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Using adaptive management and modelling to improve nitrogen and water use efficiency in crop production: A case study using annual ryegrass

by

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Submitted in partial fulfilment of the requirements for the degree PhD (Agronomy) in the faculty of Natural and Agricultural Sciences
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LIST OF ACRONYMS AND ABBREVIATIONS

ADF	Acid detergent fibre
asl	Above sea level
ANOVA	Analyses of variance
CEC	Cation exchange capacity
CL	Critical level
CP	Crude protein
CP_{max}	Maximum crude protein
CP_{min}	Minimum crude protein
CP_{opt}	Optimum crude protein
D	Index of agreement
DAP	Days after planting
Dr	Deep drainage
DWAF	Department of Water Affairs and Forestry
ETo	Reference evapotranspiration
FAO	Food and Agriculture organization
FC100	Common scientific practice
FC80	Irrigated 80% of FC100 - deficit irrigation
FC60	Irrigated 60% of FC100 - deficit irrigation
G	Soil heat flux
GDD	Growing degree day
Gen-cal	General irrigation guideline
H	Sensible heat flux
I	Irrigation
IUE	Irrigation use efficiency
LAI	Leaf area index
LSD	Least significant difference
MAE	Mean absolute error of measured values
ME	Metabolisable energy
MIUE	Marginal irrigation use efficiency
N_c	Critical nitrogen concentration
NDF	Neutral detergent fibre
NEWSWB	New Soil Water Balance
NNI	Nitrogen nutrition index
NUE	Fertiliser nitrogen use efficiency

N_{MB}	Nitrogen mass balance
N_{init}	Initial soil inorganic nitrogen
N_{min}	Mineralisable nitrogen
NPN	Non-protein nitrogen
NTP	non-true protein
N_{fer}	Nitrogen input from fertiliser
N_{up}	Above ground crop nitrogen uptake
N_{soil}	Adaptive nitrogen
N_{water}	Adaptive water
P	Precipitation
R	Runoff
r^2	Coefficient of determination
Rn	Net irradiance
RR20	Leaving 20 mm deficit
SOM	Soil organic matter
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
WFD	Wetting front detector
WUE	Water use efficiency
WK25	Common farmers practice of 25 mm
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

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DECLARATION

I, Melake Kessete Fessehazion, hereby declare that this dissertation for the degree PhD (Agronomy) at the University of Pretoria is my own work and has never been submitted by myself at any other University. The research work reported is the result of my own investigation, except where acknowledged.

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Abstract

Poor management of nitrogen (N) fertilisers and water in agro-ecosystems reduces yield, quality and N-use efficiency, and leads to pollution. The objective of this study was to improve irrigation and N management for planted pastures through adaptive management with simple tools and modelling. Field experiments were conducted in 2007 and 2008 at Cedara (KwaZulu Natal) and Hatfield (Gauteng) using annual ryegrass as a case study under a range of N and irrigation application strategies. Collected data sets were also used to calibrate and validate the SWB-Pro (simple) and SWB-Sci (detailed) model versions. After validation, the model was used to develop irrigation calendars and strategies, and estimate irrigation requirements for annual ryegrass.

The highest forage yields were produced when N application rates ranged between 30 to 60 kg N ha^{-1} for each growth cycle, except for the first 2-3 growth cycles when there was high soil N carryover from the previous season. The current farmers' recommendation (fixed N application rate of 50 kg ha^{-1} per growth cycle) maximised biomass but reduced pasture quality. Adaptive strategies based on nitrate concentration in wetting front detectors at different depths, reduced fertiliser N application by 28–32% and reduced potentially leachable residual soil N, while improving forage quality without yield reduction. The rate 30-40 kg N ha^{-1} per growth cycle provided a compromise between forage yield and quality.

The SWB model performed well in simulating ryegrass growth, leaf area index, forage yield, root zone soil water deficit, daily evapotranspiration, biomass N uptake and soil nitrate. Site specific and monthly variable irrigation calendars were developed using the SWB-Pro model, for four major milk producing areas of South Africa. The simpler monthly irrigation calendars can be used in the absence of irrigation monitoring tools or more accurate site specific

calendars. The SWB-Pro model requires relatively few and simple inputs. However, irrigation monitoring/scheduling with the aid of real time modelling or measurements is better than calendars developed using the SWB-Pro model with long-term historical weather data.

The SWB-Sci model showed ways of improving water use efficiency using ‘room for rain’ and ‘mildly deficit irrigation’ approaches in high rainfall areas. Scenario modelling demonstrated that the best management strategy of achieving maximum yield together with low N leaching is by integrating N and water management. This integrated management can be based on the wetness of the soil and nitrate concentration in the deep root zone using wetting front detectors. The model can be used to generate monitoring protocols such as depth of wetting front detector placement and selecting N thresholds to be used for adaptive management.

Setting approximate thresholds for wetting depth and nitrate concentration is a first step in implementing an adaptive management strategy. However, the challenge is to find monitoring tools which allow effective implementation of the strategy. In this study, the wetting front detector proved to be a robust, on-farm water and nitrate monitoring tool which is relatively simple and cost effective. Should it become widely adopted, farmers are expected to improve these thresholds as more experience is gained. The SWB model could also be used to evaluate alternative thresholds for adaptive N and water management.

