WATER USE AND NITROGEN APPLICATION FOR IRRIGATION MANAGEMENT OF ANNUAL RYEGRASS AND KIKUYU PASTURE PRODUCTION

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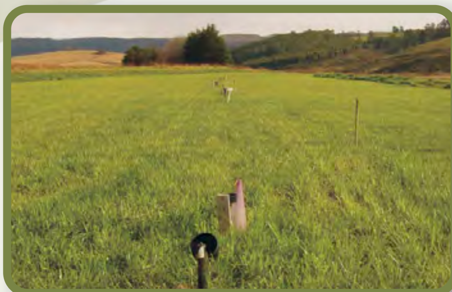

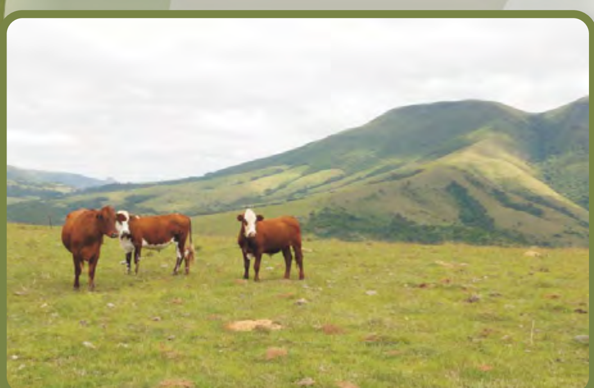

WATER RESEARCH COMMISSION

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Report to the

WATER RESEARCH COMMISSION

by

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executive summary

1. OVERVIEW OF THE STUDY

To meet the increasing demand for animal protein as human populations increase, there is a need to increase water (and land) productivity. Natural veld cannot fulfil this need alone and must be supplemented with irrigated and fertilised planted pastures. This requires intensive use of fertilisers and water, which leads to a higher cost of production and a greater risk of environmental pollution. Thus, farmers are under pressure to decrease their share of water and fertiliser usage, whilst at the same time, produce sufficient pasture to supply the protein (i.e. milk) demand of a growing population more efficiently.

In South Africa, annual ryegrass (*Lolium multiflorum*) and kikuyu (*Pennisetum clandestinum*) are the most widely grown pasture species under irrigation. They are mainly used in dairy farming enterprises. Shortages of water and nitrogen can, however, be limiting factors for the production of these pastures. By using appropriate irrigation and nitrogen management tools, water and nitrogen productivity of the pasture species can be improved.

For sustainable pasture production in dairy farming, the best possible fertiliser and water regimes are required to attain high biomass yield to maximise profit and minimise the impact on the environment. The most appropriate and cost effective management strategy is to integrate irrigation and nutrient (especially nitrogen) inputs, since they cannot be managed independently.

To accurately identify the knowledge gaps of the existing planted pastures irrigation and nitrogen fertiliser strategies, an extensive literature review was performed. To assess the problems, detailed field trials at Cedara, Pietermaritzburg, and the University of Pretoria's Hatfield Experimental Farm were carried out. Based on the results from these trials, the Soil Water Balance (SWB) model was calibrated and validated. The model was used to develop site specific irrigation guidelines and calendars.

2. OBJECTIVES OF THE STUDY

The aim and objectives as specified in the terms of reference of this solicited project were:

Aim:

To promote efficient irrigation management of grass pastures (emphasis on ryegrass and kikuyu) by synthesizing available knowledge and generating new knowledge for improving water use efficiency by pastures.

Specific Objectives

1. Estimate water requirement/use (modelling) with respect to:
   - Irrigation strategies
   - Managing pastures
   - Managing grazing
   - Simple ways to monitor, e.g. soil water status, compaction, root development, dry matter status
2. Identify knowledge gaps based on inputs required (soil-plant-atmosphere) by existing models.
3. Generate information on growth analysis and water balance studies for

important grasses (ryegrass and kikuyu) in important areas (KZN midlands, E-Cape coast) required for modelling.

4. Determine water requirements of the selected pastures through testing and evaluation of the model.
5. Extrapolate irrigation requirement estimates using models.
6. Develop generic guidelines for efficient irrigation management of grass pastures (for both existing pastures and for planned pastures) with specific reference to rye grass and kikuyu and addressing irrigation strategies and pasture management.

The main objective of this project was to optimise the growth of ryegrass through efficient use of water and nitrogen (N) fertilisation. One of the tools for achieving this was the use of numerical models for which base-line information is needed for parameterisation and testing. Hence a number of crop/pasture models were reviewed (Appendix A) and the SWB model and DairyMod were selected. However, since the objective of the project was mainly to estimate water use and not milk production the SWB model was used. Considering the use of a large number of data sets and time consuming determination of input parameters required for the pasture specific models, relatively simple models (such as the SWB) are more applicable. The major problem with adoption of models by the farmers is their complexity, therefore, there should be trade-offs between accuracy and simplicity. The SWB model is being used to simulate crop growth and soil water balance of several cereals, vegetable and tree crops. Therefore, it is better to use a model which is locally known by farmers and consultants instead of introducing another new model. The model is available on the web and can be downloaded free of charge. As a result the SWB model was calibrated and validated and after satisfactory evaluation the model was used to predict the water requirements of annual ryegrass in the major pasture growing areas of South Africa.

3. HATFIELD EXPERIMENTAL FARM TRIAL ON WATER USE OF ANNUAL RYEGRASS

Experiments were conducted to determine the effects of different water levels in combination with different N fertiliser applications on the growth rate and dry matter production, quality, water use and water use efficiency of annual ryegrass under a rain shelter on the Hatfield Experimental Farm of the University of Pretoria for two seasons. Higher frequency of irrigation coupled with high nitrogen application significantly improved the dry matter yield. Canopy size influenced the Leaf area index (LAI) which in turn affects the yield. The study showed that the treatments that were irrigated twice weekly and top-dressed with 60 kg N ha^{-1} after each cut consumed the most water, and this resulted in the production of higher yield, maintenance of the largest leaf area index and higher interception of the incoming solar radiation. The increase in these parameters may be due to the sufficient water and nitrogen fertiliser that induces rapid cell elongation as a result of higher water potential, higher turgor pressure and higher photosynthetic processes.

The decrease in the frequency of water application resulted in an increase in the dry matter content (DMC), digestibility, metabolisable energy (ME) and crude protein (CP) values. Nitrogen application had an effect on the WU, as less water was used in the treatments that received no nitrogen. Highest crop coefficient (Kc) value recorded was in the optimal range and this indicated that the treatments were not over-irrigated. As the irrigation interval increased, more water was depleted from the soil profile. Depletion rates increased as the season progressed but generally it was minimal in the frequently irrigated treatments. Increase in water use efficiency (WUE) was achieved by reducing the frequency of irrigation from twice a week to once a week without causing significant yield loss. A possible reason for the increase in the WUE by reducing the irrigation frequency could be ascribed in part to reduced evaporation from the soil resulting from the lower wetting frequency of the deficit irrigation treatments. Within the same irrigation frequency, higher WUE was achieved by alleviating a limiting factor, N fertiliser, in this case, through increases in dry matter production. The highest WUE was achieved by irrigating once every two weeks. However, in some treatments, the WUE was not improved with the reduction in the frequency of irrigation as the water saved was overshadowed by yield loss.

In summary, it can be said that pasture production was be positively associated with soil water content, water stress can improve the quality of the pasture, N fertiliser will increase the forage yield response to soil water content and WUE will increase by alleviating a limiting factor, N fertiliser in this case were accepted. A logical extension of this work would be to do the trial in an open field to analyse the effect of irrigation and nitrogen fertilization on the growth, yield and quality of the pasture and then extrapolate the results to other sites and soil types using models.

4. CEDARA RESEARCH STATION TRIAL ON WATER AND NITROGEN USE OF ANNUAL RYEGRASS

For all the treatments, over 80% of the roots were found at the top 0.3 m and the majority (>98%) rooting depth was 0.6 m. Root biomass of treatments were averaged throughout the year (no significant differences between treatments) and the values ranged from 500 to 600 kg ha^{-1}.

The major soil water extraction was observed from the top 0.4 m, and about 70% of the extraction was mostly from the top 0.2 m ascribed to the high root density in the surface layers. All treatments showed similar trends of soil water extraction, though the rate of depletion was higher at higher levels of nitrogen.

There were significant differences in applied irrigation and water used between treatments. Seasonal irrigation use efficiency of adaptive water (N_{water}) treatment was significantly higher than that of N mass balance (N_{MB}) treatment. The seasonal water application N_{water} was 44 mm lower than N_{MB} where mass balance calculations were used for N applications in both treatments. The N_{water} strategy showed a potential to increase water and irrigation use efficiencies, the slim benefit in this study was because the crop was not stressed. More N and water can even be saved by combining both adaptive N and irrigation strategies.

Generally, for most growth cycles, the highest forage yields were produced when N application rates ranged between 30 to 60 kg N ha^{-1} $cycle^{-1}$, except for the first growth cycles when there was high soil N carryover from the previous season. The amount of N fertiliser required for achieving a maximum forage yield and quality varies widely among growth cycles depending on soil N availability. N fertiliser application for the first two to three cycles did not improve forage yield but reduced quality (high CP).

Consequently, the current farmers' recommendation (fixed N application rate of 50 kg ha^{-1} per growth cycle) aimed at maximising biomass yield may not improve animal performance for all growth cycles. Similar overall animal performance or milk yield can be achieved by applying less N fertiliser and compensating the reduced yield with an improved quality of forage (lower CP), while also minimising environmental impact. This is important for a pasture based system, because farmers do not have the option of mixing rations to balance the change in pasture crude protein during the season.

Adaptive nitrogen fertiliser and irrigation management (Chapter 3) were effective in reducing N application without reducing forage yield. At the same time N and water use efficiencies were improved and the potential for N leaching reduced. Seasonal N application was reduced by 28% when components of the N balance (e.g. N mineralisation, N carry-over from previous growth cycle, etc.) were measured at the start of each cutting cycle (N_{MB}). However, the expense of such monitoring may not be justifiable on economic grounds. The adaptive approaches showed that N savings from routine monitoring could also be realised through a simpler adaptive approach based on thresholds for the nitrate concentration in the soil solution. Adaptive approaches of reduced N (N_{soil}) and water (N_{water}) applications resulted in 27% and 32% less N application than the baseline recommendations from the South African Department of Agriculture, respectively. Both adaptive treatments resulted in an improvement of forage quality with no yield reduction, and a lower risk of N leaching.

Apart from the early season harvests, the current study showed that the optimum N application per cycle was between 30-60 kg N ha^{-1} in 2007 and 40 kg N ha^{-1} in 2008. Hence, N application rate of 30-40 kg N ha^{-1} per growth cycle should give optimum forage yields and with CP concentrations within the boundaries of optimum CP and maximum CP. No fertiliser may be required for the first 2-3 growth cycles, when CP was very high, and this can be confirmed by considering soil N.

The trade-off between yield and quality will depend on whether the pasture is managed for grazing or indoor ration based dairy production. For pasture based systems, trading-off forage yield for better forage quality is important. This can be achieved by reducing N application because high application rates reduce forage quality and energy value. However, for indoor ration based dairy production, targeting maximum biomass yield would be better because the feed can be supplemented with low-cost roughages.

5. EVAPOTRANSPIRATION ESTIMATION OF RYEGRASS USING THE ENERGY BALANCE METHOD

Accurate prediction of crop evapotranspiration (ET) is a pre requisite for effective irrigation by matching the water requirement of pastures. A major potential source of error in ET determined by the soil water balance method is uncertainty in drainage from the zone sampled or any upward movement of water from a lower wetter zone into the zone sampled. Therefore, in this study for validating the SWB model evapotranspiration of ryegrass was estimated using the energy balance method. The measurements of eddy covariance system (EC) and surface renewal (SR) were conducted for three growth cycles (11th September to 6th of November 2008). The measurements of eddy covariance and surface renewal systems were used for estimating sensible heat flux (H) and the latent heat flux being obtained as the residual in the energy balance equation.

Reference evaporation (FAO 56) varied from less than 1 mm on rainy days to greater than 6 mm in the hot spring and summer periods. These data were used to predict the atmospheric evaporative demand of the site and used to develop crop coefficients of annual ryegrass. During the three regrowth cycles water use ranged from 0.5 mm during rainy days to 6 mm on sunny days.

Crop coefficients (Kc) of optimally fertilised annual ryegrass were developed for three individual regrowth cycles during spring and summer. Kc was calculated as ET/ETo. ET was determined from ET measurements of EC and SR methods. There was high variation of Kc among days ranging from 0.7 to 1.1, for most of the days and regrowth cycles depending on the evaporative demand of the day.

6. MODELLING WATER USE OF ANNUAL RYEGRASS

This study has shown that the current irrigation guidelines of 25 mm of irrigation per week for most temperate grasses, including ryegrass, leads to over-irrigation in the cooler part of the season or under-irrigation in the warmer part of the season. To use the model for determining irrigation requirements and developing irrigation calendars, the SWB model was validated at two sites for different irrigation treatment practices. The model performed well in simulating ryegrass growth and above ground biomass production (leaf area index and forage yield), root zone soil water deficit and daily evapotranspiration.

Once the performance of the SWB model was satisfactory, site specific water requirements of ryegrass were developed for four major milk producing areas of South Africa (KwaZulu-Natal Midlands, Eastern Highveld, Eastern Cape and Southern Cape). The model can also be used by farmers or consultants to develop their own calendars with relatively few simple inputs. The model is available on the web and can be downloaded free of charge.

7. ESTIMATION WATER USE OF KIKUYU USING REMOTE SENSING

The aim of this study was to evaluate the suitability of using remote sensing technology to improve the spatial monitoring of pasture including estimates of evaporation and biomass. Several different forms of quantitative remote sensing tools have been developed over time, and include the flux type models, e.g. Surface Energy Balance Algorithms for Land (SEBAL). For this application, pastures growing in the Eastern Cape were selected for the SEBAL and SWB modelling. Kikuyu which is a C_4 pasture specie comprises the greater part of irrigated summer and autumn pasturage for milk production in the region of the Eastern Cape of South Africa.

The SEBAL model simulated a mean daily evaporation during winter of 2.04 ± 0.07 mm day^{-1} compared to summer mean values of 6.79 ± 2.13 mm day^{-1}. SWB model simulated similar daily evaporation in winter (2.05 ± 0.64 mm day^{-1}) while the daily evaporation during simmer was lower (4.6 ± 1.16 mm day^{-1}).

This report has demonstrated the applicability of a remote sensing tool (SEBAL), to predict evapotranspiration and biomass at a spatial resolution (30 m) suitable for irrigation scheduling. The differences in yield and growth rate between SEBAL and SWB models could be on the amount of stubble biomass left after defoliation (grazing or cutting). Therefore, further evaluation of the models using measured datasets is required. For future research in this field larger areas of intensively monitored field sites need to be found where both evapotranspiration and biomass measurements can be made together with the remote sensing measurements.

8. FUTURE RESEARCH RECOMMENDATIONS

Management of dairy farming has now attained unprecedented levels of technology largely due to the availability of practical equipment and methods for planning, managing and monitoring most facets of dairy farming. However, this does not apply to irrigation of pastures, which still tends to rely on experience and tradition despite the increasing role of pastures in milk production.

Irrigation water, nutrients and electricity can be optimised by selecting the appropriate irrigation type and scheduling technique and pasture. According to the pasture and livestock budgets of 2009/2010 N and K fertilisers represent more than 50% of the total input costs. The most appropriate and cost effective management strategy would therefore be to integrate irrigation and N inputs, since nitrogen and water cannot be managed independently. Therefore, future research should focus on integrating both irrigation and fertilisation management practices to improve the efficiency of both resources.

Due to the high cost of N fertiliser, farmers have started planting temperate legumes with tropical or temperate grass mixtures in the southern Cape and KwaZulu-Natal. Therefore, the water use of this practice and the more common practice of kikuyu over-seeded with ryegrass needs to be researched.

Currently, satellite-based remote sensing is showing promising results in estimating irrigation requirements of ryegrass/kikuyu. In the near future, this technology could become a more affordable tool for irrigation scheduling of pastures. For future research, large areas of intensively monitored field sites need to be found where both evapotranspiration and biomass measurements can be made together with the remote sensing.

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acronyms

ADF	Acid detergent fibre
ANOVA	Analyses of variance
CP	Crude protein
D	Index of agreement
DAP	Days after planting
DMC	Dry matter content
Dr	Deep drainage
DWAF	Department of Water Affairs and Forestry
ET	Evapotranspiration
ETo	Reference evapotranspiration
FAO	Food and Agriculture organization
G	Soil heat flux
GDD	Growing degree day
GE	Gross energy
H	Sensible heat flux
I	Irrigation
IUE	Irrigation use efficiency
IVOMD	In vitro organic matter digestibility
LAI	Leaf area index
LSD	Least significant difference
MAE	Mean absolute error of measured values
ME	Metabolisable energy
NDF	Neutral detergent fibre
NEWSWB	New Soil Water Balance
NUE	Fertiliser N use efficiency
N_{init}	Initial soil inorganic N
N_{min}	Mineralisable N
NPN	Non-protein nitrogen
NTP	non-true protein
N_{fer}	N input from fertiliser

N_{up}	Above ground crop N uptake
N_{soil}	Adaptive N
N_{water}	Adaptive water
NWM	Neutron water meter
P	Precipitation
PAW	Plant available water
R	Runoff
r^2	Coefficient of determination
Rn	Net irradiance
RR20	Leaving 20 mm deficit
VPD	Vapour pressure deficit
Site-cal	Site specific calendar
SWBPro	Soil Water Balance irrigator/consultant version
SWB-Sci	Soil Water Balance scientific version
TDR	Time domain reflectometer
NSC	Total non-structural carbohydrates
TP	True protein
T	Sonic temperature
$T_{cut-off}$	Cut-off temperature
T_{max}	Daily maximum air temperature
T_{min}	Daily minimum temperature
WFD	Wetting front detector
WU	Water use
WUE	Water use efficiency
Y	Forage yield
ΔQ	Soil water storage
ε	Wind direction
u	Horizontal wind velocity
v	Vertical wind velocity
w	Vertical wind velocity
z	Rooting depth
θ	Soil water content

CHAPTER 1: INTRODUCTION

1.1 RATIONALE

Irrigation uses about 62% of South Africa's surface and ground water resources at 98% assurance (DWAF, 2004). Irrigated agriculture is facing fierce competition for this substantial share of water as the water demand for industrial, domestic, municipal and other activities are increasing rapidly. There is a need to increase water (and land) productivity, to meet the increasing demand for animal protein as human populations increase and diets become more affluent. Thus, farmers are under pressure to decrease their share of water and fertiliser usage, whilst at the same time, produce sufficient pasture to supply the protein demand of a growing population more efficiently. Natural veld cannot fulfil this need alone and must be supplemented with irrigated and fertilised planted pastures. This requires intensive use of fertilisers and water, which leads to a higher cost of production and a greater risk of environmental pollution.

Due to the erratic nature of rainfall in South Africa, grasses can experience drought at any stage of growth. Hence, the yield and nutritive value will be low. In South Africa an increase in irrigated pastures in the winter rainfall and summer rainfall regions have been reported (Tainton, 2000). Supplementary irrigation in summer is usually used for tropical pasture crops such as kikuyu when spring rains are late or in periods of water stress, whereas the production of annual ryegrass pastures during winter is under irrigation. Due to the high cost of irrigation water and fertilisers during winter (Tainton, 2000) the production of pasture under irrigation is economically discouraging. Therefore, a better management system for pastures is required, and this includes scheduling the irrigation and nutrient requirement of grasses according to their utilization method and intensity. Good pasture is the cheapest source of animal feed, especially milk production. Two grass species, kikuyu (*Pennisetum clandestinum*) and annual ryegrass (*Lolium multiflorum*) are commonly used in dairy farming enterprises. Irrigated kikuyu and ryegrass or kikuyu/ryegrass mixtures form an important component of the fodder production in South Africa. These pastures are established on marginal soils not suitable for agronomic, vegetable or horticultural crops (Van Heerden and Durand, 1994).

In South Africa, returns generated from animal production enterprises make pastures one of the highest value crops produced under irrigation. It is estimated that the total area utilized for irrigated pasture production is approximately 16% of the total area under irrigation (Backeberg *et al*., 1996). Irrigated annual ryegrass is the primary sources of feed in the pasture based dairy industry and is mostly grown in the relatively higher rainfall areas particularly in the KwaZulu-Natal Midlands, the Eastern Highveld, the Eastern Cape and in winter rainfall areas of South Africa (Dickinson *et al*., 2004). Annual ryegrass has high nutritional qualities, palatability, digestible energy, protein and mineral contents (Theron and Snyman, 2004). It plays an essential role in supplying good quality grazing between the winter and summer seasons thereby dramatically improving fodder flow options in the dairy industry (Eckard *et al*., 1995).

Kikuyu (*Pennisetum clandestinum*) is the predominant summer grass pasture used for milk production along the east coast of South Africa and is also important in certain parts of the

KwaZulu-Natal Midlands. Kikuyu is a high producing grass of exceptional nutritional value if managed properly. For a farmer to obtain reasonable milk production from kikuyu, quality rather than quantity of pasture on offer is important. However, pasture management strategies should not only be directed at improving forage quality, but also to optimise the re-growth potential of the plant and the utilization by animals. Goodenough *et al*. (1984), reported that the other important pasture species, annual ryegrass (*Lolium multiflorum*), was the most widely grown species in the higher rainfall areas of South Africa. In a survey conducted in three bioclimatic regions in the KwaZulu-Natal Midlands, annual ryegrass was found to be the main irrigated species on both beef and dairy farms (Heard *et al*., 1984; Smith, 1985). It is usually over-sown to perennial summer pastures such as kikuyu. The optimum planting date for irrigated annual ryegrass in Natal Midlands is in February, hence it can be used as a source of feed in late autumn, winter, spring and early summer (Goodenough *et al*., 1984). Good management is therefore imperative in supplying better quality material between the winter and summer grazing for this practice to be a success.

Annual ryegrass is divided into two different types, namely Westerwolds and Italian. Westerwolds are true annuals and in South Africa they are generally planted in autumn, as rising temperatures and increased day length in spring causes seed set. When Italian ryegrass is sown in autumn, it will normally extend by as much as four weeks longer into the early summer than Westerwolds. This characteristic of Italian ryegrass type plays an essential role in supplying better quality material between the winter and summer grazing. Italian (annual) ryegrass was selected over perennial grass due its high forage yield during winter and its good quality for the dairy industry. Moreover, perennial ryegrass has also a problem of persistency (Eckard, 1994).

Although management of dairy farming has now attained unprecedented levels of technology, largely due to the availability of practical equipment, this does not apply to N fertilisation and irrigation of pastures. In spite of the increasing role of pastures in milk production, there are still trends to rely on experience and tradition even for managing the most important pasture production factors. Irrigation water and nutrients are resources that can be optimised by selecting an appropriate irrigation type, scheduling technique and pasture type (i.e. N fixing legumes and/or crops with high water use efficiency). For a sustainable pasture production, the best possible fertiliser and water regimes are required in order to attain high biomass yield with minimum inputs, which maximises profit whilst minimising the impact on the environment. The most appropriate and cost effective management strategy would therefore be to integrate irrigation and nutrient (especially N) inputs, since nitrogen and water cannot be managed independently.

Despite the latest fertiliser and irrigation application equipment and scientifically based guidelines, it can be seen that there are knowledge gaps between research and farming practices. A number of experiments have been carried out throughout the country on the effect of nitrogen on yield and quality of grass pastures; however, there is a lack of reliable information and data pertaining to ryegrass water requirements to facilitate efficient irrigation management.

Many researchers have worked on the modelling of grass production but the integration of water and nitrogen in relation to irrigation strategies and fertilizer management have not been totally addressed. Therefore, the challenge is to accurately understand and describe the interaction between water and nitrogen using pasture growth model(s) and develop practical on-farm equipment and methods for planning and monitoring. Model(s) can be used to accurately schedule irrigation and fertilizer by applying the correct amount of water and N, thereby minimizing nitrogen leaching and ensuring efficient water use. Alternative methods to address these gaps are needed to be investigated and applied in practice in order to increase nutrient and water use efficiency on farm level. Therefore, the focus the study will be to integrate both irrigation and nitrogen management in order to improve the efficiency of both resources.

The Water Research Commission initiated and funded a 5 year solicited project to study the irrigation management of ryegrass and kikuyu pastures under different management conditions (WRC K5/1650: Guidelines for irrigation management in pasture production, WRC knowledge review, 2006). The main objective was to study water use of these pastures. In this report the focus was given to ryegrass because it is the main irrigated pasture in the dairy industry. Hence, field experiments were conducted in 2007 and 2008 at Cedara and Hatfield research sites for measuring water use and calibrating and validating the selected model (i.e. SWB). Some pilot measurements of kikuyu yield and water use were also conducted for evaluating the SEBAL model. Finally water use and irrigation guidelines were developed for the major pasture growing areas of South Africa.

1.2 Background

More than 80% of South Africa is an arid to semi-arid area with an unreliable rainfall. This makes most of the country unsuited for intensive agriculture such as dairy farming under dryland conditions (Gertenbach, 2006). Grasses are often grown under dryland conditions, however, there is a trend towards greater use of irrigation by farmers to improve reliability of yield of pastures. Therefore, major planted pastures are under full or supplemental irrigation. It is estimated that the total area utilized for irrigated pasture production is approximately 16% of the total area of pastures under irrigation. The most common irrigated pastures are ryegrass, kikuyu and lucerne. Irrigated ryegrass and dryland kikuyu with supplemental irrigation are the primary sources of feed in the pasture based dairy industry and are mostly grown in the relatively higher rainfall areas particularly in the KwaZulu-Natal Midlands, the Eastern Highveld, the Eastern Cape and in winter rainfall areas of South Africa (Dickinson *et al.*, 2004).

In spite of the high inputs the returns generated from animal production enterprises make pastures one of the highest value crops produced under irrigation. Irrigated pastures have resulted in a significant increase in grazing capacity and animal production per unit area compared to natural grasslands. Improved productivity has been reported with the application of fertilisers and liming under high rainfall areas and with irrigation under low rainfall areas.

Pastures are often established on heavy and shallow soils that would not normally be considered for irrigation. Limited rooting depths and the need to integrate irrigation and grazing management further aggravate the situation. Judicious integrated irrigation and N managements are therefore, essential not only to utilise these resources effectively and maintain production and profitability, but also to prevent serious leaching and environmental loading of nutrients (especially N).

The growth of plants is determined by the accumulation of dry matter as affected by environment. Three important processes regulating the growth of plants are a) *uptake of water*, which constitutes approximately 70-90% of the crop mass; b) *photosynthesis* (i.e.

the light dependant reduction of carbon dioxide from the air), which accounts for about nine-tenths of the remaining DM, and (c) *uptake of minerals* which accounts for the rest of the DM (Dovrat, 2003). Water and mineral uptake occur by transfer across the soil-root interface. Although water accumulation is the major contribution to growth, photosynthesis (i.e. CO_2 assimilation) is quantitatively the limiting process on which accumulation of water and minerals depend. The exposure of grass species to variable climatic conditions, determines if the growth of the species vary within a season and amongst seasons.

The primary cultural practices, however, which affect growth and development of grasses, have a direct effect on the water use efficiency of annual ryegrass. The most important pasture management practices are irrigation, fertilization, and defoliation (Dovrat, 2003). Many dairy farmers are applying the New Zealand's principles of pasture management based on perennial pastures. The reason for this being is that there is insufficient data on plant water requirements, water use and rooting depths of the species frequently being irrigated. One way of ascertaining the effective rooting depth of species, is to establish the depth to which the grass is drying the soil without experiencing significant stress (Crosby, 2003). With respect to all the information available on irrigating pastures in South Africa and the rest of the world, it is essential that there is a basic understanding of what practices are currently being used by farmers.

In semiarid regions, water is the primary contributor to grassland production (Whitney, 1974). Productivity of ryegrass is greatly affected by shortages of water because the plant gets all the nutrients necessary for growth from the soil. Therefore, the development of well-established pasture requires good growing conditions with no water stress. This leads to higher yields and better nutritive valued pasture (Dovrat, 2003). In some situations, irrigation may give little or no advantage, especially in humid areas. Water deficits, even for short periods, limit metabolic processes in plants, which may reduce growth rates. The aim of irrigation management is to maintain a continuous supply of water within the root zone between the extremes of excessive dryness or wetness.

1.2.1 Irrigation guideline

As a general rule, ryegrass needs about 1200 mm of water for the growing season (Dickinson *et al.*, 2004). In the summer rainfall regions of South Africa a 25 mm per week of irrigated water is being used based on A pan evaporation figures which are 3 to 4 mm per day (Tainton, 2000). Jones (2006) also recommended 25 mm per week for the production of annual ryegrass in the KwaZulu-Natal.

Irrespective of the difference of climate and soil factors, most researchers reported a rate of 25 mm irrigation per week (minus rainfall), when studying management factors of annual ryegrass to avoid drought (Goodenough *et al.*, 1984; Van Heerden, 1986; Eckard, 1989). However, according to Steynberg *et al.* (1993) there existed a 20% variation in the production potential of temperate species between seasons. In South Africa more variation can be expected where exceptional rainfall distribution exists. Therefore, a single set of irrigation norms to schedule irrigation for pastures in South Africa was insufficient (Steynberg *et al.*, 1993). The impression exists that the extraction amount for both temperate and subtropical pasture species should be used. It is expected that temperate species grown in the cooler seasons will be able to extract less than 25 mm per week. Rooting depths play an important role in determining the extraction amounts but this topic requires further investigation. Many recommendations made by researchers, consultants or extentionists seem to use the same rule of thumb when irrigating pastures, however, there is no consistency.

Annual ryegrass is characterised by a shallow root system which make it susceptible to rapidly developing soil-water deficits (Dovrat, 1993). When soil moisture status is used as a criterion for irrigation, the rooting depth of a particular pasture should be determined. In South Africa a shallow rooting depth of 0.3 m was used to determine irrigation requirement for planted pasture (Green, 1985; Van Vuuren, 1997). When stressed to moisture, annual ryegrass has a large concentration of roots in the upper 0.25 m horizon, with a substantial reduction in root density with depth (Dovrat, 1993). For annual ryegrass, effective rooting depths and soil water extractions ranging between 0.6-1.5 m were reported (Steynberg *et al.*, 1994; Theron and Van Rensburg, 1998; Theron and Snyman, 2004). In general, ryegrass absorbed most of the moisture from 10 to 40 cm and in some cases from 0.70 m when the soil was relatively dry. Additionally soil texture is very important to decide on how much and when to irrigate. From the literature there exists no exact water requirements for different species and no definite criteria for the irrigation of these species. Water use is seldom monitored and irrigation is applied only to prevent limited water availability.

Water use efficiency (WUE) can be defined as the mass of harvestable part of the plant per amount of water used. It includes the total amount of water needed for plant growth, including water lost through evapotranspiration from the soil and plant surfaces. Atmospheric demand, soil moisture availability and other cultural practices such as fertilization, different cultivation practices and defoliation methods can influence water use of pasture. Nevertheless the water use of grasses is strongly affected by the grass growth rate, length of season and soil surface coverage.

Annual ryegrass is considered to be highly water use efficient because of its quick establishment from seed, withstanding defoliation in six weeks after germination and because of its high growth rate (Eckard, 1994). Dovrat (1993) also classified annual ryegrass as a very efficient user of soil water. In general the dry matter yield tends to increase as the moisture availability in the soil increases. Similarly, a linear increase in DM is expected up to the maximum threshold, from which a quadratic increase will be showed under optimum environmental and soil moisture conditions (Steynberg *et al.*, 1993).

Most experiments conducted using ryegrass reported a WUE of 10-22 kg DM ha^{-1} mm^{-1} (Steynberg, 1993; Theron and Van Rensburg, 1998) with optimum cultural practices. WUEs increased from 12-22 kg DM ha^{-1} mm^{-1} when N fertiliser applications increase from 150 to 450 kg N ha^{-1} $year^{-1}$ (Theron and Van Rensburg, 1998). If natural grazing had been fertilized well, it would have had a WUE of 10 kg DM ha^{-1} mm^{-1}. Planted pastures, therefore, have the potential to utilize water more efficiently than natural grazing, depending on the species and environmental factors.

1.2.2 Nitrogen guideline

Nitrogen (N) fertiliser has been increasingly used on pastures as an effective and flexible management tool to help farmers meet the feed requirements of livestock (McKenzie *et al.*, 2003). According to FAO, N fertilizer use on pastures has increased 7-fold from 1960 to 2000 (Tilman *et al.*, 2002). Commercial fertilizers are normally used as sources of nitrogen in ryegrass production, but because of increasing energy costs and international demand (Smil, 1999), the prices are continuing to escalate.

The main effect of N fertilization on grasses is to increase the yield and quality of harvestable material. N fertilizer benefits grass by increasing herbage yield and protein content of sward, however, its benefits may be limited when other macro and micronutrients are limited. Because N plays such a key role in determining the yield and quality of pasture, an important decision is how much N to apply and when this should be done. The demand of a pasture to N fertilizer can be influenced by other environmental factors such as water, radiation and other nutrients. Therefore, the optimum N will vary from season to season, year to year and from place to place, depending on weather conditions, soil fertility and age of the stand. With adequate soil moisture, pastures can make greater use of available N than under dry conditions. Therefore, different soil moisture is likely to cause high fluctuation in yield and quality of pasture at higher rates of N. The N levels need to be adequate to exploit the full production potential of grasses that are to be evaluated.

According to Miles (2007) the optimum N for maximum yield of annual ryegrass was between 200 and 400 kg N ha^{-1} $year^{-1}$. Application of N more than 300 to 350 kg N was found to be in excess for optimum growth of annual ryegrass (Eckard, 1989; Eckard *et al.*, 1995). High applications of N may cause nitrate toxicity to grazing animals (Eckard 1990). Goodenough *et al.* (1984) top-dressed the first application of fertilizer when the annual ryegrass seedlings attained a height of about 0.1 m. In another trial by Marais *et al.* (2003) each plots received N at a rate of 50 kg ha^{-1} after each cut in which the plots were harvested 9 times at 4 weekly intervals over the growing season. However, economical optimum levels of dry matter production may require much less N than for the maximum yield.

As a result, farmers apply high N rates to ensure a maximum forage yield (Eckard, *et al.*, 1995). Forage yield response of annual ryegrass to N fertiliser rate is positive up to the current fixed N rate application recipe of 50 kg ha^{-1} per $cycle^{-1}$ (Eckard *et al.*, 1995). Forage quality, however, could start to decline even before attaining the maximum forage biomass yield. High fertiliser N application can lead to:1) Excessive forage crude protein (CP) concentrations, leading to an increase non-protein N content (Reeves *et al.*, 1996). For ruminants, a minimum CP concentration of 12% is required for microbial digestion (Peyraud and Astigarraga, 1998) and 17% for optimum milk production. CP concentrations greater than 17%, almost 80% of the additional CP is lost from the rumen and excreted in urine (Van Vuuren, *et al.*, 1992; Tas *et al.*, 2006). CP concentrations greater than the maximum of 22%, may drastically increase nitrate levels in forage which leads to nitrate and ammonia toxicity, imbalances in mineral metabolism (Coombe and Hood, 1980) and metabolic disorders. 2) It can also reduce energy or non-structural carbohydrates (NSC), intake (Marais *et al.*, 2003) and milk yields (Tas *et al.*, 2006), as energy is used to digest excess protein at the expense of milk production. Nash *et al.* (2008) reported better energy production per dry matter yield with 30 kg N ha^{-1} $cycle^{-1}$ application rate than 60 kg ha^{-1} $cycle^{-1}$ even if the highest biomass yield was obtained at 60 kg ha^{-1} $cycle^{-1}$. Available energy is more important than forage biomass and new quality parameters such as non-structural carbohydrates or metabolisable energy are becoming more useful (Hoekstra *et al.*, 2007). 3) Reduce palatability usually due to high low dry matter content (high moisture content) results as a result of high N application. Even if, N fertiliser effects on ryegrass were not significant there is a tread by animal to reject pastures with high N content. 4) High N application could also result in soil acidification (Miles and Hardy, 1999) and be a source pollution of water resources by increasing the risk of N losses.

The effectiveness of applied N in increasing pasture production is usually expressed as the N fertiliser use efficiency. The nitrogen use efficiency (NUE) in pasture systems is commonly measured as the amount of forage DM produced for each unit of applied N (kg DM/kg N) (Eckard *et al.,* 1995), and thus is also referred to as the magnitude of pasture response to N fertiliser. This magnitude is dependent on the severity of the N shortage in the soil, pasture species composition, climate, N fertiliser application rate, soil type and other factors that influence plant growth.

NUEs reported under South African conditions vary significantly ranging from 10 to 80 depending on N rates, defoliation practices (cutting or grazing) and N management. NUEs decreased from 60 to 38 kg DM kg N^{-1} when N fertiliser applications increased from 150 to 450 kg N ha^{-1} $year^{-1}$ (Theron and Van Rensburg, 1998). Eckard (1994) reported 25-34 at different sites of KwaZulu-Natal when 200 kg N ha^{-1} $year^{-1}$ was applied. Morrison *et al.* (1980) used a NUE threshold of 10 kg DM kg N^{-1} as economical to asses an optimum N rate for pastures.

Applied N not taken up by plants or immobilized in the soil organic pool is vulnerable to losses from runoff, leaching and volatilisation (Sumanasena *et al.*, 2004). These losses of N are of serious environmental concern. Elevated N concentrations in surface waters are believed to be a major contributing factor to the increasing eutrophication of these waterways (Tarkalson *et al.*, 2006). So, with N fertiliser providing considerable benefit to agriculture, but also having a substantial impact on the environment, it is important to strike a balance between economic benefit and environmental risk. A key way to achieve this balance is to improve NUE.

1.2.3 Modelling

Generally radiation, temperature, water (Tanner and Sinclair, 1983) and nutrients are the most important environmental factors that influence growth and quality of pastures. These environmental factors however, determine the major processes responsible for the production potential of a plant, which include the interception of solar radiation by the leaf canopy, conversion of the intercepted radiant energy to plant dry matter (DM), and partitioning of the DM produced between plant components (Dovrat, 2003).

With advances in computer technology, a wide range of models crop simulation models have been used extensively to quantify the change in yield potential at different levels of management and climatic variability. It was also proved that the simulation studies can supplement the field studies in decision making (Bahera and Panda, 2003). Models can predict accurately the growth, development and yield of crop by incorporating complex processes with the help of soil, daily weather and management inputs, assist growers select best management options. It can thus be a lot more locally precise than the various current static approaches used for generalized irrigation and N recommendations. The service of a model, once developed, can be provided at much lower cost than other tools. Also, a model can serve as a great learning tool, allowing for the exploration of the field dynamics and understanding of current conditions and recommendations.

Results acquired from computer simulation can be used in conjunction with data collected from field experiments to better understand systems and to extrapolate findings in time and space. This can save money and the time required for conducting long-term intensive field experiments for gathering information on potential crop production with different resources. In the absence of monitoring methods, models can also be used to explore better irrigation management strategies in order to increase irrigation use efficiency and determine site specific irrigation requirements or calendars. Considering the use of a large number of data sets and time consuming determination of input parameters required for the specific pasture models, relatively simple models (such as the SWB) may be more applicable. According to Stevens *et al.* (2005), the major problems with adoption of models by the farmers is their complexity, therefore, there should be trade-offs between accuracy and simplicity. The SWB model is being used to simulate crop growth and soil water balance of several cereals, vegetable and tree crops, therefore, it is better to use a model which is locally known by farmers and consultants instead of introducing another new model. The model is available on the web and can be downloaded free of charge.

1.3 Research objectives

General objectives

To promote efficient irrigation management of grass pastures (emphasis on ryegrass and kikuyu) by synthesizing available knowledge and generating new knowledge for improving water use efficiency by pastures.

