescue (cv. Iewag) ($m^2 m^{-2}$)	Lucerne ($m^2 m^{-2}$)	Fescue (cv. Demeter) ($m^2 m^{-2}$)	Kikuyu ($m^2 m^{-2}$)
24/12/02	-	4.85	-	-
15/01/03	6.44	5.17	6.95	1.95
03/02/03	7.99	6.83	5.82	1.2
15/02/03	5.91	6.05	4.21	1.29
25/02/03	6.49	5.27	5.29	2.91

Table 7 A. Dry matter ($kg\ m^{-2}$) of four planted pastures during the growing period of December 2002 - February 2003

Date	Fescue (cv. Iewag) ($kg\ m^{-2}$)	Lucerne ($kg\ m^{-2}$)	Fescue (cv. Demeter) ($kg\ m^{-2}$)	Kikuyu ($kg\ m^{-2}$)
24/12/02	-	0.3	-	-
15/01/03	0.34	0.39	0.37	0.16
03/02/03	0.76	0.69	0.54	0.22
15/02/03	0.63	0.76	0.48	0.23
25/02/03	0.61	1.05	0.59	0.34

Table 8 A. Fresh yield (FY) and dry matter (DM) in ($kg\ m^{-2}$) for the growing period of December 2002 - February 2003

Pasture Crops	FY ($kg\ m^{-2}$)	DM ($kg\ m^{-2}$)
Fescue (cv. Iewag)	2.61	0.59
Lucerne	3.27	0.86
Fescue (cv. Demeter)	2.71	0.61
Kikuyu	1.96	0.49

Table 9 A. LAI ($m^2 m^{-2}$) of three planted pastures during the growing period of March 2003 - May 2003

Date	Fescue (cv. Iewag) ($m^2 m^{-2}$)	Lucerne ($m^2 m^{-2}$)	Fescue (cv. Demeter) ($m^2 m^{-2}$)
11/03/03	–	2.55	_
18/03/03	–	5.51	_
11/04/03	2.26	5.67	1.24
17/04/03	3.80	5.95	2.49
30/04/03	6.40	3.47	5.53

Table 10 A. Dry matter (kg m^{-2}) of three planted pastures during the growing period of March 2003 - May 2003

Date	Fescue (cv. Iewag) (kg m^{-2})	Lucerne (kg m^{-2})	Fescue (cv. Demeter) (kg m^{-2})
11/03/03	_	0.43	_
18/03/03	_	0.56	_
11/04/03	0.17	0.45	0.09
17/04/03	0.32	0.42	0.20
30/04/03	0.67	0.52	0.67

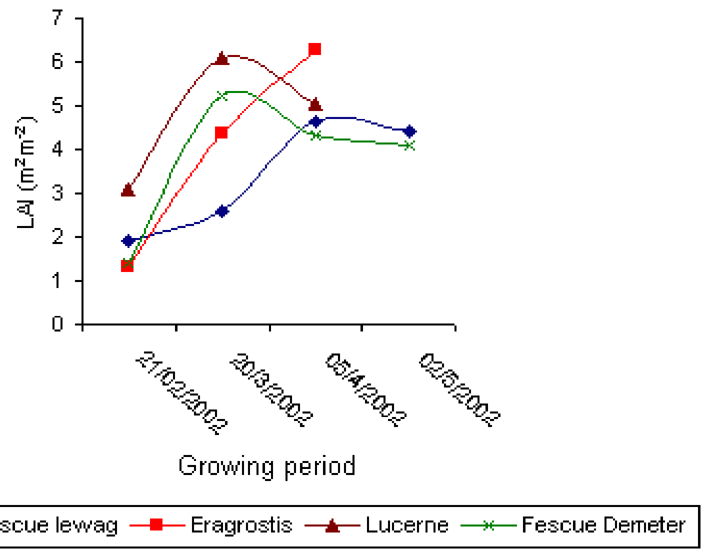


Figure 1 A. LAI (m^{2}m^{-2}) vs Growing period of 4 pasture crops (January - May 2002)

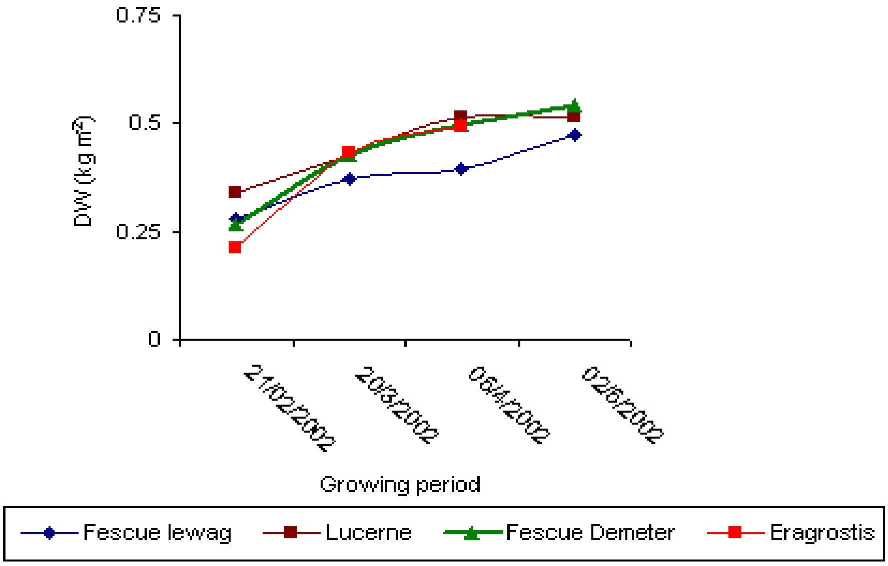


Figure 2 A. DM (kg m^{-2}) vs Growing period of 4 pasture crops (January -May 2002)

Appendix B

Field water balance

Table B1. Field water balance of Fescue (cv. Iewag) measured from NWM acess tubes during the growing period of February 2002 - May 2002

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
27/11/01	A	20cm	0.314				B	20cm	0.328			
		40cm	0.391					40cm	0.371			
		Total (mm)	141					Total (mm)	139.8			
23/01/02	A	20cm	0.439				B	20cm	0.46			
		40cm	0.477					40cm	0.492			
		Total (mm)	183.2	89.4	42	47		Total (mm)	190.4	89.35	50.6	38
12/02/02	A	20cm	0.388				B	20cm	0.388			
		40cm	0.399					40cm	0.399			
		Total (mm)	157.4	123.1	-25	148		Total (mm)	157.4	123.05	-33	156
20/03/02	A	20cm	0.402				B	20cm	0.402			
		40cm	0.404					40cm	0.404			
		Total (mm)	161.2	230.3	4	226		Total (mm)	161.2	230.25	3.8	226
18/04/02	A	20cm	0.389				B	20cm	0.389			
		40cm	0.399					40cm	0.399			
		Total (mm)	157.6	113.6	-4	117		Total (mm)	157.6	113.6	-3.6	117
02/05/02	A	20cm	0.37				B	20cm	0.369			
		40cm	0.376					40cm	0.376			
		Total (mm)	149.2	15	-8	23		Total (mm)	149	15	-8.6	24
				571		**563.05**				**571**		**562**

θ	Volumetric water content (mm) calibrated from the NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 2. Field water balance of Fescue (cv. Iewag) measured from two NWM acess tubes during the growing period of September 2002 - December 2002

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
09/07/02	A	20cm	0.41				B	20cm	0.41			
		40cm	0.42					40cm	0.42			
		Total (mm)	166	128.3	17	111.25		Total (mm)	166	128.3	17.2	111
25/09/02	A	20cm	0.38				B	20cm	0.38			
		40cm	0.42					40cm	0.42			
		Total (mm)	159	181.2	-7.2	188.4		Total (mm)	159	181.	-7.2	188
09/10/02	A	20cm	0.36				B	20cm	0.38			
		40cm	0.40					40cm	0.39			
		Total (mm)	152	55	-6.6	61.6		Total (mm)	154.4	55	-4.6	60
01/11/02	A	20cm	0.33				B	20cm	0.32			
		40cm	0.35					40cm	0.36			
		Total (mm)	137	57.55	-15.4	72.95		Total (mm)	135	57.6	-19.2	77
15/11/02	A	20cm	0.34				B	20cm	0.31			
		40cm	0.36					40cm	0.37			
		Total (mm)	139.8	64.95	2.8	62.15		Total (mm)	137	64.95	1.8	63
				487		**496**				**487**		**499**

θ	Volumetric water content (mm) calibrated from the NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 3. Field water balance of Fescue (cv. Iewag) measured from two NWM acess tubes during the growing period of December 2002 - February 2003

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
02/12/02	A	20cm	0.286				B	20cm	0.305			
		40cm	0.349					40cm	0.332			
		Total (mm)	127	4.95	-12.8	17.75		Total (mm)	127.4	4.95	-9.6	14.55
23/12/02	A	20cm	0.406				B	20cm				
		40cm	0.429					40cm				
		Total (mm)	167	111.4	40	71.4		Total (mm)				
09/01/03	A	20cm	0.407				B	20cm	0.3966			
		40cm	0.432					40cm	0.4078			
		Total (mm)	167.8	71.8	0.8	71		Total (mm)	160.89	183.2	33.488	149.712
30/01/03	A	20cm	0.366				B	20cm				
		40cm	0.407					40cm				
		Total (mm)	154.6	73.4	-13.2	86.6		Total (mm)				
15/02/03	A	20cm	0.282				B	20cm	0.3218			
		40cm	0.339					40cm	0.3362			
		Total (mm)	124.2	31.8	-30.4	62.2		Total (mm)	131.6	105.2	-29.29	134.49
28/02/03	A	20cm	0.374				B	20cm	0.3987			
		40cm	0.417					40cm	0.3842			
		Total (mm)	158.2	100.6	34	66.6		Total (mm)	156.59	100.6	24.988	75.6121
				394		375				393		374

θ	Volumetric water content (mm) calibrated from the NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 4. Field water balance of Fescue (cv. Iewag) measured from two NWM acess tubes during the growing period of February 2003 - May 2003