CHAPTER 1

GENERAL INTRODUCTION

1.1 RATIONALE

Irrigation uses about 62% of South Africa’s surface and ground-water resources (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 (Smil, 2002). 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 for animal production to supply the protein demand of a growing population more efficiently.

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. Annual ryegrass (Lolium multiflorum) is one of the most common irrigated pastures in the pasture based dairy industries (Dickinson *et al.*, 2004). It 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).

Management of dairy farming has now attained unprecedented levels of technology, largely due to the availability of user friendly equipment. In spite of this, there are still trends to rely on experience and tradition for managing irrigation and nitrogen (N) fertilisation. Irrigation water and N are resources that can be optimised by selecting an appropriate irrigation system, scheduling technique and pasture (i.e. N fixing legumes and/or species with high water use efficiency). For sustainable pasture production, the best possible fertiliser and water management is required in order to attain high biomass yield with minimum inputs, which maximises profit whilst minimising impact on the environment. The most appropriate and cost effective management strategy would therefore be to integrate irrigation and N inputs, since N and water cannot be managed independently (Rawnsley *et al.,* 2009).

A number of experiments have been done throughout the country on the effect of N on yield and quality of grass pastures (Eckard, 1994); however, there is a lack of reliable information and data pertaining to annual ryegrass water requirements as affected by N to facilitate efficient irrigation and fertilisation management. Many researchers have worked on the modelling of grass production but the integration of water and nitrogen in relation to irrigation strategies and fertiliser management have not been totally addressed. Despite recent developments in the latest fertiliser and irrigation application equipment and scientifically based guidelines, it can be seen that there are still knowledge gaps between research and farming practice. The challenge is to accurately understand and describe the interaction between water and N in addressing the gaps with alternative methods to the current practice. Practical on-farm equipment and/or models are required to accurately recommend the correct amount of water and N, thereby minimizing N leaching and maximising production and quality at lowest cost. Therefore, the focus of this study is to integrate both irrigation and N management in order to improve the efficiency of both resources.

The Water Research Commission initiated and funded a five-year study on irrigation and N management of planted pastures under different management conditions (WRC K5/1650). The main objectives were to develop irrigation, N and other management guidelines of irrigated planted pastures for the major pasture growing areas of South Africa. Hence, field experiments were conducted in 2007 and 2008 at Cedara and Hatfield as case studies using annual ryegrass for testing selected on-farm equipment (FullStop® wetting front detector) and model (Soil Water Balance) and managing N and irrigation.

1.2 IRRIGATED PASTURE PRODUCTION IN SOUTH AFRICA

More than 80% of South Africa is arid to semi-arid, with unreliable rainfall. This makes most of the country unsuitable 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 the reliability of yield of pastures. It is estimated that the total area utilized for irrigated pasture production is approximately 16% of the total area under irrigation in South Africa. The most common irrigated pastures are ryegrass, kikuyu (*Pennisetum clandestinum*) and lucerne (*Medicago sativa*). 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 Natal Midlands, the Eastern Highveld, the Eastern Cape and in the winter rainfall areas of South Africa (Dickinson *et al*., 2004).

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 normally extends the growing season by as much as four weeks longer than Westerwolds into the early summer. This characteristic of Italian ryegrass types plays an essential role in supplying better quality material between winter and summer grazing. Italian (annual) ryegrass is usually selected over perennial ryegrass due to its high forage yield during winter and its good quality for the dairy industry. Moreover, perennial ryegrass also has a problem of persistency (Eckard, 1994).

Plant growth is determined by the accumulation of dry matter as affected by the environment. Three important processes regulating the growth of plants are uptake of water, photosynthesis (i.e. radiant dependent reduction of carbon dioxide from air) and uptake of nutrients (Dovrat, 2003). Primary pasture cultural management practices (irrigation, fertilisation, and defoliation) which affect growth and development of grasses, have direct effects on the water use efficiency of annual ryegrass (Reeves *et al*., 1996; Peyraud and Astigarraga, 1998). In South Africa, many dairy farmers are applying New Zealand principles of pasture management which are based on perennial pastures (Findlay, 2005). The reason for this is that there are not enough accurate local data on water requirements, water use and rooting depth of irrigated annual ryegrass pasture.

1.2.1 Irrigation guideline

In semiarid regions, water is the primary contributor to grassland production (Whitney, 1974). The development of well-established pasture requires favourable growing conditions with no water stress. This leads to higher yields and good nutritive valued pasture. In some situations, irrigation may give little or no advantage, especially in humid areas. Under hot climatic conditions, water deficits, even for short periods, limit metabolic processes, which may reduce growth rates. Therefore, the aim of irrigation management is to maintain a favourable supply of water within the root zone between the extremes of excessive dryness or wetness.

In South Africa, as a general rule of thumb, annual ryegrass needs about 1200 mm of water for a growing season (Dickinson *et al*., 2004). In summer rainfall regions a rate of 25 mm per week of water is used, and this was calculated from class A pan which is typically 3 to 4 mm per day in the winter (Tainton, 2000). Jones (2006) also recommended 25 mm per week for the production of annual ryegrass in KwaZulu Natal. Regardless of differences in climatic and soil factors, most agriculturalists recommend 25 mm irrigation per week (minus rainfall), when reporting management factors of annual ryegrass to avoid drought (Goodenough *et al*., 1984; Van Heerden, 1986; Eckard, 1989; Harris and Bartholomew, 1991; Le Roux *et al*., 1991). However, according to Steynberg *et al.* (1993), there is a 20% variation in production potential of temperate species between seasons due to weather and rainfall distribution. Therefore, a single set of irrigation norms to schedule irrigation for pastures was clearly insufficient (Steynberg *et al.*, 1993).