Specific objectives:

1. Estimate water requirement/use (Modelling) with respect to:
   - Irrigation strategies
   - Managing pastures
   - Managing grazing
   - Simple ways to monitor, e.g. soil water status, compaction, root development, dry matter status
2. Identify knowledge gaps based on inputs required (soil-plant-atmosphere) by existing models.
3. Generate information on growth analysis and water balance studies for important grasses (ryegrass and kikuyu) in important areas (KZN midlands, Eastern Cape coast) required for modelling.
4. Determine water requirements of the selected pastures through testing and evaluation of the model.
5. Extrapolate irrigation requirement estimates using models.
6. Develop generic guidelines for efficient irrigation management of grass pastures (for both existing pastures and for planted pastures) with specific reference to ryegrass and kikuyu and addressing irrigation strategies and pasture management.

In this report "*Water Use and Nitrogen Application for Irrigation Management of Annual Ryegrass and Kikuyu Pasture Production*", objectives 1-5 are addressed whilst the last objective is reported in "*Irrigation Guidelines for Annual Ryegrass*".

1.4 Approach

The fundamental objective of this project is to optimise the growth of ryegrass through efficient use of water and N fertilisation. One of the tools for achieving this will be numerical models like SWB and SEBAL for which base-line information is needed for parameterisation and testing. To accurately identify the knowledge gaps of the existing planted pastures irrigation and nitrogen fertiliser strategies, extensive literature review was done. To assess the problems, detailed field trials at Cedara, Pietermaritzburg, and at the University of Pretoria's Hatfield Experimental Farm, Pretoria, were carried out. Based on the results from these trials, the SWB model was calibrated and validated. Therefore, the model was used to develop site specific irrigation guidelines and calendars.

CHAPTER 2: HATFIELD EXPERIMENTAL FARM TRIAL ON WATER USE OF ANNUAL RYEGRASS (*Lolium multiflorum*)

2.1 Introduction

In South Africa, annual ryegrass is one of the most widely grown cool season pasture species. It is grown by commercial farmers for intensive dairy, lamb and beef production. It is best adapted to areas with long seasons of cool, moist weather, well drained soils but can be tolerant to a wide range of soils and climates. The optimum planting date for irrigated annual ryegrass in South Africa is in February, hence it can be used as a source of feed in late autumn, winter, spring and early summer (Goodenough *et al.*, 1984). It is a high yielding pasture with high nutritional qualities, high palatability, digestibility, metabolisable energy, protein and minerals. It can be grazed and used for hay or silage. This characteristic plays an essential role in supplying good quality material between the winter and summer grazing.

The primary cultural practices which affect growth and development of irrigated pastures (irrigation, fertilisation and defoliation management) ensure sustainable animal production. The rate of growth, leaf area index, canopy resistance and rooting conditions are affected directly by these cultural practices. Irrigation in particular plays an important role in pasture production, as it greatly affects the total yield and quality of the forage produced. Due to the wide variation in climatic conditions in different areas, it is not possible to have only one pasture management programme that can be directly applied to a specific site. To increase the quality and quantity of both annual and perennial pastures in intensive farming systems in times when rainfall is limiting, it is essential to irrigate these pasture species. Steynberg *et al.* (1994) concluded that a single set of irrigation norms to schedule irrigation for pastures in South Africa was insufficient. Water use is seldom monitored by farmers and irrigation is generally only applied to prevent water stress. Limited research has been conducted to determine guidelines for irrigating different pastures widely used in agriculture, particularly in intensive animal production systems, such as dairy farming. To date, a few researchers have conducted detailed research on the water and management requirements of annual ryegrass in South Africa (Heard *et al.*, 1984; Goodenough *et al.*, 1984; Smith, 1985; Eckard, 1994; Theron and Snyman, 2004). Detailed information on the water use and water use efficiency (in terms of quality and dry matter) together with economic analyses was reported. Limited water not only affected productivity but also altered the quality of the forage, in particular the protein content (Marais *et al.*, 2003). However, the use of intensive irrigation management systems on planted pastures with respect to the quantity of water applied, according to crop water requirements, needs further investigation.

After moisture, nitrogen is the most important determinant factor affecting the growth and yield of planted pastures. Irrigated ryegrass or kikuyu and ryegrass mixtures form an important component of intensive fodder production in South Africa. These pastures are established on marginal soils not suitable for agronomic, vegetable or horticultural crops (Van Heerden and Du Rand, 1994). Despite the cost factor the application of nitrogen is still widely recommended for these pastures, although the use of inexpensive sources of N such as manure and/or legumes may become economically viable in the future. The most common N fertilisers used in South Africa are urea, limestone ammonium nitrate (LAN) and ammonium sulphate (Rethman, 1987). No differences in the dry matter responses were reported between different N sources by Rethman (1987), Eckard (1989) although, Miles and Hardy (1999) reported the highest yields from LAN, followed by urea and the lowest from ammonium sulphate. In addition, the acidification associated with N fertilisation was higher when 400 to 600 kg N ha^{-1} $year^{-1}$ was used, especially with the ammonium sulphate (Miles and Hardy, 1999). The proper timing of application of N and irrigation also increased the efficiency of use of fertilisers and reduced the rate of volatilization. Because N plays such a key role in determining the yield and quality of pastures, important decisions on how much and when to apply N must be made. The main effect of N fertilisation on grasses is to increase the yield and quality of harvestable material. The benefits of N fertiliser may, however, be limited when other macro and micronutrients are limited. The response to N fertiliser can also be influenced by other environmental factors such as water, temperature and other nutrients (Miles and Hardy, 1999). Therefore, the optimum N will vary from season to season, year to year and from site to site, depending on weather conditions, soil fertility and age of the stand. In general, when using N fertiliser farmers should ensure that the price is right, N use efficiency is promoted and that low environmental impact is targeted. Detailed studies on the effect of different levels of nitrogen and water availability on annual ryegrass had not yet been done. To address these factors, the following hypotheses were tested in the experiment:

1. Pasture production will be positively associated with soil moisture content,
2. Water stress can improve the quality of the pasture,
3. N fertiliser will increase the DM response to soil moisture content,
4. The grass will use water more efficiently under water limiting than under non-limiting conditions
5. WUE will increase by alleviating a limiting factor, N fertiliser in this case.

Bearing these in mind, the experiment was done in 2007 and 2008. The main aspects of pasture production under irrigation and N fertilisation of annual ryegrass (*Lolium multiflorum* cv. Agriton) including yield, growth, quality, water use and water use efficiency will be discussed.

2.2 Materials and methods

2.2.1 Experimental site

To exclude rainfall effects on the proposed irrigation treatments, the experiment was conducted under a rain shelter at the Hatfield Experimental Farm of the University of Pretoria (S25º45' and E28º16'). The area has an elevation of 1327m above sea level, with an average annual rainfall of 670 mm (Annandale *et al.*, 1999). The soil of the experimental site is classified as a silt clay loam of the Hutton form that belongs to the Suurbekom family with a clay content of 26-37% (Soil Classification Working Group, 1991). To create suitable conditions for good soil and seed contact, the field was ploughed with a disc plough and rotavated. Prior to the commencement of the study, 12 soil samples were taken randomly from the experimental site. A composite of the 12 samples was then analysed for C, P, exchangeable cations (Ca, K, Mg and Na), ammonium-N (NH_4-N) and nitrate-N (NO_3-N) and sulphate (Table 2.1).

Table 2.1 Soil analysis for the composite soil sample

Soil parameter	value
C (%)	0.99
NH_4 (mg kg^{-1})	1.51
NO_3 (mg kg^{-1})	61.60
SO_4 (mg kg^{-1})	0.07
P (mg kg^{-1})	118.9
Ca (cmol kg^{-1})	8.568
K (cmol kg^{-1})	0.265
Mg (cmol kg^{-1})	8.894
Na (cmol kg^{-1})	0.373

2.2.2 Experimental layout

A 149.5 m^2 (6.5 m x 23.0 m) block was divided into 27 plots of 3.0 m^2 (1.5 m x 2.0 m) each, with an interspacing of 0.5 m between each plot (Figure 2.1). In both seasons, superphosphate and potassium chloride were applied at planting. In the first week of June 2007, annual ryegrass (*Lolium multiflorum* cv. Agriton) was planted at a seeding rate of 30 kg ha^{-1}. Sprinkler irrigation was used for seven weeks until the grass was well established, and thereafter to control the water use more efficiently drip irrigation commenced. In the 2008 season, the grass was planted in April and sprinkler irrigation was used for eight weeks before the commencement of drip irrigation. The lateral spacing between the dripper lines and the distance between drippers in the line was 0.3 m. Irrigation was applied to individual plots depending on the soil water deficit to field capacity. Weeding was conducted manually during the course of the trial.

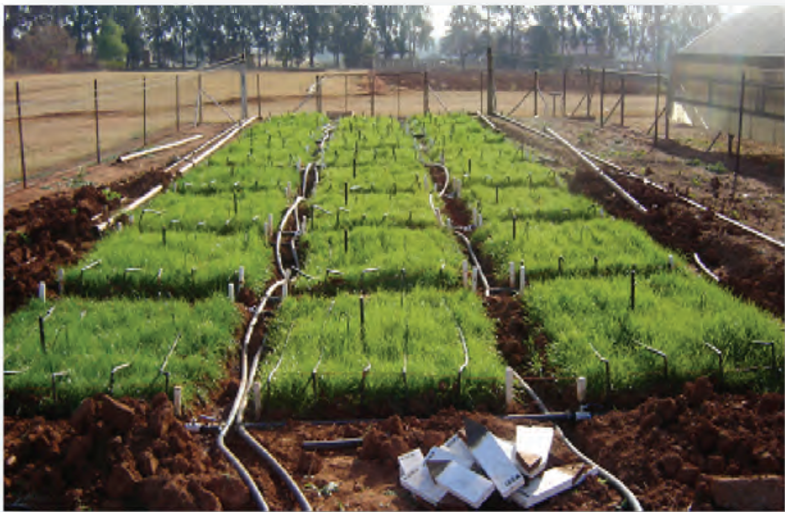

Figure 2.1 Experimental layout at the Hatfield Experimental Farm

2.2.3 Treatments

In each plot, a neutron probe access tube was installed and the soil water content was calculated using a neutron water meter. Three levels of irrigation were applied, namely W1: irrigation of once every two weeks to field capacity, W2: irrigation of once weekly to field capacity and W3: irrigation of twice a week to field capacity. At the beginning of each season, the soil profiles of all the plots were brought to field capacity. Soil water deficit measurements were made using a neutron water meter model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). The cumulative water deficit of the profile was calculated over a soil depth of 1.2 m, but irrigation was based on the upper 0.8 m of the soil profile as the roots of the grass were concentrated in the top 0.7 m. Three nitrogen treatments, namely N1: 0 kg N ha^{-1}, N2: 30 kg N ha^{-1} and N3: 60 kg N ha^{-1} were applied after each cut. The nitrogen was applied as a top dressing in the form of limestone ammonium nitrate (28% N).

2.2.4 Data collection

Weather

Weather data was collected from an automatic weather station located near the experimental site. The automatic weather station consisted of an LI 200X pyranometer (LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, an electronic relative humidity and temperature sensor installed in a Gill screen, an electronic cup anemometer (MET ONE, Inc. USA) to measure wind speed, an electronic rain gauge (RIMCO, R/TBR tipping bucket rain gauge, Rauchfuss Instruments Division, Australia) and a CR 10X data-logger (Campbell Scientific Inc., USA). Table 2.2 shows a summary of the monthly rainfall, maximum and minimum temperatures of 2007 and 2008 for the experimental site downloaded from the automatic weather station.

Table 2.2 Monthly rainfall, maximum (T_{max}) and minimum (T_{min}) temperatures of the Hatfield Experimental Farm, Pretoria for 2007-2008

Month	2007			2008		
	Rainfall (mm)	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	T_{max} (°C)	T_{min} (°C)
Jan	56.4	31.0	15.8	228.7	26.8	15.9
Feb	38.3	32.5	16.3	59.5	29.8	15.7
Mar	14.3	31.1	15.3	144.3	26.7	14.5
Apr	19.2	27.4	12.3	18.1	25.0	9.5
May	0.0	23.9	6.2	37.6	22.9	7.9
Jun	34.1	20.3	4.8	8.7	21.2	4.7
Jul	2.8	20.4	3.8	1.6	20.2	4.0
Aug	0.0	23.5	6.1	0.0	24.3	7.7
Sep	31.2	29.3	12.7	0.0	26.9	9.4
Oct	142.0	24.6	12.5	33.1	30.0	14.4
Nov	48.9	27.9	14.7	165.7	28.2	15.7
Dec	170.3	27.5	15.3	74.1	30.2	17.1

Yield and growth

Every 28 days yield was measured by sampling plant material from a 0.09 m^2 area from each of the 27 plots to a height of 50 mm above the soil surface. In each season the pasture was harvested four times. In the first season (2007), the first growth cycle (harvest 1) was harvested on August 23, the second growth cycle (harvest 2) on September 20, the third growth cycle (harvest 3) on October 18 and the fourth growth cycle (harvest 4) on November 15. In the second season (2008), the first growth cycle (harvest 1) was harvested on July 15, the second growth cycle (harvest 2) on August 12, the third growth cycle (harvest 3) on September 9 and the fourth growth cycle (harvest 4) on October 7. The sample was partitioned into stem and leaves and for dry matter yield determination, the sample was oven dried for 72 hours at 67 °C to a constant mass. Leaf area index (LAI) was a growth parameter measured using an LI 3100 belt driven leaf area meter (LiCor, Lincoln, Nebraska, USA) every two weeks. The first sampling date, Day 14 (D14), was taken two weeks after the cutting date and the second sampling date, Day 28 (D28), was taken two weeks later.

Leaf:stem ratio

To determine the leaf:stem ratio, fresh mass was determined immediately after cutting and then the samples were hand-separated into leaf blade and stem components and oven dried for 72 hours at 67 °C to a constant mass. The components were then weighed and the leaf blade dry weight was divided by the stem dry weight to calculate the leaf:stem ratio.

Chemical composition

For the quality analyses, samples were dried and milled to pass through a 1mm sieve and representative samples were stored in airtight containers. Analyses for quality was done in the University of Pretoria Nutrilab for dry matter content (DMC), *in vitro* organic matter digestibility (IVOMD), crude protein (CP), ash and metabolisable energy (ME). The DMC (AOAC 2000, procedure 934.01), IVOMD (using rumen fluid from cannulated sheep), CP (calculating N content using a Leco N analyser, Leco Corporation, St. Joseph, MI, USA, and multiplying by 6.25), ash (AOAC 2000, procedure 942.05), NDF and gross energy (GE; MC – 1000 Modular Calorimeter, Operators Manual) were analyzed by their respective procedures. Metabolisable energy (ME) was calculated using equation 2.1 as follows:

$$ME = 0.82 \times GE \times IVOMD \qquad (2.1)$$

Calculations and statistical analysis

Water use (*ET*) in mm was calculated using equation 2.2.

$$ET = I + P - Dr - \Delta S - R \qquad (2.2)$$

where *I* stands for the applied irrigation in mm, *P* is precipitation in mm (the value of *P* is zero because the experiment was under a rain shelter), *Dr* is drainage in mm (assumed to be negligible), *ΔS* is change in soil water storage in mm and *R* is runoff in mm (assumed to be negligible).

The crop coefficient (K_C) was calculated as follows:

$$Kc = \frac{ET}{ETo} \quad (2.3)$$

where *ET* was calculated using equation 2.2 and the daily reference evapotranspiration (ET_O) was calculated using the Penman-Monteith equation from data collected by an automatic weather station at the site using the FAO 56 method (Allen *et al.,* 1998).
Water use efficiency (*WUE*) in kg ha^{-1} mm^{-1} was calculated as follows:

$$WUE = \frac{Y}{ET} \quad (2.4)$$

where *Y* is yield in kg ha^{-1} and *ET* is water use in mm.

Nine treatment combinations of three water levels and three nitrogen levels were replicated three times. The plots were in a complete randomised block design and the data was analysed using the Statistical Analysis System (SAS) program for Windows v9.2 (Statistical Analysis System Institute Inc., 2002). Least significant difference (LSD) was calculated at the 5% significance level to compare the treatment means using the Student's t-test.

2.3 Results and discussion

2.3.1 Growth and yield

Dry matter yield

The dry matter (DM) yield of the first season was significantly ($P<0.05$) influenced by treatment interactions between the amount of water and N fertiliser applied except for the first growth cycle. Within each growth cycle the treatments had significant differences in the dry matter yields. W3 was significantly higher in yield than W2 and W1, while the yield of W2 was also significantly higher than that of W1. The same is also true for the nitrogen treatment. The highest yield obtained averaged over nitrogen treatment was from the W3 treatment, the highest being 2.3 t ha^{-1} in the third growth cycle.

With respect to the nitrogen treatment, the highest yield of 2.6 t ha^{-1} was produced in the N3 treatment of the second growth cycle. Production increased significantly with an increase in the frequency of irrigation and fertiliser application (Table 2.3). This could be due to the favourable conditions associated with the grass not being stressed, as the yield was lower from the stressed plots. In the first season (2007), the highest yield in most of the treatments was achieved in the second regrowth cycle which was in September. This could mainly be attributed to the fertiliser carry-over from the first growth cycle and the time of harvest. The time of harvest for the highest yield corresponds well with the results obtained by Le Roux *et al.* (1991). They reported that the peak production rate of annual ryegrass is in August/September.

Table 2.3 Dry matter yield (t ha^{-1}) of annual ryegrass for the first growing season (2007)

	Main Effect	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Total
Water (W)	W1	1.09c‡	1.91c	1.88c	1.69c	6.57c
	W2	1.20b	2.12b	2.02b	1.86b	7.20b
	W3	1.36a	2.24a	2.26a	2.13a	7.99a
Nitrogen (N)	N1	0.71c	1.43c	1.30c	1.24c	4.70c
	N2	1.42b	2.19b	2.26b	1.99b	7.87b
	N3	1.52a	2.64a	2.58a	2.45a	9.19a
Significance	W	**	**	**	**	**
	N	**	**	**	**	**
	WxN	Ns	**	*	*	*

*‡Values in each column followed by the same letters were not significantly different; ** significant at P<0.01; * significant at P<0.05; W= water treatment; N= nitrogen treatment; WxN= water and nitrogen interaction; Ns= non significant*

The DM yield of the second season was significantly ($P<0.05$) influenced by WxN treatment interactions. Table 2.4 shows that within each regrowth cycle, some of the treatment combinations had significant differences in the dry matter yields while there was no significant difference between others. The highest cumulative total yield of 10.9 t ha^{-1} and 10.6 t ha^{-1} over four harvests was achieved by W3N3 and W2N3, treatments receiving water twice and once a week with the highest nitrogen application, respectively. There was no significant difference ($P>0.05$) between these two treatments but they differ significantly from the other treatments. The response to irrigating once or twice a week at N3 was non significant as there was no difference in the yield between W2N3 and W3N3. These results indicate that the soil was wet enough to fulfil the demand, hence increasing the water use efficiency by applying once a week.

Table 2.4 Interaction between water and nitrogen treatments on the individual and total DM yield (t ha^{-1}) for the second season (2008)

Treatment	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Total
W1N1	0.90e‡	0.93e	0.97e	0.81e	3.61f
W1N2	2.01b	1.96bc	2.02c	1.91cd	7.90c
W1N3	2.13b	2.26b	2.36b	2.20bc	8.95b
W2N1	1.15d	1.15e	1.19e	1.08e	4.57e
W2N2	1.96b	1.93c	2.05c	2.07c	8.01c
W2N3	2.58a	2.71a	2.70a	2.65a	10.64a
W3N1	1.60c	1.60d	1.67d	1.64d	6.51d
W3N2	2.16b	2.20bc	2.40b	2.45ab	9.21b
W3N3	2.70a	2.73a	2.83a	2.72a	10.98a

‡Means within columns with the same letter do not differ significantly (P>0.05)

The cumulative dry matter productions of the treatments for both seasons are shown in Figure 2.2. The highest yield was obtained from the treatment with the high water and high nitrogen application. As the season changed from winter to summer there was a decrease in the growth of the pasture and thus a decrease in the dry matter production. Figure 2.3 illustrates the DM production pattern for the treatments fertilised with the highest nitrogen with different irrigation frequencies. Peak production was attained in September and after that the production started to decrease as the temperature became warmer. This is mainly attributed to the grass being a cool season pasture. The effect of increased irrigation and nitrogen application had a positive effect on the total yield produced. Generally, for the same level of water availability, yield increased with increasing nitrogen application. However, from the unfertilised plots the highest yield was obtained when plots were irrigated twice a week.

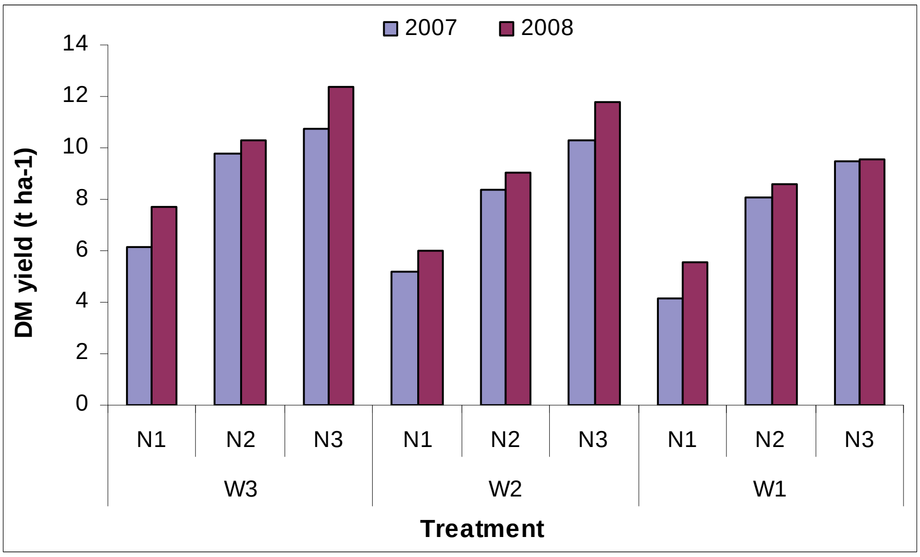

Figure 2.2 Total DM yield for both seasons (2007 and 2008)

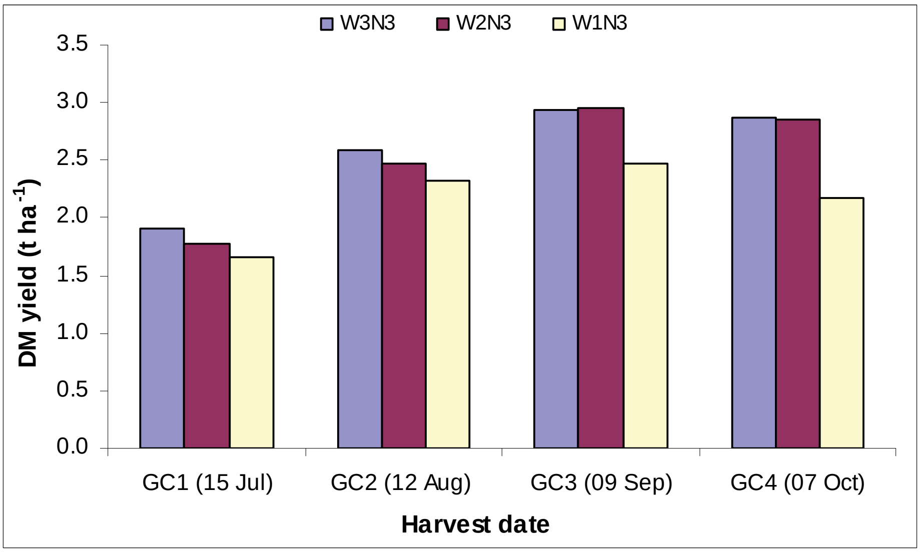

Figure 2.3 DM yield over the season of N3 treatment with different irrigation frequencies

GC= growth cycle

Leaf area index

Both during 2007 and 2008 the leaves of the treatments without water and nitrogen stress grew vigorously and retained the highest LAI throughout the growing season. In D14 of both seasons (Table 2.5) LAI was significantly affected by the main effects and WxN treatment interactions. In D28 of both seasons (Table 2.5) LAI was significantly affected by the main effects. However, the effect of the treatment's interaction (WxN) on LAI was not significant (P>0.05) in the second season (Table 2.5). Highest LAI of 4.93 m^2 m^{-2} was recorded from W3 treatment averaged over the nitrogen application, while the lowest LAI of 4.33 m^2 m^{-2} was recorded from the W1 treatments. However, there was no significant difference between W1 and W2 treatments. With respect to the N application, the highest LAI of 5.19 m^2 m^{-2} was obtained in the N3 treatment, followed by 4.76 m^2 m^{-2} in the N2 and 3.80 m^2 m^{-2} in the N1 treatment.

Table 2.5 Mean leaf area indices (LAIs) of annual ryegrass for the two growing seasons (2007 and 2008)

Main Effect		2007		2008	
		D14	D28	D14	D28
Water (W)	W1	2.49c‡	3.17c	2.84c	4.33b
	W2	2.75b	4.21b	3.02b	4.49b
	W3	3.01a	4.71a	3.44a	4.93a
Nitrogen (N)	N1	2.04c	3.22c	2.40c	3.80c
	N2	2.90b	4.36b	3.28b	4.76b
	N3	3.32a	5.06a	3.62a	5.19a
Significance	W	**	**	**	**
	N	**	**	**	**
	WxN	**	*	**	Ns

*‡Values in each column followed by the same letters were not significantly different; ** significant at P<0.01; * significant at P<0.05; Ns= not significant W= water treatment, N= nitrogen treatment, WxN= water and nitrogen interaction; D14 and D28= sampling dates*

Larger LAIs were associated with greater yield. Canopy leaf area index increased with crop growth as the plots that received higher nitrogen and irrigated twice weekly, produced higher DM productions. The higher LAI values may be due to the sufficient water and N fertiliser application that induce rapid cell elongation due to the higher water potential and, therefore, higher turgor pressure and thus increased DM production. Insufficient water with no fertiliser application has a negative impact on grass leaves and was the main consequence of LAI reduction in the treatments that received water every two weeks with no N fertiliser application. The treatments with low water and no nitrogen application had fewer numbers of leaves and lesser tiller development. Figure 2.4 shows that LAI of 5.45 m^2 m^{-2} from W3N3 was significantly higher from the other treatments while the lowest LAI of 2.67 m^2 m^{-2} was recorded from the treatments that received water every two weeks with no nitrogen application. From these results, it can clearly be seen that the impact of water and nitrogen shortages had a main effect for the reduction of the LAI and also reduced DM production from these treatments.

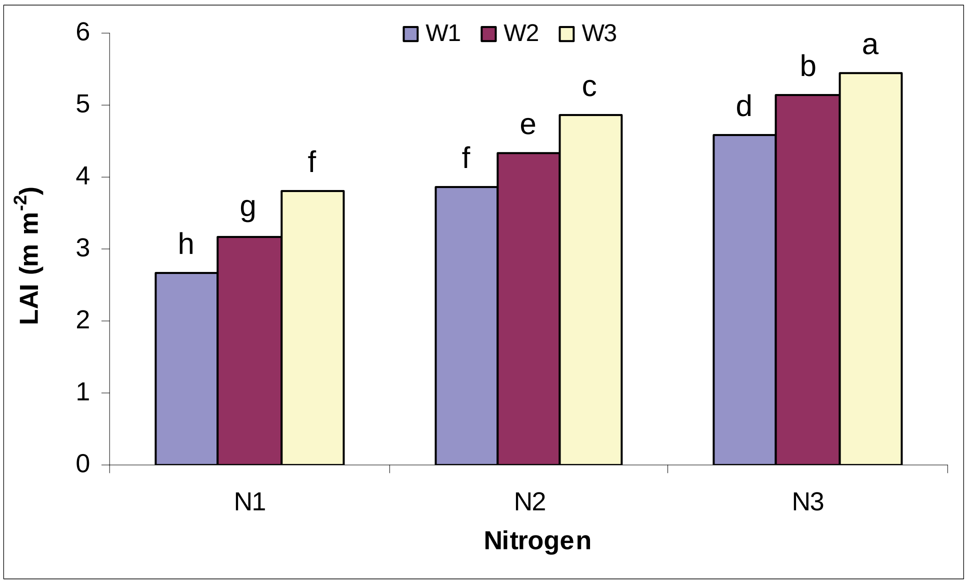

Figure 2.4 **Leaf area index (LAI) of annual ryegrass at 28 days after cutting (D28) for the first season (2007)**

2.3.2 Forage quality

Leaf:stem ratio

The leaf:stem ratio of grasses is an important factor affecting diet selection, quality, and intake of forages. A higher proportion of forage leafiness is often associated with a higher nutritive value because leaves contain more protein and less fibre than stems. An estimate of leaf:stem ratio is commonly based on a labour-intensive process of hand separating leaf and stem of a grass sample. Table 2.6 illustrates the leaf:stem ratios for the first growing season (2007). Leaf:stem ratios declined over the growing season with the lowest being recorded in the third and fourth growth cycles. The highest leaf:stem ratio was recorded for treatments with high frequency of irrigation and highest nitrogen application while the lowest was recorded for treatments with low frequency of irrigation and no nitrogen. Generally, the measure of leafiness decreased as the season progressed. This is because the grass becomes reproductive and the amount of stem increases relative to the leaf material. Any decrease in the leaf:stem ratio has a negative effect on the quality of the grass. Crude protein is more concentrated in the leaves while the stem is high in fibre content, so as the grass becomes older the amount of leaf decreases while the amount of non-leaf material (including stem, leaf sheath and inflorescence) increases, thereby decreasing the quality of the grass.

Table 2.6 Leaf:stem ratios of annual ryegrass the first season (2007)

Main effect		Cycle 1	Cycle 2	Cycle 3	Cycle 4
Water (W)	W1	0.485b[‡]	0.473b	0.450b	0.433b
	W2	0.492b	0.474b	0.454b	0.432b
	W3	0.550a	0.526a	0.498a	0.481a
Nitrogen (N)	N1	0.441c	0.430c	0.413b	0.392c
	N2	0.500b	0.478b	0.451b	0.438b
	N3	0.586a	0.565a	0.538a	0.515a
Significance	W	**	*	*	*
	N	**	**	**	**
	WxN	Ns	Ns	Ns	Ns

*[‡]Values in each column followed by the same letters were not significantly different; ** significant at P<0.01; * significant at P<0.05; Ns= not significant W= water treatment, N= nitrogen treatment, WxN= water and nitrogen interaction.*

Dry matter content

In both seasons, the dry matter content (DMC) was significantly influenced (P<0.01) by the time of harvest (H), water (W) and nitrogen (N) fertiliser as well as the interactions between HxW (Table 2.7). It was, however, not significantly influenced (P>0.05) by WxN and also by HxWxN treatment interactions. Dry matter content of 10.5% to 15.5% was measured in the current study (Table 2.7) and similar results were obtained by Meeske *et al*. (2006). In both seasons, with respect to the time of harvest, the fourth harvest (H4) recorded the highest DMC. This was significantly higher (P<0.01) than the third (H3), second (H2) and first (H1) harvests. As the season progressed, the DMC increased and this could be due to the initiation of flowering stems and a decrease in the leaf:stem ratio. The highest DMC of 15.5% with respect to the frequency of irrigation was recorded in the first season for the treatment that was irrigated once every two weeks while the lowest, a DMC of 10.5%, was recorded in the second season for the treatment that was irrigated twice a week. The probable reason for the lower DMC in the W3 could be due to the higher water availability that leads to the dilution of organic matter, as high yields were produced from these treatments. Nitrogen application also had a significant effect on the DMC. The highest DMC of 14.1% with respect to the nitrogen treatment was recorded in the first season for the N1 treatment while the lowest DMC of 12.4% was recorded in the second season for the N3 treatment.

Table 2.7 DM content (% DM) of annual ryegrass for the first (2007) and second (2008) seasons

Main Effect		2007	2008
Harvest (H)	H1	12.2d‡	11.1d
	H2	13.1c	12.1c
	H3	13.7b	13.2b
	H4	15.3 a	14.7a
Water (W)	W1	15.5a	15.4a
	W2	13.7b	12.4b
	W3	11.5c	10.5c
Nitrogen (N)	N1	14.1a	13.2a
	N2	13.5b	12.8b
	N3	13.2c	12.4c
Significance	H	**	**
	W	**	**
	HxW	*	*
	N	**	**
	HxN	**	Ns
	WxN	Ns	Ns
	HxWxN	Ns	Ns

*‡Values in each column followed by the same letters were not significantly different; ** significant at P<0.01; * significant at P<0.05; Ns= not significant, H= time of harvest, W= water treatment, N= nitrogen treatment, HxW= time of harvest and water interaction, HxN= time of harvest and nitrogen interaction, WxN= water and nitrogen interaction, HxWxN= interaction between time of harvest, water and nitrogen*

Water availability had a significant effect on the DMC in each harvest (Figure 2.5). The treatment that was irrigated once every two weeks recorded the highest DMC in the fourth harvest H4. Low frequency of irrigation coupled with harvesting towards the end of the season, yielded a higher DMC (Figure 2.5). As the season progressed, the increase in the DMC could be explained by the fact that the stem of the grass was mature and the grass entered into a stage of flowering. Low DMC may reduce animal productivity as a result of low DM intake. South African *Lolium multiflorum* cultivars have a relatively low dry matter content which has definite negative connotations.

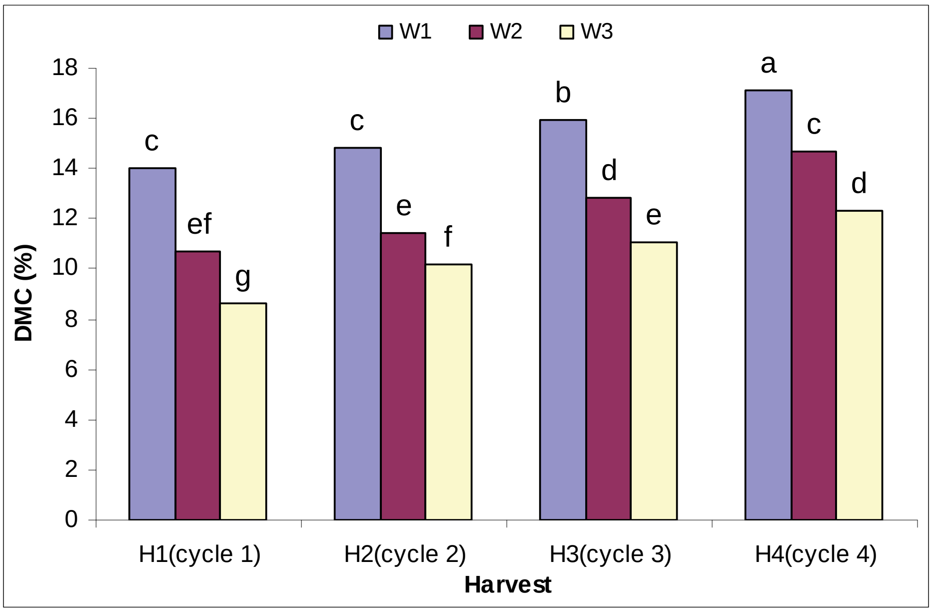

Figure 2.5 Interaction between time of harvest and water on the dry matter content (DMC %) of annual ryegrass grown in the second growing season (2008)

Neutral detergent fibre

Table 2.8 shows that the neutral detergent fibre (NDF) content was not significantly influenced (P>0.05) by water and nitrogen treatment interactions or by the main effects of these factors. The NDF values remained relatively constant across all treatments. The fact that the NDF value being constant between the treatments was totally unexpected. The highest NDF contents were registered on treatments that had been irrigated once every two weeks. The NDF values ranged from 38.2% DM to 40.9% DM. The same ranges of results were also reported by Meeske *et al.* (2006). Generally, NDF is an estimate of the cell wall concentration. Typically, lower NDF concentration equates with greater nutritive value, but excessively low forage NDF concentrations can result in digestive problems (NRC, 2001). Because leaves have low NDF concentrations, they are consumed more readily than stems. Hence, increasing the leaf:stem ratio will have a positive influence on the quality of the pasture.

Table 2.8 Chemical composition of annual ryegrass in the 2008 season

Main Effect		IVOMD %	NDF %	ME %	ASH %	CP %
Water (W)	W1	83.18a[‡]	40.93a	11.76a	11.13a	28.58a
	W2	80.49a	39.71a	11.33b	11.91a	26.01b
	W3	75.66b	38.21a	10.67c	11.27a	23.55c
Nitrogen (N)	N1	80.78a	39.94a	11.49a	12.10a	24.12c
	N2	79.37a	38.49a	11.28a	11.26ab	25.77b
	N3	79.17a	40.42a	11.01b	10.94b	28.24a
Significance	W	**	Ns	**	Ns	**
	N	Ns	Ns	*	*	**
	WxN	Ns	Ns	*	Ns	Ns

*[‡]Values in each column followed by the same letters were not significantly different; ** significant at P<0.01; * significant at P<0.05; W= water treatment; Ns= non significant; N= nitrogen treatment; WxN= water and nitrogen interaction; IVOMD – in vitro organic matter digestibility; NDF=neutral detergent fibre; ME=metabolisable energy; CP=crude protein.*

Metabolisable energy

Metabolisable energy (ME) is one of the first limiting nutrients for dairy cows grazing high quality pasture making it necessary to feed an energy rich supplementation if higher production is to be achieved. Metabolisable energy concentrations between 10.6 MJ kg^{-1} DM and 11.7 MJ kg^{-1} DM. This was within the expected range for annual ryegrass (Table 2.8). Meeske *et al.* (2006) reported ME vales for annual ryegrass in the range of 10.3 MJ kg^{-1} DM to 12.2 MJ kg^{-1} DM. The ME value was significantly influenced (P<0.05) by WxN treatment interactions. Irrigating once every two weeks (W1) was significantly higher than W2 and W3. Generally, as the frequency of irrigation was decreased the ME values increased (Figure 2.6). Nitrogen (N) applications also had a significant effect on the ME value. As the N levels were increased the ME values decreased. The possible reason for this could be when the frequency of irrigation increases, the grass growth becomes more vigorous, and this decreases the leaf:stem ratio, thereby decreasing the digestibility. This in turn decreased the ME values as there is a positive relationship between digestibility and ME concentration.

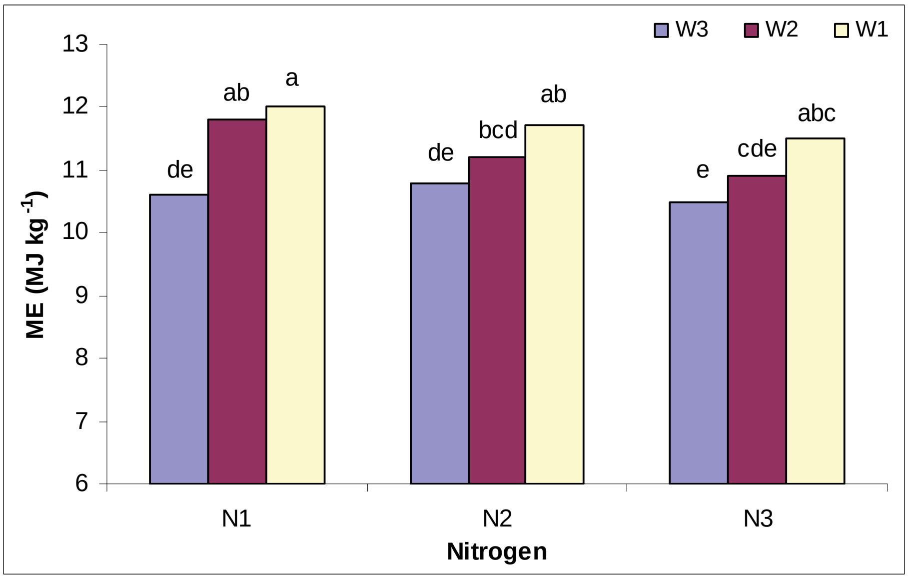

Figure 2.6 Metabolisable energy (MJ kg^{-1} DM) of annual ryegrass grown in 2008

Ash

The ash content was not significantly influenced (P>0.05) by water and nitrogen treatment interactions but was significantly affected (P<0.05) by an increase in the nitrogen application (Table 2.8). There was no significant effect (P>0.05) by the frequency of irrigation on the ash content but, it decreased slightly with the increase in nitrogen fertiliser. The highest ash contents were recorded on those treatments receiving no nitrogen. The ash content ranged from 10.9% DM to 12.1% DM. These values are higher than the values reported by Meeske *et al.* (2006) for annual ryegrass. The slight increase in the ash content indicates a higher mineral content in the grass.