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
11/03/03	A	20cm	0.38				B	20cm	0.385			
		40cm	0.4					40cm	0.426			
		Total (mm)	156		-2.2			Total (mm)	162.2		137	
18/03/03	A	20cm	0.387				B	20cm	0.39			
		40cm	0.43					40cm	0.41			
		Total (mm)	163.4		7.4			Total (mm)	160		-2.2	
04/04/03	A	20cm	0.39				B	20cm	0.38			
		40cm	0.4					40cm	0.43			
		Total (mm)	158		-5.4			Total (mm)	162		2	
16/04/03	A	20cm	0.4				B	20cm	0.39			
		40cm	0.43					40cm	0.41			
		Total (mm)	166		8			Total (mm)	160		-2	
29/04/03	A	20cm	0.36				B	20cm	0.38			
		40cm	0.41					40cm	0.39			
		Total (mm)	154		-12			Total (mm)	154		-6	
13/05/03	A	20cm	0.33				B	20cm	0.35			
		40cm	0.387					40cm	0.37			
		Total (mm)	143.4		-10.6			Total (mm)	144		-10	

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 5. Field Water balance of Lucerne measured from NWM acess tubes during the growing period of February 2002 - May 2002

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
27/11/01	A	20cm	0.3				B	20cm	0.32			
		40cm	0.35					40cm	0.38			
		Total (mm)	129	0	-14.49	14.4874		Total (mm)	139	0	-4.4	4.5
23/01/02	A	20cm	0.36				B	20cm	0.36			
		40cm	0.38					40cm	0.38			
		Total (mm)	148	56.3	19.2	37.0956		Total (mm)	148	56.3	8.6889	47.6
12/2/002	A	20cm	0.37				B	20cm	0.37			
		40cm	0.35					40cm	0.35			
		Total (mm)	144	97.85	-4.011	101.861		Total (mm)	144	97.85	-4.011	101.9
20/03/02	A	20cm	-	-	-	-	B	20cm	0.41			
		40cm	-	-	-	-		40cm	0.38			
		Total (mm)	-	-	-	-		Total (mm)	158	216.55	14.207	202.3
18/04/02	A	20cm	0.38				B	20cm	0.38			
		40cm	0.36					40cm	0.36			
		Total (mm)	148	313.4	3.55	309.8		Total (mm)	148	96.8	-10.66	107.5
02/05/02	A	20cm	0.35				B	20cm	0.35			
		40cm	0.35					40cm	0.35			
		Total (mm)	141	15	-6.645	21.6449		Total (mm)	141	15	-6.645	21.6
				483		**484**				**482**		**485**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 6. Field water balance of Lucerne measured from two NWM acess tubes during the growing period of September 2002 to December 2002

Sampling date	Tube	Depth	θ	P+I	Δ Q	ET
09/07/02	A	20cm	0.3716			
		40cm	0.3631			
		Total (mm)	146.95	115.7	5.9	109.8
25/09/02	A	20cm	0.3179			
		40cm	0.3227			
		Total (mm)	128.13	146.2	-18.8	165.0
09/10/02	A	20cm	0.3267			
		40cm	0.3182			
		Total (mm)	128.97	40.2	0.8	39.3
01/11/02	A	20cm	0.3286			
		40cm	0.3146			
		Total (mm)	128.65	36.6	-0.3	36.9
				338		**351**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 7. Field water balance of Lucerne measured from two NWM acess tubes during the growing period of December 2002 - February 2003

Date	Tube	Depth	θ	P+I	Δ Q	ET
02/12/2002	A	20cm	0.2703			
		40cm	0.2972			
		Total (mm)	113.48	28.8	-15.2	43.96909
23/12/2002	A	20cm	0.3933			
		40cm	0.3712			
		Total (mm)	152.92	111.4	39.4	71.96703
09/01/2003	A	20cm	0.3977			
		40cm	0.3764			
		Total (mm)	154.82	71.8	1.9	69.90027
30/01/2003	A	20cm	0.3247			
		40cm	0.3438			
		Total (mm)	133.69	73.3	-21.1	94.43015
15/02/2003	A	20cm	0.2916			
		40cm	0.3006			
		Total (mm)	118.44	15.3	-15.2	30.54606
28/02/2003	A	20cm	0.3565			
		40cm	0.3609			
		Total (mm)	143.48	58.6	25.1	33.56071
				359.2		344.3

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 8. Field water balance of Lucerne mθsured from two NWM acess tubes during the growing period of February 2003 - May 2003

Sampling date	Tube	Depth	P+I	ΔQ	ET
2003/11/03	A	20cm	0.3605		
		40cm	0.347		
		Total (mm)	141.5	-1.98	
18/03/03	A	20cm	0.3577		
		40cm	0.3415		
		Total (mm)	139.8	-1.66	
2003/04/04	A	20cm	0.3353		
		40cm	0.3274		
		Total (mm)	132.5	-7.29	
16/04/03	A	20cm	0.3641		
		40cm	0.342		
		Total (mm)	141.2	8.67	
29/04/03	A	20cm	0.2962		
		40cm	0.3092		
		Total (mm)	121.1	-20.15	
13/05/03	A	20cm	0.2792		
		40cm	0.2992		
		Total (mm)	115.7	-5.39	

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 9. Field water balance of Fescue (cv. Demeter) measured from NWM acess tubes during the growing period of February 2002 to May 2002

Date	Tube	Depth	θ	P+I	ΔQ	ET	Tube	Depth	θ	P+I	ΔQ	ET
27/11/2001	A	20cm	0.319				B	20cm	0.31			
		40cm	0.406					40cm	0.41			
		Total (mm)	145					Total (mm)	144			
23/01/2002	A	20cm	0.427				B	20cm	0.42			
		40cm	0.497					40cm	0.47			
		Total (mm)	184.8	94.3	39.8	54.5		Total (mm)	178	94.3	33.8	60.5
12/02/2002	A	20cm	0.378				B	20cm	0.37			
		40cm	0.413					40cm	0.41			
		Total (mm)	158.2	104.05	-26.6	130.65		Total (mm)	155	104.05	-23	127.1
20/03/2002	A	20cm	0.412				B	20cm	0.42			
		40cm	0.446					40cm	0.44			
		Total (mm)	171.6	204.1	13.4	190.7		Total (mm)	172	204.1	16.8	187.3
18/04/2002	A	20cm	0.392				B	20cm	0.39			
		40cm	0.419					40cm	0.42			
		Total (mm)	162.2	91	-9.4	100.4		Total (mm)	162	91	-9.4	100.4
				493		**476**				**508.45**		**475**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 10. Field water balance of Fescue (cv. Demeter) measured from two NWM acess tubes during the growing period of September 2002 - December 2002

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	ΔQ	ET
09/ 7/ 2002	A	20cm	0.388				B	20cm	0.4			
		40cm	0.443					40cm	0.44			
		Total (mm)	166.2	85	4	81.7		Total (mm)	166	85.7	3.8	81.9
25/9/2002	A	20cm	0.372				B	20cm	0.38			
		40cm	0.402					40cm	0.42			
		Total (mm)	154.8	111	-11.4	123.3		Total (mm)	161	111.9	-5.4	117.3
09/10/2002	A	20cm	0.368				B	20cm	0.35			
		40cm	0.409					40cm	0.39			
		Total (mm)	155.4	27	0.6	26.6		Total (mm)	147	27.2	-13.2	40.4
01/11/2002	A	20cm	0.307				B	20cm	0.31			
		40cm	0.348					40cm	0.33			
		Total (mm)	131	36	-24.4	60.9		Total (mm)	128	36.5	-19.4	55.9
				261.2		**292.4**				**261.2**		**295**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 11. Field water balance of Fescue (cv. Demeter) measured from two NWM acess tubes during the growing period of December 2002 - February 2003

Date	Tube	Depth	θ	P+I	ΔQ	ET	Tube	Depth	θ	P+I	Δ Q	ET
02/12/2002	A	20cm	0.274				B	20cm	0.27			
		40cm	0.322					40cm	0.3			
		Total (mm)	119.2	28.9	-11.8	40.7		Total (mm)	115	28.9	-13.2	42.1
23/12/2002	A	20cm	0.397				B	20cm	0.38			
		40cm	0.438					40cm	0.41			
		Total (mm)	167	140	47.8	92.2		Total (mm)	157	140	42.2	97.8
09/01/2003	A	20cm	0.396				B	20cm	0.41			
		40cm	0.435					40cm	0.4			
		Total (mm)	166.2	158.1	-0.8	158.9		Total (mm)	162	158.1	4.8	153.3
30/01/2003	A	20cm	0.362				B	20cm	0.37			
		40cm	0.412					40cm	0.41			
		Total (mm)	154.8	78.9	-11.4	90.3		Total (mm)	155	78.9	-6.8	85.7
15/02/2003	A	20cm	0.296				B	20cm	0.3			
		40cm	0.342					40cm	0.34			
		Total (mm)	127.6	38.3	-27.2	65.5		Total (mm)	127	38.3	-28.2	66.5
28/02/2003	A	20cm	0.374				B	20cm	0.38			
		40cm	0.416					40cm	0.41			
		Total (mm)	158	79.8	30.4	49.4		Total (mm)	158	79.8	30.8	49
				524		**497**				**524**		**494**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 12. Field water balance of Fescue (cv. Demeter) measured from two NWM acess tubes during the growing period of February 2003 - May 2003

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
2003/11/03	A	20cm	0.38				B	20cm	0.38			
		40cm	0.413					40cm	0.42			
		Total (mm)	158.6		0.6			Total (mm)	160		2.6	
18/03/03	A	20cm	0.392				B	20cm	0.38			
		40cm	0.427					40cm	0.42			
		Total (mm)	163.8		5.2			Total (mm)	161		0.8	
2003/04/04	A	20cm	0.388				B	20cm	0.39			
		40cm	0.419					40cm	0.42			
		Total (mm)	161.4		-2.4			Total (mm)	161		-0.4	
16/04/03	A	20cm	0.398				B	20cm	0.4			
		40cm	0.432					40cm	0.43			
		Total (mm)	166		4.6			Total (mm)	165		4	
29/04/03	A	20cm	0.37				B	20cm	0.37			
		40cm	0.412					40cm	0.4			
		Total (mm)	156.4		-9.6			Total (mm)	154		-10.6	
13/05/03	A	20cm	0.334				B	20cm	0.33			
		40cm	0.393					40cm	0.37			
		Total (mm)	145.4		-11			Total (mm)	140		-14.2	