Annual ryegrass is characterised by a shallow root system which make it susceptible to rapidly developing soil-water deficits (Dovrat, 1993). When soil water status is used as 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). Under water stressed conditions, annual ryegrass has a large concentration of roots in the upper 0.25 m horizon, with a substantial reduction in root density with depth (Gonzalez-Dudo *et al.,* 2005). 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; Gonzalez-Dudo *et al.*, 2005). In general, annual ryegrass absorbed most water from 0.1 to 0.4 m and in some cases from 0.7 m when soil was relatively dry. One way of ascertaining effective rooting depth of a species, is to establish the depth to which soil is drying without the crop experiencing significant stress (Crosby, 2003). In addition, soil texture is very important to decide on how much and when to irrigate. Irrigation management, however, is one aspect that is seldom monitored and measured.

1.2.2 Water use efficiency

Water use efficiency (WUE) can be defined as harvestable biomass per volume of water used (Wallace, 2000). It includes the total amount of water needed for plant growth, including water lost through evapotranspiration from the soil and plant surfaces (Van Vuuren, 1997). Atmospheric demand, soil water availability and other cultural practices such as fertilisation, different cultivation practices and defoliation methods can influence water use of pasture. Nevertheless, water use of grasses is strongly affected by growth rate, length of season and soil surface coverage.

Most experiments conducted using annual ryegrass report a WUE of 10 - 22 kg DM ha^{-1} mm^{-1} (Johns and Lazenby; 1973; Steynberg *et al.*, 1993; Theron and Van Rensburg, 1998; Callow *et al.*, 2000) with optimum cultural practices. Water use efficiencies increased from 12 to 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). Smika *et al.* (1965) report that if natural grazing is fertilized well, it will have 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 species and environmental factors.

1.2.3 Nitrogen guidelines

Nitrogen fertiliser continues to be a major input influencing yield and quality of irrigated annual ryegrass in South Africa. Improved productivity has been reported with the application of N fertiliser in high rainfall areas and under irrigation in low rainfall areas. It 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; Abassi *et al.*, 2005). According to the Food and Agriculture Organisation (FAO), N fertiliser use has increased 7-fold from 1960 to 2000 (Tilman *et al.,* 2002). Commercial fertilisers are normally used as sources of N in pasture production, but because of increasing energy costs and international demand (Smil, 2002), N prices continue to escalate.

Current N recommendations for annual ryegrass in South Africa are based on the target yield, maximising forage yield per unit area, with little focus on quality and without considering environmental concerns (Eckard *et al.,* 1995). Van Vuuren (1997) recommended N application in small frequent amounts. Nitrogen application increases yield, mainly due to an increase in number of tillers and as a result of leaf expansion. Pasture growers usually split the annual recommended N equally into the number of cuts, regardless of soil and environmental variations between growth cycles (Eckard *et al.,* 1995; Miles; 2007). As the amount of N applied per cut increases, so does the water use of the pasture. With the same rate of N, water use was higher when N was applied every month than once every two months (Eckard, 1994).

According to Miles (2007), optimum N for maximum yield of annual ryegrass was between 200 to 400 kg N ha^{-1} year^{-1}. Marais *et al.* (2003) applied N fertiliser at a rate of 50 kg ha^{-1} for each cut. Nitrogen application rates of 300 to 350 kg N ha^{-1} year^{-1} were found to be optimum for growth of annual ryegrass (Eckard, 1989; Eckard *et al.,* 1995). However, economical optimum levels of dry matter production may require much less N than those for maximum yield.

1.2.4 Effects of excessive N fertiliser

Farmers usually apply high N rates (at least 50 kg ha^{-1} cycle^{-1}) to ensure maximum forage yield (Miles, 2007). In addition to being wasteful, high fertiliser N application can lead to:

- Forage yield imbalances (optimum growth in some growth cycles and deficiency in others) (Eckard, 1990; Eckard *et al*., 1995).

- Excessive forage crude protein (CP) concentrations, leading to an increased 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% is optimum for milk production. At CP concentration levels 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). Crude protein 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.

- Reduced 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 unit dry matter yield with 30 kg N ha^{-1} cycle^{-1} than with 60 kg ha^{-1} cycle^{-1}, even if the highest biomass yield was obtained at the higher rate. 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).

- Reduced palatability, usually due to reduced dry matter content (high moisture content) as a result of high N application (Theron and Van Rensburg, 1998). Even if N fertiliser effects on annual ryegrass were not significant there is a trend by animals to reject pastures with high N content.

- Soil acidification and the pollution of water resources by increasing the risk of N losses (Miles and Hardy, 1999; Monaghan *et al*., 2007).

1.2.5 Nitrogen use efficiency

The effectiveness of applied N in increasing pasture production is usually expressed as the N fertiliser use efficiency (NUE). The NUE in pasture systems is commonly measured as the amount of forage DM produced for each unit of applied N (Zemenchik and Albrecht, 2002), 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, climate, N fertiliser application rate, soil type and other factors that influence plant growth (Abassi *et al.,* 2005).