Crude protein

As expected for annual ryegrass, the crude protein (CP) content ranged from 23.5% DM to 28.5% DM (Table 2.8). Similar results were also obtained by Meeske *et al.* (2006). The National Research Council (NRC, 2001) recommended that forage with CP content of 15-17% will maintain high producing dairy cows on grazed pastures. The results show that all treatments have greater than 15% CP content, so practically these can satisfy the CP requirement of high producing dairy cows. The highest CP was recorded for the treatments irrigated once every two weeks with the highest nitrogen application, while the lowest was recorded for the treatment with the highest frequency of irrigation and no nitrogen. Interactions between water and nitrogen were not significant (P>0.05). Results are thus presented only for the main effects. The CP content of N3 was significantly higher (P<0.05) than of N2 and N1, nevertheless, the CP content of N2 was significantly higher (P<0.05) than of N1. Increase in N fertilisation rates resulted in an increase in the CP content. The CP content of W3 was significantly higher (P<0.05) than both W2 and W1, while W2 was significantly higher than W1. Generally, as the frequency of irrigation increased the CP content decreased significantly (P<0.05). This may be due to the dilution of nutrients with the increase in production. These results correspond well with the results of Sumanasena *et al.* (2004) who reported that the lower CP contents with frequent applications of water were associated with nitrogen leaching and the inability of ryegrass to absorb nitrogen in soils with moisture content near saturation point.

In vitro organic matter digestibility

The range in *in vitro* organic matter digestibility (IVOMD) was between 75.6% DM to 83.1% DM (Table 2.8). Theron and Snyman (2004) reported slightly lower (72% to 81%) IVOMD values. Differences could be related to different amounts of fertiliser, growing conditions, stage of maturity at the time of harvest and defoliation intervals. The DM digestibility of annual ryegrass is generally high in the early season of growth, but may decrease as the season advances. The IVOMD was not significantly influenced ($P>0.05$) by WxN treatment interactions or by the level of N fertilisation, but the frequency of irrigation had a significant effect ($P<0.05$). Plots irrigated once every two weeks (W1) had a significantly higher IVOMD value than W2 and W3. Increases in the frequency of water application resulted in lower IVOMD values. The reason for the higher IVOMD values with the decrease in the frequency of irrigation could be due to the fact that the grass increasing in the leaf:stem ratio, which in turn increases the digestibility. These are in line with the results obtained by Thompson *et al*. (1989) who reported that better digestibility was recorded under water stressed than under non-stressed conditions. In the current study, N fertiliser rate did not significantly influence IVOMD as there was no significant difference in the IVOMD from the different N fertiliser applications, although Valente *et al*. (2000) reported that nitrogen fertiliser may cause a slight decrease in the digestibility of Italian ryegrass. The age of plants at harvest has a more profound effect on the digestibility than does fertilisation.

2.3.3 Soil water, water use and water use efficiency

Soil water depletion

The effect of different irrigation treatments on plant available water (PAW = water content at field capacity minus water content at wilting point) content is shown in Figure 2.7. The period shown is from the start of the treatment to the date of last harvest. After calculating the deficit, plots were irrigated to field capacity. Within one growth cycle, W3 was irrigated eight times, while W1 was irrigated only twice. As expected, the soil profile of the W3 treatment maintained higher water content and tended to be wet consistently throughout the season. More water was depleted from the soil as irrigation interval increased. This was especially noticeable for the W1 treatment, as irrigation depth ranged from 40-50 mm per application, whilst for W3, the range was from 10-15 mm per application (Figure 2.7). From the figure, it is clear that W1 had the highest soil water deficits throughout the season. This treatment had the lowest seasonal water consumption and recorded the lowest dry matter yields proving that this treatment was water stressed. Towards the end of the season, more water was depleted from the soil. This could be related to the higher evapotranspiration due to the increase in temperature. Within the same irrigation frequency, more water was depleted in the N3 treatments than from the N1 treatments. This could be due to the higher transpiration rates from the higher LAI evident for the N3 treatments.

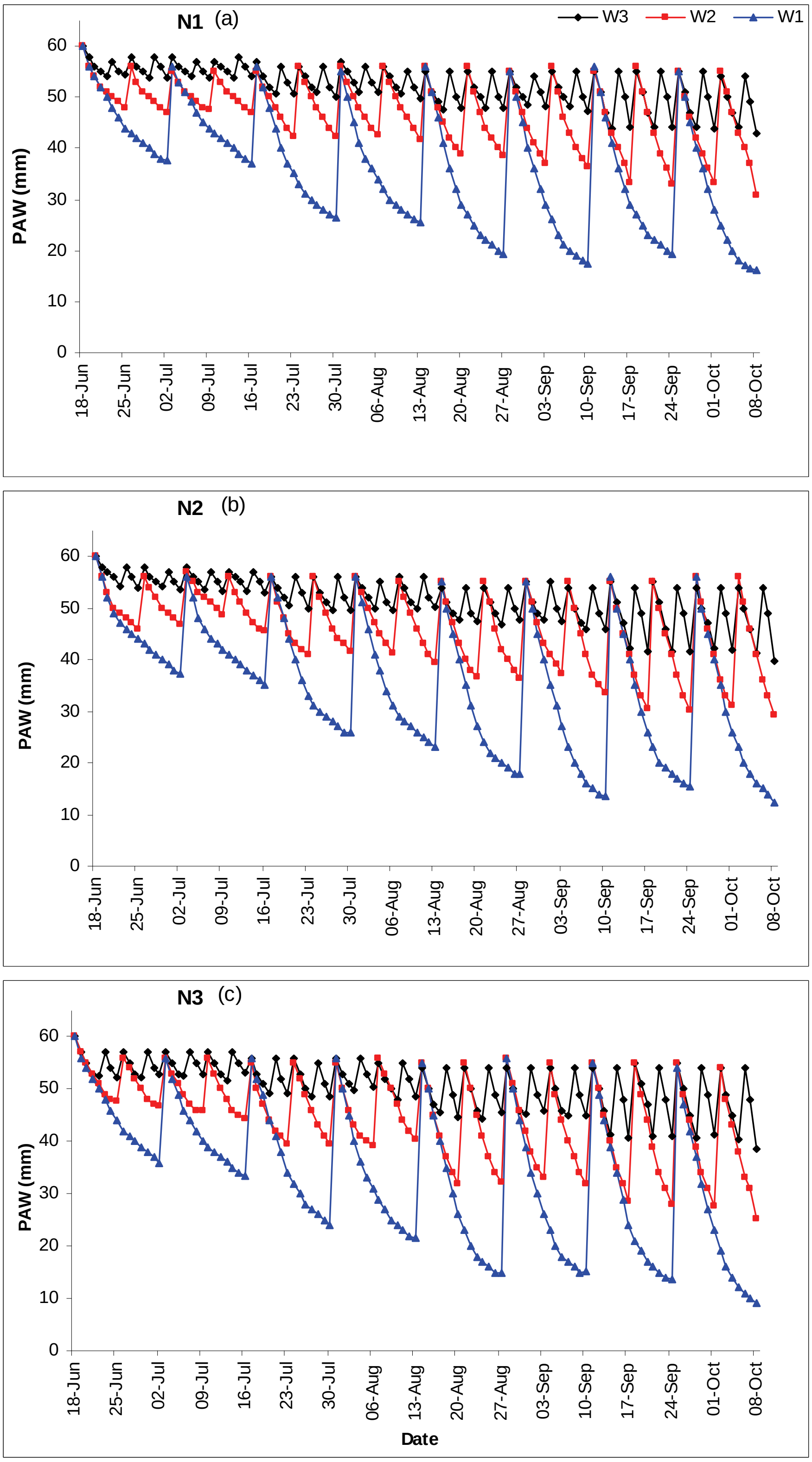

Figure 2.7 Soil water depletion patterns in the root zone of annual ryegrass in the second growing season (2008) for (a) N1; (b) N2 and (c) N3 with three irrigation frequencies W1, W2 and W3 each. PAW= plant available water

Water use

Water use (WU) was calculated as the sum of water applied during the growing season and the soil water deficit at the end of the season. In the first season the highest cumulative water use averaged over the nitrogen treatment was 429 mm for the W3 treatment while the lowest cumulative water use was 333 mm for the W1 treatment (Table 2.9). The highest cumulative water use for the nitrogen treatment averaged over the frequency of irrigation was 416 mm for the N3 treatment and the lowest was 346 mm for the N1 treatment. In the second season the highest cumulative water used with respect to the water treatment was 384 mm for the W3 treatment and the lowest was 297 mm for the W1 treatment. With respect to the nitrogen application treatments the highest cumulative water used was 371 mm for the N3 treatment and the lowest was 316 mm for the N1 treatment (Table 2.9).

Table 2.9 Water use (mm) of annual ryegrass at the Hatfield Experimental Farm, Pretoria (2007-2008)

Main Effect		2007					2008				
		Cycle 1	Cycle 2	Cycle 3	Cycle 4	Total	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Total
Water (W)	W1	69c[‡]	85c	86c	93c	333c	48c	71c	87c	91c	297c
	W2	74b	101b	100b	109b	384b	52a	76b	99b	120b	347b
	W3	81a	110a	114a	124a	429a	53a	81a	106a	144a	384a
Nitrogen (N)	N1	68c	90c	90c	98c	346c	47c	71c	90c	108c	316c
	N2	75b	100b	99b	109b	383b	50b	76b	96b	120b	342b
	N3	81a	106a	110a	119a	416a	55a	81a	107a	128a	371a
Significance	W	**	**	**	**	**	**	**	**	**	**
	N	**	**	**	**	**	**	**	**	**	**
	WxN	*	*	**	**	**	*	Ns	**	*	**

*[‡]Values in each column followed by the same letters were not significantly different;** significant at P<0.01; * significant at P<0.05; Ns= not significant, W= water treatment, N= nitrogen treatment, WxN= water and nitrogen interaction.*

These values are for a total of four harvests per season. In both seasons, the cumulative WU was significantly influenced ($P<0.05$) by WxN treatment interactions (Table 2.9). Irrigating twice a week (W3) was significantly higher ($P<0.05$) than W2 and W1 while for the nitrogen treatment, N3 was significantly higher ($P<0.05$) than N2 and N1. The main reason for the differences in the water use could be due to the increased dry matter (DM) production with increased frequency of water and higher nitrogen application. Higher dry matter was produced in the treatments that received more water and were top-dressed with the highest nitrogen level. These treatments had higher leaf area index (LAI) and the transpiration rate was greater, thereby increasing the total water use.

Generally, WU increased as the frequency of irrigation increased. Within the same irrigation frequency, WU increased with increasing nitrogen application. In the first season, the highest WU of 464 mm was recorded for the W3N3 treatment, while, the lowest water use of 306 mm was recorded for the treatment that received water once every two weeks with no nitrogen application (Figure 2.8). The W3N1 treatment was not significantly different ($P>0.05$) from the W2N2 treatment. As the irrigation interval increased from twice a week (W3) to once every two weeks (W1), the amount per application increased accordingly, but the total amount of water applied throughout the whole season decreased because of the lower irrigation frequency. In the second season, the treatment that was irrigated twice weekly with the highest nitrogen application, used the most water, a total of 423 mm while the lowest, a total of 282 mm was recorded for the treatment that was irrigated once every two weeks with no nitrogen application (Figure 2.9). The higher water use in the frequently irrigated treatments could be attributed to the high evapotranspiration rate associated with a large canopy and high water availability. Wallace (2000) indicated that more frequent irrigation encourages water loss through evapotranspiration. There was no significant difference between W3N2 and W2N3 and also between W3N1 and W2N2 in 2008 (Figure 2.9). Even though the frequency of irrigation of these treatments varies, the reason for the non significant difference in water use could be due to the higher application of nitrogen fertiliser that led to the production of higher yield which in turn leads to higher transpiration.

For each treatment, the amount of water applied was lower in the second season than the first season (Figures 2.8 and 2.9). This may be due to the higher reference crop evapotranspiration (ET_O) values recorded in the first season (Figure 2.10). In 2007, the cumulative ET_O value over the period of the growing season was 414 mm while in the second season the cumulative ET_O value was only 370 mm. The ET_O and WU were highly correlated, as can be seen when ET_O increases. As would be expected, the crop coefficient (K_C) values followed the same order as the WU, with W3N3 having the highest K_C value of 1.12 in the first season and a K_C value of 1.14 in the second season. The higher K_C values indicate a higher DM production from these plots as the K_C value is affected by the canopy cover and surface wetness. These values show that the grass was not over-irrigated as values of K_C over 1.2 indicate over-irrigation (Allen *et al.*, 1998).

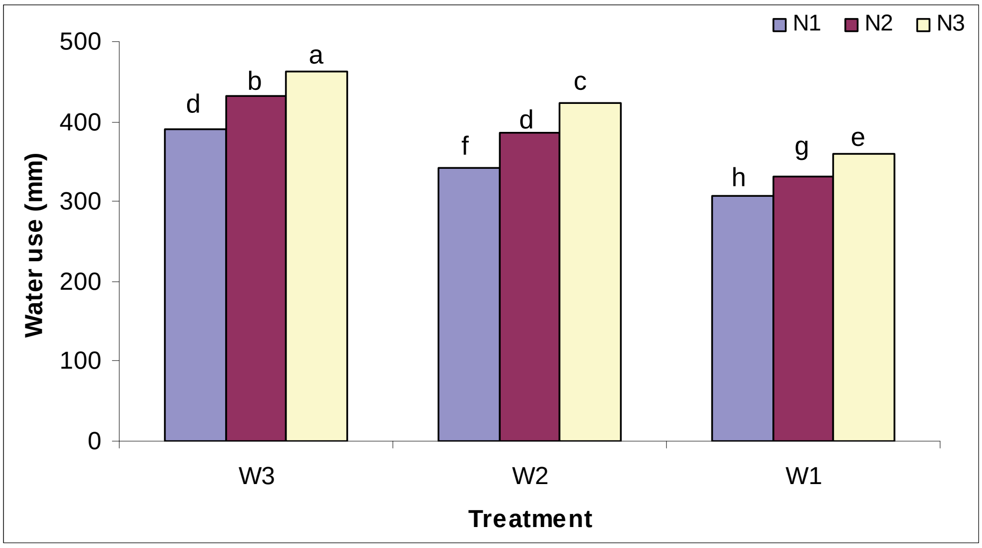

Figure 2.8 Cumulative water use (mm) of annual ryegrass in the first growing season (2007)

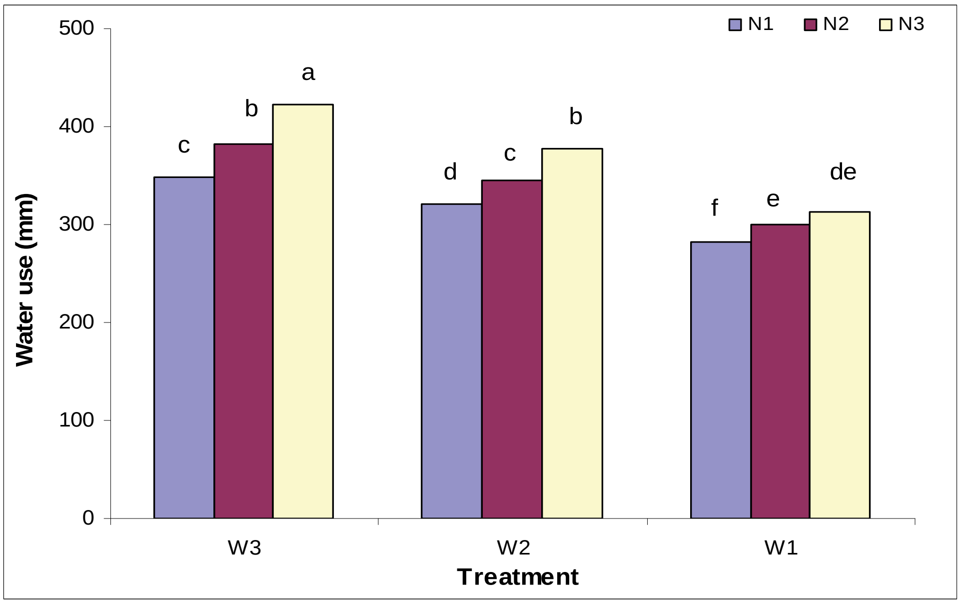

Figure 2.9 **Cumulative water use (mm) of annual ryegrass in the second growing season (2008)**

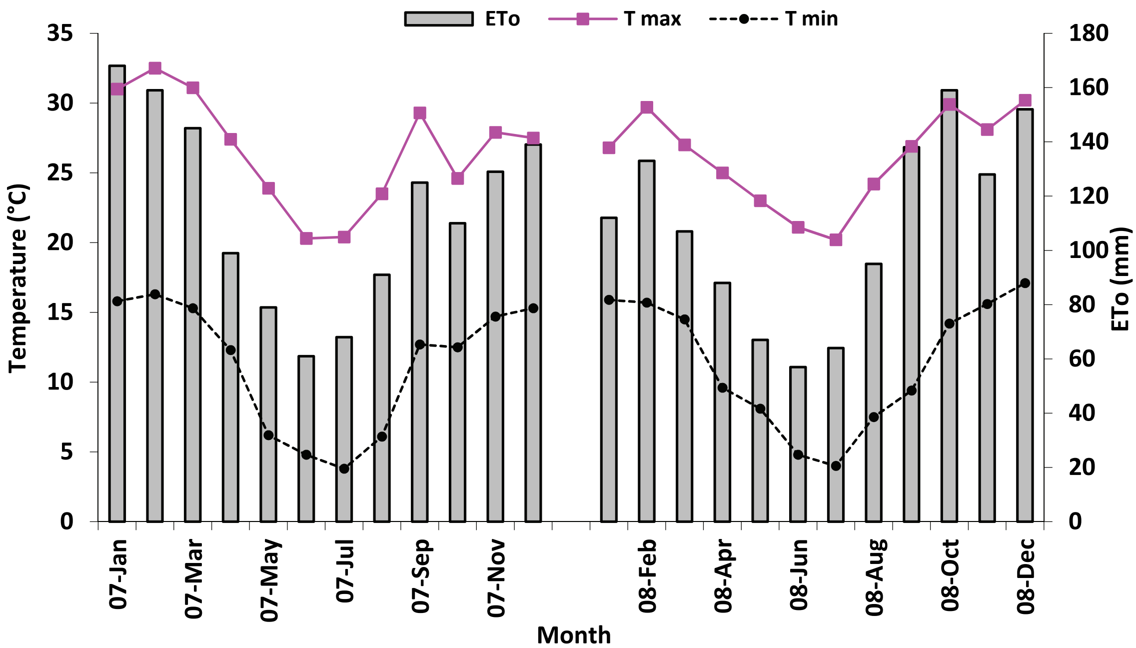

Figure 2.10 **Monthly evapotranspiration, maximum and minimum temperatures of the Hatfield Experimental Farm, Pretoria for 2007 and 2008**

Water use efficiency

In both seasons there were significant differences ($P<0.05$) in the WUE of the treatments with respect to total yield. Water was used more efficiently in the W1 treatment followed by W2 and W3. The increase in WUE for the W1 treatment could be ascribed in part due to reduced evaporation from the soil, resulting from a lower wetting frequency as these treatments were being irrigated once every two weeks. Even though maximum yield was obtained from the W3 treatments, they recorded the lowest WUE. The low WUE may be due to the fact that frequently watered treatments had higher evaporation. In both seasons, the treatments that were irrigated once every two weeks recorded the highest WUE for N2 and N3, but for N1, these treatments recorded the lowest WUE, where in these cases N fertiliser was the limiting factor. The reason for this could be because of the very low dry matter production due to water and nitrogen stress. Nitrogen fertilisation significantly increased ($P<0.05$) WUE averaged over the irrigation treatment (Figures 2.11 and 2.12). Within the same irrigation frequency treatments, plots that were top-dressed with more nitrogen had higher WUE. This could be attributed to the fact that more DM was produced with increasing N application. In the first season (2007), for the high N treatments, highest WUE of 26.4 kg ha^{-1}mm^{-1} was recorded for W1, followed by 23.7 kg ha^{-1}mm^{-1} for W2 and 22.5 kg ha^{-1}mm^{-1} for W3 (Figure 2.11).

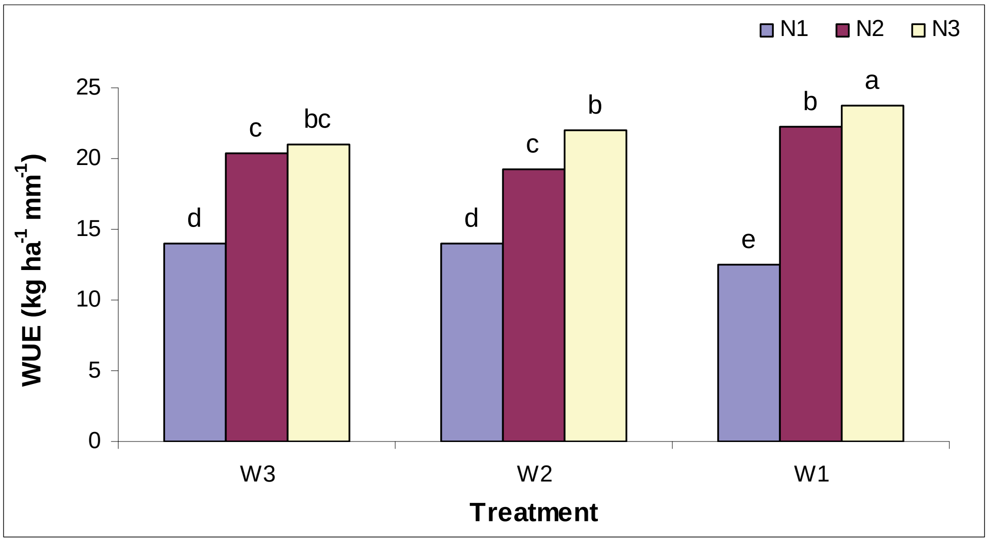

Figure 2.11 Water use efficiency (WUE) of annual ryegrass in the first (2007) growing season

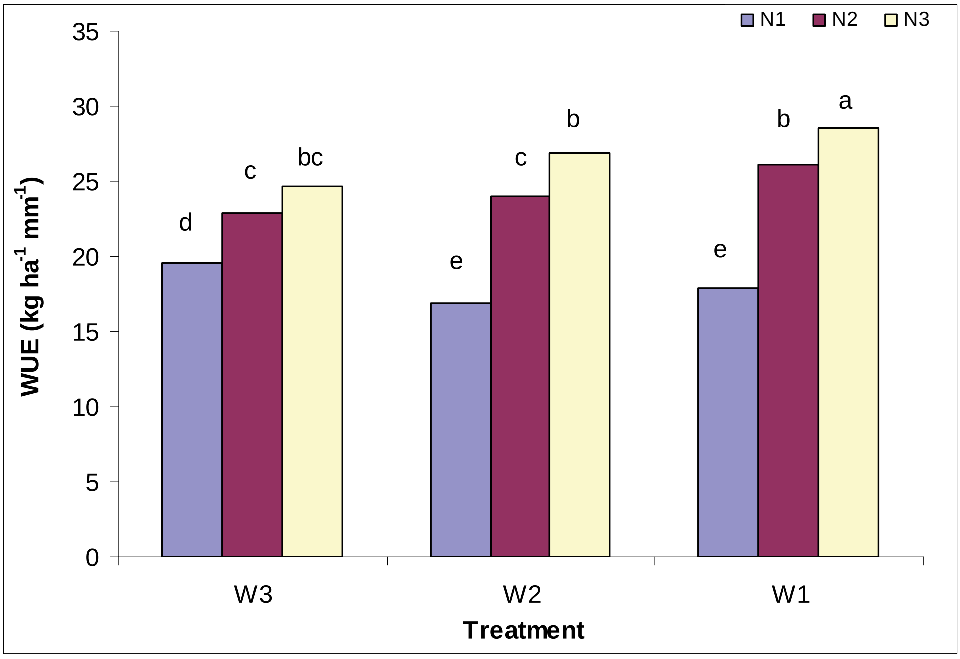

Figure 2.12 Water use efficiency (WUE) of annual ryegrass in the second (2008) growing season

The increase in WUE was mainly due to the large reduction in the amount of water as W1 used 77% of the water used by W3 while the yield was reduced by only 8%. In this study, water stress did improve WUE, as the highest WUE was recorded in the treatment that was irrigated once every two weeks. Because less water was used, the WUE was higher in the second season (Figure 2.12). This could be due to the lower evaporative demand in the second season as shown in Figure 2.8. In the second season, for the high N, highest WUE of 28.6 kg $ha^{-1}mm^{-1}$ was recorded in the W1 treatment, followed by 26.9 kg $ha^{-1}mm^{-1}$ for W2 and 24.6 kg $ha^{-1}mm^{-1}$ for W3. In both seasons the treatment with no nitrogen application recorded the lowest WUE throughout the season (Figures 2.11 and 2.12). The main reason for this could be because the dry matter production from these treatments was very low.

Figure 2.13 illustrates the trend of WU, ET_O and WUE between the four harvests of the non-stressed treatment (W3N3) in the second season. From the figure, it is clearly seen that as the season progressed ET_O increased thereby increasing WU. The reason for the increase in WU could be due to the increase in atmospheric demand as a result of higher temperatures. When we look at the vapour pressure deficit (VPD) for the growing season, there was an increase with time over the four harvests. The average VPD for the first harvest (15 Jul) was 0.99 kPa. This increased to 1.16 kPa in the second harvest (12 Aug) and then to 1.48 kPa in the third harvest (09 Sep) and in the final harvest (07 Oct) to 1.86 kPa. The increase in VPD had a major impact on the increase of WU. Even though the WU increased as the season progressed, the WUE decreased because there was a decrease in dry matter production. This was especially noticeable for the fourth harvest (07 Oct), as air temperature exceeded the cut-off temperature ($T_{cut\text{-}off}$) of the grass, which is around 25 ^{O}C (Hunt and Thomas, 1985). Above this temperature, annual ryegrass will decrease DM production, even if water and fertiliser are non-limiting. During the fourth growth cycle, about 48% of days recorded temperatures higher than the cut-off temperature ($T_{cut\text{-}off}$). There were three occasions in which the maximum temperature was higher than the cut-off temperature for three consecutive days. This decrease in DM production due to the cut-off temperature being exceeded and an increase in WU due to a higher ET_O led to a decrease in the WUE not only in this treatment but also in all the others.

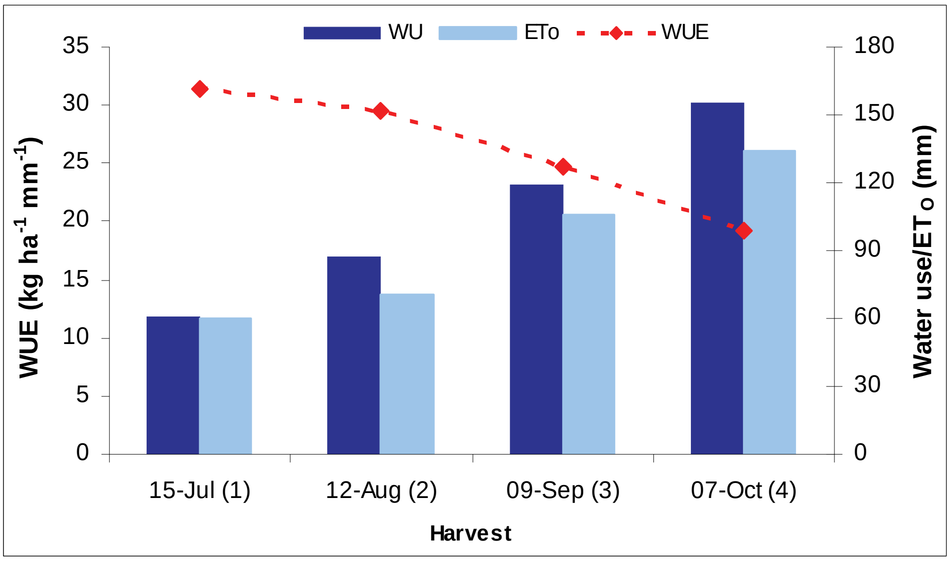

Figure 2.13 Water use (WU), reference evapotranspiration (ET_O) and water use efficiency (WUE) of the W3N3 treatment of annual ryegrass in the second growing season (2008)

2.4 Conclusions

From the experiments conducted during 2007 and 2008 irrigation and nitrogen fertiliser application affected the dry matter yield and LAI significantly. Higher frequency of irrigation coupled with high nitrogen application significantly improved the dry matter yield. Canopy size influenced the LAI which in turn affected the yield. In this study, the effect of irrigation and nitrogen application on DM yield and LAI were investigated and the study showed that the treatments that were irrigated twice weekly and top-dressed with 60 kg N ha^{-1} after each cut consumed the most water, and this resulted in the production of higher yield, maintenance of the largest leaf area index. The highest cumulative yield of 10.98 t ha^{-1} over four harvests was recorded in the second season, with a LAI of 5.19 m^2m^{-2}. However, there was no significant difference in yield between the treatments that were irrigated twice weekly and once a week at the high N application. The non-significant difference in yield could be due to the grass's ability to use water stored in the soil profile, hence all the treatments were filled to field capacity at the beginning of each season. The increase in these parameters may be due to the sufficient water and nitrogen fertiliser that induces rapid cell elongation as a result of higher water potential, higher turgor pressure and higher photosynthetic processes. However, the treatments that were irrigated once every two weeks with no N application consumed the least water, resulting in low DM production and maintenance of the lowest leaf area index. Water and nitrogen deficits resulted in a statistically significant yield reduction, compared to the treatments with no stress. Results from this experiment show that dry matter yield and LAI can be increased through the application of increased irrigation and nitrogen fertiliser. This proves that the pasture production was positively associated with the soil water and fertiliser content.

Nutritive value is another aspect that needs to be evaluated with respect to pastures. In this study, the ryegrass recorded a high IVOMD, CP and ME values while the leaf:stem ratio and DMC was of acceptable levels. The nutritive values of the grass ranged between 10.6 and 11.7 MJ kg^{-1} for ME, 23.5-28.5% for CP, 75.6-83.1% for IVOMD and 10.2-15.3% DMC. These values recorded are still sufficiently high for dairy farming as digestibility values greater than 65%, ME values greater than 9% and CP values higher than 18% can safely support the maintenance plus production requirement of animals. It was also noted that the growth cycle had a significant effect on the dry matter content, the highest being on the fourth harvest while the leaf:stem ratio decreased as the season progressed. The decrease in the frequency of water application resulted in an increase in the DMC, digestibility, ME and CP values. The level of nitrogen had a significant effect on the DMC, ME and CP. An increase in the nitrogen application increased the CP but decreased the DMC and ME. It can therefore be concluded that water stress did improve the quality of the pasture by increasing the DMC, IVOMD, ME and CP contents. The results of this study highlight that under optimal conditions of growth, the nutritive quality of the ryegrass is able to meet the requirements of even high producing dairy cows, provided that animals consume sufficient DM to achieve this level of production.

The amount of available water is declining as a result of pressure from other competing factors (domestic, recreation and industrial), hence the need to improve WUE. In agricultural production it is possible to make best use of the available water efficiently through irrigation scheduling. Two of the important variables used to quantify plant water usage are WU and WUE. Generally, WU of annual ryegrass varies depending on region, climate, cultivar and stage of growth. Results from this study indicate that in both seasons WU was highest in the treatment that was irrigated twice a week and top-dressed with the

60 kg N ha^{-1} after each cut. Nitrogen application had an effect on the WU, as less water was used in the treatments that received no nitrogen. The highest cumulative water used over four harvests was 464 mm in the first season and 423 mm in the second season. The decrease in the WU could be due to the lower atmospheric demand as the ET_O was lower in the second season. Highest K_C value of 1.14 was recorded in W3N3, the treatment with the highest water use and this indicates that the treatment was not over-irrigated. As the irrigation interval increased, more water was depleted from the soil profile. Depletion rates increased as the season progressed but generally it was minimal in the frequently irrigated treatments. Increase in WUE was achieved by reducing the frequency of irrigation from twice a week to once a week without causing significant yield loss. A possible reason for the increase in the WUE by reducing the irrigation frequency could be ascribed in part to reduced evaporation from the soil resulting from the lower wetting frequency of the deficit irrigation treatments. Within the same irrigation frequency, higher WUE was achieved by alleviating a limiting factor, N fertiliser, in this case, through increases in dry matter production. The highest WUE was achieved by irrigating once every two weeks. However, in some treatments, the WUE was not improved with the reduction in the frequency of irrigation as the water saved was overshadowed by yield loss. Increasing the WUE is beneficial, however, high WUE on its own is not necessarily an indication of the best irrigation scheduling method as one may need to quantify the trade-off between yield loss because of low levels of irrigation and the economical advantage that would be achieved by saving water. It can be concluded that at the expense of dry matter production, the highest WUE was achieved under water limiting conditions. Also, within the same irrigation frequency, N fertiliser applications increased the WUE through increases in the dry matter production.

The input costs of ryegrass under irrigation and fertilisation are high and that is why production should not only be high but the feed must be of a high quality. Water and nitrogen deficiency can limit the production of pastures. By adopting appropriate irrigation and nitrogen management strategies, we can improve the yield and quality of these pastures. Proper and efficient irrigation management minimises water loss due to runoff, deep percolation, surface evaporation and reduction of leached of nutrients, while better nitrogen management increases production and forage quality. Based on the data from this experiment, it can be concluded that by irrigating once a week and fertilising with 60 kg N ha^{-1} after each harvest, optimum yield can be achieved and a higher WUE. In areas where the scarcity of water is a crucial issue, high water use efficiency at the expense of some dry matter yield could be achieved. Fewer irrigation frequencies, depending on the type of soil and climate, are required during the initial stages of growth so as to save both water and fertilizer. On the other hand, where there is no shortage of water, the farmer's choice could be to irrigate more frequently and maximize transpiration so as to have a maximum dry matter production.

CHAPTER 3: CEDARA RESEARCH STATION TRIAL ON WATER AND NITROGEN USE OF ANNUAL RYEGRASS (*Lolium multiflorum*)

3.1 Introduction

As reported in the previous chapter (from Hatfield trial in Chapter 2), ryegrass was more responsive to N than water. Moreover, the cost of nitrate leaching is usually many times greater than the cost of using too much water. For adoption purposes, it is better to advise a farmer to save nitrogen and water in an integrated way instead of only water because currently the cost of nitrogen fertilizer is as serious problem as water if not higher. Since irrigation and N cannot be managed independently, the experiment at Cedara was conducted to manage N and water in an integrated way. Hence an adaptive approach was used to manage irrigation based on the wetness and soil nitrate concentrations.

Global use of nitrogen (N) fertiliser has increased more than seven-fold since the 1960's (Smil, 1999). Only half of this nitrogen is recovered in harvested crops, with the remainder entering aquatic and atmospheric systems, contributing to one of the main human-induced perturbations to the earth's environment (Smil, 1999). Despite decades of research on matching fertiliser applications to crop requirements, agriculture remains a major source of environmental contamination, especially cause as a result on poor irrigation management (Tamminga, 1992). Past research has provided a fairly robust management guideline for famers, such as applying 50 kg N ha^{-1} per growth cycle (Eckard *et al.,* 1995). Such rigid guidelines could be improved by 1) soil N testing to estimate N mineralisation and N carry-over between harvests (Collins and Allinson, 2004; Miles, 2007) 2) mass balance accounting to match inputs and outputs (Hatfield and Prueger, 2004) and 3) improving irrigation practices (Sumanasena et al., 2004). However, taking the appropriate measurements, for example by soil coring, would be expensive and time consuming for each harvest (Collins and Allinson, 2004), particularly as nitrate levels can change rapidly during the growing season after rain or irrigation.

Adaptive management (Walters 1986) is an approach that is between a guideline, on the one hand, and trying to measure or estimate all components of the system, on the other (like using an N mass balance approach where components such as leaching, volatilisation and denitrification are difficult to measure or estimate). Adaptive management is generally considered to be the best approach for managing systems with high uncertainty, or where it is impossible or impractical to collect all the necessary information (Lee, 1993). Although usually used for addressing complex socio-ecological problems, adaptive management may also be a sensible strategy for the seemingly relatively straight forward problem of optimising N nutrition and crop water supply.

Successful adaptive management hinges on our ability to identify a threshold which is easy to measure and that can be linked to action and on-going learning (Stirzaker *et al.*, 2010). Since monitoring is expensive, we seek a measurement that can integrate many of the processes involved in the soil water balance and N cycle, in this case the use of a wetting front detector (WFD) which is a passive lysimeter that approximates the water and nitrate moving past a certain depth in the soil profile (Stirzaker, 2003; Van der Laan *et al.*, 2010). The objectives of this chapter are to test the hypotheses that adaptive N and water management approaches can 1) reduce the recommended N application without compromising yield, 2) maintain or improve forage quality, 3) improve water use efficiency, and 4) minimise potential for nitrate leaching.

3.2 Materials and methods

3.2.1 Site description and general crop management

The experiment was conducted at the Department of Agriculture research station at Cedara located in the midlands of KwaZulu-Natal mistbelt, one of the main milk producing areas of South Africa (altitude 1076 m above sea level, S29°32'; E30°17'). The site had previously been used for long-term ryegrass cultivar and breeding research. It had the same management history, which confirms less variability in soil factors that might result from different cultural and management practices of the site.

The site has mean monthly pan evaporation and rainfall between 80-160 mm and 20-140 mm respectively (Figure 3.1). The site has a summer dominated mean annual rainfall of 876 mm, reference evapotranspiration of 1511 mm and an annual rainfall deficit of 560 mm. Mean annual rainfall (March to November) does not satisfy the crop requirement of annual ryegrass for most of the months during the growing season. Hence, the production of annual ryegrass is under full irrigation during late autumn, winter and spring, and supplementary irrigation is required during summer.

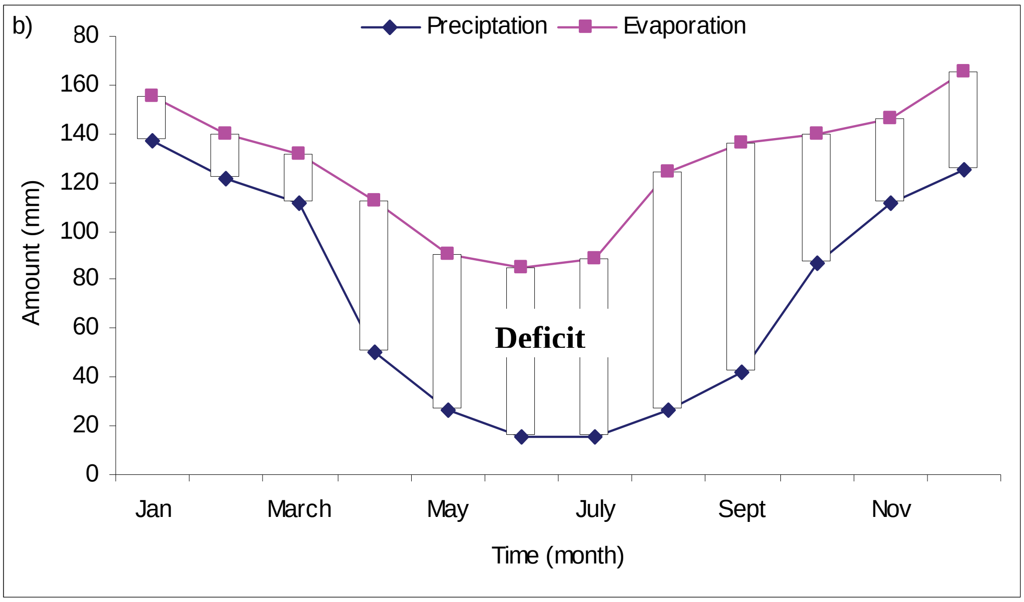

Figure 3.1 Long-term mean monthly precipitation and pan evaporation of the Cedara site
(Source, ARC – Soil, Water and Climate Institute)

Prior to the commencement of the trial in 2007, replicate undisturbed soil core samples were collected to a depth of 1 m for determination of basic soil physical properties (Table 3.1). Water retention, hydraulic conductivity, particle size, water content (saturation, field capacity and permanent wilting point) were determined from undisturbed core samples. In both years, the fertility status of the soil was determined prior to planting by taking soil samples from the top 0.3 m. The soil samples were analysed for organic matter, N, P, K, pH, EC, macro and micro elements (Table 3.1). The site has a deep, red, kaolinitic Hutton soil, Hayfield family (Soil Classification Working Group, 1991) with a clay loam texture to a depth of 0.4 m, with a heavier clay soil from 0.4 to 1.0 m. 20 kg P ha^{-1} (super phosphate) was incorporated at planting. Both N (limestone ammonium nitrate) and K (potassium chloride) top dressings were applied within two days of each cutting. The seasonal recommended K (200 kg K ha^{-1}) was divided by the expected number of growth cycles, while the N regime was determined by the treatment.