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 13. Field Water balance of Eragrostis measured from two NWM acess tubes during the growing period of February 2002 - May 2002

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
27/11/2001	A	20cm	0.336				B	20cm	0.33			
		40cm	0.395					40cm	0.4			
	Total	Total (mm)	146.2						145			
23/01/2002	A	20cm	0.38				B	20cm	0.38			
		40cm	0.429					40cm	0.43			
	Total	Total (mm)	161.8	81.4	15.6	65.8		Total (mm)	162	81.4	16.8	64.6
12/02/2002	A	20cm	0.408				B	20cm	0.41			
		40cm	0.429					40cm	0.43			
	Total	Total (mm)	167.4	108	5.6	102.4		Total (mm)	167	108	5.6	102.4
20/03/2002	A	20cm	0.437				B	20cm	0.42			
		40cm	0.382					40cm	0.43			
	Total	Total (mm)	163.8	215.45	-3.6	219.05		Total (mm)	170	215.45	2.4	213.1
18/04/2002	A	20cm	0.385				B	20cm	0.39			
		40cm	0.416					40cm	0.43			
	Total	Total (mm)	160.2	98.6	-3.6	102.2		Total (mm)	163	98.6	-6.6	105.2
02/05/2002	A	20cm	0.349				B	20cm	0.37			
		40cm	0.391					40cm	0.41			
	Total	Total (mm)	148	15	-12.2	27.2		Total (mm)	156	15	-7.6	22.6
				518		**516**				**518**		**508**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 14. Field water balance of Eragrostis measured from two NWM acess tubes during the growing period of September 2002 - December 2002

Date	Tube	Depth	θ	P+I	ΔQ	ET	Tube	Depth	θ	P+I	Δ Q	ET
09/ 7/ 2002	A	20cm	0.374				B	20cm	0.39			
		40cm	0.424					40cm	0.43			
		Total (mm)	159.6	109.6	11.6	98		Total (mm)	163	109.6	7.8	101.8
25/9/2002	A	20cm	0.38				B	20cm	0.38			
		40cm	0.429					40cm	0.41			
		Total (mm)	161.8	141.9	2.2	139.8		Total (mm)	157	141.9	-6.8	148.8
09/10/2002	A	20cm	0.408				B	20cm	0.42			
		40cm	0.429					40cm	0.44			
		Total (mm)	167.4	38	5.6	32.4		Total (mm)	173	38	16.6	21.4
01/11/2002	A	20cm	0.345				B	20cm	0.33			
		40cm	0.382					40cm	0.37			
		Total (mm)	145.4	36.8	-22	58.8		Total (mm)	139	36.8	-34.2	71

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 15. Field water balance of Eragrostis measured from two NWM acess tubes during the growing period of December 2002-February 2003

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
02/12/2002	A	20cm	0.329				B	20cm	0.32			
		40cm	0.387					40cm	0.38			
		Total (mm)	143.2	55.6	-2.2			Total (mm)	139	55.6	0.2	55
23/12/2002	A	20cm	0.418				B	20cm	0.4			
		40cm	0.447					40cm	0.43			
		Total (mm)	173	135	29.8	105		Total (mm)	165	135	26	109
09/01/2003	A	20cm	0.42				B	20cm	0.41			
		40cm	0.445					40cm	0.43			
		Total (mm)	173	101.8	0	101		Total (mm)	167	101.8	2	99
30/01/2003	A	20cm	0.349				B	20cm	0.36			
		40cm	0.412					40cm	0.42			
		Total (mm)	152.2	73.7	-20.8	94		Total (mm)	156	73.5	-11.4	85
15/02/2003	A	20cm	0.294				B	20cm	0.31			
		40cm	0.366					40cm	0.39			
		Total (mm)	132	19.8	-20.2	39		Total (mm)	141	198.8	-15.2	34
28/02/2003	A	20cm	0.358				B	20cm	0.37			
		40cm	0.409					40cm	0.41			
		Total (mm)	153.4	148.6	21.4	127		Total (mm)	156	148.6	15	133
				534		**468**				**534**		**518**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Table B 16. Field water balance of Kikuyu measured from two NWM acess tubes during the growing period of December 2002 - February 2003

Date	Tube	Depth	θ	P+I	Δ Q	ET	Tube	Depth	θ	P+I	Δ Q	ET
02/12/2002	A	20cm	0.306				B	20cm	0.26			
		40cm	0.346					40cm	0.32			
		Total (mm)	130.5					Total (mm)	115			
23/12/2002	A	20cm	0.398				B	20cm	0.39			
		40cm	0.428					40cm	0.42			
		Total (mm)	165.1	141.6	34.6	106.9		Total (mm)	162	141.6	46.9	94.7
09/01/2003	A	20cm	0.4				B	20cm	0.4			
		40cm	0.429					40cm	0.41			
		Total (mm)	165.8	158.1	0.7	157.4		Total (mm)	162	158.1	-0.2	158.4
30/01/2003	A	20cm	0.381				B	20cm	0.38			
		40cm	0.42					40cm	0.41			
		Total (mm)	160.3	78.9	-5.5	84.4		Total (mm)	157	78.9	-5	84.1
15/02/2003	A	20cm	0.354				B	20cm	0.34			
		40cm	0.398					40cm	0.38			
		Total (mm)	150.5	38.3	-9.8	48.1		Total (mm)	144	38.3	-13	51.7
28/02/2003	A	20cm	0.385				B	20cm	1.39			
		40cm	0.417					40cm	0.42			
		Total (mm)	160.5	5.85	9.9	-4.0		Total (mm)	164	5.85	19	-14.1
				422		**392**				**422.8**		**375**

θ	Volumetric water content (mm) calibrated from NWM at the site
P+I	Rainfall and irrigation (mm)
Δ Q	Change in storage (mm)
ET	Evapotranspiration (mm)

Appendix C

Plant analysis

Table C 1. Plant analysis results of five planted pastures irrigated with Na_2 SO_4 rich mine water (Syferfontein, Summer 2002/2003)

Date	Site	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	SO_4 (%)	Cu (mg kg^{-1})	Fe^{2+} (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
01/29/2002	Fescue I	4.61	0.43	3.72	0.95	0.86	0.02	3.64	30	489	522	36
01/29/2002	Lucerne	4.63	0.32	4.2	1.27	0.94	0.02	3.92	30	225	258	26
01/29/2002	Fescue D	5.56	0.37	4.35	1.14	1.02	0.02	2.16	30	198	131	20
01/29/2002	Eragrostis	4.63	0.31	3.21	1.46	1.15	0.01	2.1	35	204	150	20
01/29/2002	Kikuyu	4.22	0.3	3.82	1.39	0.89	0.02	2.6	45	504	287	39
02/15/2002	Fescue I	1.69	0.26	2.14	0.29	0.4	1.42	1.65	15	153	74	29
02/15/2002	Lucerne	3.02	0.21	2.78	1.13	0.32	0.36	1.5	17	218	54	41
02/15/2002	Fescue D	1.36	0.24	2.37	0.26	0.38	0.66	1.33	15	252	113	87
02/15/2002	Eragrostis	1.45	0.27	2.61	0.36	0.41	0.33	1.72	35	624	98	51
04/22/2003	Fescue I-1	2.18	0.35	2.27	0.35	0.54	1.46	2.71	8	153	75	20
04/22/2003	Fescue I-2	2	0.33	2.3	0.33	0.53	1.34	1.65	8	159	75	44
04/22/2003	Fescue I-3	1.87	0.34	1.89	0.35	0.55	1.4	2.4	6	110	75	29
04/22/2003	Lucerne	2	0	2.38	1.33	0.36	1.19	1.82	12	123	47	35
05/02/2003	Fescue D	2.06	0.29	2.56	0.36	0.56	0.96	2.87	8	134	87	30
05/02/2003	Fescue D	1.91	0.3	2.22	0.34	0.54	1.04	2.67	8	129	110	23
05/02/2003	Fescue D	1.99	0.29	2.32	0.34	0.53	1.11	2.38	9	123	95	32
05/02/2003	Lucerne	3.31	0.21	2.38	1.33	0.36	1.19	1.83	11	123	47	35
05/02/2003	Lucerne	3.35	0.22	3.14	1.1	0.36	1.16	2.09	11	113	36	41
05/02/2003	Lucerne	3.25	0.2	2.59	1.12	0.35	1.2	1.46	11	128	53	35

Fescue I…..Fescue (cv. Iewag) Fescue D…… Fescue (cv. Demeter)

Appendix D

Soil analysis

Table D 1. Soil chemical analysis results of Kikuyu field (October 2002, Soil Science Laboratory, University of Pretoria).

Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
					Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
S1-S5	0-20	6.2	385	4.34	0.888	0.008	1.27	1.755	23.209	0.29	19.581	3.26	3.438
S1-S5	20-40	6.4	312	1.5	1.083	0.006	1.418	1.127	30.624	0.261	24.618	2.213	2.872
S1-S5	40-60	7.5	135	1.48	0.327	0.004	0.408	0.65	31.58	0.261	26.781	2.255	0.54
S1-S5	60-8/0	8.2	88.8	1.72	0.156	0.003	0.202	0.524	31.75	0.318	26.41	-0.098	0.671

Table D 2. Soil chemical analysis results of five planted pastures field (October 2002, Soil Science Laboratory, University of Pretoria).

Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
					Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO$_4^{2-}$ me 100g^{-1}
Fescue I	0-20	7.5	6.35	2.29	1.323	0.003	1.984	5.025	27.526	0.399	32.081	6.482	5.832
Fescue I	20-40	7.2	492										
Fescue I	40-60	7.3	2.76	2.16	1.113	0.008	1.495	1.165	29.682	0.394	25.327	0.99	2.782
Fescue I	60-80	7.9	330										
Lucerne	0-20	7.5	2.55	1.6	1.091	0.011	0.938	0	25.063	0.521	19.299	6.635	3.645
Lucerne	20-40	6.9	338										
Lucerne	40-60	7.2	232	1.66	0.964	0.009	0.678	1.319	27.984	0.681	23.016	3.228	1.609
Lucerne	60-80	8.1	1.27	1.08	0.29	0.002	0.225	0.784	32.651	0.412	20.506	2.937	0.725
Lucerne	80-100	8.7	137										
Fescue D	0-20	7.3	2.21	2.55	1.029	0.011	0.941	2.538	17.74	0.567	17.896	6.576	3.463
Fescue D	20-40	7.1	383										
Fescue D	40-60	7.6	344	1.27	1.766	0.011	1.441	1.066	34.019	0.549	25.381	2.046	3.029
Eragrostis	0-20	7.4	162	4.61	0.173	0.007	0.172	1.166	16.75	0.576	17.103	6.643	0.919
Eragrostis	20-40	6.9	1.92	1.87	1.111	0.007	1.104	1.325	25.891	0.404	24.071	2.309	2.619
Eragrostis	40-60	7.1	326										
Eragrostis	60-80	7.8	1.5										
Eragrostis	80-90	8.1	250	1.27	0.786	0.006	0.722	0.624	25.418	0.314	16.634	1.096	1.602
Kikuyu	0-20	7.9	229	6.98	0.021	0.001	0.023	0.108	17.401	0.915	21.037	10.007	
Kikuyu	20-40	7.3	2.05										0.132
Kikuyu	40-60	7.7	141	2.14	0.386	0.006	0.441	0.736	26.517	0.651	29.837	2.637	1.173
Kikuyu	60-80	8.5	2.9										
Kikuyu	80-100	7.4	351	2.35	1.068	0.008	1.183	1.783	22.841	0.419	25.145	4.721	3.306
Out pivot	0-20	7.2	3.31										
Out pivot	20-40	7.9	115	1.87	0.364	0.005	0.264	0.536	38.565	0.657	22.031	1.749	0.632
Out pivot	40-60	8.1	97	1.92	0.317	0.004	0.197	0.476	39.41	0.724	24.155	2.201	
Out pivot	60-80	8.4	0.9										0.62
Out pivot	80-100	8.5	81	1.26	0.139	0.003	0.106	0.469	35.246	0.698	26.304	2.817	

Table D 3. Soil chemical analysis results of five planted pastures field (May 2003, Soil Science Laboratory, University of Pretoria).

Site	Depth (cm)	pH	EC mS m^{-1}	P mg kg^{-1}	Soluble Cations				Exchangeable cations				
					Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	Ca^{2+} cmol(c) kg^{-1}	K^{+} cmol(c) kg^{-1}	Mg^{2+} cmol(c) kg^{-1}	Na^{+} cmol(c) kg^{-1}	SO_4^{2-} me $100g^{-1}$
Fescue I	0-20	8.2	176	0	0.122	0.006	0.193	1.412	15.376	0.738	24.621	12.907	1.301
Fescue I	20-40	7.7	377	0	0.955	0.008	1.521	3.697	21.28	0.493	30.124	9.535	4.316
Fescue I	40-60	7.8	371	0	1.123	0.006	1.892	1.738	28.546	0.421	33.622	6.362	3.519
Fescue I	0-20	7.7	229	0	0.261	0.01	0.329	1.664	19.129	0.795	21.933	11.786	1.671
Lucerne	20-40	7.3	335	0	1.184	0.01	1.203	2.393	23.645	0.593	23.282	6.75	3.261
Lucerne	40-60	7.5	190	0	0.751	0.006	0.581	1.094	28.919	0.574	26.702	4.917	1.676
Fescue D	0-20	7.3	304	0	0.409	0.011	0.552	2.506	21.027	0.781	23.274	10.291	1.678
Fescue D	20-40	7.1	295	0	1.328	0.011	1.467	1.559	26.396	0.656	28.285	5.279	2.901
Fescue D	40-60	7.7	183	0	0.819	0.008	0.722	0.616	34.29	0.634	28.125	3.438	1.822
Fescue D	60-80	8.2	136	0	0.331	0.004	0.424	0.631	30.586	0.487	33.032	4.249	1.024
Eragrostis	0-20	7.2	233	0	0.337	0.009	0.41	1.708	17.007	0.605	20.536	8.261	1.88
Eragrostis	20-40	6.9	261	0	0.903	0.009	1.08	1.382	19.684	0.426	23.898	5.064	2.818
Eragrostis	40-60	7.5	215	0	0.786	0.005	0.91	0.637	27.387	0.417	24.892	3.373	1.96
Eragrostis	60-80	8	209	0	0.818	0.005	0.978	0.61	28.003	0.394	23.178	2.661	1.823
Kikuyu	0-20	7.3	270	0	0.59	0.01	0.683	1.919	20.048	0.701	25.2	9.399	2.727
Kikuyu	20-40	7.1	264	0	0.902	0.005	1.199	1.146	21.532	0.437	29.459	5.3	2.572
Kikuyu	40-60	8.3	166	0	0.419	0.004	0.578	0.723	29.65	0.443	31.396	4.114	1.284
Kikuyu	0-20	7.3	173	0	0.255	0.006	0.371	1.099	19.534	0.628	26.254	9.697	1.346
Kikuyu	20-40	7.1	263	0	0.853	0.007	1.11	1.345	21.431	0.56	29.054	5.971	2.644
Kikuyu	40-60	7.6	185	0	0.681	0.006	0.704	0.822	25.545	0.572	31.518	4.493	1.408
Kikuyu	60-80	8.4	111	0	0.245	0.004	0.335	0.624	28.127	0.556	32.216	4.343	0.736
Out pivot	0-20	7.1	26	0	0.075	0.002	0.087	0.038	19.265	0.425	23.986	0.192	0.098
Out pivot	20-40	7.4	26	0	0.087	0.003	0.111	0.042	20.501	0.439	27.501	0.319	0.166

Appendix E

Soil water analysis

Table E 1. Water analysis results of the soil solution from a field of Fescue (cv. Iewag) collected at 0.40 m depth (Syferfontein, Republic of South Africa)

Sampling date	pH	EC	Ca^{+2}		Mg^{+2}		K^{+1}		Na^{+1}		$SO4^{-2}$		Cl^{-1}		SAR		TDS
		mS m^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-}	mg l^{-1}	$(\text{mmol } l^{-1})^{1/2}$	g l^{-1}
07/01/02	6.9	156	57	1.425	41	1.69	1.81	0.05	235	10.2	300.4	3.1	14.6	0.41	33.6	5.8	0.6498
20/03/02	7.4	311	40	1	75	3.09	4.49	0.11	580	25.2	473.3	4.9	45.3	1.28	76.5	12.5	1.2181
18/04/02	7.9	321	96	2.4	75	3.09	12	0.31	625	27.2	223.2	2.3	25.2	0.71	67.6	11.6	1.0564
16/05/02	8.2	318	91	2.275	75	3.09	1.45	0.04	710	30.9	210.8	2.2	53.4	1.51	77.9	13.3	1.1417
06/06/02	7.5	314	74	1.85	70	2.88	3.38	0.09	660	28.7	1049.8	10.9	92.1	2.60	77.8	13.2	1.9493
11/07/02	7.2	459	152	3.8	140	5.76	2.09	0.05	845	36.8	1926.7	20.1	88.1	2.49	69.9	11.9	3.1539
24/12/02	6.7	405	281	7.025	267	10.98	4.84	0.12	2360	102.7	1854.7	19.3	63.9	1.80	142.6	24.2	4.8314
09/01/03	7.7	295	58	1.45	53	2.18	1.6	0.04	1410	61.3	702.8	7.3	11.1	0.31	189.3	32.2	2.2365
30/01/03	8.1	225	58	1.45	40	1.65	2.69	0.07	970	42.2	996.6	10.4	7	0.20	138.6	24.0	2.0743
28/02/03	6.5	209	69	1.725	65	2.67	11.9	0.30	460	20.0	865	9.0	36.3	1.02	56.2	9.5	1.5072
11/03/03	7.2	458	160	4	106	4.36	7.09	0.18	1230	53.5	2063.4	21.5	240.2	6.78	106.7	18.5	3.8067
01/04/03	7.5	405	189	4.725	96	3.95	3.2	0.08	1360	59.2	2614.1	27.2	57.4	1.62	113.9	20.1	4.3197
STD Err	**2.1**	**128.5**	**69**	**1.71**	**59**	**2.44**	**3.61**	**0.092**	**549**	**23.9**	**785.1**	**8.2**	**60.5**	**1.71**	**42.3**	**7.3**	**1.326**

pH	measure of acidity or alkalinity of solution
EC	degree of salinity
SAR	relative proportion of sodium ions in water sample to those of calcium and magnesium
TDS	total dissolved salts

Table E 2. Water analysis results of the soil solution from a field of Lucerne collected at 0.40 m depth (Syferfontein, Republic of South Africa)