Nitrogen use efficiencies reported under South African conditions vary significantly, and range from 10 to 80 kg DM kg N^{-1} depending on N rates, defoliation practices (cutting or grazing) and N management strategies. 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 kg DM kg N^{-1} at different sites in 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 immobilised 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 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 have a balance between economic benefit and environmental risk.

1.3 HOW CAN NITROGEN AND IRRIGATION EFFICIENCIES BE IMPROVED?

Due to a shortage of irrigation water, an ever increasing cost of N fertilisers and environmental concerns, current irrigation and N guidelines need to be improved. Considerable research in irrigation and N management strategies has been conducted to improve irrigation water and N efficiency, reduce losses and increase harvestable yield and quality (Wallace, 2000). Possible strategies are: 1) improving irrigation practice with better irrigation scheduling (Sumanasena *et al.,* 2004), 2) accounting for N carryover between harvests and/or accounting for mineralisable N (Collins and Allinson, 2004; Miles, 2007), 3) adaptive management using simple tools to manage both water and fertiliser (Stirzaker *et al.,* 2010; Hyytiäinen *et al.,* 2011), and 4) use of modelling to integrate the effects of weather, soil, crop and management practices (Rawnsley *et al.,* 2009).

1.3.1 Irrigation scheduling

Irrigation scheduling is the decision of when and how much water to apply (Johns and Lazenby, 1973). The aim is to determine the amount of irrigation water to apply and the time for application, thereby maximising irrigation efficiencies. Accurate irrigation scheduling plays an important role in deciding the income of a dairy enterprise by affecting pasture yield and quality; irrigation and nutrient input and energy usage; and environmental pollution. Appropriate irrigation scheduling can lead to increased profits without compromising the environment by increasing productive water use and by reducing run-off, deep percolation below the root zone with nutrient leaching and soil water evaporation. 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).

Farmers are able to get optimum forage yield and quality and improve NUE (reduce N leaching and runoff) by applying the right amount of water at the right time by selecting an appropriate irrigation technique. Direct on-farm techniques (soil, plant or atmospheric) are the best ways to schedule irrigation. However, according to a survey conducted by Stevens *et al*. (2005) most South African farmers (about 72%) were not using objective irrigation scheduling. Instead they were using past experience. The main reasons given to Stevens *et al*. (2005) for South African farmers not using irrigation scheduling techniques were: 1) failure to appreciate the net benefit from irrigation scheduling and the lack of reliable user-friendly irrigation scheduling techniques; 2) high cost of equipment; 3) information collecting and processing was time consuming; and 4) some of the equipment needed more technical knowledge.

An irrigation calendar is a simple guideline or chart that indicates when and how much to irrigate. Calendar based irrigation scheduling provides irrigators with an inexpensive and convenient strategy to estimate irrigation timing and amount. Such calendars allow irrigators to minimise effects of over or under-irrigation by matching water application to pasture water requirements (Whitfield and Qassim, 2004). Moreover, with intensive pastures and rotational grazing management, the farm must be divided into plots or paddocks to facilitate efficient fodder flow for the animals throughout the season. Hence, installing irrigation scheduling tools in all paddocks may not be economical. Using irrigation calendars, therefore, may yield extra benefit in pasture as compared to water management in other crops.

Deficit irrigation scheduling was reported to be successful for pastures to reduce irrigation water inputs and reduce N leaching, thereby increasing water and N use efficiencies and income (Sumanasena *et al.,* 2004; Rawnsley *et al.,* 2009). Neal *et al*. (2011) were successful in achieving maximum forage yields with deficit irrigation for a range of tropical and temperate pastures. In another experiment, Rawnsley *et al.* (2009) used mild deficit irrigation to increase irrigation use efficiency and reduce N leaching. Sumanasena *et al.* (2004) used a range of deficit irrigation strategies to reduce N and P leaching from mixed pasture.

1.3.2 Allowances for nitrogen mineralisation and carryover

Recent studies have shown that N availability is extremely dynamic and is associated with weather, soil water and rate of mineralisation (Collins and Allinson, 2004; Hatfield and Prueger, 2004). In warm weather, soil N availability is usually high because of rapid mineralisation, while in cold weather mineralization is slow, and N less available. In wet seasons N can be leached because nitrates dissolve easily in soil water, and N can be lost to the atmosphere by denitrification. This makes it hard to know how much N is actually needed at any given stage (growth cycle) and reduces farm profits and causes potentially high environmental losses to both surface and ground-water (nitrate leaching) and to the atmosphere (ammonia volatilization and denitrification). Applying the current recommended N (50 kg ha^{-1} per growth cycle) could be deficient in some years (growth cycles), whilst in others the same amount of fertiliser could be adequate or excessive (Andraski and Bundy, 2002; Collins and Allinson, 2004; Miles, 2007).

A fertilisation strategy that takes into account the nutrients currently available in the soil can provide economic benefits as compared to one in which the amount of fertiliser is fixed at the beginning of each growth cycle. This more flexible nutrient regime can reduce unnecessary fertilisation when the soil is rich in nutrients and increase the growth potential of a crop when nutrients in the soil are inadequate.

A range of N management strategies has been investigated to improve N efficiency, reduce losses and increase harvestable yield and quality. Some of these strategies are to avoid applying N during winter (Eckard, 1994), or account for N carryover between harvests and/or account for mineralisable N (Collins and Allinson, 2004; Miles, 2007). The strategy of no N application during winter (June and July), however, has been criticised, as pasture is critically dependent on N fertiliser for growth and survival (Eckard, 1994) due to very low rates of mineralisation in winter. These strategic N applications are mainly dependent on environmental effect on crop growth rate and N release from mineralisation. According to Miles (2007), N fertiliser application could be reduced between 85 to 174 kg ha^{-1} per year (depending on soil carbon content), by including mineralisable soil N inputs in N recommendations for pastures.