Italian ryegrass (*Lolium multiflorum*) cultivar 'Agriton' was planted on the 6th of March in 2007 and 25th of March 2008 at a seeding rate of 30 kg ha^{-1} and a Cambridge Roller was used to facilitate good contact between the seed and soil. Recommended planting dates for this region is between mid-February and mid-April each year. Two weeks after emergence, 2-4-D amine herbicide was sprayed against broad leaf weeds. Fenoxaprop-p-ethyle 'Puma Super' was also used to control *Eleusine indica* (L.) Gaertn. (goosegrass) which is a common invasive weed of irrigated pastures.

3.2.2 Irrigation system and scheduling

A dragline sprinkler irrigation system with a sprinkler spacing of 12 m was used. Plots were 12 m wide and 36 m long with a border spacing between plots of 12 m (Figure 3.2). A distribution test was conducted by placing manual raingauges according to the guidelines proposed by Koegelenberg and Breedt (2003). The system has an acceptable uniformity Christian uniformity (CU) ranging from 82 to 92%, and distribution uniformity (DU) of 79 to 81%. To maximize the efficiency and to reduce wind drift, irrigation was applied at low wind speed conditions. The sprinkler irrigation system has a delivery rate of 4.0 mm h^{-1}. Each plot had its own sprinkler lines and was irrigated independently by determining the deficit to field capacity using the Diviner-2000 capacitance probe to a depth of 0.6 m (Sentek®, Australia). Plots were irrigated once a week during autumn, spring and summer; and once every two weeks in winter. Treatments were refilled to field capacity except in summer (where about 15 mm soil deficit was left for rain) and on occasion for the adaptive water management treatment included in this study in 2008 (where irrigation was based on nitrate levels).

Table 3.1 Selected soil physical and chemical properties of the experimental site

Physical[§]	0-0.2 m	0.2-0.4 m	0.4-1.0 m		Chemical[β]	2007	2008
Clay (%)	34.3 (2.9)[φ]	37.4 (5.8)	45.0 (3.5)		Total N (%)	0.32 (0.02)	0.29 (0.03)
Silt (%)	33.9 (3.0)	33.5 (2.5)	25.8 (1.2)		Organic C (%)	2.8 (0.21)	3.2 (0.16)
Sand (%)	31.8 (1.6)	29.1 (6.4)	29.2 (2.8)		pH (KCl)	4.6 (0.11)	4.4 (0.17)
Saturation (m^3 m^{-3})	0.498 (0.009)	0.481 (0.032)	0.498 (0.019)		P (mg kg^{-1})	28 (8)	24 (5)
Field capacity (m^3 m^{-3})	0.337 (0.014)	0.331 (0.005)	0.329 (0.046)		K (mg kg^{-1})	173 (21)	208 (23)
Wilting point (m^3 m^{-3})	0.206 (0.012)	0.212 (0.016)	0.192 (0.018)		Ca (mg kg^{-1})	712 (29)	820 (17)
Bulk density (kg m^{-3})	1220 (27)	1280 (24)	1170 (46)		Mg (mg kg^{-1})	156 (12)	202 (14)

[§]Soil physical properties were determined in 2007 prior to planting. [φ]Standard deviations. [β]Soil chemical analysis was conducted in both years prior to planting. Ammonium acetate was used for K, Ca and Mg extraction. Organic carbon and nitrogen were estimated by mid-infrared spectroscopy. P measured with Bray I.

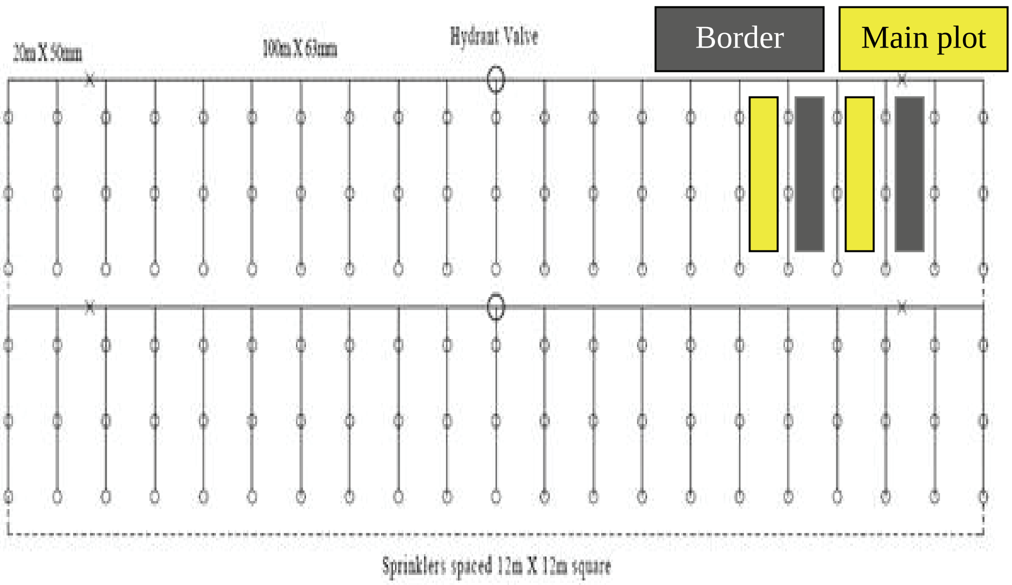

Figure 3.2 Layout of dragline sprinkler system and placement of raingauges for uniformity test of the dragline sprinkler irrigation system

3.2.3 Instrumentation

Weather station

A fully automated weather station has been installed on the site. The data was used as input to run the SWB model. This station measures solar radiation, temperature (maximum and minimum), wind speed and direction, rainfall and relative humidity. These parameters will be used as inputs for the models to be used.

Diviner 2000, TDR and Watermark sensors

In this trial access tubes of diviner-2000 were installed at the centre of each plot the mid-lines of each contours (Figure 3.3). TDR and Watermark sensors were installed at depths 0.10, 0.20, 0.30, 0.45, 0.60, 0.75, 0.90 m and 1.05 m (Figure 3.3). This was done for continuous monitoring of soil water (TDR probes) and watermark (water potential). Whilst it may seem at first unnecessary to adopt three different methods of measuring water content at the trial, each of these methods differ in their mode of operation. Beyond comparing their respective levels of accuracy the potential use of these instruments in real-time monitoring of pastures by farmers will be assessed.

Wetting front detector (WFD)

WFDs were installed by augering a hole to depths of 0.15, 0.30, 0.45 and 0.60 m in each plot for monitoring depth of wetting and soil solution N concentration. The root zone was determined through soil core sampling to a depth of 1 m, with the majority of roots found in the top 0.6 m.

A WFD is a funnel-shaped, passive lysimeter, used for managing irrigation, salinity and nutrition (Stirzaker and Hutchinson, 2005). When the soil around the WFD approaches 3 kPa suction during or shortly after irrigation or rainfall, free water is produced at the base of the funnel. The water passes through a filter, is collected in a reservoir, and activates a magnetically latched float. WFD can be useful for farmers to understand the movement of the wetting front when irrigating their pastures. A WFD tells how deep the wetting front has moved. It is buried in the soil and pops up an indicator flag when a wetting front reaches it. The WFD comprises a specially shaped funnel, a filter and a mechanical float mechanism. The funnel is buried in the soil within the root zone of the plants. When rain falls or after irrigation, water moves downwards through the root zone. The infiltrating water converges inside the funnel and the soil at the base becomes so wet that water seeps out of it, passes through a filter and is collected in a reservoir. This water activates a float, which in turn operates an indicator flag above the soil surface. If the soil is dry before irrigation, the wetting front will not penetrate deeply because the dry soil absorbs most of the water. A long irrigation would be needed to activate a detector. However, if the soil is relatively wet before irrigation, it cannot store much more water, so the wetting front penetrates deeply. The detector retains a sample of water which can be extracted via a tube using a syringe and analysed for its salt and nitrate concentration (Stirzaker, 2003).

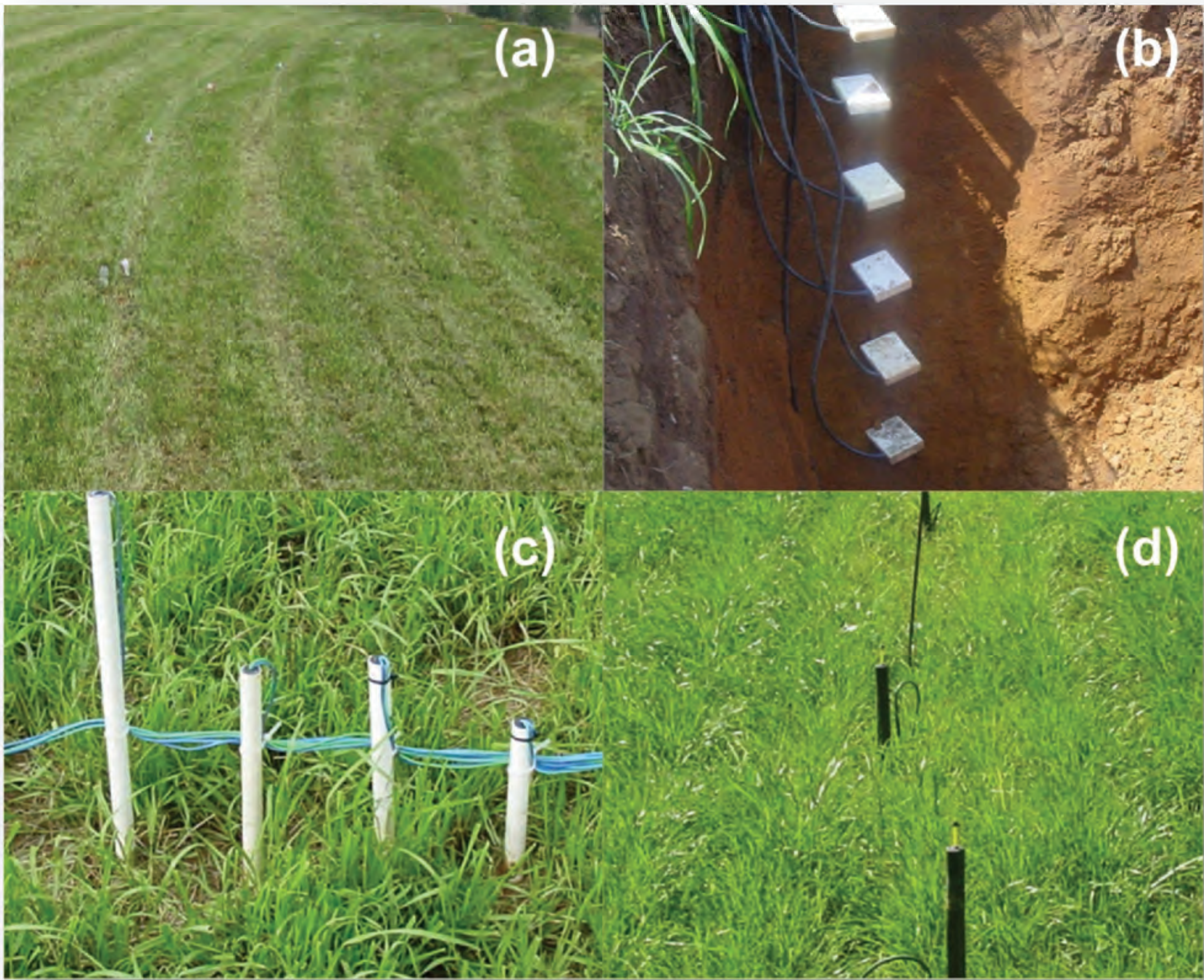

Figure 3.3 **Instruments using for monitoring soil water a) Diviner 2000 access tubes, b) TDR probes, c) watermark sensors and d) wetting front detectors installed at Cedara site**

3.2.4 Treatments

Three treatments in 2007 and seven treatments in 2008 were set up in a randomised block design with three replications. In 2007, the experiment included three fixed N rate applications over eight harvests; representing high (N_{60}: 60 kg N ha^{-1}), and medium (N_{30}: 30 kg N ha^{-1}) forage target yields and a control with zero N (N_0). To avoid differential carry-over effects from 2007 affecting the treatments in 2008, the second year trial was carried out on different plots. The experiment was changed in 2008 because in the first two to three growth cycles of 2007, forage yields between N treatments were similar. In addition there were also high soil solution nitrate levels in the high N application rate treatment (N_{60}), which could be a source of potential leaching. Therefore, in 2008, treatments were improved by estimating/measuring components of the N balance (such as soil N, mineralisation and crop N uptake) or by using a simpler method (adaptive management). The data collected in 2007 were used to derive the management thresholds for the adaptive N and water treatments for 2008. In 2008, treatments included four fixed N rates and one treatment based on N mass balance calculations. In 2008, there were also two adaptive treatments, the first reducing N input and the second reducing irrigation input, both based on nitrate measurements from WFDs. A detailed description of the 2008 treatments follows:

i) Fixed N application rates

No N was applied at planting to take advantage of high levels of residual N, but N rates of 0, 20, 40 and 60 kg N ha^{-1} (N_0, N_{20}, N_{40} and N_{60}) were applied after each harvest. The aim of this series of treatments was to provide the response curve for N.

ii) N mass balance (N_{MB})

This treatment represents the strategy of measuring components of the N cycle to get N applications as accurate as possible. N application was estimated from target crop N uptake and adjusted downwards to account for initial soil nitrate and estimated mineralisable N, hence simplifying the N mass balance (Asadi *et al.,* 2002) equation to:

$$N_{fer} = N_{up} - N_{init} - N_{min} \qquad 3.1$$

Where: N_{fer} is N input from fertiliser; N_{up} is above ground crop N uptake; N_{init} is initial soil inorganic N and N_{min} is predicted mineralisable N. The mass balance approach used here assumes atmospheric N inputs and gaseous N losses through denitrification and volatilisation to be negligible. Although there could be substantial N leaching at the beginning (due to rainfall and a shallow root system) and towards the end of the season (rainfall and a low canopy cover due to fewer tillers), in this study, for the purpose of calculating N application in this treatment, N leaching was assumed to be negligible, as the pasture was irrigated to field capacity in winter and in summer a soil deficit of about 15 mm was left after irrigation to provide a buffer for storing rainfall and minimising leaching.

N_{up} was estimated as the product of target forage yield and N content based on the N dilution curve of annual ryegrass as reported by Marino et al. (2004). Marino *et al.* (2004) established the critical plant N concentration (N_c) for annual ryegrass as:

$$N_c = 4.08\ DM^{-0.38} \qquad 3.2$$

Where, N_c is the critical total N concentration (%) in forage that produces the maximum amount of biomass, dry matter (DM) forage yield is expressed in t ha^{-1}; 4.08 is an empirical coefficient that represents the N_c at 1 t ha^{-1}; and -0.38 characterises the rate of reduction in N_c during growth. The relationship is apparently independent of environmental conditions (Lemaire et al., 2008). An uptake of 62 kg N ha^{-1} was estimated for a yield of 2.0 t ha^{-1}, with critical N concentration of 3.1% using the N dilution curve (Marino *et al.*, 2004).

N_{init} was the average of nitrate measurements from the WFDs (installed to a depth of 0.6 m) which responded after irrigation or rainfall. The last irrigation of the previous growth cycle was used as initial soil N for the following growth cycle. The solution concentration in mg L^{-1} was converted to kg N ha^{-1} using the volumetric soil water content (θ) of the active rooting depth of ryegrass (D) with equation (3). This assumes that the resident nitrate concentration in the soil solution was well mixed and therefore equal to nitrate concentration in the mobile soil solution sampled by the detectors. This assumption may, however, not be completely accurate, but this provides a logical means to estimate available nitrate in soil when expensive and time consuming soil analyses are not available. Nitrate N is the dominant form of inorganic N in agricultural soils and NH_4-N forms are usually excluded in soil testing (Vazquez *et al.,* 2006), hence NH_4 was assumed to be low and similar in all treatments.

$$N_{int} = (0.226\ WFD_{NO3}\ \rho_w\ \theta\ D)/100 \qquad 3.3$$

Where: N_{int} is estimated initial N in kg ha^{-1}; WFD_{NO3} (mg L^{-1}) is average nitrate concentration measured from WFDs that recorded fronts just prior to harvest; D is the rooting depth (0.6 m); θ is water content at 3 kPa suction (0.41 m^3 m^{-3}) when the sample is collected; ρ_w is the density of water (1000 kg m^{-3}) and 0.226 is the factor for converting nitrate to nitrate-N and 100 is a conversion factor to kg ha^{-1}. N_{min} was predicted from initial organic carbon from the soil samples collected at the beginning of the season (Figure 3.4). Miles (2007) developed approximate N release curves for this study region based on soil organic carbon and long term weather data for soils with non-limiting C:N ratios.

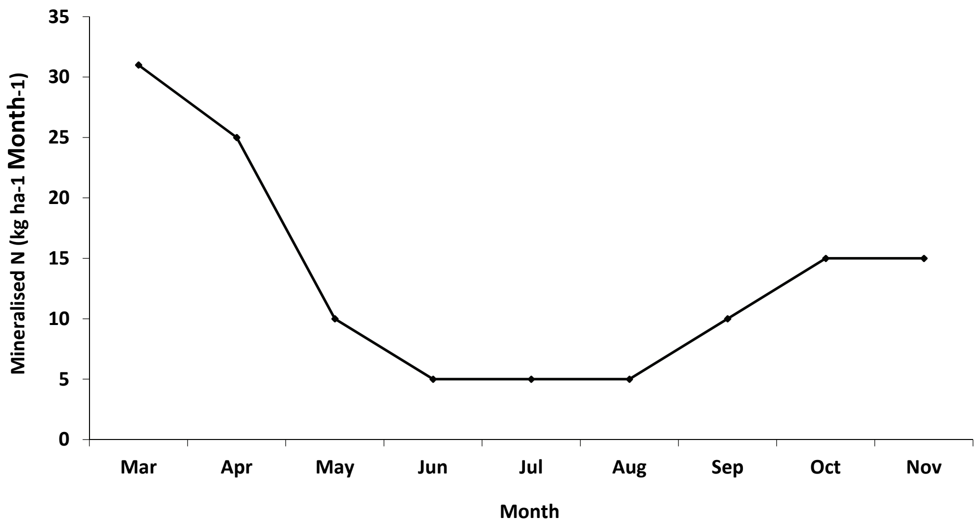

Figure 3.4 Monthly N mineralisation estimates based on organic carbon collected at the beginning of the season

iii) Adaptive N (N_{soil})

In this treatment, mean soil solution nitrate concentration of 50 mg l^{-1} was selected as the optimum level by considering both yield and crop quality (Figure 3.5). This value was between the nitrate concentration levels which were detected by WFDs in the soil solution of the N_{30} and N_{60} treatments in 2007. This was a compromise between attaining maximum yield (N_{60} treatment) and optimum quality (N_{30}). As a result, in 2008, N applied for the re-growth after harvest was based on average soil solution nitrate concentrations from all WFDs that responded to the last irrigation/rainfall event of the previous growth cycle. When average soil solution nitrate concentrations exceeded 50 mg L^{-1}, no N was applied. When concentrations were below 25 mg L^{-1}, the recommended 50 kg N ha^{-1} was applied. In between these levels (25-50 mg L^{-1}), half of the recommended rate (25 kg N ha^{-1}) was applied (Table 3.2).

Table 3.2 Treatments in 2007 and 2008: fixed N application rates (N_0, N_{20}, N_{30}, N_{40}, N_{60}), N application based on mass balance calculation (N_{MB}), adaptive N management (N_{soil}) and adaptive water management (N_{water})

Fixed rates				N_{MB} (2008)		N_{soil} (2008)		N_{water} (2008)	
2007	N rate[§]	2008	N rate	Soil NO_3[β]	N rate	Soil NO_3	N rate	Soil NO_3	Next irrigation
N_0 N_{30} N_{60}	0 30 60	N_0 N_{20} N_{40} N_{60}	0 20 40 60	As initial N in mass balance calculation	equation 3.1	>50 25-50 <25	0 25 50	WFD_{30}>25 WFD_{45} >25	Reduced Cancelled

[§]N rates in kg ha^{-1} $cycle^{-1}$. [β]Soil solution nitrate in mg L^{-1}.

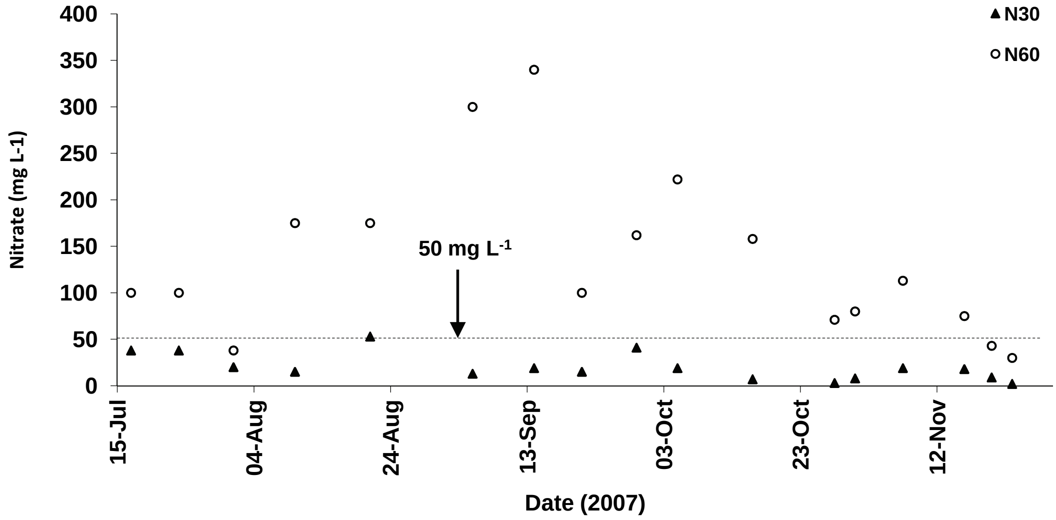

Figure 3.5 Mean nitrate concentrations of wetting front detectors installed at all depths in treatments which received 30 kg N ha^{-1} cycle $^{-1}$ (N_{30}) and 60 kg N ha^{-1} cycle $^{-1}$ (N_{60}) in 2007 (dotted horizontal line represents nitrate threshold level)

iv) Adaptive water (N_{water})

Results from 2007 showed that soil solution nitrate increased with higher inputs of fertiliser (Figures 3.6a and 3.6b). We hypothesise that high N concentrations at 0.30 and 0.45 m depths increase the probability of N leaching. This adaptive water treatment involved reducing irrigation in response to the depth that irrigation or rainfall penetrated, and to the nitrate concentration of the water sample (Table 3.1). Soil solution nitrate concentration of 25 mg L^{-1} (5.6 mg NO_3-N L^{-1}) was taken as threshold. If concentrations collected from the 0.30 m deep WFD exceeded 25 mg L^{-1}, the irrigation amount was reduced by watering only until the magnetically latched float of the 0.15 m WFD was activated (Figure 3.6a). If the concentrations from the 0.45 m WFD exceeded 25 mg L^{-1}, the scheduled irrigation event was cancelled (Figure 3.6b).

Adaptive management is about designing and carrying out management actions as experiments from which one can learn. Therefore, the thresholds for the adaptive management treatments were somewhat arbitrarily selected in the knowledge that they would be improved with experience.

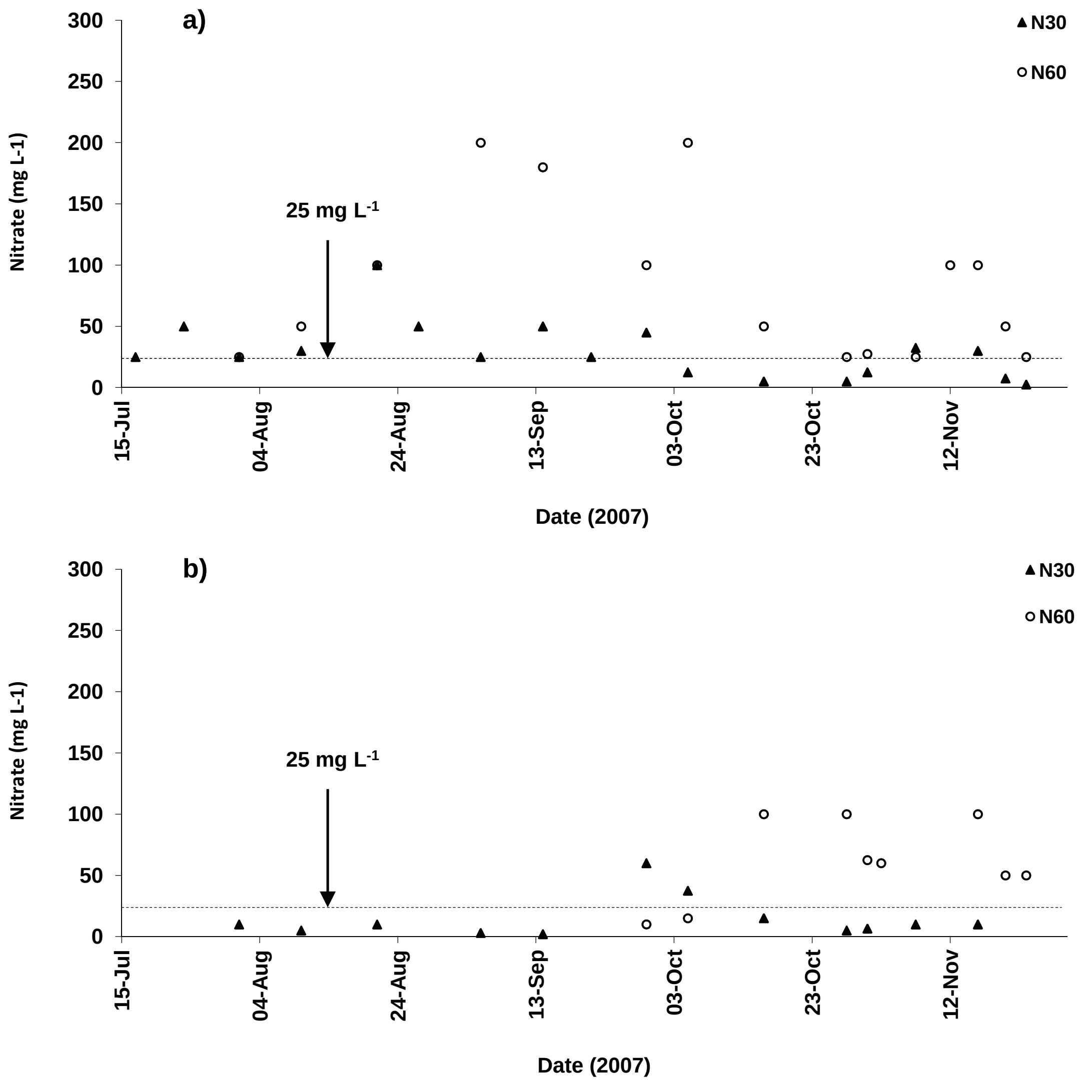

Figure 3.6 Nitrate concentrations of wetting front detectors installed at a) 0.30 m and b) 0.45 m in treatments which received 30 kg N ha^{-1} cycle $^{-1}$ (N_{30}) and 60 kg N ha^{-1} cycle $^{-1}$ (N_{60}) in 2007 (dotted horizontal line represents nitrate threshold level)

3.2.5 Data collection

Yield and quality

The pasture was defoliated at the two to three leaf stages. For yield and quality (crude protein, true protein, non-true protein, non-structural carbohydrates, neutral detergent fibre and acid detergent fibre) determination, a total of nine samples per treatment (three from each plot) were collected from 1 m^2 quadrants to a stubble height of 50 mm. After taking the samples, the whole field was harvested with a tractor mower to a height of 50 mm. Forage dry matter (DM) was determined by oven drying the samples at 70 °C to constant masses. Samples were milled to pass through a 0.1 mm sieve and were kept in bottles until quality analyses could be performed. Nitrogen was determined by Kjeldahl analysis (AOAC, 2000) and crude protein (CP) was calculated as N x 6.25. True protein (TP) was determined using the trichloroacetic acid (TCA) precipitation method. Non-true protein was calculated as difference between crude and true protein. Total non-structural carbohydrates (NSC) were analysed as reducing sugars following quantitative hydrolysis to monosaccharides (Marais and Evenwell, 1983). The neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentrations were determined according to Van Soest *et al.* (1991) method.

Root growth

Rooting pattern of ryegrass was evaluated with minirhizotron and by taking destructive root core samples (Figure 3.7). Minirhizotron soil tubes were installed at selected treatments at an angle of 25^o for estimating the root length. For the determination of root biomass undisturbed soil core samples were taken by auguring up to depth of 1.0 m. Roots were collected from the cores by washing the samples, using a fine sieve (0.5 mm) and removing non-root materials by hand. Root dry mass was determined after the roots were dried at 70 °C.

Figure 3.7 Minirhizotron soil tubes and root core sampler used for measuring root length and biomass

Soil N

Soil solution samples were collected from WFDs the day following an irrigation/rainfall event, in order to standardise the sampling time and to allow for some soil water redistribution within the profile. For each sample, nitrate concentration was analysed using paper colour nitrate test strips (Merck KGaA, Germany). Soil cores were also sampled to a depth of 2 m in September and November 2008 from each plot using an auger. Nitrate was determined with an auto-analyzer after extraction using 1M KCl. Potential nitrate leaching (free draining) was determined as the difference in nitrate measurements below the root zone between two successive core sampling dates (September and November).

3.2.6 Calculations and statistical analysis

Crop water use or evapotranspiration of varying treatments was estimated using the soil water balance equation according to Jovanovic and Annandale (1999):

$$ET = P + I - R - Dr - \Delta S \qquad 3.4$$

Where: P is precipitation, I is irrigation, R is runoff, Dr is deep drainage below the rooting depth (0.6 m), and ΔS represents soil water storage. All terms are expressed in mm. R was assumed to be negligible because of a dense pasture cover and relatively level field. Precipitation that exceeded soil water deficit to field capacity in the 0.6 m profile was considered to be lost as drainage. A positive ΔS indicates a gain in soil water storage. ΔS was estimated from soil water content measurements with a Diviner probe between two irrigation intervals to a depth of 0.6 m.

Irrigation (IUE), water (WUE) and fertiliser N (NUE) use efficiencies were calculated using:

$$IUE = \text{Forage yield}/I \qquad 3.5$$

$$WUE = \text{Forage yield}/ET \qquad 3.6$$

$$NUE = (\text{Forage yield from fertilised treatment} - \text{Forage yield from } N_0)/\text{Applied N} \qquad 3.7$$

Analyses of variance (ANOVA) for forage yield, crude protein, nitrogen use, irrigation applied, water use, irrigation and water use efficiencies, and soil solution nitrate concentrations were conducted using SAS (SAS, 2002). Multiple comparisons of means were performed using LSD_{Tukey} at a significance level of $P < 0.05$.

3.3 Results and discussion

3.3.1 Weather

Monthly mean minimum and maximum temperatures, and monthly total precipitation recorded from a weather station during the study period are shown in Table 3.3. Total precipitation over the growing period (March to December) at the study site was 557 mm in 2007 and 441 mm in 2008. The seasons were drier than the long-term average of 611 mm for this period. Monthly mean minimum and maximum temperatures were similar to the long-term mean values.

Table 3.3 Monthly mean minimum (T_{min}) and maximum (T_{max}) temperature, and total precipitation recorded during the 2007 and 2008 growing seasons, Cedara, South Africa

Year	Parameter	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.
2007	T_{min} (°C)	25.1	23.6	23.3	19.6	20.5	22.0	23.8	21.3	23.1
	T_{max} (°C)	13.7	10.9	4.3	1.8	1.3	3.7	10.4	11.2	12.3
	Rain (mm)	68.2	34.7	10.0	32.6	0	14.2	17.5	155.5	77.4
2008	T_{min} (°C)	24.7	22.2	23.2	19.4	21.1	22.9	22.8	22.3	23.7
	T_{max} (°C)	13.2	9.0	7.4	4.2	2.9	5.9	5.9	12.9	13.3
	Rain (mm)	3.0	71.3	8.2	21.9	13.0	5.4	42.6	37.5	82.2

3.3.2 Forage yield

The total numbers of growth cycles were eight in 2007 and seven in 2008 (Table 3.4). The higher number of cycles in 2007 was due to early planting and late ending of the season. Forage biomass produced was between 5.9 t ha^{-1} (N_0) and 15.6 t ha^{-1} (N_{60}). The maximum yields were in close agreement with the values reported by Eckard *et al.* (1995) from Cedara, which ranged from 12.5 to 15.4 t ha^{-1}. However, the yields from N_0 were lower than those of Eckard *et al.* (1995), which could be due to differences in season, soil N availability, cultivar and pasture management practices.

Table 3.4 Forage yield, total N application rates and fertiliser N use efficiency (NUE) of annual ryegrass under a range of fixed N rate (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) treatments in 2007; and fixed N rates (0, 20, 40, 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60}), N mass balance (N_{MB}), and adaptive N (N_{soil}) and water (N_{water}) treatments in 2008

Treatment	2007								
	07 May cycle 1	11 June cycle 2	11 July cycle 3	08 Aug cycle 4	04 Sep cycle 5	27 Sep cycle 6	24 Oct cycle 7	20 Nov cycle 8	Total
N_0	2.06a[§]	1.71a	1.16b	0.90c	0.61c	0.65c	0.53c	0.61c	8.23c
N_{30}	2.06a	1.72a	1.46a	1.23b	1.76b	1.77b	1.87b	1.35b	13.21b
N_{60}	2.09a	1.79a	1.58a	1.66a	2.35a	1.98a	2.35a	1.81a	15.61a

Treatment	Yield (t ha^{-1})							
	28 May cycle 1	01 July cycle 2	07 Aug cycle 3	05 Sep cycle 4	01 Oct cycle 5	24 Oct cycle 6	16 Nov cycle 7	Total
N_0	1.10a	1.91a	0.95d	0.76c	0.41c	0.46c	0.41c	5.9c
N_{20}	1.08a	1.96a	1.54c	1.44b	1.34b	1.54b	1.10b	10.0b
N_{40}	1.04a	2.02a	2.10a	2.08a	1.95a	1.97a	1.82a	13.0a
N_{60}	1.09a	2.03a	2.14a	2.16a	2.28a	2.06a	2.05a	13.8a
N_{MB}	1.12a	1.97a	1.97ab	1.96a	2.05a	1.81ab	1.80a	12.7a
N_{soil}	1.05a	2.07a	1.91ab	2.02a	2.20a	1.92a	1.95a	13.1a
N_{water}	1.16a	1.98a	1.84b	2.01a	2.17a	1.94a	1.92a	13.0a

[§] *Values followed by the same letter within a column are not significantly different.*

In 2007, maximum forage yields were obtained with N_{60} (Table 3.4) while the optimum quality was for the N_{30} treatment (Table 3.5). In 2008, in all growth cycles, there were no significant forage yield differences between fixed N rates (N_{40} and N_{60}) and N_{MB}, N_{soil} and N_{water}, except N_{water} in the third cycle (Table 3.4). In both years, there were no significant differences in forage yield between treatments in the first two growth cycles (Tables 3.4). As the seasons progressed, however, significantly different forage yields were exhibited showing the effect of N fertiliser, probably as a result of profile N depletion and reduced N mineralisation (Figure 3.4). The significantly low forage yield of N_{water} in the third cycle of 2008 could be due to water stress as one irrigation event was cancelled. This did not occur in the fifth cycle when irrigation was skipped because of high rainfall (Table 3.3).

3.3.3 Forage quality

Forage crude protein (CP) concentrations above 220 g kg^{-1} DM may drastically increase nitrate levels, leading to nitrate toxicity (Marais et al., 2003) and increases the risk of N losses from cows through urinary excretion (Tas *et al.*, 2006). Crude protein concentrations exceeded this threshold in the N_{60} treatment (272 g kg^{-1} DM), while it was close to 220 g kg^{-1} DM in the N_{soil}, N_{water}, N_{40}, and N_{MB} treatments (Table 3.5).

There were significant differences in seasonal mean CP, TP (true protein) and NTP (non-true protein) concentrations between treatments in both years (Table 3.5). In both years, noticeable increases of NPN were observed in N_{60} than the rest of the treatments. In 2007, the CP, TP and NPN of treatment N_{30} were 19, 9 and 37% lower than treatment N_{60}. In 2008, variable N treatments had 32, 7 and 39% lower than N_{60}. As N application exceeds pasture requirement the increase in CP will mostly be in the form of non-true protein while negligible increase in TP. TP increases up to certain level (22%CP), however, above this level the CP will be stored in non-true protein form and excessive nitrates (Marais *et al.,* 2003).

The NSC (non-structural carbohydrates) showed inverse relationship with CP (Table 3.5). NSC was significantly affected by the different N levels where the highest NSC values were observed from N_0, and the lowest from N_{60} treatment. N_{60} showed significantly lower NSC than the rest of the treatments, however, all the other treatments revealed similar and non-significant NSCs. The NSC ranges recorded from this study were similar to the values reported by Hopkins *et al.* (2002). Increased CP concentrations are at the expense of available energy (NSC) for animals (Hoekstra *et al.,* 2007). Therefore, similar overall animal performances can be observed by applying less N fertiliser and compensating the reduced yield with a good quality forage (lower CP and higher NSC).

There was an increase in ADF (acid detergent fibre) and NDF (neutral detergent fibre levels as N application increased (Table 3.5). However, significantly different NDF were observed only in 2008. This is primarily due to a decrease in leaf to stem ratio as nitrogen level increases. High quality forage is recognised by its high leaf to stem ratio, since leaves are more digestible than other plant parts. In highest N rate, there will be high transpiration and loss of water, which could encourage the growth of less digestible thicker vascular vessels (Hopkins *et al.,* 2002). NDF and ADF were the least affected parameters as a result of N application (Table 3.5). The inconsistency in these parameters among the treatments was because these parameters are more affected by the plant growth stage and time of harvesting rather than by N application. In general, the NDF and ADF values are close to the optimum ranges of 400 and 300 g kg^{-1} DM, respectively. There were no significant differences in ADF in both years, showing similar digestibility. However, significantly different ($P<0.05$) levels of NDF values were observed in 2008, which may show a reduced intake at high N application (Hopkins *et al.,* 2002; Marais *et al.,* 2003).