Sampling date	pH	EC	Ca^{+2}		Mg^{+2}		K^{+1}		Na^{+1}		$SO4^{-2}$		Cl^{-1}		SAR		TDS
		mS m^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-}	mg l^{-1}	(mmol $l^{-1})^{1/2}$	g l^{-1}
07/01/02	7.3	388	257	6.43	183	7.53	7.4	0.19	780	33.93	1712	17.83		0.0	52.6	9.1	2.94
20/03/02	6.6	525	308	7.70	177	7.28	3.32	0.08	862	37.49	2576.9	26.84	28.6	0.8	55.4	9.7	3.96
04/04/02	8.5	319	106	2.65	73	3.00	1.61	0.04	630	27.4	1350.7	14.07	7.6	0.2	66.6	11.5	2.17
18/04/02	7.7	434	381	9.53	260	10.70	1.8	0.05	760	33.06	147.2	1.53	14.1	0.4	42.5	7.4	1.56
16/05/02	8.2	362	145	3.63	94	3.87	1.71	0.04	730	31.75	627	6.53	22.2	0.6	66.8	11.6	1.62
11/07/02	6.8	481	219	5.48	144	5.92	1.07	0.03	495	21.53	1104.5	11.51	67.5	1.9	36.7	6.4	2.03
24/07/02	8.2	484	214	5.35	139	5.72	2.65	0.07	825	35.89	2038.2	21.23	22.2	0.6	62.1	10.8	3.24
15/11/02	6.5	354	142	3.55	75	3.09	19.9	0.51	1	0.043	1367.2	14.24	129.4	3.7	0.09	0.0	1.73
24/12/02	7.2	304	87	2.18	59	2.43	6.23	0.16	1370	59.59	1212.1	12.63	47.8	1.3	160.5	27.8	2.78
09/01/03	7.4	341	279	6.98	92	3.78	4.51	0.12	1670	72.64	1521.7	15.85	17.1	0.5	122.6	22.1	3.58
30/01/03	6.9	4.5	236	5.90	107	4.40	3.18	0.08	1290	56.11	2983.6	31.08	12.6	0.4	98.5	17.5	4.63
28/02/03	6.8	543	311	7.78	172	7.08	6.83	0.17	1720	74.82	3045.9	31.73	94.7	2.7	110.7	19.4	5.35
11/03/03	7	547	245	6.13	131	5.39	5.1	0.13	1360	59.16	2706.5	28.19	53.4	1.5	99.2	17.4	4.50
STD Err	**0.7**	**144.6**	**86**	**2.16**	**57**	**2.33**	**4.94**	**0.13**	**493**	**21.4**	**902.3**	**9.40**	**37.7**	**1.1**	**42.1**	**13.1**	**1.26**

pH	measure of acidity or alkalinity of solution
EC	degree of salinity
SAR	relative proportion of sodium ions in water sample to those of calcium and magnesium
TDS	total dissolved salts

Table E 3. Water analysis results of the soil solution from a field of Fescue (cv. Demeter) collected at 0.40 m depth (Syferfontein, Republic of South Africa)

Sampling date	pH	EC	Ca^{+2}		Mg^{+2}		K^{+1}		Na^{+1}		$SO4^{-2}$		Cl^{-1}		SAR		TDS
		mS m^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	$(mmol\ l^{-1})^{1/2}$	g l^{-1}
07/01/02	5.1	641	498	12.5	320	13.16	9.01	0.23	930	40.45	3126.6	32.57	148	4.17	45.9	7.99	5.0316
14/02/02	8	280	192	4.8	148	6.09	0.81	0.02	437	19.01	1515.7	15.79	16.6	0.47	33.5	5.76	2.3101
20/03/02	6.9	289	100	2.5	62	2.55	1.09	0.03	536	23.31	1042.2	10.86	8.6	0.24	59.6	10.37	1.7499
04/04/02	8.5	474	285	7.1	158	6.50	1.82	0.05	850	36.97	1350	14.06	23.2	0.65	57.1	10.02	2.668
18/04/02	7.5	446	474	11.9	286	11.76	1.91	0.05	760	33.06	459.4	4.79	17.6	0.50	38.9	6.80	1.9989
16/05/02	8.2	451	156	3.9	117	4.81	12.00	0.31	950	41.32	952.6	9.92	21.1	0.60	81.3	14.00	2.2087
11/07/02	6.3	219	58	1.5	47	1.93	5.40	0.14	880	38.28	1844.3	19.21	106.7	3.01	121.5	20.81	2.9414
24/07/02	6.9	514	252	6.3	179	7.36	1.19	0.03	850	36.97	2442.1	25.44	77.5	2.19	57.9	10.00	3.8018
15/11/02			164	4.1	160	6.58	11.00	0.28	0.8	0.03	3426.1	35.69	101.7	2.87	0.06	0.01	3.8636
24/12/02	8.6	405	277	6.9	99	4.07	3.78	0.10	1730	75.25	1877.9	19.56	44.3	1.25	126.2	22.69	4.032
09/01/03	7.2	338	248	6.2	92	3.78	1.04	0.03	1630	70.90	1472.6	15.34	27.2	0.77	125	22.44	3.4708
28/02/03	6.8	148	56	1.4	31	1.28	2.56	0.07	372	16.18	573.8	5.98	12.6	0.36	56.4	9.89	1.048
01/04/03	7.4	462	158	4.0	140	5.76	3.79	0.10	1510	65.68	2303.5	23.99	63.4	1.79	123.7		4.1787
STD Err	**1**	**133.1**	**139**	**3.6**	**85**	**3.71**	**3.93**	**0.10**	**504**	**23.42**	**912.1**	**10.31**	**44.5**	**1.27**	**41**	**7.22**	1.3662

pH measure of acidity or alkalinity of solution
EC degree of salinity
SAR relative proportion of sodium ions in water sample to those of calcium and magnesium
TDS total dissolved salts

Table E 4. Water analysis results of the soil solution from a field of Eragrostis collected at 0.40 m depth (Syferfontein, Republic of South Africa)

Sampling date	pH	EC	Ca^{+2}		Mg^{+2}		K^{+1}		Na^{+1}		$SO4^{-2}$		Cl^{-1}		SAR		TDS
		$mS\ m^{-1}$	$mg\ l^{-1}$	$mmol\ l^{-1}$	$mg\ l^{-1}$	$mmol\ l^{-1}$	$mg\ l^{-1}$	$mmol\ l^{-1}$	$mg\ l^{-1}$	$mmol\ l^{-1}$	$mg\ l^{-1}$	$mmol\ l^{-1}$	$mg\ l^{-1}$	$mmol\ l^{-1}$	$mg\ l^{-1}$	$(mmol\ l^{-1})^{1/2}$	$g\ l^{-1}$
07/01/02	7.1	333	95	2.375	87	3.579	6.34	0.1621	630	27.4	1147.3	11.951	52.4	1.4781	66.04	11.231	2.018
14/02/02	8.2	245	289	7.225	203	8.35	0.93	0.0238	301	13.09	1375.7	14.3302	41.3	1.165	19.2	3.3175	2.2109
20/03/02	6.9	373	142	3.55	89	3.661	6.68	0.1708	724	31.49	1479.8	15.4146	44.3	1.2496	67.4	11.727	2.4858
18/04/02	8.4	273	85	2.125	75	3.085	2.48	0.0634	535	23.27	229.1	2.38646	9.1	0.2567	59.8	10.195	0.9357
16/05/02	8.5	365	188	4.7	121	4.977	0.56	0.0143	685	29.8	510.2	5.31458	0	0	55.1	9.578	1.5048
11/07/02	6.7	430	174	4.35	124	5.101	11.9	0.3043	925	40.23	1809.1	18.8448	78	2.2003	75.8	13.088	3.122
24/07/02	7.8	469	172	4.3	141	5.8	2.48	0.0634	825	35.89	2019.7	21.0385	71	2.0028	65.9	11.292	3.2312
15/11/02	6.8	504	204	5.1	152	6.253	3.47	0.0887	1	0.043	1951.2	20.325	104.2	2.9394	0.08	0.0129	2.4159
24/12/02	8.7	345	103	2.575	76	3.126	2.53	0.0647	1570	68.29	1041	10.8438	58.4	1.6474	165.9	28.601	2.8509
09/01/03	7.8	326	238	5.95	88	3.62	1.97	0.0504	1600	69.6	1177.7	12.2677	50.9	1.4358	125.3	22.497	3.1566
30/01/03	7.6	2.6	75	1.875	46	1.892	2.07	0.0529	900	39.15	1258	13.1042	24.2	0.6827	115.7	20.169	2.3053
28/02/03	7.1	293	82	2.05	52	2.139	3.23	0.0826	1240	53.94	1425	14.8438	31.2	0.8801	151.5	26.353	2.8334
11/03/03	7	495	18	0.45	94	3.867	3.97	0.1015	1360	59.16	1512.9	15.7594	27.2	0.7673	181.7	28.472	3.0161
01/04/03	7.4	408	177	4.425	100	4.114	2.76	0.0706	1370	59.59	2325.8	24.2271	48.3	1.3625	116.4	20.393	4.0239
STD Err	**0.7**	**127.4**	**73**	**1.84**	**42**	**1.72**	**2.93**	**0.075**	**476**	**20.7**	**565**	**5.8852**	**27.5**	**0.775**	**53.8**	**9.029**	**0.779**

pH	measure of acidity or alkalinity of solution
EC	degree of salinity
SAR	relative proportion of sodium ions in water sample to those of calcium and magnesium
TDS	total dissolved salts

Table E 5. Water analysis results of the soil solution from a field of Kikuyu collected at 0.40 m depth (Syferfontein, Republic of South Africa)

Sampling date	pH	EC	Ca^{+2}		Mg^{+2}		K^{+1}		Na^{+1}		SO4^{-2}		Cl^{-1}		SAR		TDS
		mS m^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	mmol l^{-1}	mg l^{-1}	(mmol l^{-1})$^{1/2}$	g l^{-1}
15/11/02	6.7	490	362	9.05	279	11.48	9.5	0.24	0.75	0.03	2021.8	21.06	140.5	3.96	0.04	0.01	0.01
24/12/02	7.8	635	921	23.03	824	33.90	2.39	0.06	1900	82.64	3736.3	38.92	323.8	9.13	64.3	10.95	10.95
09/01/03	7.6	304	219	5.475	98	4.03	0.94	0.02	1420	61.77	1334.6	13.90	30.2	0.85	112.8	20.03	20.03
30/01/03	7.8	1.91	77	1.925	51	2.10	0.96	0.02	505	21.97	1318	13.73	9.1	0.26	63.1	10.95	10.95
28/02/03	7.1	438	223	5.575	159	6.54	2.86	0.07	1360	59.16	2360.7	24.59	48.8	1.38	98.4	17.00	17.00
11/03/03	7.5	453	108	2.7	93	3.83	2.39	0.06	1150	50.02	2423.3	25.24	67	1.89	114.7	19.58	19.58
01/04/03	7.3	458	205	5.125	138	5.68	0.6	0.02	1450	63.07	2596.8	27.05	57.4	1.62	110.7	19.19	19.19
STD Err	**0.4**	**199.4**	**288**	7.199	**270**	11.10	**3.08**	0.08	**645**	28.06	**829.7**	8.64	**108**	3.05	**41.8**	7.28	7.28

pH	measure of acidity or alkalinity of solution
EC	degree of salinity
SAR	relative proportion of sodium ions in water sample to those of calcium and magnesium
TDS	total dissolved salts