1.3.3 Adaptive management

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 (Holling, 1978; Walters, 1986; Lee, 1993). Adaptive management is the process of refining a management strategy in response to evaluating its success. It requires field measurement data and observations for local conditions, and evaluates success based on scientific principles and local experience (Walters, 1986). It is a learning process, so that the grower is able to adopt practices that make sense for his own specific conditions to increase profits and reduce environmental impacts at the same time (Lee, 1993). On-farm adaptive management programmes encourage farmers to implement management actions, monitor to observe the results of those actions, and use the results to update knowledge and adjust future management actions accordingly (Walters, 1986; Lee, 1993). Since monitoring is expensive, farmers seek a measurement that can integrate many of the processes involved in the soil water balance and N cycle (Stirzaker *et al.,* 2010; Fessehazion *et al.*, 2011; Hyytiäinen *et al.,* 2011). The challenge is to find tools which allow effective implementation of adaptive management strategy.

The dynamic nature of pasture systems increases the uncertainty of using generalised recommendations. Another means to reduce uncertainty about the yield obtained in response to input use is to apply fertiliser or irrigation based on monitoring the soil water and N balance.

However, improving N and water management at field level with frequent sampling (components of N and water balance) is expensive, complex, time consuming and impractical. A robust, on-farm monitoring indicator which is relatively simple, cost effective and readily adopted by farmers, is the FullStop® wetting front detector. It can be simultaneously used for managing irrigation water and observing N by monitoring depth of wetting and nitrate concentration of the passing wetting fronts (Stirzaker *et al.*, 2010). The challenge will be to develop useful robust guidelines from such observations.

1.3.4 Modelling

Generally radiation, temperature, water and nutrients are the most important environmental factors that influence growth and quality of pastures (Dovrat, 1993). Nitrogen and irrigation recommendations are typically developed based on field experiments conducted for few years (2-3). However, there is always high uncertainty using the results from field experiments for other sites, soils and seasons. With advances in computer technology, numerical models have been used widely to analyse and solve resource management problems such as the scheduling of irrigation and fertilisation management (Bahera and Panda, 2009). A wide range of 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 shown that simulation studies can supplement field studies in decision making (Van der Laan *et al.*, 2011). Models can predict quite accurately the growth, development and yield of crops by incorporating complex processes with the help of soil, daily weather and management inputs, to assist growers to select best management options. A modelling approach can therefore be a lot more locally accurate than the current rigid generalised irrigation and N recommendations. Once satisfied with the validation process, a model can provide a much lower cost than other scheduling tools.

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

(Annandale *et al*., 2000). This can save money and time required for conducting long-term intensive field experiments for gathering information on potential pasture 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 and N use efficiency and determine site specific irrigation requirements and calendars. Considering the use of a large number of data sets and time consuming determination of input parameters required for pasture specific models, relatively simple generic crop models (such as SWB) may be more useful. According to Stevens *et al.* (2005), the major problem with the adoption of models by farmers is their complexity. Therefore, there should be a trade-off between accuracy and simplicity.

The SWB model is used locally in South Africa to simulate crop growth and the soil water balance of several cereal, vegetable and tree crops. It is probably better to use a model which is known locally by farmers and consultants instead of introducing another new model. The model is available on the web and can be downloaded free of charge.

1.4 HYPOTHESIS AND OBJECTIVES

In South Africa, irrigation water and N fertiliser are the two most important inputs controlling the productivity of irrigated annual ryegrass. To increase production, there has been a tendency to adopt high application rate of fertiliser and irrigation water, often concomitantly. Besides the high cost of production, degradation of water and soil quality owing to overuse of these resources is a matter of global concern. Therefore, water and N fertiliser inputs should be carefully managed to avoid losses.

The main hypotheses formulated to be tested in this study were linking that N and water management could:

1) Increase forage quality without significant forage yield reduction;
2) Improve nitrogen and water use efficiencies, and
3) Reduce potential N leaching

The overall objectives of the study were:

1) To test whether adaptive N and water management approaches could improve the current fixed N application rate guideline;
2) To study the response of annual ryegrass forage yield and quality parameters to N application and determine the trade-offs between yield and quality;
3) To parameterise and calibrate the SWB model for annual ryegrass and to evaluate its performance under varying N levels and irrigation regimes, and.
4) To assess potential irrigation management strategies for annual ryegrass, estimate water requirement and develop site-specific irrigation calendars for major ryegrass growing regions of South Africa using the SWB model.

The approaches used to test the hypotheses and address objectives are presented in separate chapters. With this background, comprehensive field investigation (Chapters 2 and 3) and modelling (Chapters 4, 5 and 6) were undertaken using annual ryegrass. The chapters are presented in article format and are prepared according to the South African Journal of Plant and Soil authors' guidelines.