Table 3.5 Seasonal mean chemical composition (g kg^{-1} DM) of annual ryegrass the three fixed rate N treatments in 2007 and four fixed and three variable N treatments in 2008

Treatment	CP	TP	NTP	NSC	NDF	ADF
2007						
N_0	172c[§] ± 24[β]	158b ± 14	14c ± 13	115a ± 65	482a ± 63	256a ± 41
N_{30}	225b ± 36	164b ± 24	61b ± 32	71b ± 26	485a ± 65	255a ± 38
N_{60}	277a ± 41	181a ± 25	97a ± 26	42c ± 38	492a ± 71	259a ± 37
2008						
N_0	143d ± 70	118c ± 23	14d ± 5	153a ± 42	442b ± 72	242a ± 56
N_{20}	175c ± 59	126c ± 16	35c ± 12	125b ± 45	441b ± 51	240a ± 39
N_{40}	221b ± 48	149b ± 23	58b ± 34	75c ± 37	451b ± 78	248a ± 30
N_{60}	272a ± 27	167a ± 30	102a ± 15	51d ± 55	490a ± 16	251a ± 21
N_{MB}	217b ± 41	148b ± 13	58b ± 23	94c ± 37	472ab ± 44	258a ± 15
N_{soil}	228b ± 36	170a ± 18	59b ± 20	80c ± 67	478ab ± 68	242a ± 29
N_{TR}	219b ± 41	152b± 6	68b ± 33	81c ± 59	466ab ± 37	246a ± 29

[§]Values followed by the same letter within a column are not significantly different. [β]Standard deviation between growth cycles. Crude protein content (CP), True protein (TP), non-true protein (NTP), total non-structural carbohydrates (NSC), neutral detergent fibre (NDF) and acid detergent fibre (ADF).

In spite of its high yield, there is great concern regarding the quality of annual ryegrass due to too high forage CP concentration (Marais *et al.,* 2003). For lactating cows, forage CP concentration above 220 g kg^{-1} DM may drastically increase nitrate levels, leading to nitrate toxicity, increasing NPN (Reeves *et al.*, 1996), and reducing NSC (energy) and intake (Marais, *et al.*, 2003). This may result in reduced rate of milk production as more energy is used to digest the excess protein at the expense of milk production; and increases the risk of N losses from cows through urinary excretion (Tas *et al.*, 2006). Crude protein contents of the variable N treatments were not as high as the high fertiliser rate (N_{60}), and were lower than the maximum 220 g kg^{-1} DM. The other quality parameters of the adaptive N and water treatments were either improved or were similar to the N_{30} and N_{40} treatments. Any strategy which is useful in reducing CP without significant reduction in yield and other quality parameters; will have beneficial effect in improving NSC content of pasture. Therefore, more energy will be available to animals to balance the ingested CP.

3.3.4 Root growth

For all the treatments, over 80% of the roots were found at the top 0.3 m and the majority (>98%) rooting depth was 0.6 m (Figure 3.8). The root dry mass didn't show significant difference between difference N and irrigation treatments, however, there was a clear difference in percentage of root mass distribution. Higher root mass was obtained from N fertilised treatments compared to the control. Though no significant, root dry mass was higher in the high N rate treatments than (N_{60}) low N (N_{20}) treatments. The majority root system of ryegrass was at the top 0.6 m. However, a root system up to 1 m was observed from the minirhizotron san. The deep root system could be encouraged by the well-drained clay loam soil type of the site. Figure 3.8 shows root biomass of treatments averaged throughout the year and the values range from 500 to 600 kg ha^{-1}.

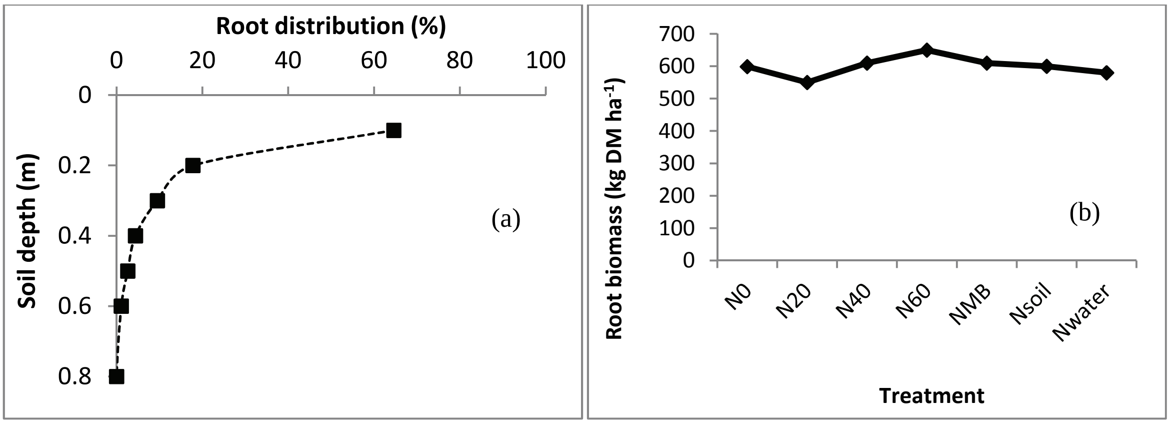

Figure 3.8 Mean root a) percentages distribution in the soil profile and b) biomass of annual ryegrass for non limiting N and water treatment

3.3.5 Soil water

The major soil water extraction observed from the top 0.4 m, and about 70% of the extraction was mostly from the top 0.2 m (Figure 3.9). This could be due to the root system of ryegrass, where 80% were found at the top 0.3 m. As the season progressed, however, there was a decrease in water content throughout the soil profile up 0.6 m. All treatments showed similar trend of soil water extraction, though the rate of depletion is higher at higher levels of nitrogen.

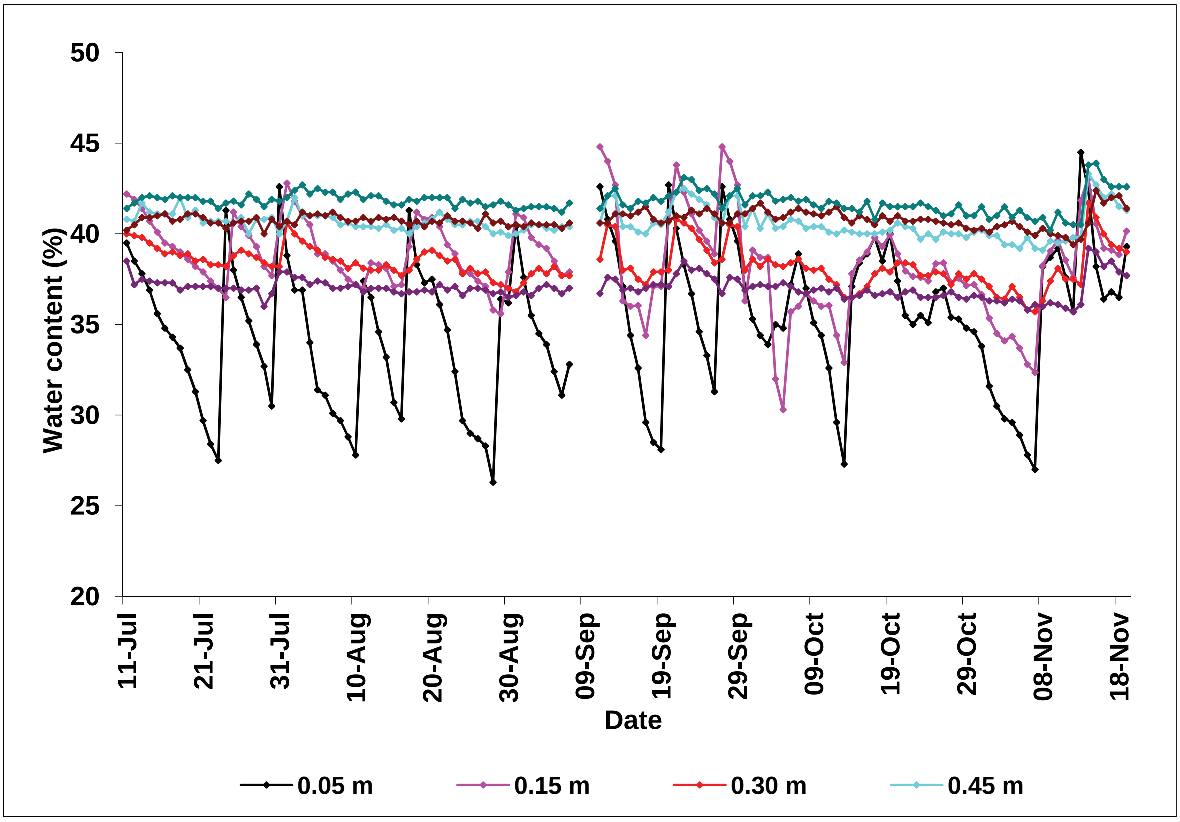

Figure 3.9 Volumetric soil water content as affected by rainfall and irrigation at different depths of the soil profile

Figure 3.10 shows matric potential of ryegrass at different depths for the one of the treatments. The variation in matric potential was highest at the top 0.5 m and decreases as the soil depth increase. The major fluctuations were observed at the top 0.45 m, and the potential was near 0 kPa after events of irrigation or rainfall. For most of the season the range in matric potential was between -20 and -70 kPa. The lower matric potential during summer was however, due to the irrigation scheduling technique used, which was leaving room for rain. There was a decrease in matric potential in November, however, no sign of wilting of pasture was observed. This could be due to the deeper root system of ryegrass and high water holding capacity of the soil at the site (clay loam to clay).

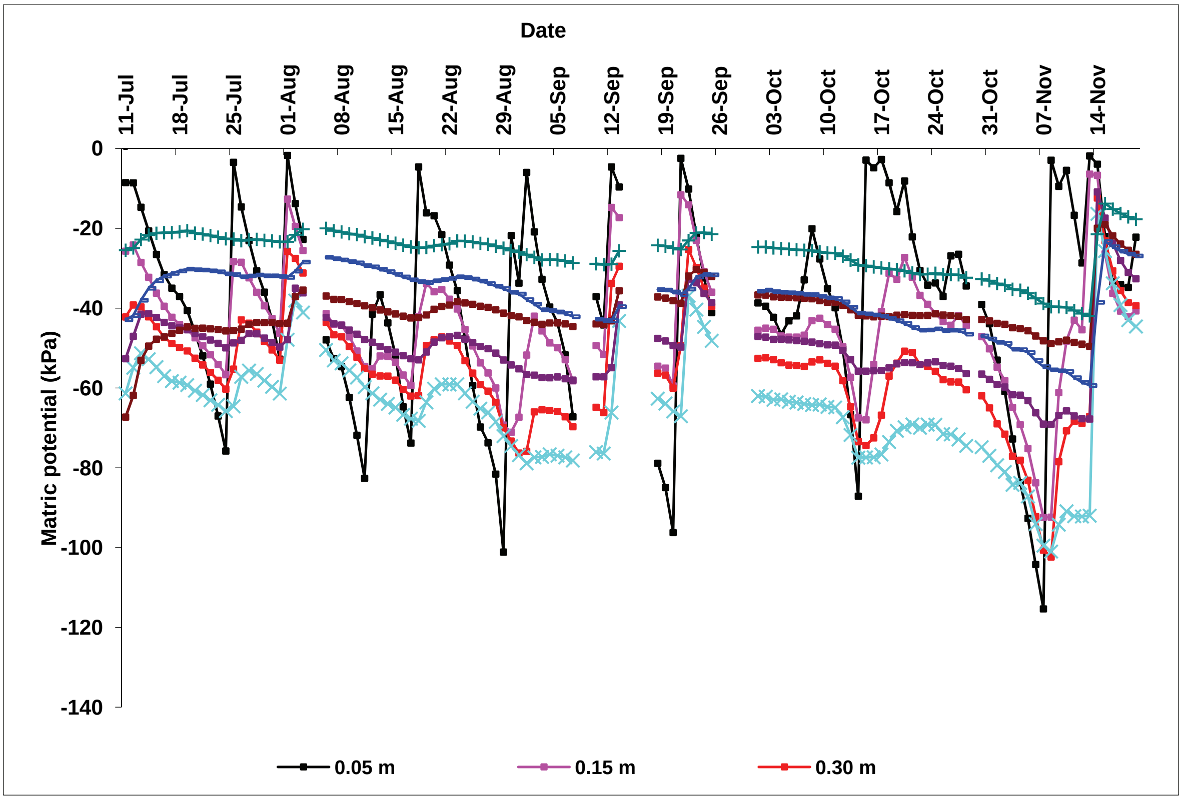

Figure 3.10 **Soil matric potential as affected by rainfall and irrigation at different depths of the soil profile**

3.3.6 Water use efficiency

Total irrigation, precipitation, water use, irrigation and water use efficiencies are presented in Table 3.6. In both years, there were significant differences in applied irrigation and water used between treatments (Table 3.6). In 2008, significantly lower irrigation was applied to N_{water} than N_{MB}. This was due to reduced amount or cancellation of irrigation events as a result of deep WFD response. In the N_{water} treatment in 2008, irrigations were cancelled on the 23rd of July in growth cycle three and the 27th of September in growth cycle five (Figure 3.11). On both occasions, WFDs at 0.45 m had responded to rainfall. At the beginning of the fourth (August 10) and fifth (September 7) growth cycles, irrigations were reduced according to the N threshold trigger and the pasture was irrigated only until the 0.15 m deep WFDs responded.

Seasonal irrigation use efficiency of Nwater was significantly higher than that of N_{MB}. The seasonal water application N_{water} was 44 mm lower than N_{MB} where mass balance calculations were used for N applications in both treatments. The N_{water} strategy showed a potential to increase water and irrigation use efficiencies, the slim benefit in this study was because the crop was not stressed. More N and water can even be saved by combining both adaptive N and irrigation strategies.

Table 3.6 Total irrigation (I: mm), evapotranspiration (ET: mm), irrigation use efficiency (IUE: kg DM ha^{-1} mm^{-1}) and water use efficiency (WUE: kg DM ha^{-1} mm^{-1}) of annual ryegrass under a range of fixed N rates (0, 30, 60 kg ha^{-1} $cycle^{-1}$ for N_0, N_{30}, N_{60}) treatments in 2007 and fixed N rate (0, 20, 40, 60 kg ha^{-1} $cycle^{-1}$ for N_0, N_{20}, N_{40}, N_{60}), N mass balance (N_{MB}), and adaptive N (N_{soil}) and water (N_{water}) treatments in 2008.

Treatment	I	ET	IUE	WUE
2007				
N_0	435b§	701b	18.8b	12.5b
N_{30}	529a	779a	26.9a	18.3a
N_{60}	565a	816a	29.2a	20.6a
2008				
N_0	343c	493d	17.5d	12.2c
N_{20}	382ab	547bc	26.2c	18.3b
N_{40}	384ab	564ab	33.9ab	23.0a
N_{60}	408a	571a	33.9ab	24.2a
N_{MB}	411a	563ab	30.9b	22.5a
N_{soil}	396ab	561ab	33.1ab	23.4a
N_{water}	367bc	529c	35.5a	24.6a

§Values followed by the same letter within a column are not significantly different.

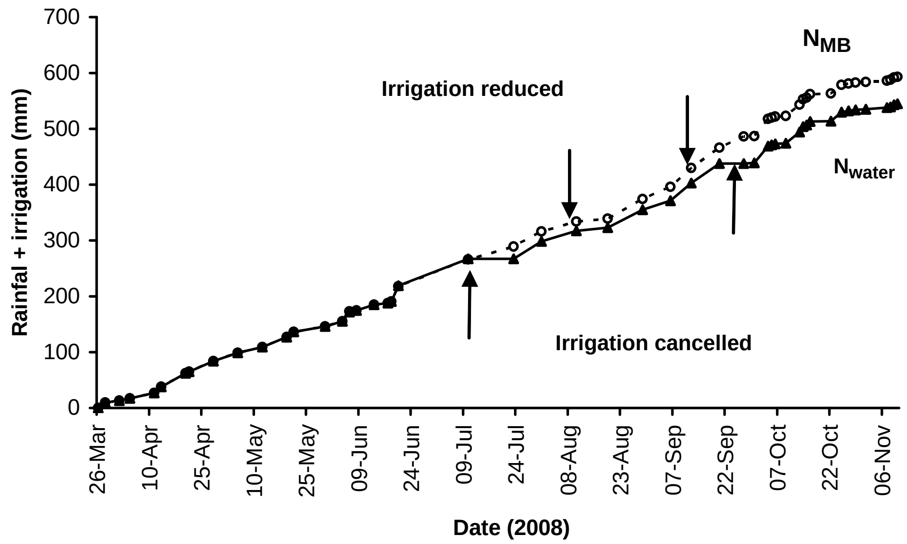

Figure 3.11 Rainfall plus irrigation for N mass balance (N_{MB}) and adaptive water (N_{water}) treatments in 2008 (upward arrows show cancellation of irrigation events and downward arrows reduced irrigation amount)

3.3.7 Nitrogen rates and N use efficiency

Seasonal N fertiliser recommendation for annual ryegrass by the South African Department of Agriculture (SADA) is 350 kg N ha^{-1} per year (usually 50 kg N ha^{-1} per cycle) for a target forage yield of 12 t ha^{-1} $year^{-1}$. As there were no yield differences between N_{40} and N_{60}, it was assumed that the recommended 50 kg N ha^{-1} per cycle would have produced a similar yield. Therefore, the recommended N rate of 50 kg N ha^{-1} per cycle was used as the benchmark against which certain N treatments are compared. When all the parameters required in the N_{MB} approach were measured or calculated, N application was reduced by 28%, from a recommended 300 kg N ha^{-1} per year (50 kg N ha^{-1} per cycle for six cycles) to only 216 kg N ha^{-1} per year. However, the much simpler approaches of adjusting N or irrigation according to threshold values from a WFD reduced applications by 27% (220 kg N ha^{-1}) and 32% (205 kg N ha^{-1}) respectively, compared with the annual recommendation, with no significant impact on yield (Table 3.7). The most marked N fertiliser input reductions using adaptive management strategies were in the second growth cycle when reductions of 100% were observed for both adaptive N treatments with respect to SADA recommendations. In the 3rd cycle, reductions of 60% in N_{soil} and 23% in N_{water} were observed with respect to SADA recommendations (Table 3.7).

Table 3.7 Total N application rates (kg ha^{-1}) and fertiliser N use efficiency (NUE: kg DM kg^{-1} N) of annual ryegrass under a range of fixed N rates (0, 30, 60 kg ha^{-1} $cycle^{-1}$ for N_0, N_{30}, N_{60}) treatments in 2007 and fixed N rate (0, 20, 40, 60 kg ha^{-1} $cycle^{-1}$ for N_0, N_{20}, N_{40}, N_{60}), N mass balance (N_{MB}), and adaptive N (N_{soil}) and water (N_{water}) treatments in 2008.

Year	Treatment	N rate	NUE
2007	N_0	0	-
	N_{30}	280	20.8
	N_{60}	460	15.4
2008	N_0	0	-
	N_{20}	120	33.4a[§]
	N_{40}	240	29.1ab
	N_{60}	360	21.7b
	N_{MB}	216	30.9a
	N_{soil}	220	32.4a
	N_{water}	205	34.1a

[§]Values followed by the same letter within a column are not significantly different.

Generally, fertiliser use efficiencies (NUE) were higher in 2008 than 2007 (Tables 3.7), probably because no N was applied in the first growth cycle of 2008. An additional growth cycle and higher forage yields obtained from the N_0 treatment could also possibly explain reduced fertiliser NUE in 2007. In 2008, adaptive N and water management showed significantly higher NUE compared to the fixed rate of N_{60}.

3.3.8 Potential leaching

Soil NO_3 concentrations from WFDs (Figure 3.12) and soil coring (Figure 3.13) increased with increase in fertiliser application rate. The N_{MB}, adaptive N (N_{soil}), and water (N_{water}) treatments showed similar soil solution nitrate concentrations, which were mostly lower than the South African (DWAF, 1993) permissible drinking water standard of 44.5 mg NO_3 L^{-1} (10 mg NO_3-N L^{-1}) in all growth cycles except for the first (Figure 3.12), where there was high initial inorganic N and mineralised organic N after tillage (Figure 3.4). The soil solution collected from deep WFDs may not directly be considered to be leaching because the WFDs are not responsive to slow rates of drainage. However, the results do help to identify conditions when nitrate leaching is likely to occur, as shown by deep soil coring (Figure 3.13).

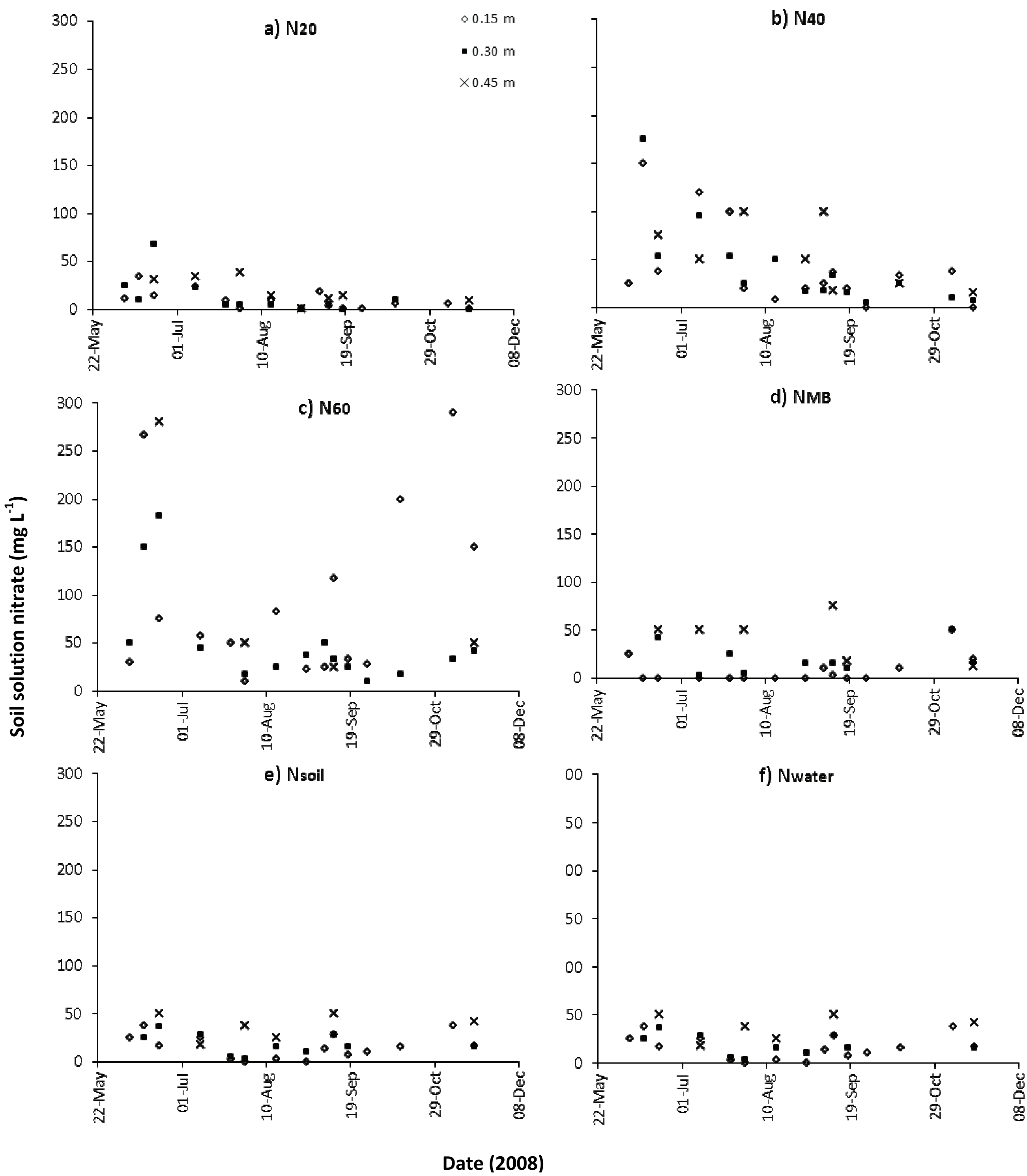

Figure 3.12 Soil solution nitrate concentrations collected from 0.15 (◇), 0.30 (▪) and 0.45 (x) m deep wetting front detectors installed in the a) 20 kg ha^{-1} cycle^{-1} (N_{20}), b) 40 kg ha^{-1} cycle^{-1} (N_{40}), c) 60 (N_{60}) kg ha^{-1} cycle^{-1}, d) N mass balance (N_{MB}), e) adaptive N (N_{soil}) and f) adaptive water (N_{water}) treatments in 2008

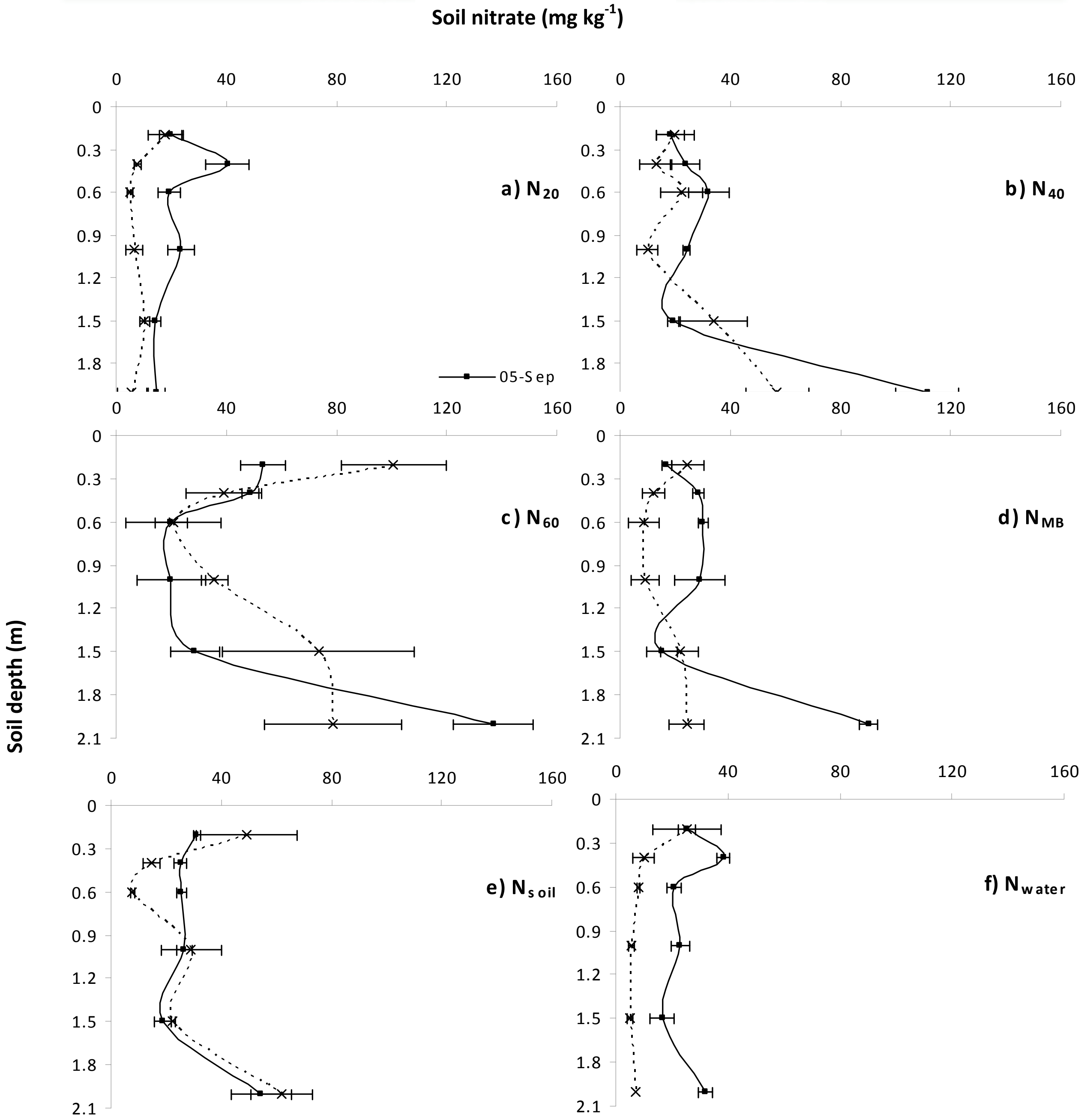

Figure 3.13 Soil nitrate concentrations (mg kg^{-1}) collected from soil cores in September (solid line) and November (dotted line) for the a) 20 kg ha^{-1} cycle^{-1} (N_{20}), b) 40 kg ha^{-1} cycle^{-1} (N_{40}), c) 60 (N_{60}) kg ha^{-1} cycle^{-1}, d) N mass balance (N_{MB}), e) adaptive N (N_{soil}) and f) adaptive water (N_{water}) treatments in 2008

Both adaptive N and water treatments showed relatively lower NO_3 concentrations (soil solution and core samples) than treatment N_{40}, even though the seasonal N application was similar. For example, mean NO_3 concentrations collected from 0.45 m WFDs in the N_{40} treatment were significantly higher than those of the adaptive treatments (Table 3.13). Differences in soil nitrate at 2 m between the September (before the rainy season) and November (end of growing season) soil core sampling dates were more than 50 mg kg^{-1} for the N_{40} and N_{60} fixed rate treatments (Figure 3.13). The difference in nitrates in the adaptive treatments were, however, less than 25 mg kg^{-1} showing the advantages of adaptive N treatments in reducing the risk of N leaching.

3.4 Conclusions

Results from the first and second seasons showed that the optimum N application per cycle was between 30-60 and 40-60 kg N ha^{-1} respectively, close to the current recommendation of 50 kg N ha^{-1} per cycle. Seasonal N application could be reduced by 28% when many of the components of the N balance were measured at the start of each cutting cycle (N_{MB}). However, the expense of such monitoring may not be justifiable on economic grounds. The trial showed that N savings from intensive monitoring could also be realised through a much simpler adaptive approach based on thresholds for the nitrate concentration in the soil solution. With respect to the baseline recommendations from the South African Department of Agriculture, N application was reduced by 27% and 32% respectively in the two adaptive treatments (reduced N application and reduced water application). Both adaptive treatments resulted in an improvement of forage quality with no yield reduction, and a lower risk of N leaching.

The thresholds used in this study do have weaknesses in their interpretation. For example, the WFD used to collect water samples does not respond to fronts moving at suctions drier than 2 to 3 kPa. Furthermore, the nitrate concentration of the leaching water may be different from the resident soil water which would be available to the pasture (Van der Laan *et al.,* 2010). Moreover, the thresholds were selected from just one season's data, but they could no doubt be improved.

Farmers are intuitively adaptive managers and the use of simple monitoring and thresholds presents a way to structure their learning, and they represent our simplest conceptualisation of the problem to be managed (Stirzaker *et al.,* 2010). A good adaptive manager is expected to improve these thresholds as more experience is gained. A manager could for example select a lower threshold than 25 mg L^{-1}, or alternatively he could combine the two adaptive treatments to seek alternative strategies.

CHAPTER 4: EVAPOTRANSPIRATION ESTIMATION OF ANNUAL RYEGRASS (*Lolium multiflorum*) USING THE ENERGY BALANCE METHOD

4.1 Introduction

Irrigation has been practiced for ryegrass production to maintain adequate soil water for successful pasture production. Availability of water is usually the most limiting factor due to significant increase in irrigated land and insufficient precipitation during ryegrass growing season. Accurate prediction of crop evapotranspiration (ET) is a pre requisite for effective irrigation, hence irrigation can be applied by matching water requirement of pastures.

Water use (evapotranspiration) of crops can be determined using several methods. Evapotranspiration measurements are highly variable due to variations in measurement techniques and difference in their relative accuracies. In the previous chapters ET was determined in the water balance method by noting the change in soil water content over time. ET is calculated from the change in total soil water between sampling dates plus rainfall minus any known drainage or surface runoff that may have occurred. A major potential source of error in ET determined by the soil water balance method is uncertainty in drainage from the zone sampled or any upward movement of water from a lower wetter zone into the zone sampled. Therefore, in this chapter for comparison and later (Chapter 5) for validating the SWB model evapotranspiration of ryegrass was estimated using the energy balance method.

Evapotranspiration is typically modelled using weather data and algorithms that describe surface energy and aerodynamic characteristics of the vegetation. Solar radiation is the primary energy source that drives processes of evapotranspiration. The energy balance separates net radiation from the sun to sensible which heats the air and latent heat which use for evapotranspiration. Hence in this study evapotranspiration was measured by measuring or estimating the energy balance components.

4.2 Description of the method

The energy budgets are typically evaluated within a volume that includes vegetation above the surface. The shortened energy balance equation (Allen *et al.*, 2011) is expressed as:

$$R_n = H + \lambda E + G \qquad 4.1$$

where R_n is the net irradiance, G is the soil heat flux density, H is the sensible heat flux density, and λE is the latent energy flux density. Sensible heat flux density (H) is estimated using eddy covariance (EC) and surface renewal (SR) methods and latent energy flux density (λE) or ET is obtained as the residual using the shortened energy balance equation.

Eddy covariance (EC) method provides a direct measurement of sensible heat flux (H) above extensive surfaces of homogeneous medium using high frequency air temperature (T) and vertical wind velocity (w) measurements (Swinbank, 1951). The flux is described as:

$$H = \rho c_p \overline{w'T'} \qquad 4.2$$

where ρ is the density of air (1.14 kg m^{-3}), c_p the specific heat capacity of air at constant pressure (1011 J kg^{-1} K^{-1}), w is the vertical wind velocity and T is the sonic temperature. The primes in Equation (2) indicate fluctuation from a temporal average (i.e. $w' = w - \overline{w}$) and the over bar represents a time average. The vertical wind speed is responsible for the flux across a plane above a horizontal surface. The EC method requires sensitive, expensive instruments to measure high frequency and scalar quantities. Sensors must measure vertical wind speed, sonic temperature and atmospheric humidity with sufficient frequency response to record the most rapid fluctuations important to the diffusion process (Mengistu and Savage, 2010).

The SR method is a simple and relatively inexpensive technique that is based on the principle that an air parcel near the surface is renewed by an air parcel from above (Paw U *et al.*, 2005). The parcel heats or cools while it is at the surface because of energy exchange between the air and the canopy elements. The SR method for estimating fluxes from canopies involves high frequency air temperature measurements using fine wire thermocouples. The theory of heat exchange between a surface and the atmosphere using the SR method is described as:

$$H = \alpha \rho_a c_p z \frac{a}{\tau} \qquad 4.3$$

where α is a weighting factor, a is amplitude of the air temperature ramps and τ is the total ramping period. The amplitude (a) and the ramping period (τ) were deduced using analytical solutions of Mengistu (2008) for air temperature structure function. The sensible heat flux was finally estimated from Eq. (3) using the measurement height (z) and a weighting factor (α) obtained by calibration, usually, against the EC method. The weighting factor α depends on the measurement height, canopy architecture and thermocouple size (Snyder *et al.,* 1996). Once determined, it is fairly stable and does not change from site to site regardless of weather conditions unless the surface roughness changes (Snyder *et al.*, 1996; Paw U *et al.*, 2005). For short turf grass (0.05 m tall), excellent estimates of H were obtained using α = 1, when the measurements are taken at 0.35 m and 0.70 m above the turf grass (Snyder *et al.,* 1996; Mengistu, 2008).

4.3 Materials and methods

4.3.1 Study area

The experiment was conducted from 11th of September to 6rd of November 2008 at the Department of Agriculture research station at Cedara (altitude 1076 m above sea level, S29°32'; E30°17') located in the midlands of KwaZulu-Natal mistbelt, one of the main milk producing areas of South Africa. The soil of the experimental site is characterised by a deep, red, kaolinitic soil classified as Hutton form, Hayfield family (Soil Classification Working Group, 1991). Soil type of the site is clay loam up to a depth 0.4 m and clay from 0.4 to 1 m soil depth. The pasture was irrigated with a dragline sprinkler irrigation system. The dominant wind at the site during the study period was from South East direction. The experimental plot size was 120 m x 40 m.

4.3.2 Weather data

A fully automated weather station has been installed on the site. This station measures solar radiation, temperature (maximum and minimum), wind speed and direction, rainfall and relative humidity. Irrigation amounts were measured with manual rain gauges. Manual raingauges have been positioned in each plot and the amount of irrigation water was recorded after each irrigation event.

4.3.3 Energy balance

Evapotranspiration (ET) was estimated using the shortened energy balance method, under well watered condition. Experimental plot size was 120 m x 50 m with a dominant wind direction from the South East during the study period. The measurements of eddy covariance system (EC) and surface renewal (SR) (Mengistu and Savage, 2010) were conducted for three growth cycles (11th September to 6th of November 2008). The primary use of the EC was for calibrating the α factor for the surface renewal system (Mengistu and Savage, 2010).

For eddy covariance, wind velocity and temperature (0.75 m above the ground) were measured using a three dimensional sonic anemometer (model 81000, RM Young, Michigan, USA). Sampling frequency of the three components of wind velocity, *u, v, w,* and sonic temperature *T* was 10 Hz. The two-minute averages of eddy covariance between *u, v, w* and *T* and wind direction θ = arctan v/u were calculated and stored for further analysis. For the surface renewal method, two unshielded type-E fine wire chromel-constantan thermocouples (75 µm diameter) were used to measure high frequency air temperature 0.25 m above the crop surface (Figure 4.1). The height of the thermocouples was adjusted twice a week to keep the height constant above the canopy by adjusting for measured average grass height.

Figure 4.1 Microclimatological instruments installed at the Cedara site

The measurements of eddy covariance and surface renewal systems were used for estimating sensible heat flux (H). The NR-LITE net radiometer (Kipp & Zonen, Delft, The Netherlands) placed 1.0 m above the soil surface was used to measure net irradiance (Rn). Soil heat flux (G) was measured using two soil heat flux plates (model HFT-S, REBS, Seattle, USA) placed 80 mm below the soil surface. For measuring the soil heat stored above the soil heat flux plates, thermocouples were installed at depths of 20 and 60 mm. A CS616 time domain reflectometer (TDR) was also used for measuring volumetric water content of the top 80 mm.

4.4 Results and discussion

Reference evaporation (FAO 56) varied from less than 1 mm on rainy days to greater than 6 mm in the hot spring and summer periods (Figure 4.2). These data were used to predict the atmospheric evaporative demand of the site and used to develop crop coefficients for ryegrass.

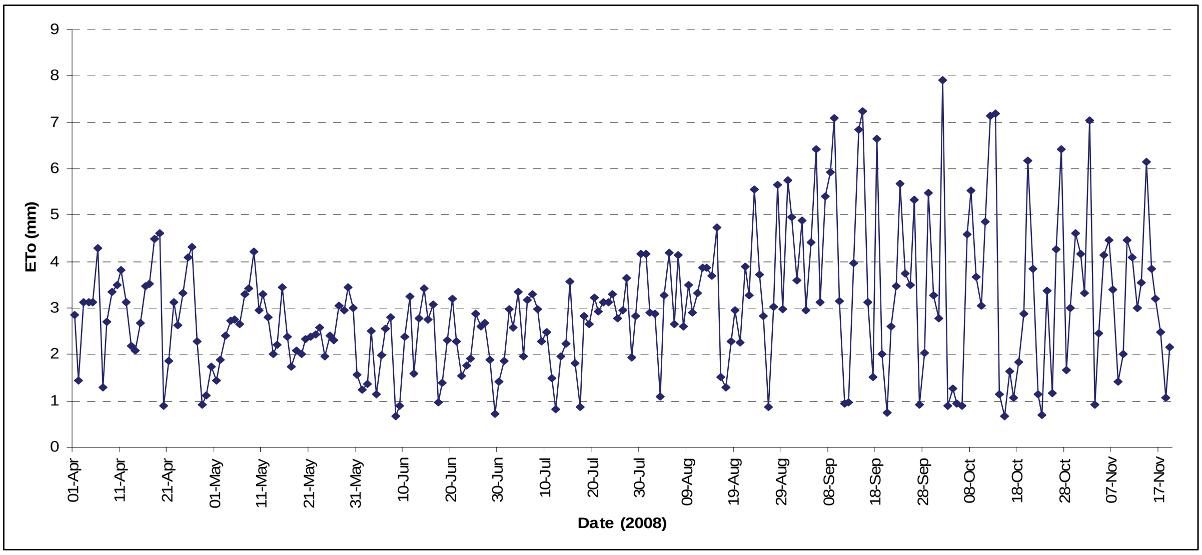

Figure 4.2 Reference evaporation between April and November 2008 at the Cedara site

Water use (evapotranspiration) estimated using eddy covariance and surface renewal methods in comparison to the reference evapotranspiration calculated using FAO-56 is shown in Figure 4.3. During the three regrowth cycles water use was ranged from 0.5 mm during rainy days to 6 mm clear and sunny days. Generally there water use estimated using SR was higher than using EC, but the difference was less than 0.5 mm day^{-1}. Cumulative measured ET for the well watered three growth cycles was 161 mm.