Table E 6 pH (H_2O) of the soil during the growing period of the five pastures

Treatment	Year	pH			
		0-20	20-40	40-60	60-80
Fescue (cv. Iewag)	Oct 2001	5.9	6.8	6.8	8.6
	Oct 2002	7.5	7.2	7.3	7.9
	May 2003	8.2	7.7	7.8	-
	Oct 2003	7.4	7.1	7.2	8.0
Lucerne	Oct 2001	6.3	6.4	7.4	8.2
	Oct 2002	7.5	6.9	7.2	8.1
	May 2003	7.7	7.3	7.5	-
	Oct 2003	7.7	7.2	8.4	-
Fescue (cv. Demeter)	Oct 2001	6.7	6.5	6.7	8
	Oct 2002	7.3	7.1	7.6	-
	May 2003	7.3	7.1	7.7	8.2
	Oct 2003	7.8	7.7	8.3	-
Eragrostis	Oct 2001	7.4	6.8	7.4	8.3
	Oct 2002	7.4	6.9	7.1	7.8
	May 2003	7.2	6.9	7.5	8
Kikuyu	Oct 2001	7.4	6.8	7.4	8.3
	Oct 2002	6.2	6.4	7.5	8.2
	May 2003	7.3	7.1	7.6	8.4

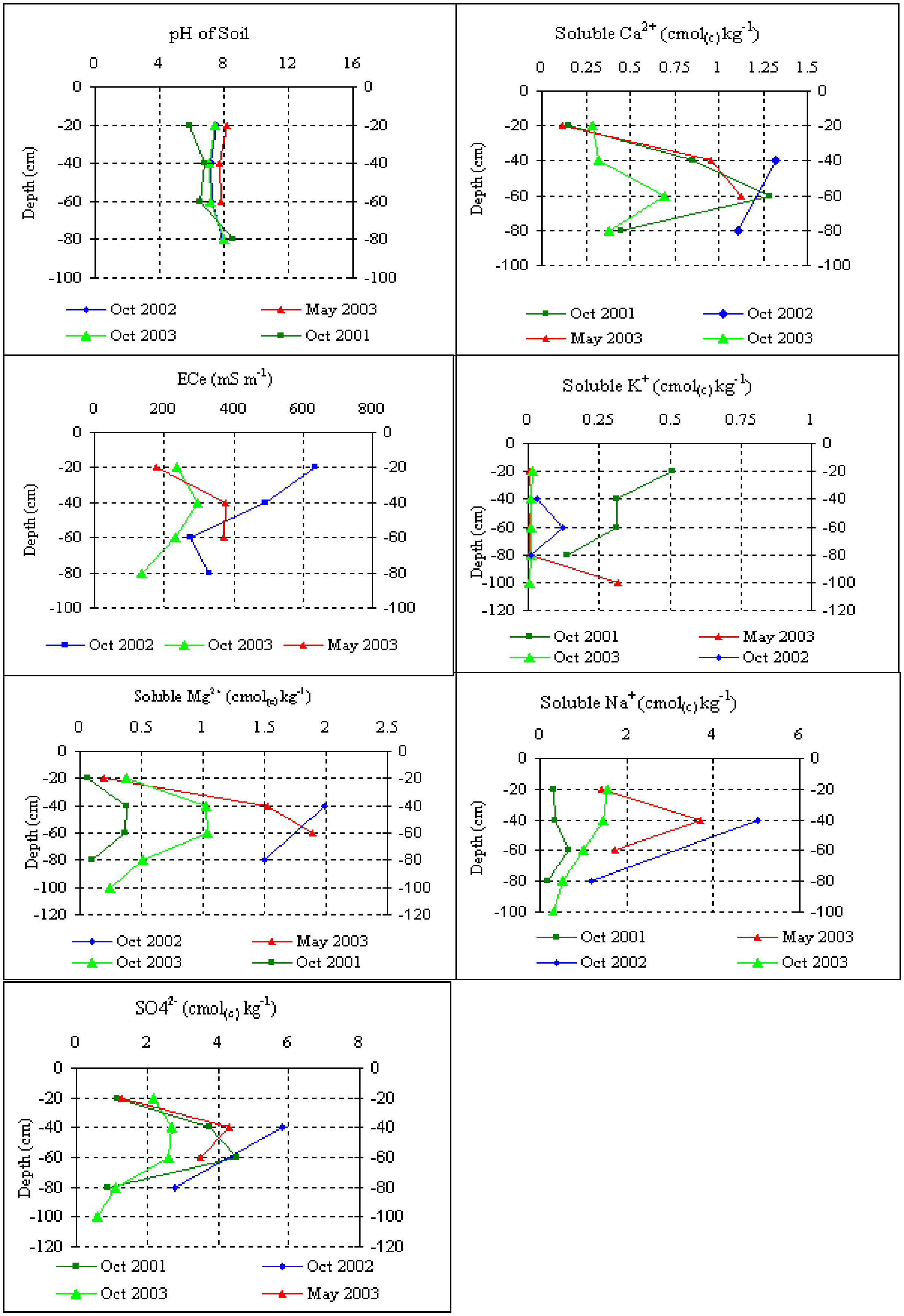


Figure E 1. Soil chemical properties of the Fescue (cv. Iewag) field during the growing period (2001 - 2003)

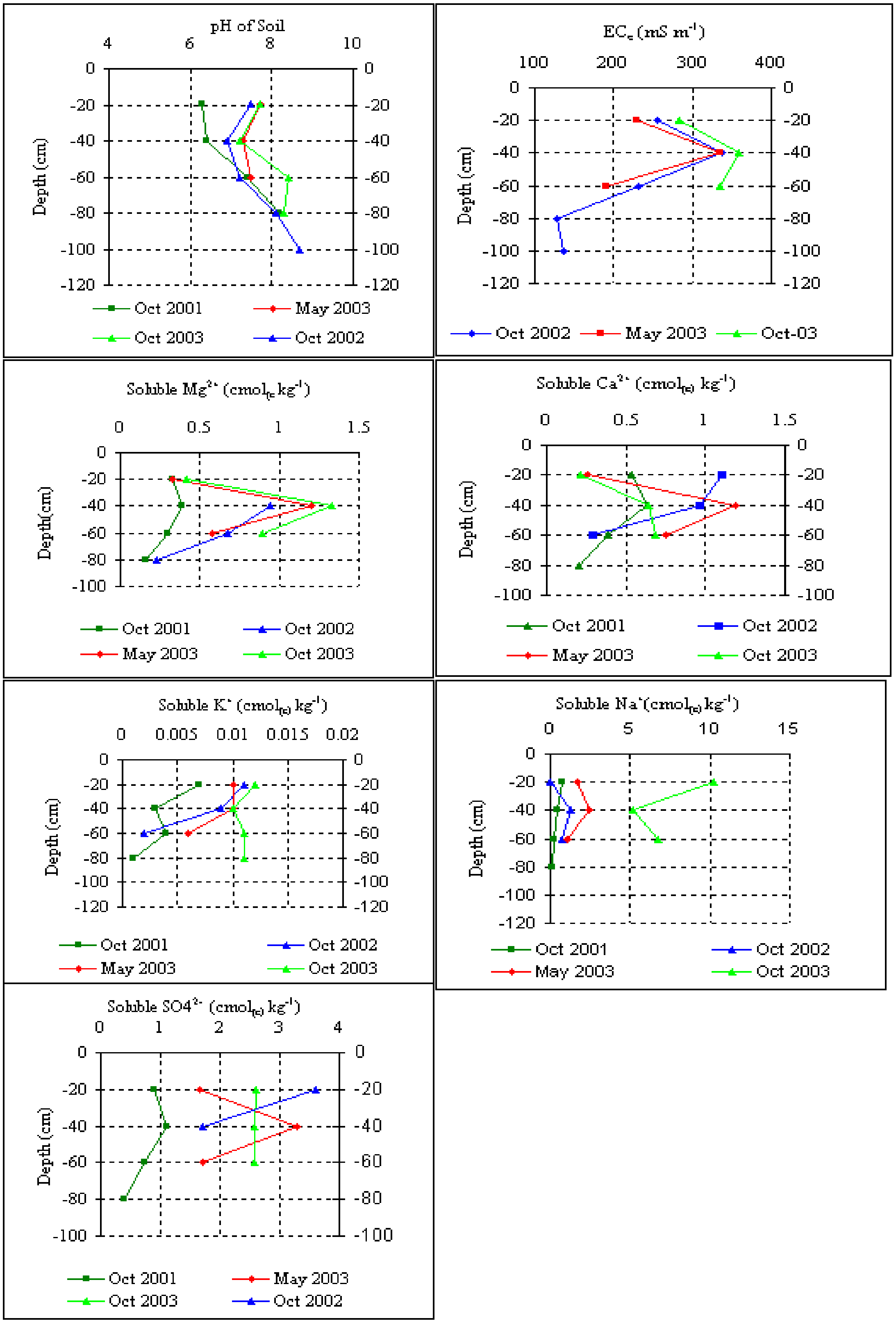


Figure E 2. Soil chemical properties of the Lucerne field during the growing period (2001 - 2003)