In Chapter two, adaptive irrigation and N management strategies are used to reduce N fertiliser and irrigation inputs without significant yield reduction and improved yield whilst reducing potential environmental pollution (N leaching). In Chapter three, responses of annual ryegrass forage yield and forage quality parameters are determined by applying different N fertiliser application rates. In Chapter four, the simple irrigation scheduling version of the SWB

(SWB-Calendar) model is calibrated and validated and calendars are developed for selected sites and soil types. In Chapter five, the scientific version of the SWB (SWB-Sci) model is calibrated and validated for a range of N fertiliser levels and irrigation regimes. In Chapter six, a range of irrigation strategies were compared with apparent current farmers' irrigation practice using the SWB-Sci model. Finally, in Chapter seven, general conclusions and recommendations are presented.

CHAPTER 2

IMPROVING NITROGEN AND IRRIGATION WATER USE EFFICIENCY OF ANNUAL RYEGRASS THROUGH ADAPTIVE MANAGEMENT

2.1 INTRODUCTION

Global use of nitrogen (N) fertiliser has increased more than seven-fold since the 1960s (Smil, 1999; Tilman *et al.,* 2002). Only half of this N 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; Steffen *et al.,* 2007). Despite decades of research on matching fertiliser applications to crop requirements, agriculture remains a major source of environmental contamination (Isermann, 1990; Tamminga, 1992; Matson *et al.,* 1997; Stirzaker, 1999; Goulding, 2000).

Irrigated pasture for milk production is an example of a high N-use agricultural system. Growth and quality are very responsive to applications of N fertiliser and since N is seen as a low cost input for the dairy industry (Tas *et al.,* 2006), excessive applications are common (Eckard *et al.,* 1995). However, high levels of N can reduce pasture quality through toxic levels of nitrate, excessive protein content, increased non-protein N and reduced metabolisable energy (Peyraud and Astigarraga, 1998).

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 (Andraski and Bundy, 2002; 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 sits 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 (Holling, 1978; Walters, 1986; 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 approximately estimates the water and nitrate levels moving past a certain depth in the soil profile (Stirzaker, 2003; van der Laan *et al.,* 2010). The objectives of this paper 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.

2.2 MATERIALS AND METHODS

2.2.1 Site description and crop management

The experiment was conducted at the Cedara Department of Agriculture Experimental Farm located in the midlands of KwaZulu-Natal, one of the main milk producing areas of South Africa (altitude 1076 m above sea level, 29°32'S; 30°17'E). The site has a summer dominated mean annual rainfall of 876 mm and reference evapotranspiration of 1511 mm. Monthly mean minimum and maximum temperatures, and monthly total precipitation recorded from a weather station during the study period are shown in Table 2.1.

Table 2.1 Monthly mean minimum and maximum 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} (℃)	13.7	10.9	4.3	1.8	1.3	3.7	10.4	11.2	12.3
	T_{max} (℃)	25.1	23.6	23.3	19.6	20.5	22.0	23.8	21.3	23.1
	Rain (mm)	68.2	34.7	10.0	32.6	0	14.2	17.5	155.5	77.4
2008	T_{min} (℃)	13.2	9.0	7.4	4.2	2.9	5.9	5.9	12.9	13.3
	T_{max} (℃)	24.7	22.2	23.2	19.4	21.1	22.9	22.8	22.3	23.7
	Rain (mm)	3.0	71.3	8.2	21.9	13.0	5.4	42.6	37.5	82.2

T_{min} is mean monthly minimum temperature; T_{max} is mean monthly maximum temperature.

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 2.2). The site has a deep, red, kaolinitic Hutton soil (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. In both years, soil fertility status was determined prior to planting. Ammonium acetate was used for K, Ca and Mg extraction. Organic carbon and N were estimated by mid-infrared spectroscopy (Ben-Dor and Banin). P measured with Bray I. Nitrate and ammonium N were analysed using 1 M KCl extraction. The soil test results of both years were similar and are presented in Table 2.2. 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 March in 2007 and 25th 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.

Table 2.2 Selected soil physical and chemical properties of the experimental site

Soil property	0 - 0.2 m	0.2 - 0.4 m	0.4 - 1.0 m
Saturation (m^3 m^{-3})	0.498	0.481	0.498
Field capacity (m^3 m^{-3})	0.337	0.331	0.329
Wilting point (m^3 m^{-3})	0.206	0.212	0.192
Bulk density (kg m^{-3})	1220	1280	1170
Clay (%)	30.6-38.1	31.0-42.6	40.1-51.9
Sand (%)	31.9-33.4	23.4-34.7	22.8-34.8
Total N (%)	0.19-0.22	0.19-0.21	0.10-0.15
Organic C (%)	2.7-3.2	2.4-2.8	0.90-1.5
pH (KCl)	4.16-4.40	4.25-4.37	4.61-4.75
P (mg kg^{-1})	23-24	15-24	3-7
K (mg kg^{-1})	173-208	94-138	26-44
Ca (mg kg^{-1})	712-820	711-743	471-653
Mg (mg kg^{-1})	156-202	162-195	167-222
Exchangeable acidity (cmol kg^{-1})	0.27-1.17	0.23-1.07	0.11-0.46
Total cations (cmol kg^{-1})	6.45-6.56	5.90-6.19	4.22-6.11
Acid saturation (%)	9-18	7-17	3-9
NO3-N (mg kg^{-1})	34.8-41.4	20.5-48.4	10.4-22.4
NH4-N (mg kg^{-1})	4.9-6.7	6.9-7.9	5.8-9.0

Soil physical properties were determined in 2007 prior to planting. Soil chemical analysis was conducted in both years prior to planting and the ranges are presented.