Crop coefficients (Kc) of optimally fertilized ryegrass were developed for three individual regrowth cycles during spring and summer (Figure 4.4). Kc was calculated as ET/ETo. ET was determined from ET measurements of EC and SR methods. There was high variation of Kc among days ranging from 0.7 to 1.1, for most of the days and regrowth cycles depending on the evaporative demand of the day. The variation in Kc among different days and regrowth cycles can be addressed by the use of mechanistic crop growth models.

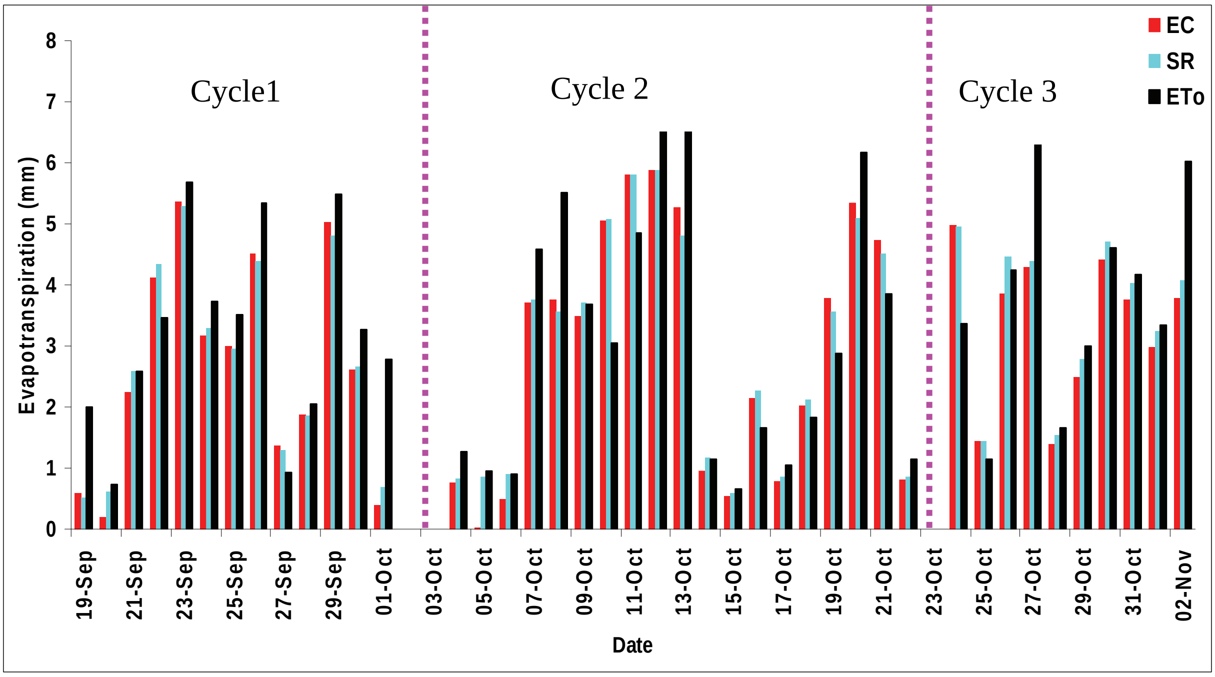

Figure 4.3 Diurnal variation in evapotranspiration estimates (mm) using the EC and SR methods from 18th September to 3rd November 2008

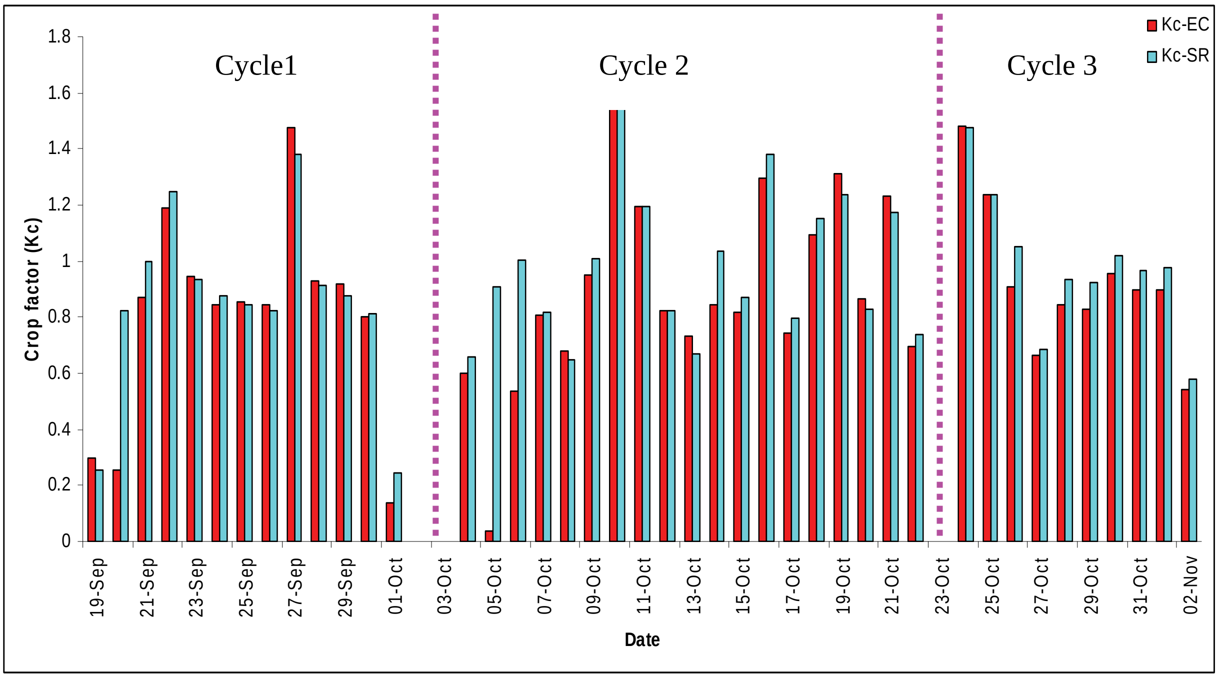

Figure 4.4 Crop coefficient variations in ryegrass calculated as a ratio of ETc estimated from EC or SR methods and ETo from 18th September to 3rd November 2008

4.5 Conclusions

This experiment was conducted to estimate evapotranspiration of ryegrass for three regrowth cycles using the eddy covariance (EC) and surface renewal (SR) techniques. These methods estimate sensible heat flux density (H), and then evapotranspiration (ET) was calculated as a residual of the shortened energy balance term involving measurements of net irradiance (Rn) and soil heat flux density (G). The water use of both methods shows similar ET estimates. Evapotranspiration (ET) measured using surface renewal varied from day to day. During the three growth cycles monitored, ET ranged from 0.5 mm during rainy days to 6.5 mm on clear, sunny days. The data was used to calibrate the models which are used in this project.

CHAPTER 5: MODELLING WATER USE OF ANNUAL RYEGRASS (*Lolium multiflorum*)

5.1 Introduction

Irrigation technologies may be adapted by commercial and emerging rural farmers for more-effective and wiser use of limited water supplies. Irrigation scheduling is the main component of water management by which irrigators decide when and how much water to apply (Hoffman *et al*., 1992). Proper scheduling can lead to increased profits without compromising the environment, by increasing productive water use and reducing unproductive water loss through run off, deep percolation below the root zone with nutrient leaching and soil water evaporation (Reinders, 2010). Several irrigation scheduling techniques of varying levels of sophistication based on soil, plant and atmospheric measurements are recommended worldwide to address the shortage of irrigation water and maximise yield (Stevens *et al.,* 2005). However, the tools required are relatively expensive and complicated making the implementation of irrigation scheduling for the average farmer difficult (Orloff and Carlson, 1997). Some monitoring tools may also not provide the most reliable method of scheduling due to soil spatial variability or by giving little information either on the amount or when water is to be applied (Hillel, 1990; Hoffman *et al.,* 1992). Using irrigation monitoring tools, however, provides reasonable and quantitative information for irrigation scheduling. A combination of one or more monitoring approaches would improve the accuracy of recommended timing and amount of irrigation to be applied.

In the last four decades, various computer models, which integrate the soil, plant and atmospheric approaches by estimating soil water balance components, have been developed for different purposes (Joyce and Kivkert, 1987; Bahera and Panda, 2009; Allen *et al*., 2011). The Soil Water Balance model (Annandale *et al.*, 1999), a real-time, generic crop growth, soil water balance and irrigation scheduling model, is one of these. Results acquired from computer simulation can be used in conjunction with data collected from field experiments to better understand systems and to extrapolate findings in time and space. This can save money and the time required for conducting long-term intensive field experiments for gathering information on potential crop production with different resources. In the absence of monitoring methods, models can also be used to explore better irrigation management strategies in order to increase irrigation use efficiency and determine site specific irrigation requirements or calendars.

The main objective of this project was to optimise the growth of ryegrass through efficient use of water and nitrogen (N) fertilisation. One of the tools for achieving this was the use of numerical models for which base-line information is needed for parameterisation and testing. Hence available crop/pasture models were reviewed from literature (see Appendix A for detailed discussion) and the SWB model and DairyMod were selected. However, since the objective of the project was mainly to estimate water use the SWB was used. Considering the use of a large number of data sets and time consuming determination of input parameters required for the pasture specific models, relatively simple models (such as the SWB) may be more applicable. According to Stevens *et al.* (2005), the major problems with adoption of models by the farmers is their complexity, therefore, there should be trade-offs between accuracy and simplicity. The SWB model is being used to simulate crop growth and soil water balance of several cereals, vegetable and tree crops (Annandale *et al.,* 2000; Jovanovic *et al*., 1999; Geremew *et al.,* 2008; Singles *et al.,* 2010). Therefore, it is better to use a model which is locally known by farmers and consultants instead of introducing another new model. The model is available on the web and can be downloaded free of charge. As a result the SWB model was calibrated and validated and after satisfactory evaluation the model was used to predict water requirement of annual ryegrass in major pasture growing areas of South Africa.

The current irrigation guideline of most temperate grasses, including ryegrass is 25 mm of irrigation water per week (Jones, 2006; Macdonald, 2006). Evaporative demand differs between locations and over time for a specific location, and as crop canopy cover varies. Therefore, a rigid guideline of 25 mm per week will lead to over or under irrigation. There is a need to determine irrigation requirements of annual ryegrass by developing site specific irrigation calendars which are simple guidelines or charts that indicate when and how much to irrigate. Calendar based irrigation scheduling, provides irrigators with an inexpensive strategy to estimate irrigation timing and amount. The irrigation requirements developed can be flexible by deducting real time measured rainfall since the last irrigation event.

The objectives of the study were to parameterise the SWB model for ryegrass and evaluate its performance under different levels of irrigation (from data reported in Chapters 2, 3 and 4). Once satisfied with model prediction capability to predict water requirement, then the model can be used for develop site specific irrigation calendars for major ryegrass growing regions of South Africa with confidence.

5.2 Model description

SWB is a mechanistic, real time, generic, crop growth, soil water balance and irrigation scheduling model, which has a user friendly interface (Annandale *et al.,* 1999). It was developed based on the NEWSWB (Campbell and Diaz, 1988). Simulations can be done with two approaches: 1) an FAO based model that calculates canopy cover from an empirical crop factor and 2) a mechanistic simulation of crop growth. The FAO approach simulates crop water use and growth relatively simply using crop coefficients for various growth stages (Jovanovic and Annandale, 1999). On the other hand, the crop growth model simulates dry matter production more mechanistically. The mechanistic crop growth model has the capability to simulate the effect of water stress on canopy size (Jovanovic and Annandale, 2000), which cannot be done by the simple FAO approach. However, this requires more detailed crop specific model parameters.

SWB estimates crop growth and water balance fluxes and storage using weather, soil and crop units. A detailed description is available in Annandale *et al.* (1999). The weather unit of SWB calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to FAO 56 recommendations (Allen *et al.,* 1998). Water movement in the soil profile is simulated using a cascading or finite difference approach.

In the crop unit, SWB calculates a daily dry matter increment as either being radiation or water limited. SWB estimates phenological development, growth and yield of a crop from emergence to maturity based on soil water status and environmental conditions. Transpiration is assumed to be equal to crop water uptake, which is a function of soil water potential, leaf water potential and root conductance. The use of thermal time in mechanistic growth model negates the need to specify length of developmental stages as crop factors modelling approach to express crop development, which varies for different planting dates and regions (Olivier and Annandale, 1998). Hence in the growth model, water-limited growth is calculated using parameters that directly limit biomass accumulation including a crop stress index and leaf water potential (Annandale *et al.,* 2000). In addition, the growth model enables an accurate description of deficit irrigation strategies, where water use is supply limited (Annandale *et al.,* 1999).

The model was parameterised and extensively tested for many crops (Annandale *et al.,* 2000; Jovanovic *et al.*, 1999; Geremew *et al.,* 2008; Singles *et al.,* 2010). To improve applicability for ryegrass pasture various defoliation practices including fixed date, thermal time and accumulated forage biomass were included in the SWB model.

5.3 Materials and methods

5.3.1 Site description and crop management

Data collected from an open field and rainout shelter during the 2007 and 2008 growing seasons were used to calibrate and validate the model. The open field experiment was conducted at the Cedara research station of the Department of Agriculture (altitude 1076 m, S29^{o}32'; E30^{o}17') in the Midlands of KwaZulu-Natal. The rainout shelter experiment was conducted at the Hatfield Experimental Farm (altitude 1327 m, S25^{o}45'; E28^{o}16') of the University of Pretoria, Pretoria. The soil at Cedara was a deep, red, kaolinitic Hutton soil with a heavy clay loam texture to a depth 0.4 m, and heavier clay soil from 0.4 to 1.0 m (Soil Classification Working Group, 1991) while that of Hatfield was a sandy loam. The irrigation systems were dragline sprinklers at Cedara and dense grid drip at Hatfield.

At both sites, annual ryegrass cultivar "Agriton" was planted in rows at a seeding rate of 30 kg ha^{-1} and spacing of 15 mm between rows. 20 kg P ha^{-1} was applied at planting while 60 kg N ha^{-1} and 25 kg K ha^{-1} was applied for each growth cycle. Access tubes were installed in each plot to monitor soil water content to a depth of 1.0 m. A large fraction of ryegrass' active root system is located in the top 0.60 m, thus root zone soil water deficit and irrigation scheduling for both sites was conducted to the 0.60 m soil depth.

5.3.2 Treatments

Two different approaches were used. The first used different irrigation strategies for growth analysis and forage yield determination and the second used micrometeorological techniques for measuring total evaporation under well watered condition. The data were used for model calibration and validation.

Irrigation strategies

At Hatfield, plots were 3.0 m^2 (1.5 m x 2.0 m) with an interspacing of 0.5 m between each plot. Plastic sheeting was inserted to a depth of 1.2 m in the interspaces to limit the movement of water between plots. Plots were irrigated twice a week (**W1**), weekly (**W2**) or once every two weeks (**W3**) to field capacity (Table 5.1). In both sites and years, treatments were replicated three times and were assigned in a randomised complete block design (Chapter 2).

At Cedara, , plots were 12 m wide and 36 m long, with a 12 m spacing between plots. Each plot had its own sprinkler lines to allow the application of independent irrigation amounts. In 2007, deficit (growth cycles one to three) and frequency (growth cycles four to eight) irrigation scheduling strategies were used (Table 5.1). For the first three growth cycles, plots were replenished to 100% (**W1**) or 60% of plant available water (field capacity – wilting point) (**W2**) weekly. For the next five growth cycles (fourth to eighth) plots were irrigated every 7 days (**W1**) or 14 days (**W2**) to field capacity. In 2008, well watered treatment plots were irrigated once a week during autumn, spring and summer; and once every two weeks in winter to field capacity (**W1**). In both years, in summer

15 mm soil deficit was left after irrigation as “room for rain”. In 2008, water stressed plots were irrigated only after harvest when N and K fertilisers were applied (**W2**).

Table 5.1 Treatments used for calibration and validation of the SWB model

Site	Year	Planting date	Treatments	Defoliation	Growth cycles	Modelling objective
Hatfield	**2007**	05/06/2007	W1 W2 W3	28 days	4	Validation
	2008	23/04/2008	W1 W2 W3	28 days	4	Validation
Cedara	**2007**	06/03/2007	W1 W2	3 leaf stage	8	Validation
	2008	25/03/2008	W1	3 leaf stage	7	Calibration
		17/04/2008	W2	3 leaf stage	5	Validation

Evapotranspiration measurement using the shortened energy balance method

Evapotranspiration (ET) under well watered conditions was estimated using the surface renewal technique to obtain the sensible heat flux and the latent heat flux (ET) obtained as the residual of the shortened energy balance equation (Savage *et al.,* 2010). To allow for adequate fetch a large field (120 m x 50 m) with a dominant wind direction from the South East during the study period was planted with annual ryegrass in April. The measurements of surface renewal (SR) (Paw U *et al.*, 2005) were conducted for three growth cycles (11th September to 6th of November 2008). An eddy covariance system (EC) was also installed from 2nd October to 6th November. The primary use of the EC was for calibrating the α factor for the surface renewal system (Mengistu and Savage, 2010).

Wind velocity and temperature (0.75 m above the ground) were measured using a three dimensional sonic anemometer (model 81000, RM Young, Michigan, USA). Sampling frequency of the three components of wind velocity, *u, v, w,* and sonic temperature *T* was 10 Hz. The two-minute averages of eddy covariance between *u, v, w* and *T* and wind direction ε = arctan v/u were calculated and stored for further analysis. For the surface renewal method, two unshielded type-E fine wire chromel-constantan thermocouples (75 µm diameter) were used to measure high frequency air temperature 0.25 m above the crop surface. The height of the thermocouples was adjusted twice a week to maintain a constant 0.25 m height above the pasture canopy.

The eddy covariance and surface renewal measurements were used to estimating sensible heat flux (H). The NR-LITE net radiometer (Kipp & Zonen, Delft, The Netherlands) placed 1.0 m above the soil surface was used to measure net irradiance (R_n). Soil heat flux (G) was measured using two soil heat flux plates (model HFT-S, REBS, Seattle, USA) placed 80 mm below the soil surface. For measuring the soil heat stored above the soil heat flux plates, thermocouples were installed at depths of 20 and 60 mm. A CS616 water content reflectometer (Campbell Scientific, USA) was used for measuring the volumetric water content of the top 80 mm soil layer.

5.3.3 Data collection

At both experimental sites, weather data, including daily values of minimum and maximum air temperature and humidity, wind speed, incoming solar radiation and precipitation, were collected from automated weather stations. Soil water contents were measured using a Diviner-2000 probe (Sentek®, Australia) at Cedara and a neutron water meter model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA) at Hatfield. Irrigation amounts were measured with manual raingauges at Cedara and with water meters at Hatfield.

At both sites, leaf area and above ground biomass were measured every 7 to 14 days by harvesting plant material from an area of 0.25 x 0.25 m to a height of 50 mm from the soil surface. The samples were hand separated into leaf and stem material. The leaf area index (LAI) was determined using an LI 3100 belt driven leaf area meter (LiCor, Lincoln, Nebraska, USA). For forage yield determination, grass was harvested at the 2 to 3 leaf stage (1 m^2) at Cedara, and every 28 days (0.0625 m^2) at Hatfield using a manual grass mower to a 50 mm stubble height. At Cedara, after sampling for forage yield and stubble biomass, the whole field was harvested to a height of 50 mm with a tractor drawn mower. Forage dry matter was determined by oven drying samples at 70°C to constant mass.

5.3.4 Model reliability test

The statistical evaluation parameters used to test the accuracy of the model were the coefficient of determination (r^2), Willmott (1982) index of agreement (D) and mean absolute error of measured values (MAE). For accurate model predictions, r^2 and D should be greater than 0.8, while MAE should be less than 20% (De Jager, 1994).

5.3.5 Model application

Long-term daily weather data (1950-2000) of precipitation, minimum and maximum temperatures for major annual ryegrass growing sites in South Africa were selected from the SWB weather database. Representative sites in four main annual ryegrass growing regions were selected. These were in the KwaZulu-Natal Midlands (Cedara), Eastern Highveld (Ermelo), Eastern Cape (Queenstown) and Southern Cape (George) (Figure 5.1). Measured long-term mean rainfall, minimum and maximum temperatures and vapour pressure deficit (estimated from temperature) of the sites are presented in Table 5.2.

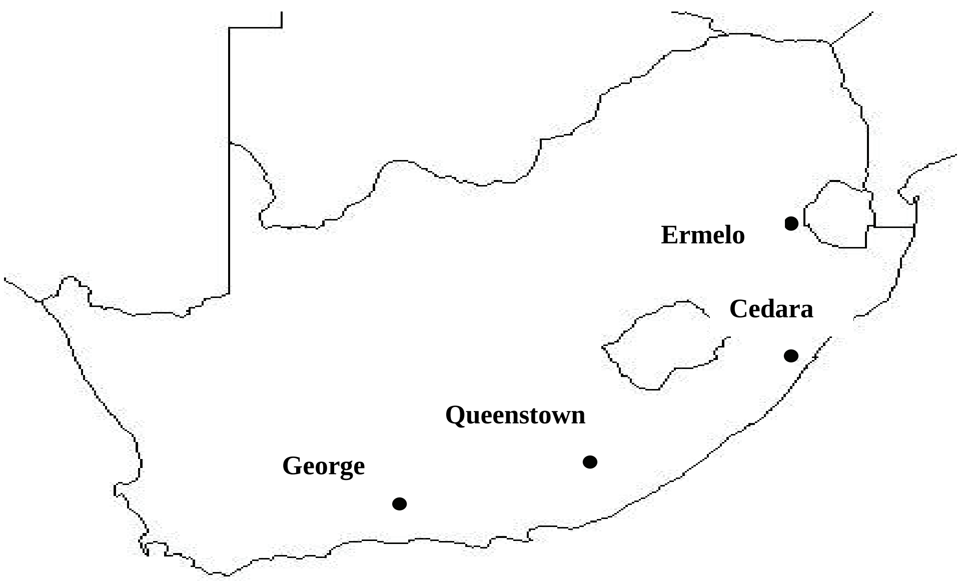

Figure 5.1 Major annual ryegrass growing areas of South Africa

Table 5.2 Long-term (1950-2000) monthly mean minimum (T_{min}) and maximum temperature (T_{max}), vapour pressure deficit (VPD) and total precipitation for the major annual ryegrass growing areas of South Africa

Year	Parameter	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.
Cedara (KwaZulu-Natal Midlands)	T_{max} (°C)	24.6	22.9	21.0	19.0	19.5	20.7	22.4	22.4	23.4
	T_{min} (°C)	13.8	10.4	6.3	2.9	3.1	5.3	8.7	10.6	12.5
	VPD (kPa)	1.48	1.58	1.50	1.44	1.48	1.50	1.54	1.44	1.41
	Rain (mm)	105	50	26	12	15	29	50	90	105
Ermelo (Eastern Highveld)	T_{max} (°C)	23.6	21.5	19.2	16.5	17.0	19.5	22.7	23.2	23.4
	T_{min} (°C)	11.4	8.1	3.7	0.1	0.1	2.9	6.8	9.5	11.2
	VPD (kPa)	1.54	1.50	1.43	1.28	1.35	1.52	1.80	1.59	1.55
	Rain (mm)	74	43	14	8	8	13	31	91	125
Queenstown (Eastern Cape)	T_{max} (°C)	26.8	22.5	20.2	17.5	18.6	20.9	23.6	24.4	26.8
	T_{min} (°C)	12.9	8.5	5.0	2.4	2.2	4.1	7.6	9.5	12.0
	VPD (kPa)	2.04	1.58	1.49	1.28	1.43	1.68	1.85	1.91	2.12
	Rain (mm)	69	38	20	14	10	18	24	46	57
George (Southern Cape)	T_{max} (°C)	23.7	21.6	20.4	19.3	18.6	18.4	19.1	20.0	21.6
	T_{min} (°C)	13.9	11.3	9.2	8.0	6.9	7.0	8.3	9.8	11.8
	VPD (kPa)	1.36	1.29	1.24	1.19	1.14	1.13	1.10	1.16	1.22
	Rain (mm)	81	72	58	44	42	74	62	71	61

Soil input parameters from the Cedara site described in Chapter 3 were used for all regions. The profile was a deep, red, kaolinitic Hutton soil with a heavy clay loam texture to a depth of 0.4 m, with a heavier clay texture from 0.4 to 1.0 m. The maximum soil depth was set to 0.4 m because most pastures are planted on marginal soils. Simulations were preformed from 1st March to 6th November (eight harvests). The first defoliation was simulated 60 days after planting and after this first harvest, the pasture was defoliated at four week intervals, in autumn and winter and three week intervals in spring. The virtual crop was irrigated with a sprinkler irrigation system and the initial soil water content at planting for all the layers was set to field capacity. This assumption was made because planting is at the end of the rainy season and it is usually safe to assume the soil profile is wet. This can be also supported from the high rainfall received during the month of February (Figure 5.2). Water requirements of annual ryegrass was predicted using a common "recipe" of 25 mm per irrigation event, but scheduling the timing according to long-term water requirement.

5.4 Results and discussion

5.4.1 Model calibration

Field data collected during 2008 from Cedara under well watered conditions were used to estimate crop specific parameters of ryegrass. Ryegrass growth parameters which were determined by Annandale *et al.* (1999) were refined in order to account for pasture specific management and cultivar differences. Crop specific growth parameters including radiation extinction coefficient, vapour pressure deficit, corrected dry matter water ratio, radiation use efficiency, specific leaf area, leaf stem partitioning parameter, growing degree days for different development stages, leaf water potential at maximum transpiration, maximum crop height and root depth (Table 5.3) were determined according to the procedure described by Jovanovic and Annandale (1999). Parameters that could not be estimated experimentally were obtained from the literature or estimated by calibrating the model against measured field data.

Table 5.3 Specific crop input parameters of ryegrass used for SWB model calibration

Parameter	Value	Unit	Source
Extinction coefficient for solar radiation	0.53	-	Annandale *et al.* (1999)
Dry matter water ratio	3.8	Pa	Measured
Radiation conversion efficiency	0.0013	kg MJ^{-1}	Annandale *et al.* (1999)
Base temperature	4	°C	Akmal and Janssens (2004)
Temperature for optimum light limited growth	15	°C	Annandale *et al.* (1999)
Cut off temperature	25	°C	Annandale *et al.* (1999)
Emergence day degrees	50	d °C	Measured
Day degrees at the end of vegetative growth	3000	d °C	Adjusted with calibration
Day degrees for maturity	3500	d °C	Adjusted with calibration
Transition period day degrees	300	d °C	Annandale *et al.* (1999)
Day degrees for leaf senescence	600	d °C	Annandale *et al.* (1999)
Maximum crop height	0.5	m	Measured
Maximum root depth	0.6	m	Measured
Fraction of TDM translocated to heads	0.01	-	Annandale *et al.* (1999)
Leaf water potential at maximum transpiration	-1500	kPa	Annandale *et al.* (1999)
Maximum transpiration	8	mm d^{-1}	Measured
Specific leaf area	25	m^2 kg^{-1}	Measured
Leaf-stem partition parameter	0.91	m^2 kg^{-1}	Measured
Fraction of total dry matter partitioned to roots	0.15	-	Measured
Root growth rate	4	m^2 kg^{-1}	Annandale *et al.* (1999)
Stress index	0.95	-	Annandale *et al.* (1999)
Total dry matter at emergence	0.0005	kg m^{-2}	Adjusted with calibration
Total dry matter after harvest	0.075	kg m^{-2}	Measured
Leaf area index after harvest	0.50	-	Measured

In Figures 5.2 to 5.7, model simulation output is displayed as lines, whilst measured data are presented in symbols given with error bars if available. Simulation generally agreed well with the measured data for all parameters during model calibration (Figure 5.2). In addition to the visual similarity between simulated and measured values, all the statistical parameters (r^2 > 0.79, D > 0.80 and MAE < 20%) imply calibration of the model was satisfactory (Table 5.4).

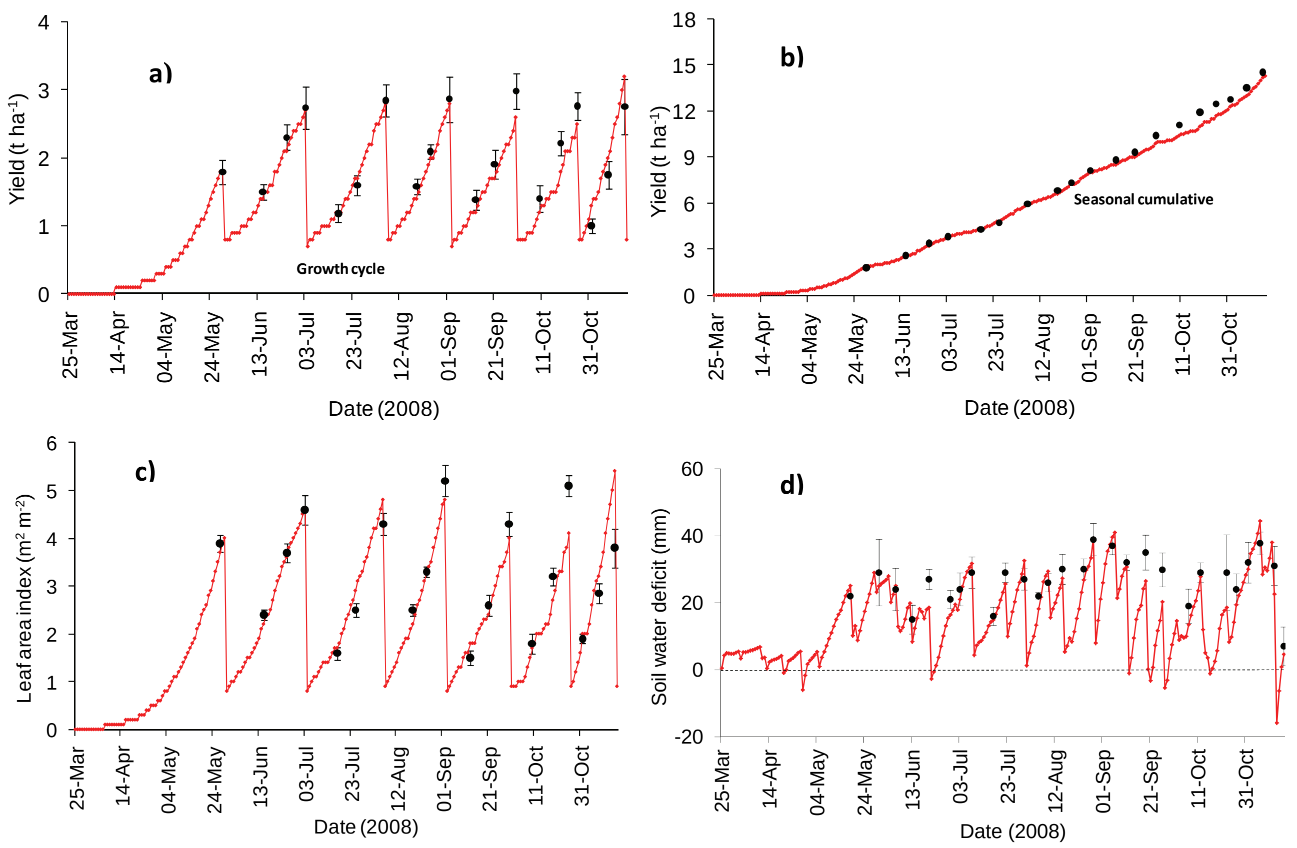

Figure 5.2 Simulated (lines) and measured data (symbols) of above ground dry matter for a) growth cycles and b) from whole season, c) leaf area index and d) soil water deficit to field capacity for model calibration of ryegrass at Cedara during the 2008 growing season (Vertical bars are the standard deviation of measured data)

Simulated and measured pasture growth (leaf area index and above ground biomass) were in good agreement (r^2 and D > 0.80 and MAE < 20%) (Figure 5.2; Table 5.4). The accuracy of the agreement between measured and simulated forage yield was improved when the model was used to simulate forage biomass yield for seasonal cumulative forage production, rather than for individual growth cycles (Table 5.4). The model tended to overestimate forage yield slightly at the end of the season. This was likely due to a reduced number of vegetative tillers and start of flowering and seed formation towards the end of the growing season (Marais *et al.,* 2003). These parameters are not simulated by the SWB generic crop growth model. However, the model simulated forage yield quite accurately for the active vegetative growing season (March to October-26 weeks), when the quality and productivity of annual ryegrass was high. The model was also able to predict profile soil water content deficit to field capacity adequately, with most parameters within acceptable ranges with r^2 and D > 0.80 and MAE < 20% (Table 5.4).

Table 5.4 Statistical parameters used for evaluation of model performance of predicted forage yield, leaf area index, soil water deficit during calibration

Parameter	N	r^2	D	MAE (%)
Forage yield (cycles)	21	0.88	0.97	9.0
Forage yield (cumulative)	21	0.99	0.99	3.8
Leaf area index	21	0.81	0.95	10.9
Soil water deficit	33	0.79	0.96	16.3

N: number of observations; r^2: coefficient of determination; D: Willmott index of agreement; MAE: mean absolute error

5.4.2 Model validation

Independent data from water stressed treatments collected from Cedara in the 2007 and 2008 and Hatfield for 2007 and 2008 were used for validating the SWB model. Model predictions were compared with measured forage yield for individual growth cycles and cumulatively for the whole season for leaf area index, root zone soil water deficit to field capacity and evapotranspiration. The statistical parameters used to evaluate the accuracy of model validation simulations are presented in Table 5.5.

Table 5.5 Statistical evaluation between observed and predicted values of forage yield and leaf area index during model validation in 2007 and 2008 seasons

Parameter	Irrigation treatment	Growth cycle yield			Cumulative yield			Leaf area index		
		r^2	D	MAE (%)	r^2	D	MAE (%)	r^2	D	MAE (%)
Cedara 2007-2008	W1-2007	0.77	0.93	12.7	0.99	0.99	2.2	0.76	0.93	14.8
	W2-2007	0.73	0.92	14.3	0.99	0.96	3.5	0.72	0.92	16.1
	W2-2008	0.92	0.97	9.7	0.99	0.99	2.7	0.90	0.93	12.3
Hatfield 2007	W1	0.95	0.97	9.0	0.99	0.99	4.9	0.91	0.95	12.8
	W2	0.94	0.95	12.9	0.99	0.98	6.8	0.94	0.96	12.1
	W3	0.88	0.96	12.1	0.97	0.98	12.2	0.90	0.90	16.3
Hatfield 2008	W1	0.98	0.98	8.1	0.99	0.98	7.0	0.80	0.92	14.8
	W2	0.92	0.95	5.3	0.99	0.99	8.6	0.81	0.94	14.0
	W3	0.86	0.85	11.6	0.95	0.97	11.3	0.77	0.86	16.2

r^2: coefficient of determination; D: Willmott index of agreement; MSE: mean standard error; MAE: mean absolute error

Forage yield and leaf area index

The simulated and measured values of forage yield for well watered and water stressed treatments during model validation periods are shown in Figure 5.3 for individual growth cycles and in Figure 5.4 for the whole season. The overall accuracy was satisfactory with all the statistical parameters within acceptable limits. Forage yield in the last growth cycle was overestimated by the model for all sites and treatments. This could be due to the onset of flowering and reduction in the number of tillers as mentioned previously. On the other hand, the model slightly underestimated forage yield in some growth cycles under water stressed conditions (Figure 5.3).

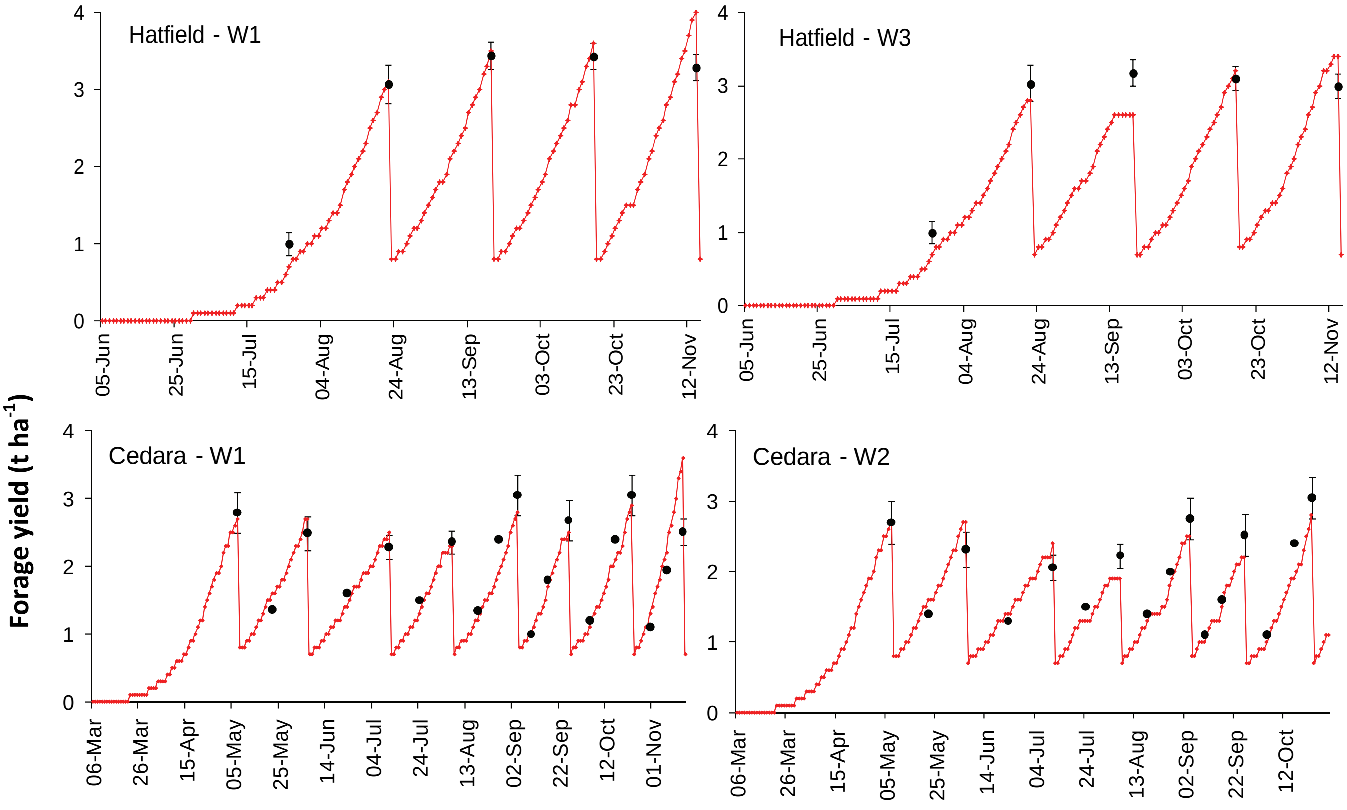

Figure 5.3 Simulated (solid lines) and measured (symbols) forage yield for individual growth cycles for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 growing season

Date

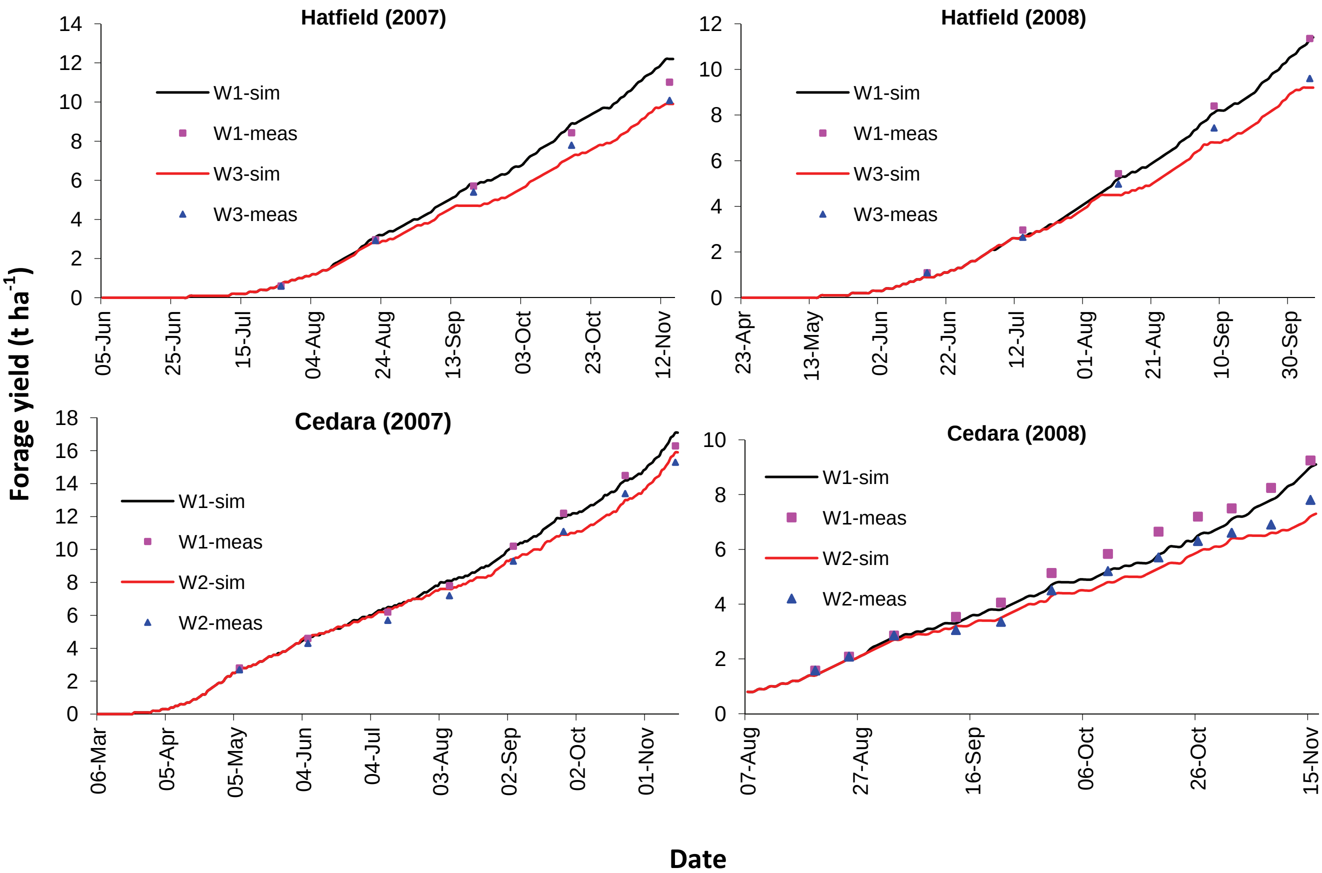

Figure 5.4 Simulated (solid lines) and measured (symbols) seasonal cumulative forage yield for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 and 2008 growing seasons

The maximum simulated and measured LAIs were in the range of measured data (4.0-6.5 m^{-2} m^{-2}) reported in the literature by Akmal and Janssens (2004). Generally, the model simulated LAI well, as the statistical parameters between modelled and observed LAIs showed good accuracy(Table 5.5), with all statistical performance evaluation parameters within the acceptable range (r^2: 0.72-0.94; D: 86-96; and MAE less than 20%). However, there the model under estimated LAI under water-stressed treatments in some growth cycles (Figure 5.5).