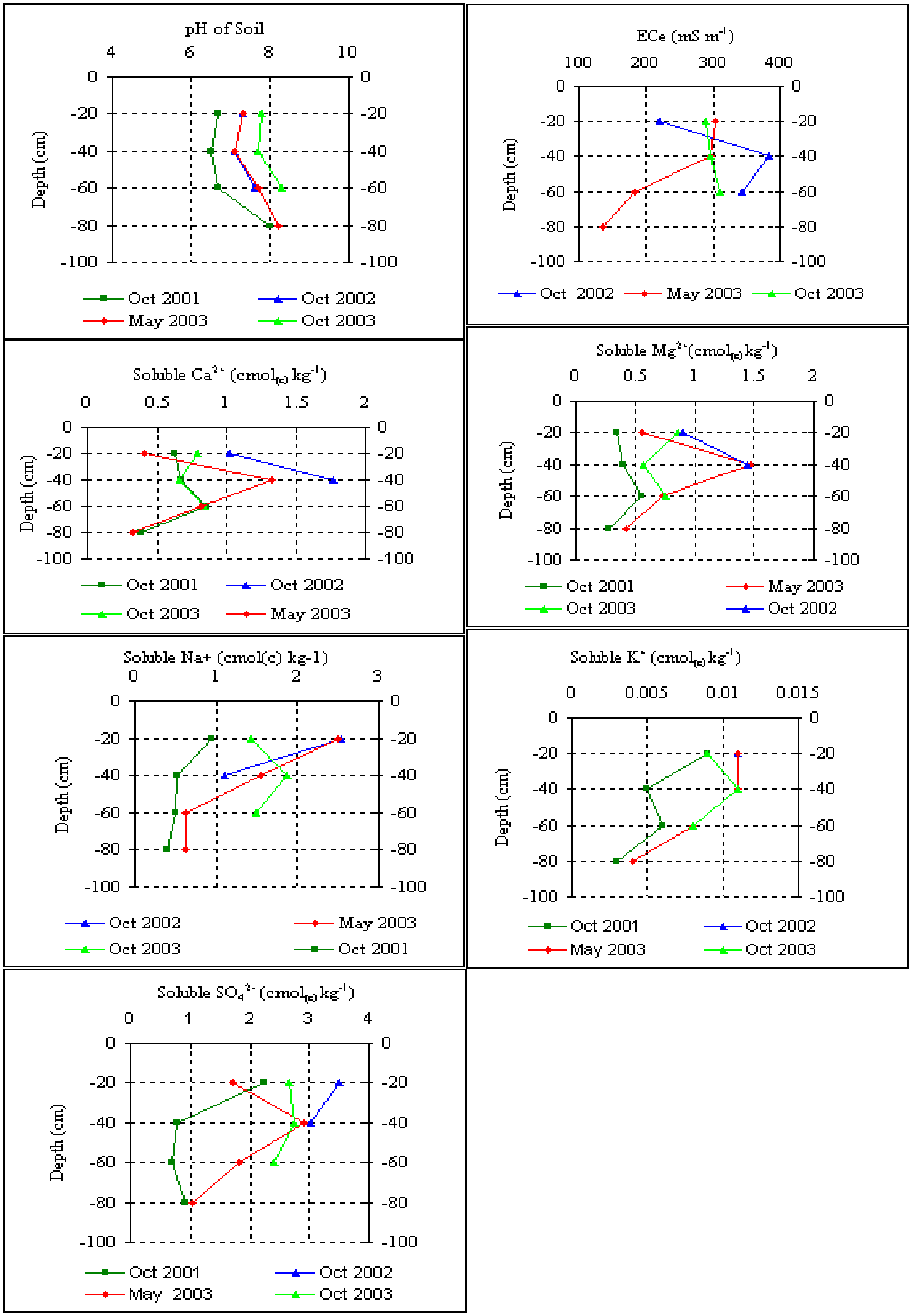


Figure E 3. Soil chemical properties of the Fescue (cv. Demeter) field during the growing period (2001 - 2003)

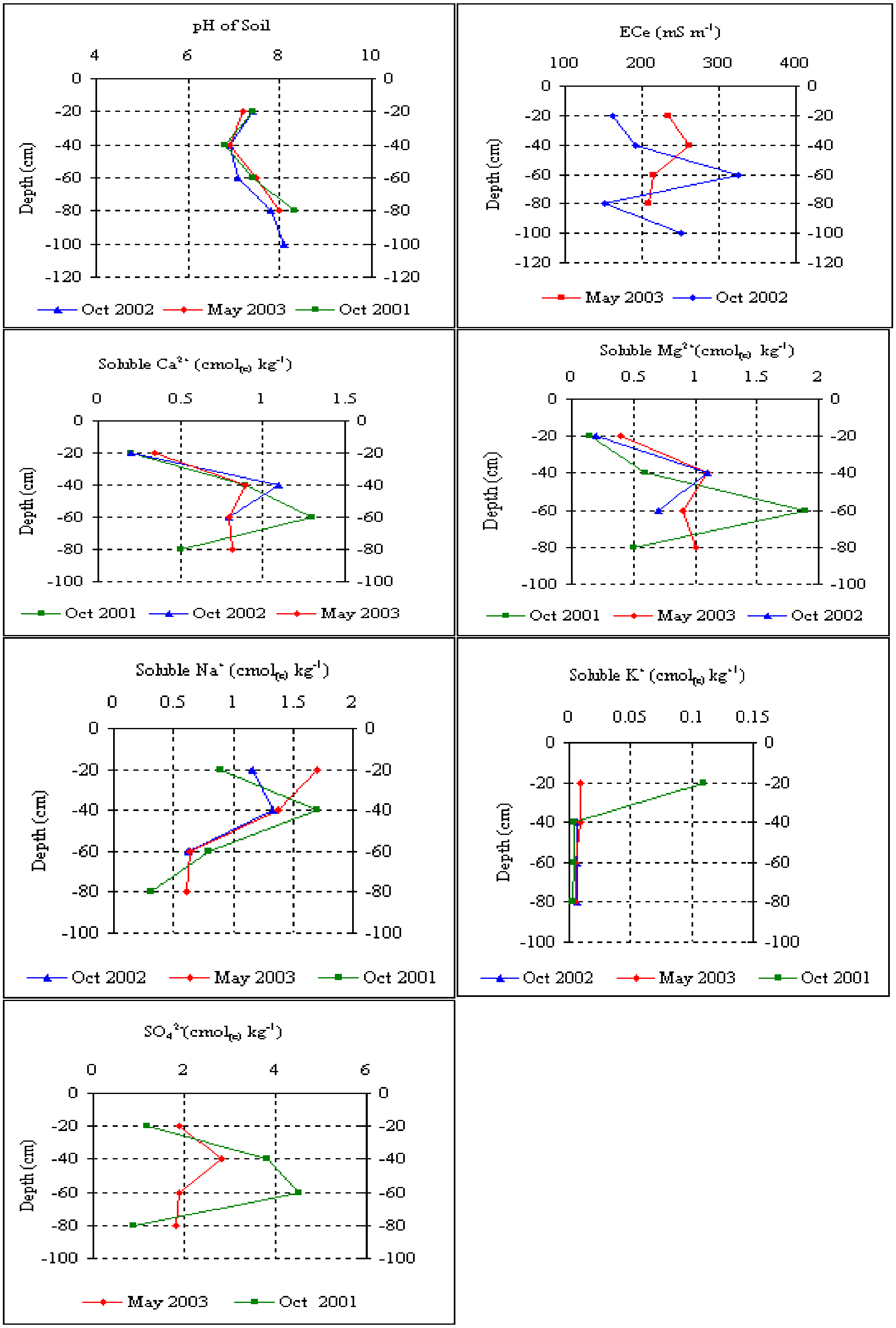


Figure E 4. **Soil chemical properties of the Eragrostis field during the growing period**