A dragline sprinkler irrigation system with a delivery rate of 4.0 mm h^{-1} and 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. 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).

A wetting front detector (WFD) is a funnel-shaped, passive lysimeter, used for managing irrigation, salinity and nutrition (Stirzaker and Hutchinson, 2005; Tesfamariam *et al.,* 2009; Van der Laan *et al*., 2010). 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 (Stirzaker, 2008). The water passes through a filter, is collected in a reservoir, and activates a magnetically latched float. A water sample can later be retrieved for analysis using a syringe. 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 (Appendix A1). Therefore, 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.

2.2.2 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. In 2008 the experiment was changed because forage yields between N treatments were similar in the first two to three growth cycles. In addition there was also high soil solution nitrate concentrations 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:

2.2.2.1 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.

2.2.2.2 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:

$$N_{fer} = N_{up} - N_{init} - N_{min} \qquad (2.1)$$

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:

$$N_c = 4.08\ DM^{-0.38} \tag{2.2}$$

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. This N dilution curve was tested using the data collected in this study and the values were in the ranges previously reported (Marino *et al.,* 2004) (Appendix A2). 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 annual ryegrass (z) with equation (2.3). 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.

$$N_{init} = (0.226\ WFD_{NO3}\ \rho_w\ \theta\ z)/100 \tag{2.3}$$

Where: N_{init} 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; z 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 2.1). 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.

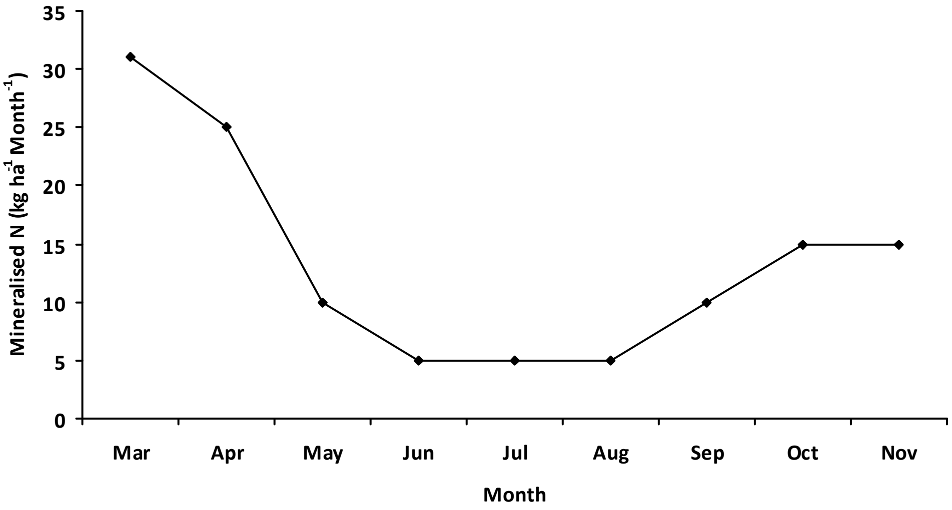

Figure 2.1 Monthly N mineralisation estimates based on organic carbon collected at the beginning of the season

2.2.2.3 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 forage quality (Figure 2.2). 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 2.3).

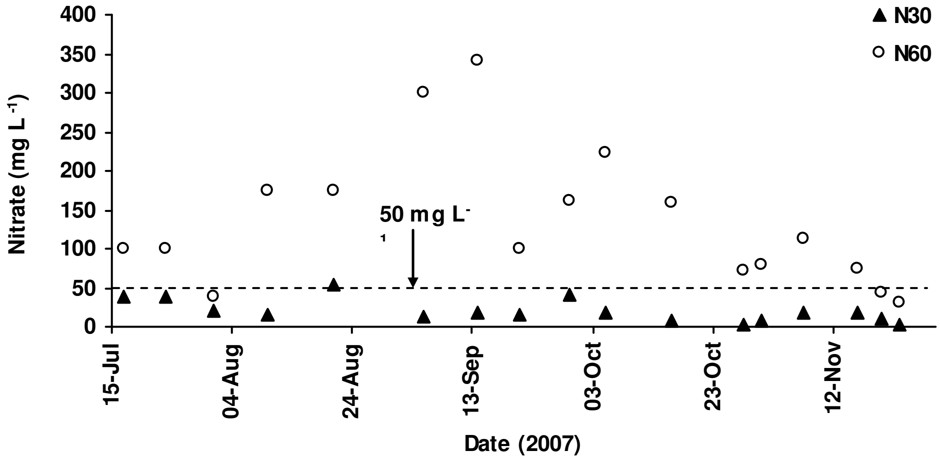

Figure 2.2 Mean nitrate concentrations of wetting front detectors installed at all depths in treatments which received 30 kg N ha^{-1} cycle $^{-1}$ (N_{30}) and 60 kg N ha^{-1} cycle $^{-1}$ (N_{60}) in 2007 (dotted horizontal line represents nitrate threshold level)

2.2.2.4 Adaptive water (N_{water})

Results from 2007 showed that soil solution nitrate increased with higher inputs of fertiliser (Figures 2.3a and b). 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 2.3). 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 2.3a). If the concentrations from the 0.45 m WFD exceeded 25 mg L^{-1}, the scheduled irrigation event was cancelled (Figure 2.3b).