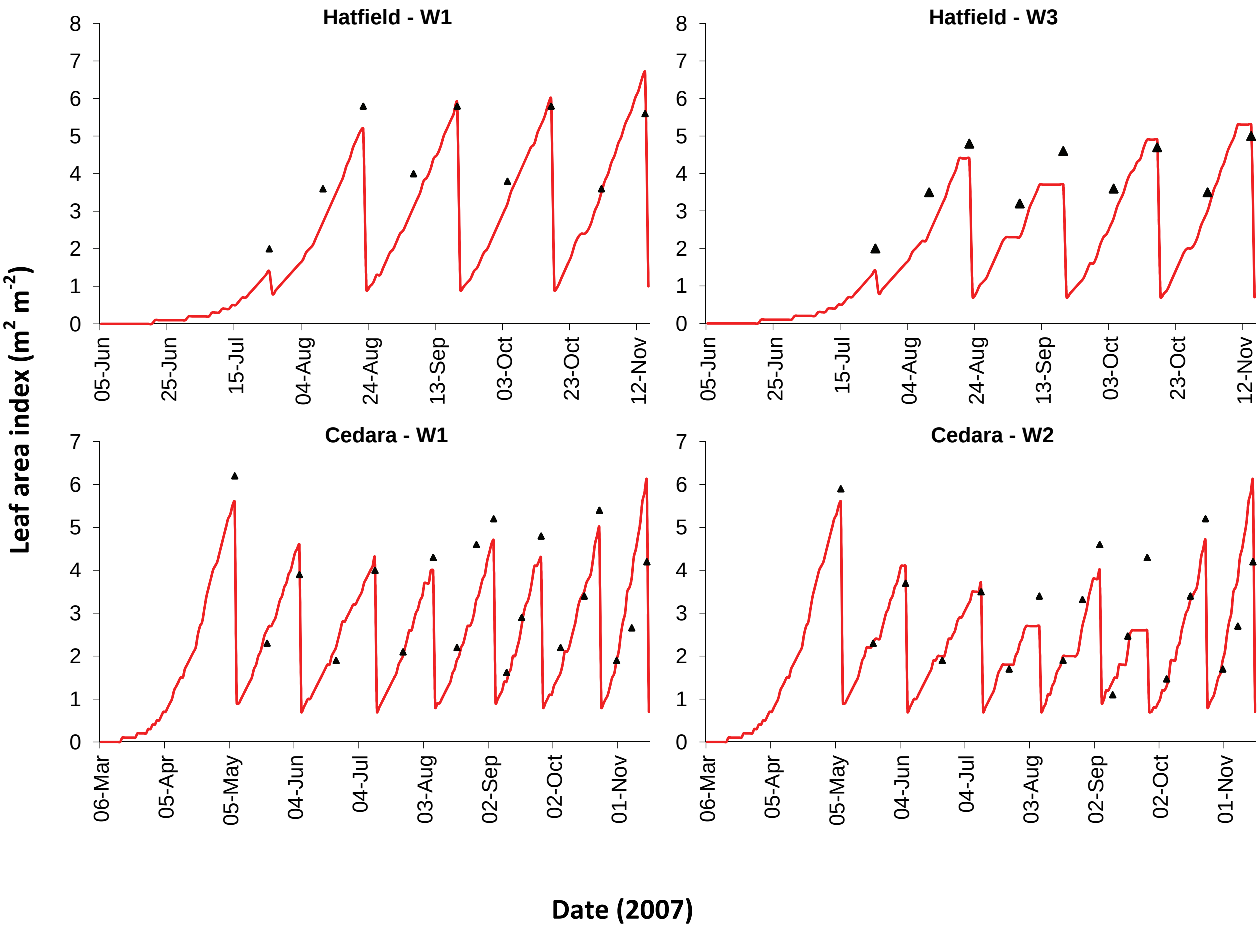

Figure 5.5 **Simulated (solid lines) and measured (Symbols) leaf area index for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 growing season**

Soil water deficit

Soil water deficit to FC predictions were less accurate (r^2: 0.30-0.75; D: 0.73-0.89; MAE: 14.2-2.6%) compared to other simulated parameters (Table 5.6), but still with reasonable agreement between measured and simulated values, especially for well-watered treatment (Figure 5.6). The lower accuracy is typical for this parameter (Todorovic *et al.,* 2009), and could be due to soil variability and inaccuracies resulting during calibration of water content measuring sensors. Considering the simplicity of the input data required to run a cascading soil water balance it can be concluded that the model simulated soil water content satisfactorily.

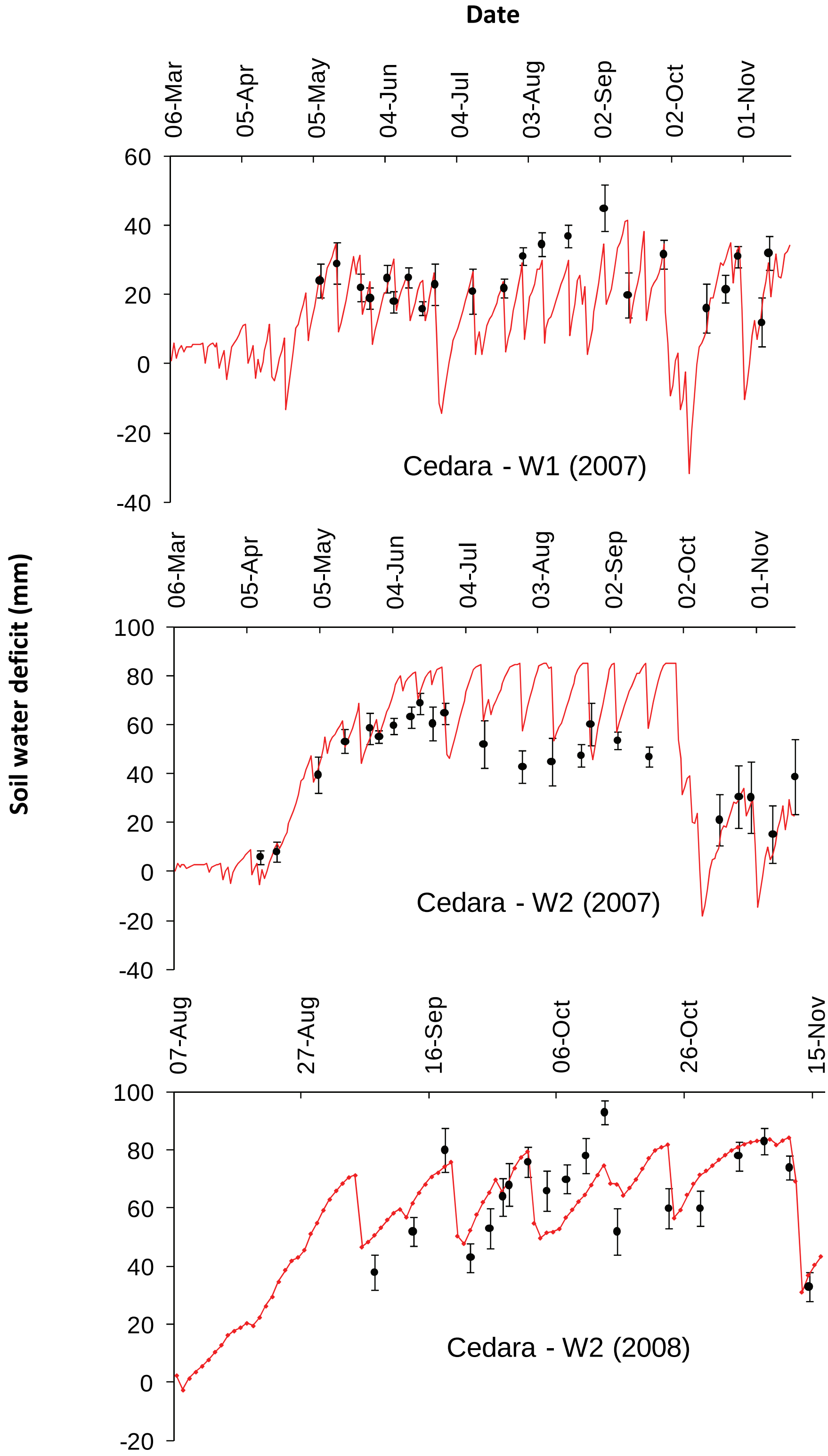

Figure 5.6 Simulated (solid lines) and measured (symbols) of the soil water deficit for the well watered (W1) and water stressed (W2) treatments for Cedara during the 2007 and 2008 growing seasons

Table 5.6 Statistical evaluation between observed and predicted values of soil water deficit to field capacity and evapotranspiration during model validation in the 2007 and 2008 seasons

Parameter		Treatment	r^2	D	MAE (%)
Soil water deficit	Cedara 2007-2008	W1-2007	0.30	0.73	22.6
		W2-2007	0.75	0.89	21.5
		W2-2008	0.52	0.83	14.2
Evapotranspiration	Cedara 2008	Well-watered	0.69	0.98	25.8

r^2: coefficient of determination; D: Willmott index of agreement; MAE: mean absolute error

Evapotranspiration

Cumulative actual ET for the three well watered growth cycles was 161 mm compared to whilst that of during the experimental period 152 mm for the simulated ET. The values of the simulated daily ET of well watered pasture were similar to the measured ones (Figure 5.7). The model, however, systematically predicted higher ET compared to measured values when ET was less than 1 mm. However, overall the model predicted ET reasonably well (Table 5.6).

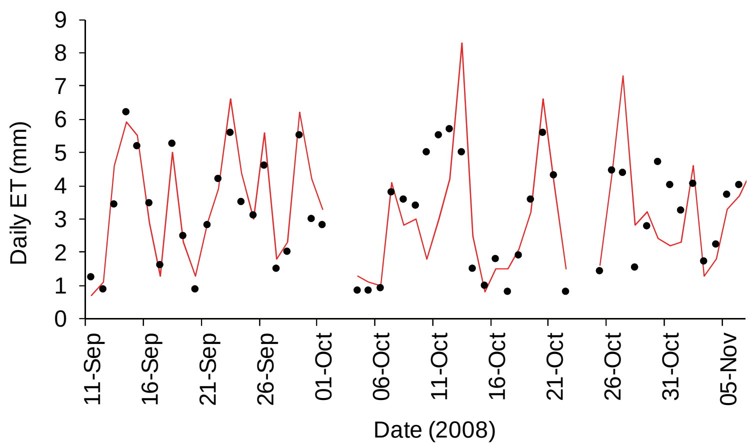

Figure 5.7 Simulated (lines) and measured (symbols) evapotranspiration of ryegrass for the Cedara site during the 2008 growing season for well watered conditions

5.4.3 Predicting water use of annual ryegrass for other areas using SWB-model

The good agreement between observed and simulated data for different sites and irrigation regimes, gives confidence that the SWB model can be used to predict long-term pasture growth and water use under different irrigation management scenarios. In this study, the SWB growth model was used to estimate irrigation requirements of ryegrass in four major milk producing areas of South Africa.

Model simulations showed variation in water use of ryegrass between years (Figure 5.8). Daily water use ranged from an average of 1.5 mm in winter (June) to 5.5 in summer (November). Long-term water use of ryegrass in the Southern Cape was relatively lower than that of the other sites.

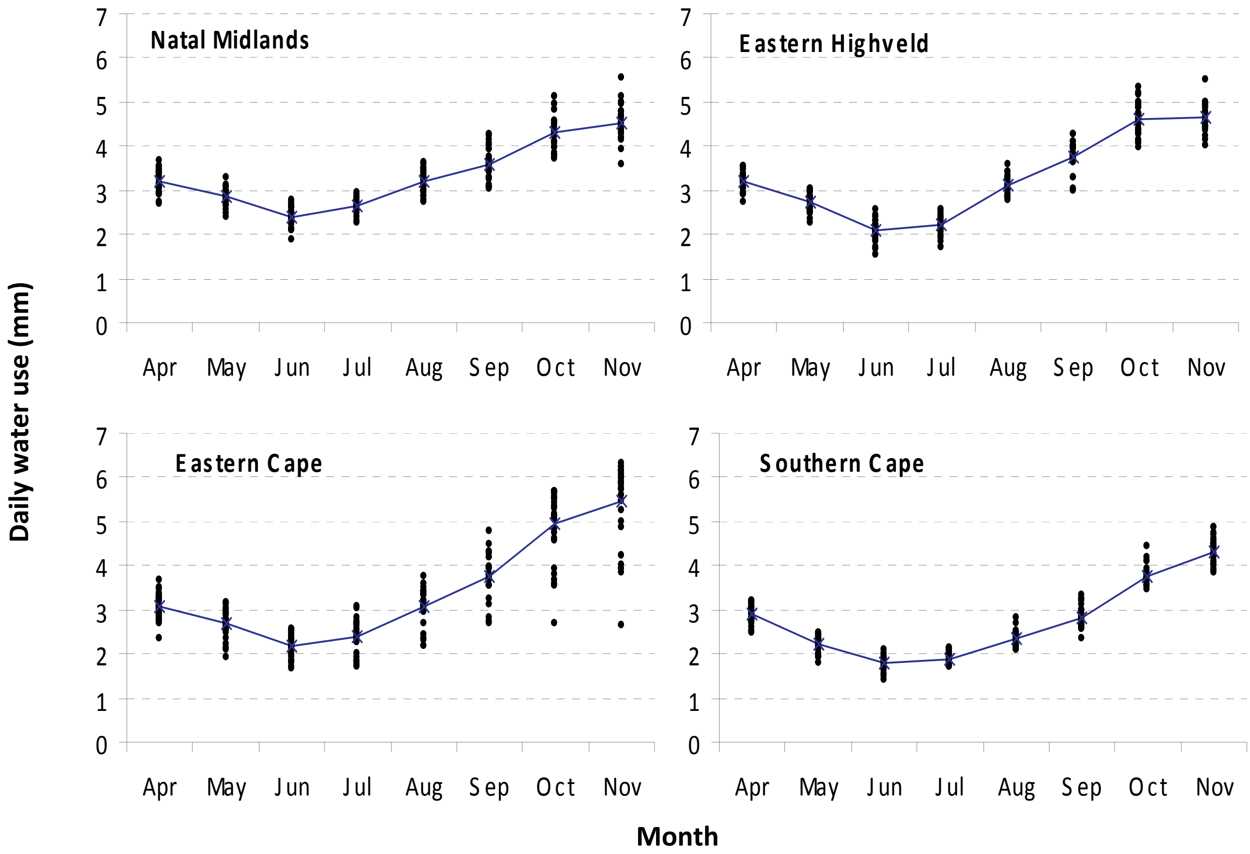

Figure 5.8 Simulated mean long-term daily water use of annual ryegrass for major milk producing areas of South Africa (points show individual season simulated water use)

There were variations in forage yields, water requirements and water use efficiency of annual ryegrass simulated using the SWB growth model (Table 5.7). In spite of the lowest water applications (581 mm), simulated forage yields were highest in the Southern Cape, which lead to the highest water use efficiency (Table 5.7). The seasonal water requirement for annual ryegrass according to current guideline (Jones, 2006) (with a fixed amount of 25 mm a week for 35 weeks) is 875 mm. Model outputs using the strategy “irrigate to field capacity when the soil deficit exceeded 25 mm” and “irrigate a fixed amount of 25 mm weekly” produced the same yield. However, the irrigation applications were higher by 131 (Eastern Cape) to 294 mm (Southern Cape) when the pasture was irrigated with a fixed amount of 25 mm a week. This would certainly be a source of water loss through runoff and deep percolation below the root zone, and leaching of nutrients would lead to yield reduction and deterioration of water quality.

Table 5.7 Seasonal forage yield, water use and water use efficiency for the long-term simulation for four major milk producing areas of South Africa

	Yield (t ha^{-1})	Water use (mm)		Water use efficiency (kg ha^{-1} mm^{-1})	
		FC	Farmer	FC	Farmer
KwaZulu-Natal Midlands	15.8 (0.89)	720 (33)	875	21.9 (1.62)	18.1 (1.01)
Eastern Highveld	14.4 (0.87)	707 (27)		20.4 (1.41)	16.5 (0.99)
Eastern Cape	13.9 (0.85)	744 (30)		18.6 (1.22)	15.9 (0.97)
Southern Cape	16.6 (1.09)	581 (22)		28.5 (2.04)	19.0 (1.24)

FC: irrigate to field capacity when the soil deficit exceeded 25 mm. Farmer: irrigate a fixed amount of 25 mm (875 mm per season). Values in brackets are standard deviations.

As expected, in all regions irrigation efficiencies were higher using “irrigate to field capacity when the soil deficit exceeded 25 mm” than “irrigate a fixed amount of 25 mm per week” (Table 5.7). Therefore, there could be opportunities to improve irrigation use efficiency of irrigated pastures by using the rainfall strategically when rainfall is high and deficit irrigation when VPD is low, in areas such as the Southern Cape (Table 5.2).

5.5 Conclusions

The SWB model was evaluated at two sites for different irrigation treatments in two ryegrass growing seasons. Simulated forage yield, leaf area index, root zone soil water deficit and daily evapotranspiration agreed with observed values well. The model was used for predicting water requirement of annual ryegrass as an example. The main strength of the SWB model is that it requires fewer crop input parameters than more detailed models but still predicts crop growth and soil water balance reasonably well. If available, accurate site specific measurements using soil water sensors that represent the whole field could be preferable over model predicted irrigation requirements.

The use of pasture specific crop growth models (such as DairyMod) may improve modelling results and also give more indication on the quality of the pasture. However, in the SWB model forage yield and quality could be optimised by wise selection of the defoliation option. Therefore, the model can be helpful to accurately manage irrigation scheduling, predict yields and estimate water requirements of ryegrass for different climatic conditions. It can also be used by farmers or consultants to develop their own calendars with relatively few simple inputs. The model is available on the web and can be downloaded free of charge.

CHAPTER 6: ESTIMATING WATER USE OF KIKUYU (*Pennisetum clandestinum*) USING REMOTE SENSING

6.1 Introduction

Remote sensing is more widely used as a spatial tool for scaling up ecosystem measurements towards landscape levels serving a wide range of applications, including applications in plant-water-carbon cycles, plant biophysical parameters, land classification and degradation. Remote sensing techniques can provide information on a variety of water resources issues including evaluating water distributions, water use by different land surfaces, water allocations, water rights, consumptive water use and, better management of ground and surface water resources. The aim of this study was to evaluate the suitability of using remote sensing technology to improve the spatial monitoring of pasture including estimates of evaporation and biomass. Several remote sensing studies have investigated the suitability of satellite platform sensors in estimating plant biophysical parameters such as leaf area index, biomass and water content (Bastiaansen and Ali, 2003; Mutanga and Skidmore, 2004; Vescovo and Gianelle, 2006; Zwart and Bastiaansen, 2007).

Several different forms of quantitative remote sensing tools have been developed over time, which follow various methodologies for retrieving useful information from the land surface, ecosystems, water bodies, and vegetation (Vescovo and Gianelle, 2006). Such tools or models include the flux type models, e.g. Surface Energy Balance Algorithms for Land (SEBAL) (Bastiaansen *et al.*, 1998) based on physical processes and, more empirical and simpler methods such as the spectral vegetation indices, e.g. Normalized Difference vegetation index, which have been used as a significant source of information (Vescovo and Gianelle, 2006). SEBAL estimates the spatial variation of most essential hydro-meteorological parameters empirically, requires field information on short wave atmospheric transmittance, surface temperature and vegetation height, does not involve numerical simulation models, calculates the fluxes independently from land cover and can handle thermal infrared images at resolutions between a few meters to a few kilometres (Bastiaansen *et al.*, 1998).

For this application, pastures growing in the Eastern Cape were selected for the SEBAL and SWB modelling. Kikuyu which is a C_4 pasture specie comprises the greater part of irrigated summer and autumn pasturage for milk production in the region of the Eastern Cape of South Africa. Kikuyu is highly productive during summer and autumn but winter and spring dry matter production is low. Forage quality of kikuyu pasture is low and consequently milk production per cow compared to temperate grass (C_3) species is low. The nutritive quality of kikuyu is determined by its unique morphology, physiology and chemical composition which could change depending on the growth stage and environmental conditions during growth (Botha *et al.*, 2008).

Although kikuyu is a productive pasture species well adapted to the main milk-producing areas of the Eastern Cape, its nutrient value is relatively. Hence cows having a predominantly kikuyu grass diet need to be supplemented. However, nutrient supplementation is costly and also requires skills to implement successfully. The strategic incorporation of legumes and other grasses into a kikuyu pasture can increase the seasonal dry matter production and quality of the pasture, with a reduction in nitrogen fertilizer needs (Botha *et al.*, 2008). Botha *et al.* (2008) reported on studies where kikuyu was over sown with different ryegrass species and /or clover. The aim of these studies was to determine the persistence and the seasonal dry matter yield, botanical composition, nutritional value, grazing capacity, milk production and milk composition of irrigated kikuyu over-sown with ryegrass and/or clovers. The treatments of each study consisted of three pasture systems. The selection of the systems was based on a request from commercial dairy farmers to evaluate existing pasture systems in terms of production potential and nutritional value. The main commercial systems were perennial or annual ryegrass over-sown annually into kikuyu (Botha *et al.*, 2008).

6.2 Materials and methods

6.2.1 Site description

Botha *et al.*, (2008) published the results of trial studies and pasture measurements undertaken on the Outeniqua Research Farm near George (33º 58’ 38’’ S and 22º 25’ 16’’ E) in the Western Cape. In these studies, kikuyu over-sown with ryegrass and clover were investigated to determine the dry matter production, botanical composition, nutritional value of these species. It was decided upon in collaboration with the research farm to select these same trials for application of the SEBAL model.

The area has a temperate climate with mean minimum and maximum air temperatures varying between 7-15ºC and 18-25ºC respectively and, a mean annual rainfall of 729 mm (Schulze *et al.*, 1997). The trials were carried out on 9 ha of an Estcourt soil type (Soil Classification Workgroup 1991) under sprinkler irrigated kikuyu pasture, divided into eight blocks. The centre coordinates of each block are listed in Table 6.1.

Table 6.1 Geographic coordinates of the trial studies undertaken by Botha *et al.*, (2008) in the year 2000 at the Outeniqua research farm

Block Number	Latitude (dd)	Longitude (dd)
1	S33.9742	E22.4175
2	S33.9735	E22.4179
3	S33.9727	E22.4184
4	S33.9721	E22.4178
5	S33.9730	E22.4169
6	S33.9736	E22.4164
7	S33.9745	E22.4160
8	S 33.9752	E 22.4156

6.2.2 SEBAL model spatial input data

Landsat remote sensing satellite imagery was downloaded from the U.S. Geological Survey website. Two cloudless, satellite images (path 183 and row 84) where selected for the winter (17 July 2000) and summer (22 November 2000) simulations. All pre-processing of remote sensing imagery was undertaken using ERDAS IMAGINE 9.3 software.

The visible and near-infrared Landsat bands have a spatial resolution of 30 m, while the thermal bands have a spatial resolution of 60 m. Visible and near-infrared bands were extracted and stacked to produce one image; while the thermal bands were extracted and stacked to produce a separate image which was re-sampled from 60 m to 30 m using the nearest neighbour sampling method. Both images were then re-projected from UTM northern hemisphere zone into the southern hemisphere zone.

A digital elevation model was extracted from the freely available Shuttle Radar Topography Mission (SRTM) database, which obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth (Farr and Kobrick, 2000). The 90 m digital elevation model available for this area was extracted and re-sampled to 30 m.

A landcover coverage was extracted from the National Landcover 2000 database. The National Landcover database was derived to generate an up-to-date land-cover map of South Africa using remote sensing data. Furthermore, this database was derived using an international land cover classification system to facilitate comparison and integration across the world (Majeke *et al*., 2006).

6.2.3 SWB model crop specific input parameters

The SWB model was calibrated and validated by Annandale *et al.* (1999) for open cast mining and the specific crop input parameters of kikuyu are presented in Table 6.2. Before using the model was further validated using data collected from Ukulinga, Pietermaritzburg. The same statistical parameters used to evaluate the model for ryegrass are also used to compare the measured versus simulated values.

Table 6.2 Specific crop input parameters of kikuyu used for SWB model calibration

Parameter	Value	Unit
Canopy extinction coefficient for solar radiation	0.5	-
Dry matter water ratio	4.5	Pa
Radiation conversion efficiency	0.0013	kg MJ^{-1}
Base temperature	10	°C
Temperature for optimum growth	25	°C
Cut off temperature**	30	°C
Emergence day degrees**	0	d °C
Day degrees at the end of vegetative growth**	5000	d °C
Day degrees for maturity**	5400	d °C
Transition period day degrees**	300	d °C
Day degrees for leaf senescence**	600	d °C
Maximum crop height*	0.4	m
Maximum root depth*	1.0	m
Fraction of total dry matter translocated to heads**	0.01	-
Leaf water potential at maximum transpiration*	-1500	kPa
Maximum transpiration*	9	mm d^{-1}
Specific leaf area*	17	m^2 kg^{-1}
Leaf-stem partition parameter*	0.7	m^2 kg^{-1}
Fraction of total dry matter partitioned to roots**	0.2	-
Root growth rate**	4	m^2 kg^{-1}
Stress index**	0.95	-
Total dry matter at emergence*	0.0025	kg^{-1} m^2
TDM after cut	1.0	t ha^{-1}

6.2.4 Weather data

Daily and monthly weather data was obtained from a weather station located at the Outeniqua experimental farm (Agricultural Research Council, 2009). Daily and monthly weather records obtained for the winter and summer simulation periods included maximum and minimum temperature, average maximum and minimum relative humidity, rainfall, A-pan evaporation, wind run, sunshine hours and average temperature.

Hourly weather data was obtained for the 17 July 2000 and 22 November 2000, from an automatic weather station at George airport (South African Weather Service, 2009). These records included temperature, rainfall wind speed, wind direction and radiation.

Table 6.3 Instantaneous and daily meteorological inputs parameters used in the surface energy balance simulations

Meteorological Parameters	Winter		Summer	
	Daily	14-day Period	Daily	14-day Period
Instantaneous air temperature ºC	14.2	-	20.3	-
Air temperature ºC	11.1	11.4	17.3	17.5
Instantaneous relative humidity %	34.0	-	73.0	-
Relative humidity %	66.5	64.9	80.0	72.0
Instantaneous wind speed $m.s^{-1}$	1.50	-	3.70	-
Wind speed $m.s^{-1}$	3.10	4.70	3.60	3.30
Transmissivity	0.72	0.54	0.74	0.53

The full details of the SEBAL model evapotranspiration and biomass routines are discussed in Bastiaanssen *et al.* (1998). The above mentioned remote sensing and weather data were used as selected inputs to the SEBAL model. The model was configured to run a daily and 14-day period (Table 6.3) simulation in winter (July 2000) and summer (November 2000).

6.3 Results and discussion

SWB was calibrated for kikuyu using data collected from Ukulinga in 2008-2009. During the calibration, measured and simulated forage yield agreed well (Figures 6.1). However, the model was not validated with independent datasets. Therefore, kikuyu simulations reported in this report are simply used to compare water use and yield estimates of kikuyu using SEBAL.

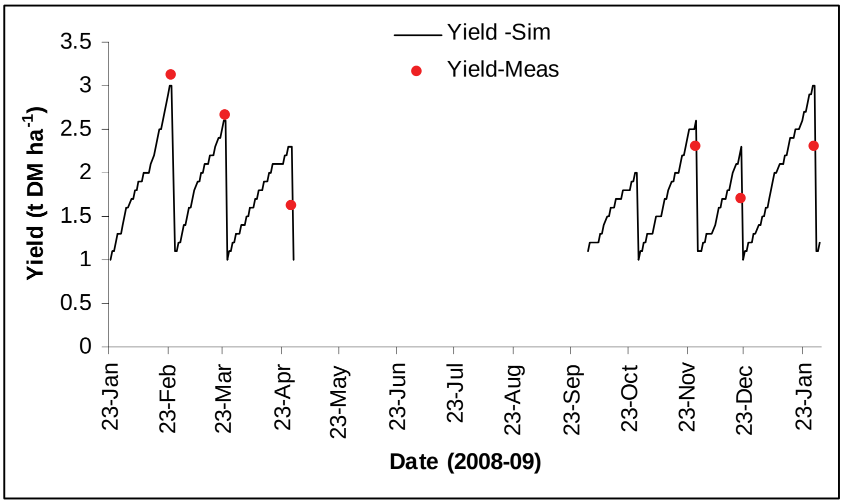

Figure 6.1 SWB model calibration for kikuyu using data collected from Ukulinga in 2008-09

Simulation results of the forage DM yield of kikuyu using the SWB model for the Outeniqua research station in 2000 are presented Figure 6.2. Total seasonal water use of kikuyu in 2000 (12 months) at the Outeniqua research station predicated with the SWB model was 1162 mm. Estimated forage yield of kikuyu during the year 2000 was 12.8 t DM ha^{-1}. Although the model requires validation with independent data sets, the data can be used to assess the accuracy of data aquired using remote sensing technologies. Since only two window periods were tested in this pilot study, the use of longer term data to predict water use and biomass needs to be the subject of a future research project.

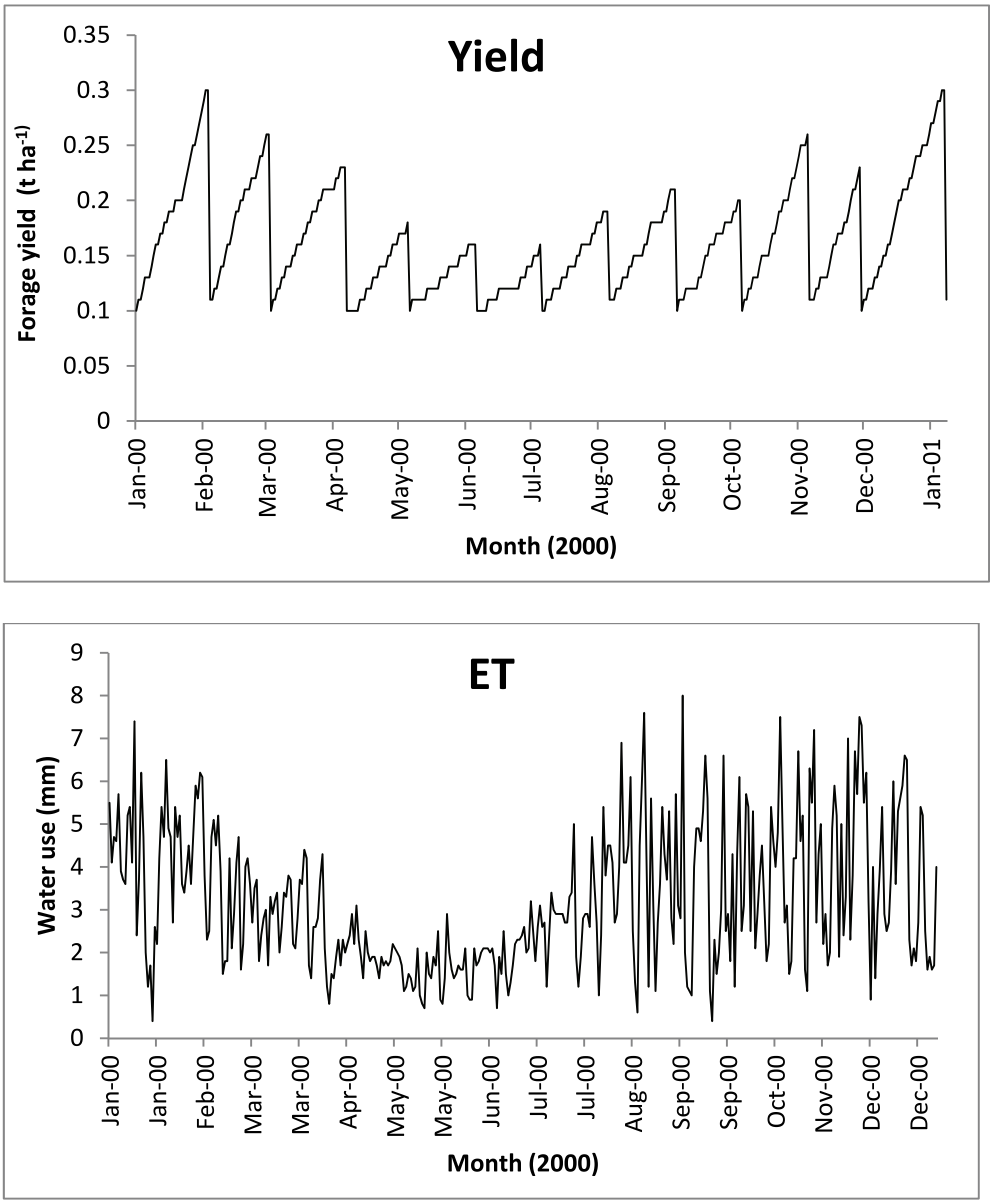

Figure 6.2 Forage yield and water use (ET) of kikuyu estimated using SWB model for Outeniqua during 2000

The results of the SEBAL model simulations for the Outeniqua research station and surrounding area are shown in Figures 6.3 to 6.6. Simulations were carried out for 14 days in winter and 14 days in summer. From these limited observations it was not possible to estimate the seasonal water use of kikuyu using remote sensing. The results do, however demonstrate the real possibility to use remote sensing for estimating water requirements and biomass production of irrigated pastures in South Africa.