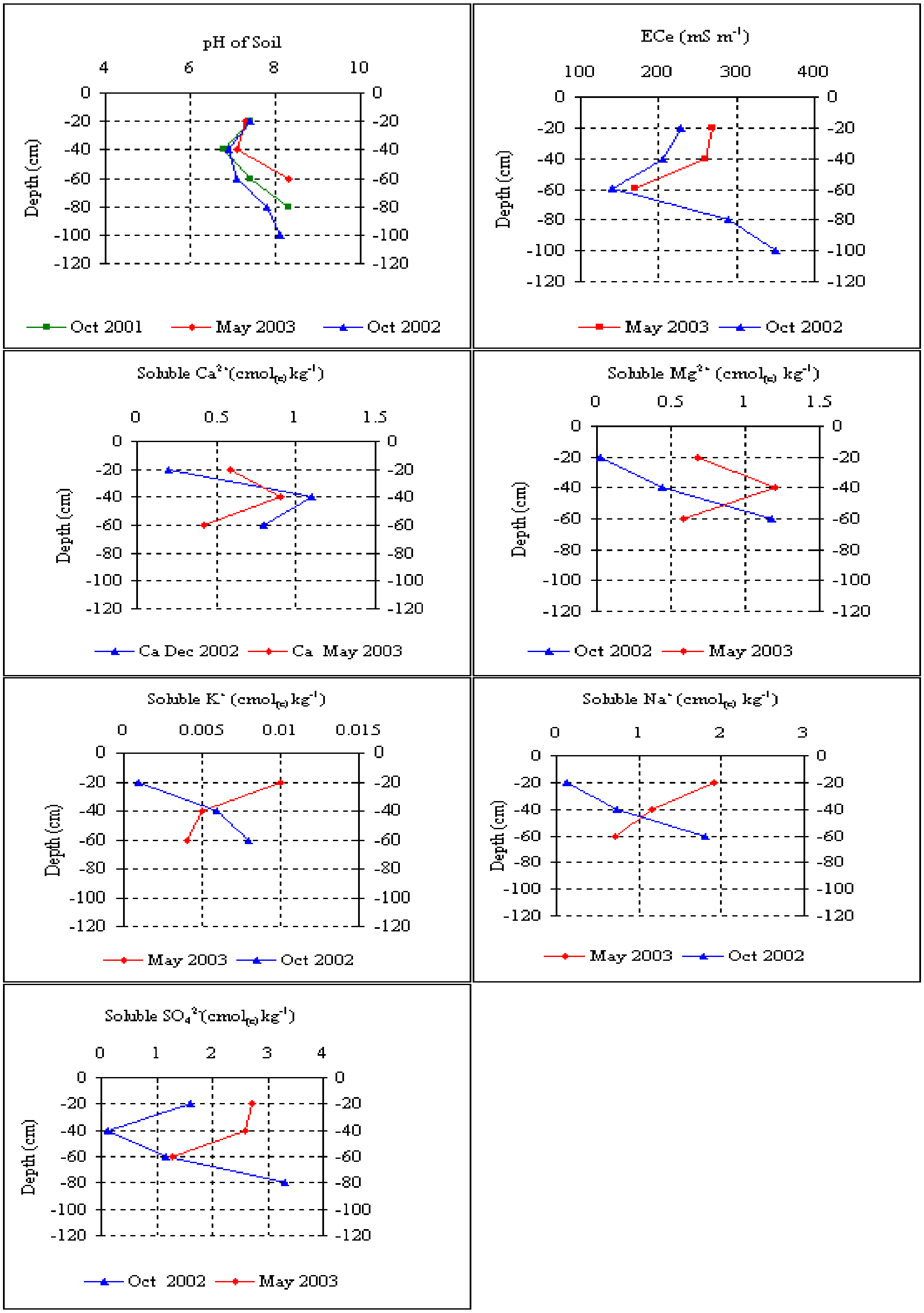


Figure E 5. Soil chemical properties of the Kikuyu field during the growing period (2002-2003)

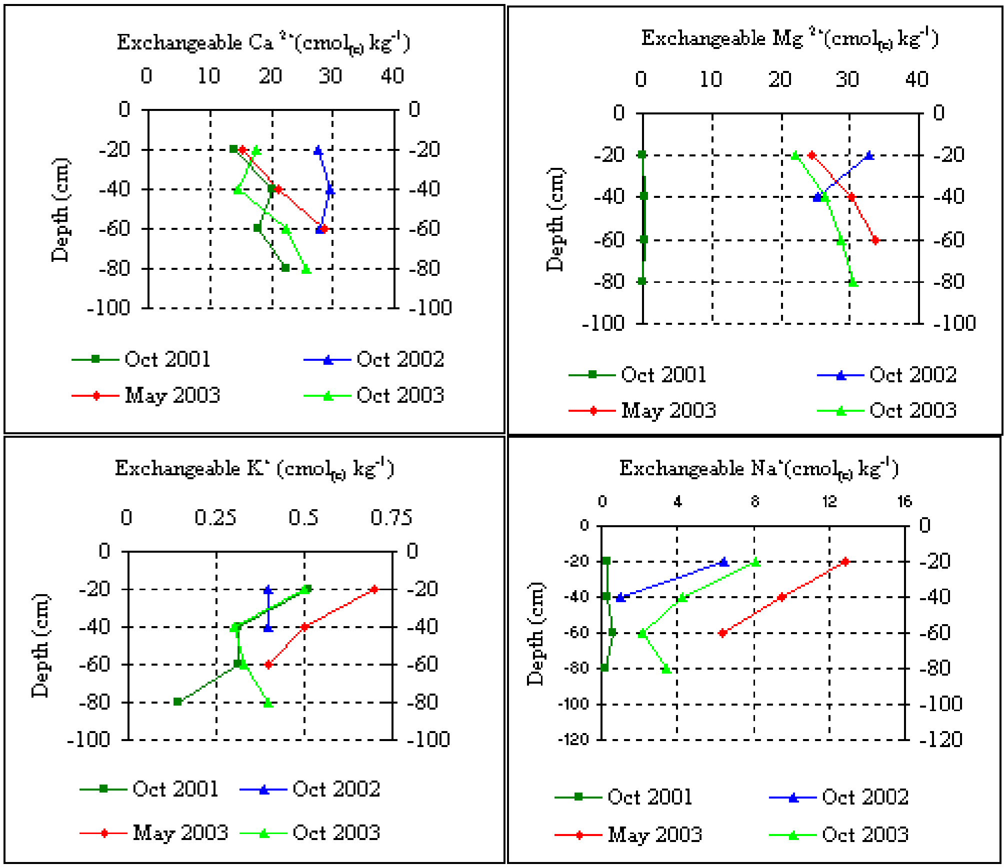


Figure E6. Depth profile of exchangeable cations under Fescue (cv. Iewag) (2001- 2003)

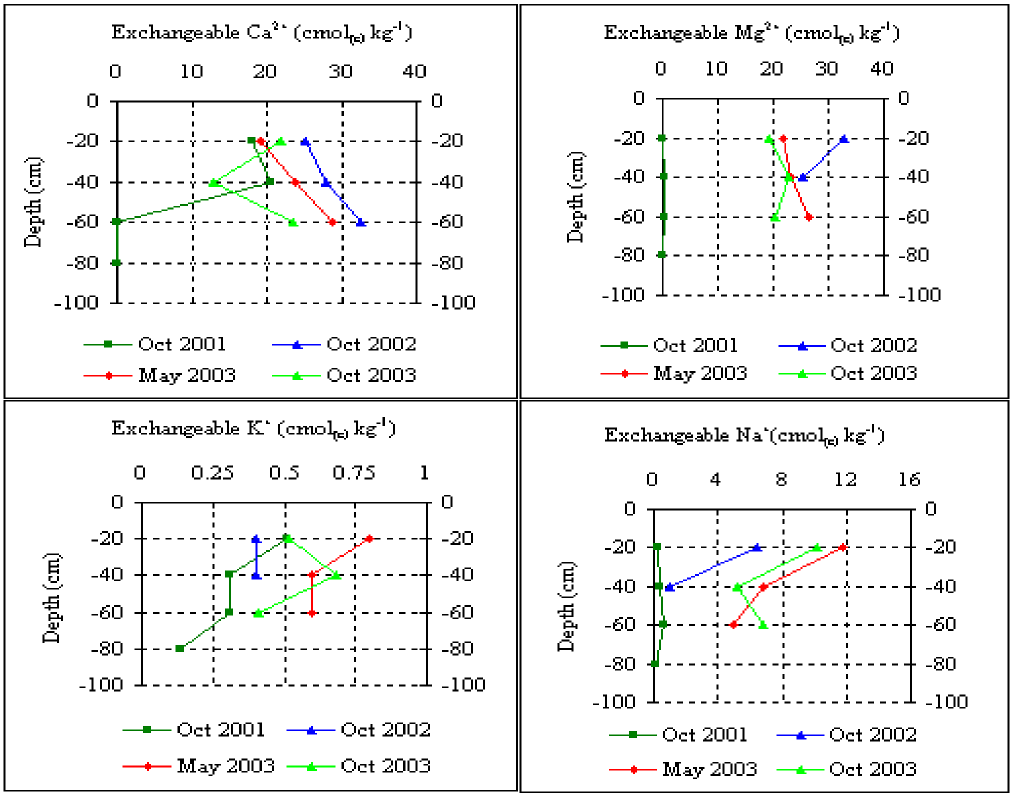


Figure E 7. Depth profile of exchangeable cations under Lucerne (2001 - 2003)

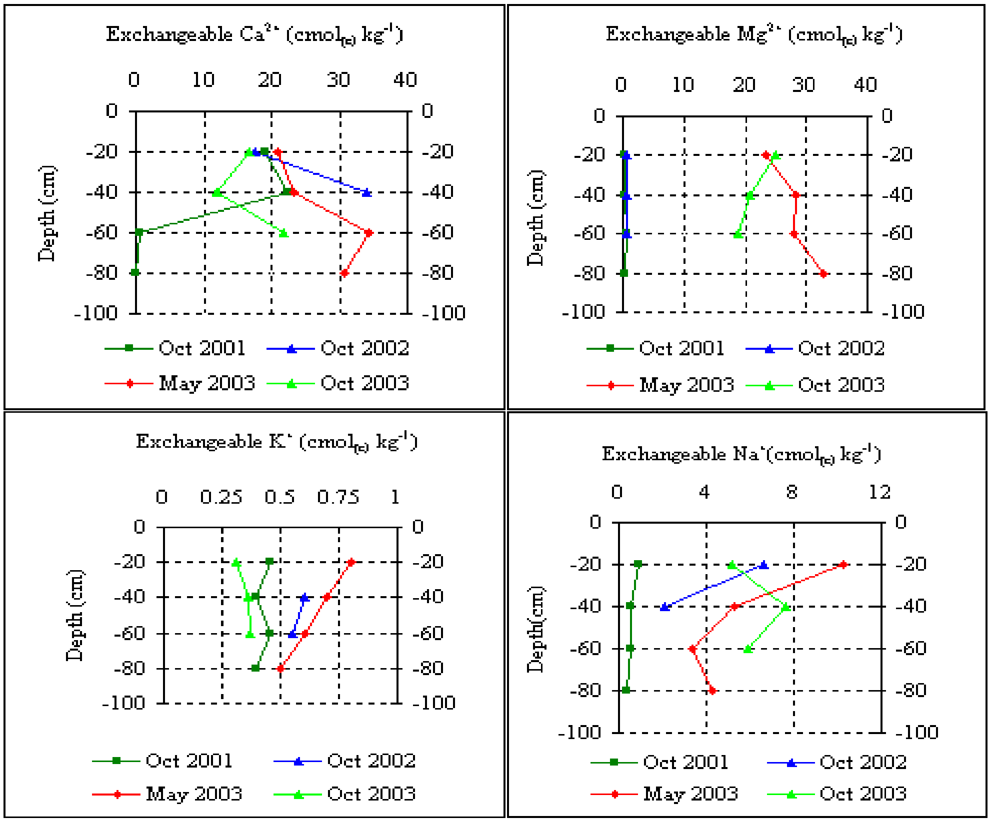


Figure E 8. Depth profile of exchangeable cations under Fescue (cv. Demeter) (2001 -2003)

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