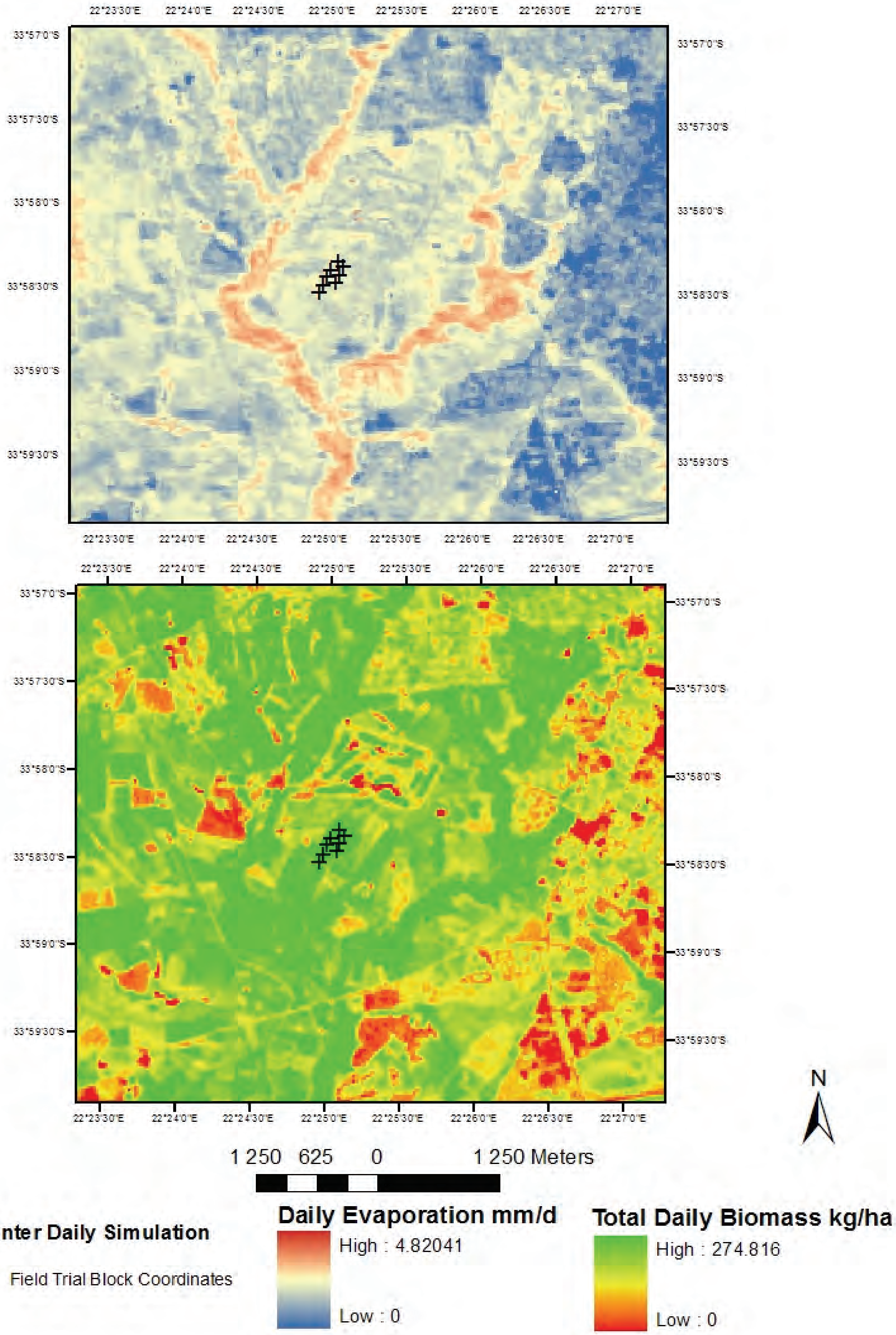

Figure 6.3 **Comparison of daily evaporation and total daily biomass simulated during winter (17 July 2000) using SEBAL model**

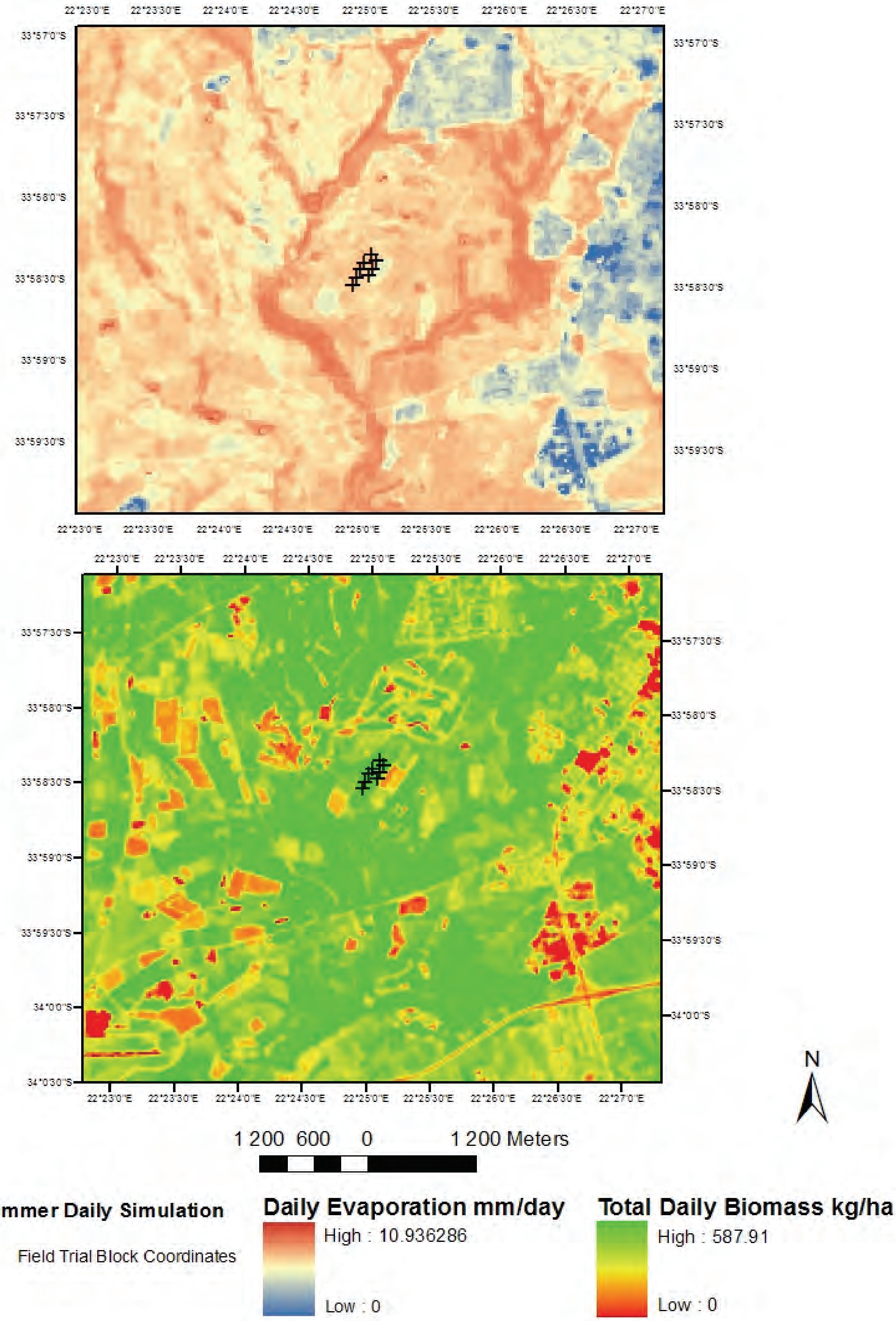

Figure 6.4 Comparison of daily evaporation and total daily biomass simulated during summer (22 July 2000) using SEBAL model

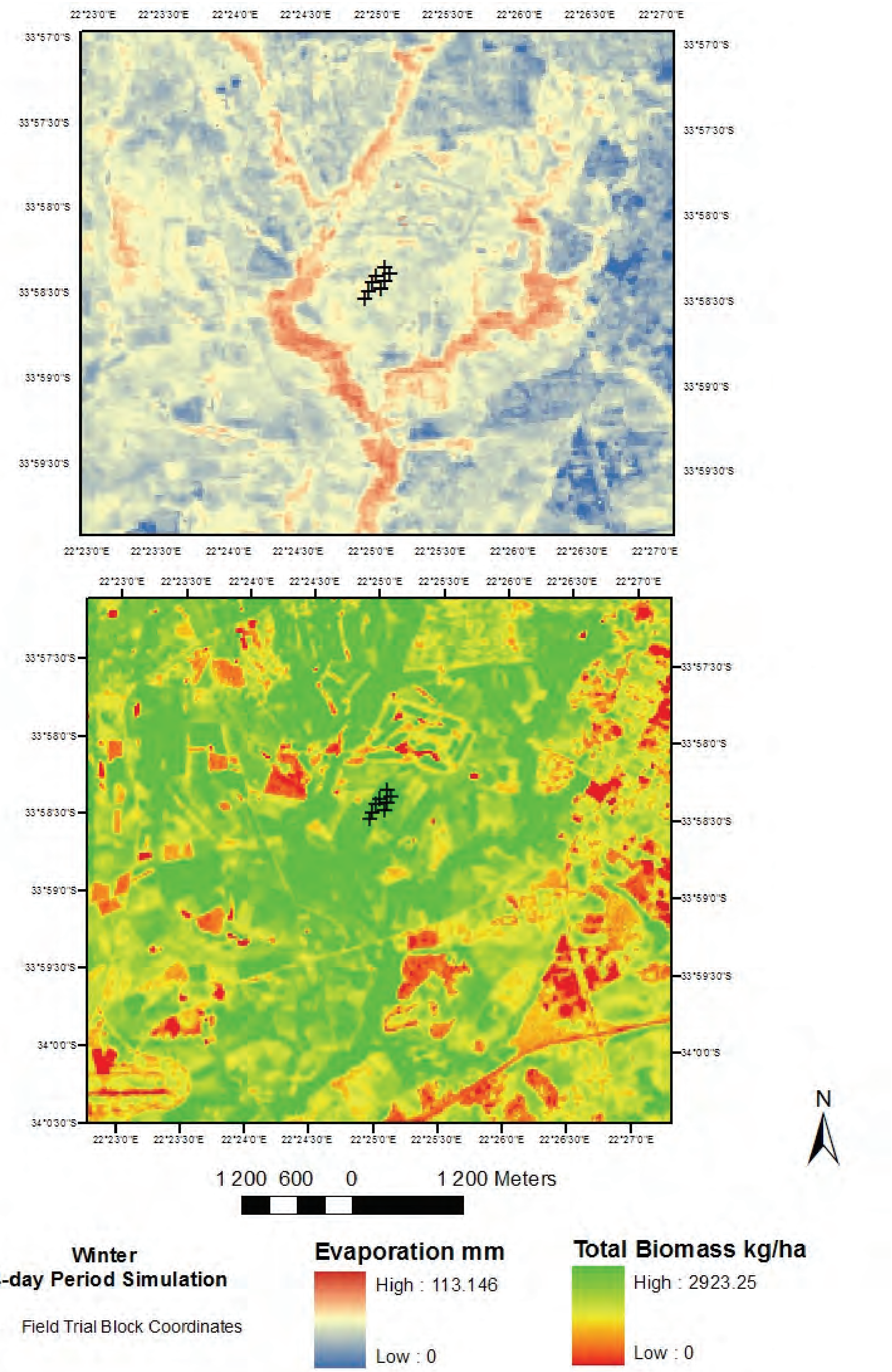

Figure 6.5 **Comparison of evaporation and total biomass simulated during winter for a 14-day period using the SEBAL model**

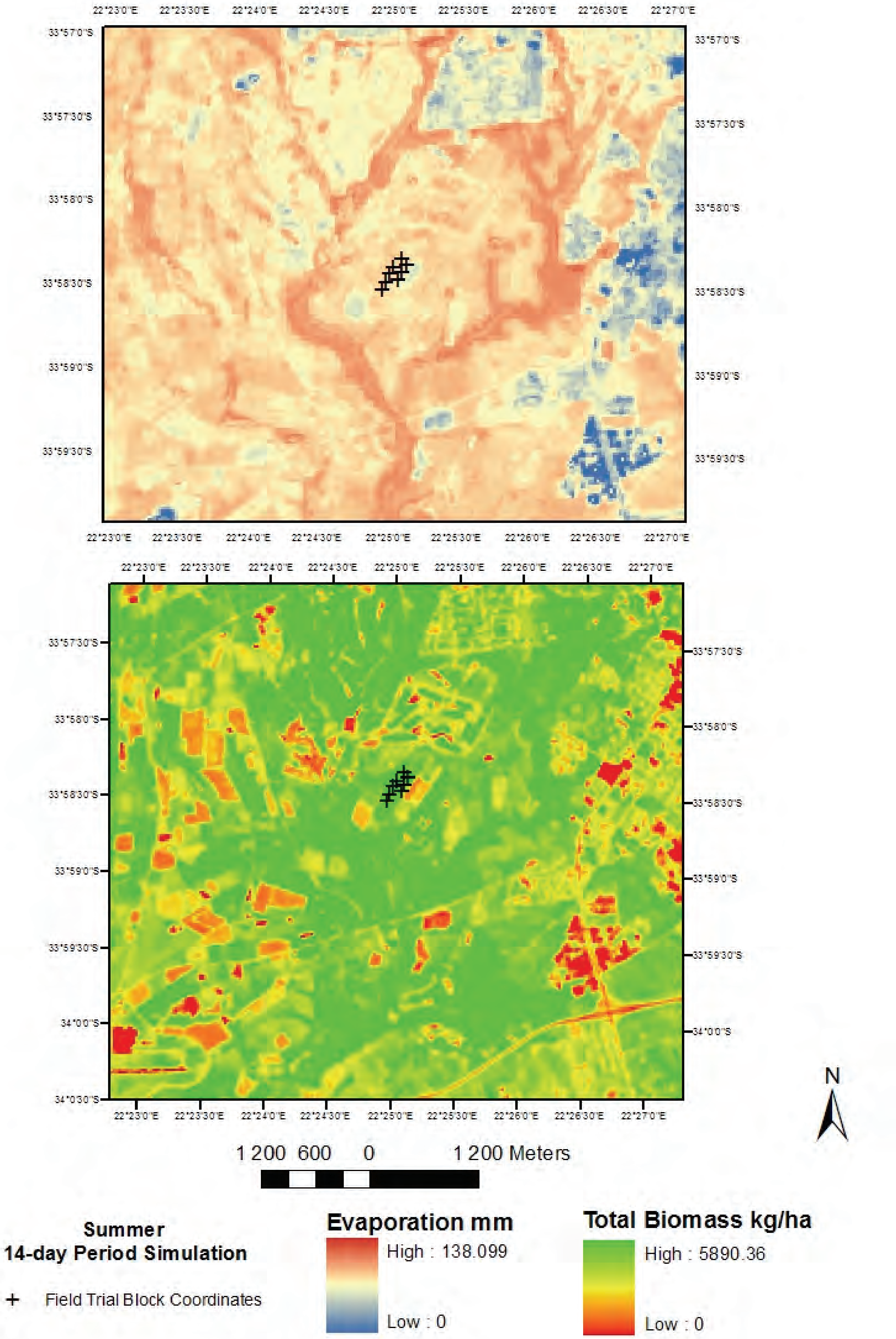

Figure 6.6 **Comparison of evaporation and total biomass simulated during summer for a 14-day period using SEBAL model**

The SEBAL model simulated a mean daily evaporation during winter of 2.04 ± 0.07 mm day^{-1} compared to summer mean values of 6.79 ± 2.13 mm day^{-1}. SWB model simulated similar daily evaporation in winter (2.05 ± 0.64 mm day^{-1}) while the daily evaporation during simmer was lower (4.6 ± 1.16 mm day^{-1}). Trends in the daily simulations indicate consistently lower mean winter values when compared to summer results. From experiment conduct in Ukulinga under kikuyu pasture, Mengistu (2007) reported maximum and average daily evapotranspiration 6 and 3.5 mm in summer, and less than 2 and 1 mm in winter.

Mean daily biomass during winter was 148.64 ± 9.15 kg DM ha^{-1} (SEBAL) and 15.46 kg DM ha^{-1} (SWB) compared to summer mean values of 472.07 ± 69.13 kg DM ha^{-1} (SEBAL) and 56.72 kg DM ha^{-1} (SWB). Results from the pasture trial studies undertaken by Botha *et al*. (2008) show that the growth rate of kikuyu during winter (July 2000) was ≤10 kg DM ha^{-1} day^{-1} which was over-sown with ryegrass. Summer pasture measurements during 2000, showed that the growth rate for kikuyu was 55 kg DM ha^{-1} day^{-1} and kikuyu-clover 60 kg DM ha^{-1} day^{-1}. According to Botha *et al*., 2008 and recent consultations regarding the surface energy balance modelling, the biomass models are currently too high (Botha, 2010).

SEBAL model estimates of evaporation and biomass over a 14-day simulation period during winter and summer 2000 are shown in Figures 6.5 and 6.6, respectively. Review of the evaporation means indicated that evaporation more than doubled during summer (82.20 ± 2.13 mm day^{-1}) and 64.40 kg DM ha^{-1} (SWB) when compared to winter simulations (31.71 ± 1.13 mm day^{-1}) and 28.20 kg DM ha^{-1} (SWB). Biomass estimates for the 14-day simulation shown a mean of 1562.09 ± 115.20 kg DM ha^{-1} (SEBAL) and 1300 kg DM ha^{-1} (SWB) during winter, and 4729.81 ± 692.63 kg DM ha^{-1} (SEBAL) and 2700 kg DM ha^{-1} (SWB) during summer.

6.4 Conclusions

This report has demonstrated the applicability of a remote sensing tool (SEBAL), to predict evapotranspiration and biomass at a spatial resolution (30 m) suitable for irrigation scheduling. The differences in yield and growth rate between SEBAL and SWB models could be on the amount of stubble biomass left after defoliation (grazing or cutting). Therefore, further evaluation of the models using measured datasets is required. For future research in this field larger areas of intensively monitored field sites need to be found where both evapotranspiration and biomass measurements can be made together with the remote sensing measurements.

CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Overview of the project

South Africa is an arid country with a very limited supply of irrigation water. It is estimated that the total area utilized for irrigated pasture production is approximately 16% of the total area under irrigation. The returns generated from these enterprises make pastures one of the higher value crops produced under irrigation in this country. However, the management of water requirements of pastures is not easy. They are often established on heavy and shallow soils that would not normally be considered for irrigation. Limited rooting depths and the need to integrate irrigation and grazing management further aggravate the position. Judicious management of irrigation is essential not only to utilize labour and water resources effectively and maintain production and profitability but also to prevent serious degradation of land. Management of dairy farming has now attained unprecedented levels of technology largely due to the availability of practical equipment and methods for planning, managing and monitoring most facets of dairy farming. However, this does not apply to irrigation of pastures, which still tends to rely on experience and tradition despite the increasing role of pastures in milk production.

7.2 Field trials

Presently, and more so in the future, irrigated agriculture will take place under water scarcity. Due to the global expansion of irrigated areas and the limited availability of irrigation water, there is a need to optimise water use efficiency. A summary of water use and yield of annual ryegrass from the experiment conducted at Cedara and Hatfield in 2007 and 2008 growing seasons is available in Table 7.1. There were differences in number of growth cycles between years and sites.

From the experiments conducted during 2007 and 2008 irrigation and nitrogen fertiliser affected the DM yield and LAI significantly. Higher frequency of irrigation coupled with high nitrogen application significantly improved the DM yield. There was no significant difference in yield between the treatments that were irrigated twice weekly and once a week at the high N application. The decrease in the frequency of water application resulted in an increase in the DMC, digestibility, ME and CP values. An increase in the nitrogen application increased the CP. It can therefore be shown that water stress did improve the quality of the pasture. Results from this study indicate that in both seasons WU was highest in the treatment that was irrigated twice a week and top-dressed with 60 kg N ha^{-1} after each cut. Nitrogen application had an effect on the water use, as less water was used in the treatments that received no nitrogen. Increase in WUE was achieved by reducing the frequency of irrigation from twice a week to once a week without causing significant yield losses. Within the same irrigation frequency, higher WUE was achieved by alleviating a limiting factor, N fertiliser, in this case, through increases in the DM yield. The highest WUE was achieved by irrigating once every two weeks. However, in some treatments, the WUE was not improved with the reduction in the frequency of irrigation as the water saved was overshadowed by yield loss. It can be concluded that at the expense of dry matter production, the highest WUE was achieved under water limiting conditions. Based on the data from this experiment, by irrigating once a week and fertilising with high N application rate after each harvest, optimum yield can be achieved with better quality pasture and a better WUE.

Table 7.1 Summary of measured water use and yield of annual ryegrass at the Cedara and Hatfield sites

Site	N rate	Year	Growth cycles	Forage yield ($t\ ha^{-1}$)	Water use (mm)	Method used
Hatfield	0	2007-08	4	4.8-5.4	320-342	Water balance
	30			7.5-8.3	344-386	
	60			9.4-10.2	378-423	
Cedara	0	2007	8	8.2	701	Water balance
	30			13.2	779	
	60			15.6	816	
Cedara	0	2008	7	5.9	493	Water balance
	20			10.0	547	
	40			13.0	564	
	60			13.8	571	
Cedara	60	2008	45 days	-	161	Energy balance

Seasonal N application could be reduced by 28% when many of the components of the N balance were measured at the start of each cutting cycle. However, the expense of such monitoring may not be justifiable on economic grounds. The trial showed that N savings from intensive monitoring could also be realised through a much simpler adaptive approach based on thresholds for the nitrate concentration in the soil solution. With respect to the baseline recommendations from the South African Department of Agriculture, N application was reduced by 27% and 32% respectively in the two adaptive treatments (reduced N application and reduced water application). Both adaptive treatments resulted in an improvement of forage quality with no yield reduction, and a lower risk of N leaching.

Farmers are intuitively adaptive managers and the use of simple monitoring and thresholds presents a way to structure their learning, and they represent our simplest conceptualisation of the problem to be managed. Adaptive management was used to schedule N fertiliser and irrigation for ryegrass. Under current ryegrass pasture management conditions, a mean nitrate concentration of 50 mg L^{-1} was found to be enough for one growth cycle. Irrigation could also be reduced or postponed based on the wetness of soil profile and nitrates in the deep layer. A good adaptive manager is expected to improve these thresholds as more experience is gained.

This experiment was conducted to estimate evapotranspiration of ryegrass for three regrowth cycles using the eddy covariance and surface renewal methods. These methods estimate sensible heat flux density (H), and then evapotranspiration (ET) was calculated as a residual of the shortened energy balance term involving measurements of net irradiance (Rn) and soil heat flux density (G). The water use of both methods showed similar ET estimates. The data were used to calibrate the models selected in this project.

During the three growth cycles monitored, ET ranged from 0.5 mm during rainy days to 6.5 mm on clear, sunny days. The crop coefficients of annual ryegrass estimated from ET measurements using soil water balance or energy balance methods ranged 0.7 to 1.1.

7.3 Modelling

The main objective of this project was to optimise the growth of ryegrass through efficient use of water and nitrogen (N) fertilisation. One of the tools for achieving this was the use of numerical models for which base-line information is needed for parameterisation and testing. Hence a number of crop models were reviewed (Appendix A) and the SWB model and DairyMod were selected. However, since the objective of the project was mainly to estimate water use and not milk production the SWB was used. Considering the use of a large number of data sets and time consuming determination of input parameters required for the pasture specific models, relatively simple models (such as the SWB) may be more applicable. According to Stevens *et al.* (2005), the major problems with adoption of models by the farmers is their complexity, therefore, there should be trade-offs between accuracy and simplicity. The SWB model is being used to simulate crop growth and soil water balance of several cereals, vegetable and tree crops (Singles *et al.,* 2010). Therefore, it is better to use a model which is locally known by farmers and consultants instead of introducing another new model. The model is available on the web and can be downloaded free of charge. As a result the SWB model was calibrated and validated and after satisfactory evaluation the model was used to predict water requirement of annual ryegrass in major pasture growing areas of South Africa.

Pasture systems are highly temporally and spatially complex, as they involve interactions among crop growth, nutrient dynamics between soil, plant and animal and pasture management systems. Hence, it is difficult to evaluate the whole system with short-term monitoring experiments. Development of site-specific pasture and irrigation management practices requires costly long-term trials. It is expensive and impractical to test multiple irrigation and other pasture management strategies in all pasture growing areas. Models can be used to extrapolate research findings (irrigation and other pasture management requirements) to pasture growing areas. Models can also be helpful in selecting the best management practices for specific sites and environmental conditions. However, models need to be parameterised, calibrated and tested with measured data.

The SWB model was evaluated at two sites for different irrigation treatments in two ryegrass growing seasons. The simulated yield and leaf area index were in good agreement with the observed values. The simulated values of root zone soil water deficit and daily evapotranspiration were also in reasonable agreement with the measured values.

This report has demonstrated the applicability of a remote sensing tool (SEBAL) to predict evapotranspiration and biomass at a spatial resolution (30 m) suitable for irrigation scheduling. The differences in yield and growth rate between SEBAL and SWB models could be on the amount of stubble biomass left after defoliation (grazing or cutting). Therefore, further evaluation of the models using measured datasets is required.

The good agreement between observed and simulated data for different sites and irrigation regimes, gives confidence that the SWB model can be used to predict long-term pasture growth and water use under different irrigation management scenarios. In this study, the SWB growth model was used to estimate irrigation requirements of annual ryegrass in four major milk producing areas of South Africa and kikuyu in the Southern Cape (Table 7.2).

Table 7.2 Summary of modelled water use and yield of annual ryegrass and kikuyu at the four different pasture growing areas of South Africa

Crop	Site	Year	Growth cycles	Forage yield (t ha^{-1})	Water use (mm)
Annual ryegrass	KwaZulu-Natal Midlands	1951-2000	8 growth cycles (March to October)	15.8 (0.89)	720 (33)
	Eastern Highveld			14.4 (0.87)	707 (27)
	Eastern Cape			13.9 (0.85)	744 (30)
	Southern Cape			16.6 (1.09)	581 (22)
Kikuyu	Southern Cape	2000	12 growth cycles (January to December)	12.8	1162

The main strength of the SWB model as compared to other detailed models is that it requires relatively few crop input parameters but still predicts crop growth and soil water balance reasonably well. The use of pasture specific crop growth models may improve modelling results and also give more indication on the quality of the pasture. However, in the SWB model forage yield and quality could be optimised by wise selection of the defoliation option. Therefore, the model can be helpful to accurately manage irrigation scheduling, predict yields and estimate water requirements of different climatic conditions. It can also be used by farmers or consultants to develop their own calendars with relatively few simple inputs.

7.4 To what extent were the objectives achieved

To promote efficient irrigation management of grass pastures (emphasis on ryegrass and kikuyu) by synthesizing available knowledge and generating new knowledge for improving water use efficiency by pastures.

Specific Objectives

1. Estimate water requirement/use (modelling) with respect to:
    - Irrigation strategies
    - Managing pastures
    - Managing grazing
    - Simple ways to monitor, e.g. soil water status, compaction, root development, dry matter status
2. Identify knowledge gaps based on inputs required (soil-plant-atmosphere) by existing models.
3. Generate information on growth analysis and water balance studies for important grasses (ryegrass and kikuyu) in important areas (KZN midlands, E-Cape coast) required for modelling.
4. Determine water requirements of the selected pastures through testing and evaluation of the model.

5. Extrapolate irrigation requirement estimates using models.
6. Develop generic guidelines for efficient irrigation management of grass pastures (for both existing pastures and for planted pastures) with specific reference to rye grass and kikuyu and addressing irrigation strategies and pasture management.

Although the terms of reference placed emphasis on modelling ryegrass and kikuyu, the research process facilitated the collection of additional valuable data for ryegrass. Generally, almost all objectives were achieved for ryegrass, however, for kikuyu only a pilot water use estimation using remote sensing was conducted. The main reasons for not conducting a kikuyu water use measurements were due to:

- The cost of carrying out similar measurements for kikuyu was prohibitive and beyond the scope of the project.
- The cultivation of kikuyu pasture is also more complicated and would have required an intensive labour input which was not available.
- Kikuyu pastures generally contain a number of different grasses and results would, therefore, be different in each system.
- Kikuyu-ryegrass systems in the Eastern Cape are very different to those in KwaZulu-Natal and this would have further complicated the research.
- Kikuyu has a mat system under the grass which would need to be considered.

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APPENDIX A – REVIEW OF PASTURE MODELS

Plant systems are complex in nature and simulating the complexity needs to include many factors. The integration of the three irrigation management methods: soil water, plant and atmospheric demand can give the best indication in estimating water use and managing irrigation. Models for soil water budgeting differ in their complexity, input requirements and degrees of accuracy. In order to be commercially available and usable they need to be user friendly with reliable accuracy of simulation. Very often the complexity of computerised systems is an obstacle to the implementation and use of models. The main objectives of modelling are to make predictions, understand the processes and study the complexity of ecosystems (Pearson and Ison, 1997; Thornley, 1998).

Pearson and Ison (1997) classified grassland models as deterministic, stochastic, mechanistic and functional. The deterministic models are developed to calculate a distinctive outcome for a given set of events. These models include any algebraic relationship and they are well suited to problems concerned with allocation of some limited resources where many alternatives exist. However, stochastic models accommodate spatial variability and are developed to quantify the degree of uncertainty caused due to spatial variability. Mechanistic models are based on dynamic rate concepts and basic processes. These are useful primarily as research tools for better understanding of the natural integrated systems. Functional models are based on capacity factors and treat processes in a simplified way with fewer inputs. Scheduling irrigation of pastures is difficult because unlike other crops, where there is a single harvest per season, the multiple harvests for pasture confounded the process. Irrigation cannot be applied too close to a cutting date as this may affect the pasture quality by reducing the intake. It may also cause a serious compaction problem under grazing conditions.

Various models for grass growth have been described for different purposes. Grassland models differed from grass growth models in the physiological, environmental and managerial factors considered to affect herbaceous production. According to Joyce and Kivkert (1987), grassland models can be categorised into six types depending on the plant growth limiting factors:

1) Empirical models are simple expressions predicting forage production as a function of one or two environmental factors. Most of the empirical models are based on a single regression equation on historical data. The models are usually based on data collected at one site over several years or data collected at several sites for only one season.
2) Modified crop growth models are agronomic crop models that have been applied to grasses. The approach was a great achievement for the development of more mechanistic models by modifying existing crop models.
3) Hydrologic models where the soil dynamics of the plant growth are detailed but above ground accumulation is treated as one component.
4) Models focusing on modelling the process of above ground production of a plant species or plant parts.
5) Models combining plant growth with livestock production and

6) Plant succession models which focus on the species composition rather than forage yield.

In order to select them most appropriate model(s) the following models were reviewed.

Soil Water Balance (SWB)

SWB is a mechanistic, real time, generic crop growth, soil water balance and irrigation scheduling model, which has a user friendly interface. It is based on the New Soil Water Balance (NEWSWB) model (Campbell and Diaz, 1988). Simulations from SWB are helpful to accurately manage irrigation scheduling, predicting yields and irrigation water requirements in different climatic conditions (Annandale *et al.*, 1999).

Simulations of SWB can be done with two types of models: 1) A mechanistic crop growth to simulate crop growth and components of soil water balance and 2) An FAO based model that calculates canopy cover from crop factor. The FAO type of model is simple generic irrigation model and which doesn't require time consuming and expensive growth analysis data for determination of crop specific parameters. However, in the FAO model the simulations of dry matter are not mechanistic and the model does not simulate the effect of water stress on canopy size (Jovanovic *et al.*, 1999). The mechanistic growth model type of model is reviewed since it is used for simulating yield of annul ryegrass.

SWB performs the calculation of crop growth and water balance using weather, soil and crop units. A detailed description of the model including weather, soil and crop are available in Annandale *et al.* (1999). The weather unit of SWB calculates the Penman-Monteith grass reference daily evapotranspiration according to the FAO recommendations (Allen *et al.*, 1998). For simulation of water movement in the soil profile SWB uses a cascading or a finite difference approach. The soil unit of the SWB divides the potential evapotranspiration in to potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area index (Ritchie, 1972). The crop unit of SWB describes phenological development, growth and yield of a crop from emergence to maturity based on crop growth factors and environmental conditions.

CropSyst

This model is similar to SWB; it is also based on the NEWSWB developed by Campbell and Diaz (1988). However, this model has many features applicable for pasture management, both under cutting and grazing conditions. CropSyst is a user-friendly, conceptually simple but sound multi-year multi-crop daily time step simulation model. The model has been developed to serve as an analytic tool to study the effect of cropping systems management on productivity and the environment. The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition and erosion. Above-ground biomass production is dependent on intercepted radiation (radiation dependent), transpiration (water-dependent) and plant nitrogen uptake (nitrogen-dependent). Each of these factors is capable of limiting crop growth. Management options include cultivar selection, crop rotation, irrigation, nitrogen fertilization, tillage operations and residue management. CropSyst provides the option of a cascading or a finite difference model (Stöckle and Nelson, 2005; Stöckle *et al*. 1997).

According to Stöckle and Nelson (2005), pasture clipping can be done either based on biomass or periodic harvests. When pasture is harvested based on biomass, a clipping event occurs if the current crop biomass reaches the maximum biomass that forces clipping. For periodic option, clipping is performed at a specified interval frequency (days). For cutting options based on biomass or the periodic defoliation modes, available harvested biomass can be removed, harvested or added as a litter to the surface of the ground.

LINGRA

LINGRA is based on LINTUL (Light INTerception and UtiLization simulator) which was originally developed for potato. It is a simulation model for productivity of perennial ryegrass. It was designed for applications such as regional yield forecasting, quantitative yield evaluation and studying the effects of climate change on grassland yields. It describes regrowth after defoliation in a mechanistic way, balanced by temperature-driven remobilisation of stored carbohydrates. It contains routines of light interception, light utilisation efficiency, carbon partitioning, tillering rate, leaf appearance rate, soil water content and evaporation by the sward. The major limitation of the model is that it needs to determine photosynthesis as an input which is difficult to parameterise and doesn't have irrigation scheduling mode (Schapendonk *et al*., 1998).

GrazeGro

GrazeGro is a herbage growth model developed for European countries to predict pasture in perennial ryegrass swards for decision support system (Barrett *et al*., 2005). GrazeGro was developed based on the existing LINGRA (Schapendonk *et al*., 1998) and redeveloped for use by dairy farmers. It was integrated with other models of herbage intake. GrazeGro is a combination of mechanistic and empirical model components. It is based on plant physiological processes at leaf and tiller level. The main additions to the LINGRA model includes its ability to predict reproductive growth, growth response to soil nitrogen and changes in herbage quality in the form of crude protein and organic matter digestibility (Barrett *et al*., 2005). Similar to LINGRA it cannot be used for management of irrigation, since it was initially developed for high rainfall temperate region. Moreover, it is also a simple model used for decision support system.

Hurley

The Hurley pasture model has plant, animal, soil, litter and water sub-models (Thornley, 1998). The plant sub-model represents the growth of vegetative grass and its response to light, temperature, nitrogen, water, harvesting and grazing. It is driven by the carbon input from photosynthesis and the N input from N uptake. The environmental parameters that affect the plant sub-model are radiation, CO_2 concentration, day length, air temperature, soil temperature and rainfall through the water sub-model. There are fluxes of both shoot and root litter sub-models.

Management may affect plant growth through removal of C and N in cutting and grazing regimes. The animal sub-model is designed to provide a simple method of calculating the rate of removal of plant tissue during grazing, the consequent C and N fluxes to the soil as urine and faeces, and release of gasses to the atmosphere. The water sub-model calculates water flow from soil to root, root to shoot, and shoot to the atmosphere for closed canopy grassland. Evaporation is calculated from solar radiation, temperature, rainfall and relative humidity. Management processes such as fertilizer application, harvesting and stocking may be applied in any pattern during the year (Thornley, 1998).

The main shortcomings of the model are:

1) Reproductive development is not included in the model, this may have limitations in predicting forage yield of annual ryegrass at late season when some of the grasses start flowering;
2) The model is mainly developed for temperate climate where there is no shortage of rainfall and doesn't have irrigation scheduling mode;
3) The model requires photosynthesis as an input parameter, which is not easy parameter to determine;
4) some parts of the plant sub-model are not calculated mechanistically; and
5) The model ignores soil evaporation and has only single soil layer.

DairyMod

This model is a biophysical simulation model of Australian dairy pasture management rotational grazing (Johnson *et al.,* 2007). The model includes the following sub-models: 1) Physiologically based pasture growth model with multiple species that can be C3, C4, perennial, annual and legume (Johnson and Thornley, 1983). 2) Animal intake based on bite mechanics which interfaces smoothly with the heterogeneous pasture growth model. Supplementary feeding is also available. 3) Energy based animal metabolism model that includes growth, pregnancy and milk production. 4) Mechanistic water dynamics model including transpiration, evaporation (from canopy, litter and soil), drainage and runoff. There is a choice of infiltration models that includes the Richard's equation or the Capacitance model. 5) Nutrient dynamics model that include organic matter turnover (from litter, dead roots, dung) and inorganic nutrient dynamics of N, P, K, S. The model includes plant uptake, leaching, atmospheric N losses and NH_4 to NO_3 transformations. 6) Fertilizer and irrigation options (Johnson *et al.,* 2007). The model has also the following specific options related to grazing:

1) A range of pasture management options including set-stocked or variable stocked continuous grazing, as well as a variety of rotational grazing strategies and cutting regimes.
2) Fixed time rotations where the stock is moved around the paddocks in some sort of sequence and where the duration between grazings for a paddock is relatively fixed. Three leaf grazing rule where optimum time to graze the paddock is when there have been three full leaf growth intervals since the last time the paddock was grazed. This can be viewed as a management approach based on the physiology of the pastures.
3) Target 10 option based on the general principle is to use knowledge about the optimum range of mass within which the pasture should be maintained,

plus the expected pasture growth rate to calculate the proportion of the farm to be grazed. The term 'Target 10' refers to the objective of achieving an increase of 10% in pasture utilization (Johnson *et al.,* 2007).

In conclusion, most pasture growth models are determined by statistical (empirical) description of physiological processes. Such models are beneficial as tools for pasture management. Lately, more mechanistic growth models have been developed. The degree of complexity for model construction depends on the intended application; a complex model for process understanding or simple model for decision support system. Models which are highly complex with extensive procedures are more applicable to knowledge synthesis and processes understanding than decision support applications. For South Africa conditions, SWB and DairyMod models can provide the best option for pasture management by considering the simplicity and applicability.

The mechanistic nature of the SWB model and its user-friendly mode as irrigation scheduling tool proves its advantages over other empirical models. The use of thermal time in SWB avoids 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). The model is already in use by farmers as irrigation scheduling tool for field and vegetable crops. Due to the above benefits of the model, the use of SWB crop model for predicting pasture can have a good potential.

DairyMod has also a good potential for application under South African conditions for the following reasons. First, it has all the growth factors including atmospheric, water and fertilization (nitrogen). Second, it has more clipping and grazing options which some of them are currently common practices in South Africa. The model is developed in Australia and the use of Australian pasture management principles by South African farmers also gives strong motive for the use of the model. Finally, it also has other animal related sub models which can make it more applicable to farmers.

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APPENDIX B – CAPACITY BULDING AND TECHNOLOGY TRANSFER

Capacity building

One PhD (Melake Fessehazion) and one MSc (Amanuel Abraha) used the data collected from this research for their study.

CSIR technical staff (Lulethu Sinuka, Joshua Xaba and Lucas Ngidi) were trained in installation, calibration, interpretation and implementation of a range of soil water (diviner probes, TDR and watermark sensors), soil N and irrigation (wetting front detectors) and root growth (minirhizotron root scanner) monitoring tools.

Technology transfer

The following papers were presented at GSSA (Grassland Society of Southern Africa), Combined Congress (Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society and the Southern African Society for Horticultural Sciences), and SANCID (South African National Committee on Irrigation and Drainage) Conference conferences:

1. Truter WF, Moodley M, Annandale JG, Everson CS, Fessehazion MK and Abraha AB (2006). Irrigation management in pasture production: a review. SANCID Symposium, 19-23 October, Mpumalanga, South Africa.
2. Abraha AB, Truter WF and Annandale JG (2008). Determining the optimal annual ryegrass growth response to different irrigation and nitrogen levels. Grassland Society of Southern Africa. 22-25 July, Badplaas, South Africa.
3. Everson CS, Fessehazion MK, Truter WF, Annandale JG and Ammann S (2008).Towards Water Use Efficiency in Irrigated Ryegrass and Kikuyu Production. Milk Producers Organization Farmers day, Cedara, August 2007.
4. Fessehazion MK, Everson CS, Annandale JG and Truter WF (2008). Forage yield and water use of annual ryegrass as influenced by irrigation regimes. Combined Congress, Grahamstown, 21-24 January 2008.
5. Fessehazion MK, Annandale JG, Truter WF and Everson CS (2008). Evaluation of the Soil Water Balance Model for annual ryegrass under different irrigation strategies. Grassland Society of Southern Africa. 22-25 July, Badplaas, South Africa.
6. Abraha AB, Truter WF, Annandale JG and Rethman NFG (2010). The integrated effects of water and nitrogen on Italian ryegrass production and its water use efficiency. Grassland Society of Southern Africa. 22-25 July, Kimberly, South Africa.
7. Fessehazion MK, Annandale JG, Everson CS, Stirzaker RJ, Tesfamariam EH, Truter WF and Abraha AB (2010). Developing irrigation and N management strategies of annual ryegrass using the SWB-Sci model. 45th Annual Congress 2010. Grassland Society of Southern Africa. 22-25 July, Kimberly, South Africa.
8. Annandale JG, Stirzaker RJ, Fessehazion MK and Everson CS (2010). Adaptive irrigation and nitrogen management using a wetting front detector. SANCID Symposium, 19-23 October, Uping, South Africa

9. Abraha AB, Truter WF and Annandale JG (2011). Water production of annual ryegrass as affected by nitrogen. Grassland Society of Southern Africa. 11-16 July, Middelburg, South Africa.
10. Fessehazion MK, Annandale JG, Everson CS, Truter WF and Stirzaker RJ (2011). Developing simple irrigation scheduling calendars using the SWB model: Ryegrass as an example. Grassland Society of Southern Africa. 11-16 July, Middelburg, South Africa.
11. Everson CS, Govender M and Fessehazion MK (2011). Quantifying evaporation and biomass of kikuyu and ryegrass pastures using remote sensing technologies. 46th Annual Congress of the Grassland Society of SA. Middelburg, SA. **Award for best presentation**.

The following papers emanated from this project has been published or will be submitted for publication:

Fessehazion MK, Stirzaker RJ, Annandale JG and Everson CS (2011). Improving nitrogen and irrigation water use efficiency through adaptive management: A case study using annual ryegrass. Agriculture, Ecosystems and Environment 141: 350-358.

At least four articles emanated from Mr Fessehazion and Mr Abraha theses will be submitted for publication in 2012.

Preliminary findings of this study were presented at the Milk Producers Organization Farmers day at Cedara in 2007.

Irrigation scheduling guidelines and calendars are published in a WRC report titled “Irrigation guidelines for annul ryegrass pasture”.