Table 2.3 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	0	N_0	0	As initial N in mass balance calculation	equation 1	>50	0	WFD_{30}>25	Reduced
N_{30}	30	N_{20}	20			25-50	25	WFD_{45} >25	Cancelled
N_{60}	60	N_{40}	40			<25	50		
		N_{60}	60						

[§] N rates in kg ha^{-1} $cycle^{-1}$.

[β] Soil solution nitrate in mg L^{-1}.

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.

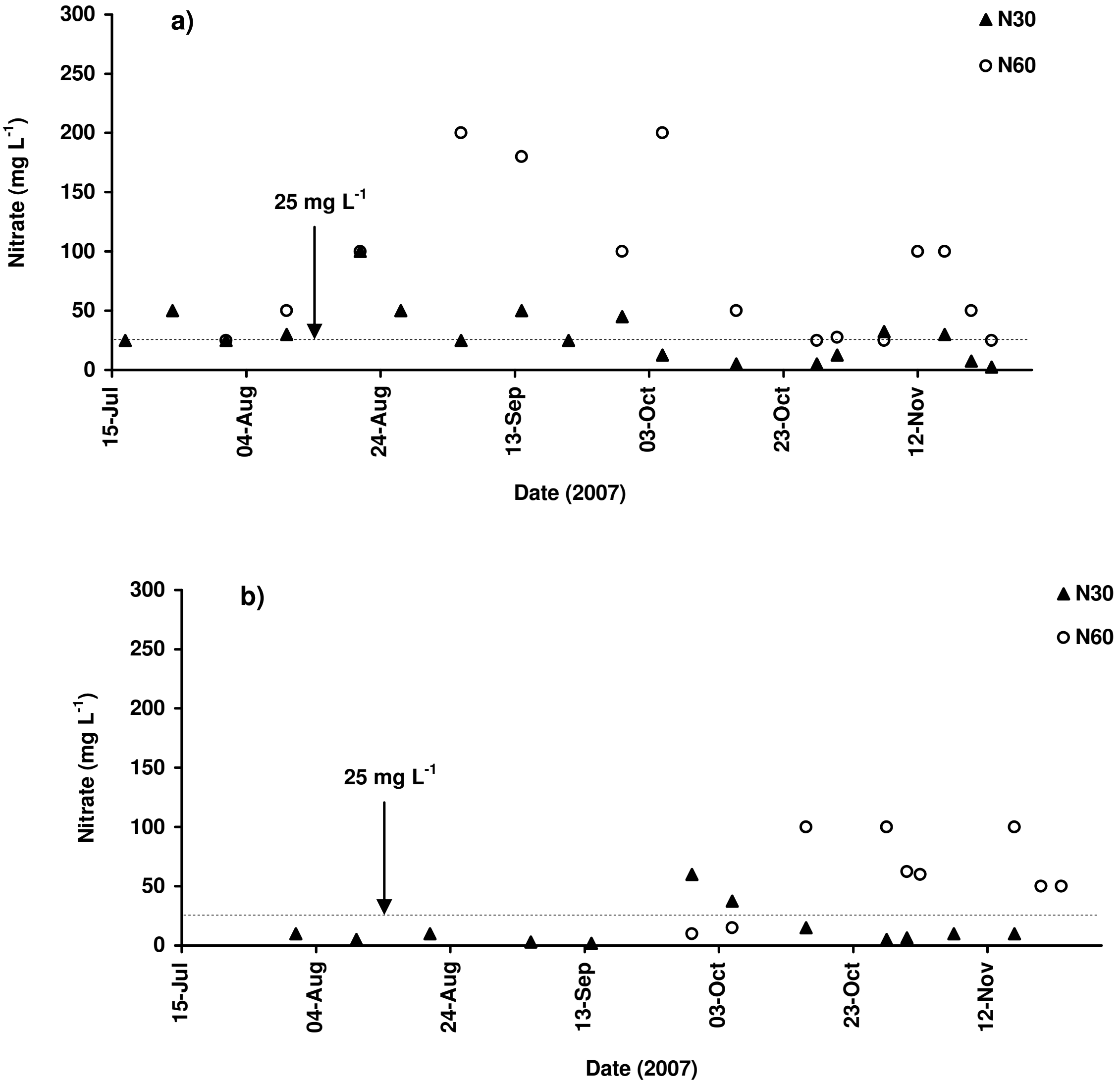

Figure 2.3 Nitrate concentrations of wetting front detectors installed at a) 0.30 m and b) 0.45 m in treatments which received 30 kg N ha^{-1} cycle $^{-1}$ (N_{30}) and 60 kg N ha^{-1} cycle $^{-1}$ (N_{60}) in 2007 (dotted horizontal line represents nitrate threshold level)

2.2.3 Data collection and calculations

The pasture was harvested to 50 mm stubble height at the two to three leaf stage from 1 m^2 quadrants using a manual grass mower. A total of nine samples per treatment (three from each plot) were collected for yield and quality determinations. After taking samples, 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. Samples were milled to pass through a 0.1 mm sieve and were kept in bottles until quality could be determined. Total N was determined by Kjeldahl analysis (AOAC, 2000) and crude protein content (CP) was calculated by multiplying total N concentration by 6.25.

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 an RQ Easy Nitrate Reflectometer (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 of nitrate measurements below the root zone between two successive core sampling dates (September and November).

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

$$ET = P + I - R - Dr - \Delta Q \qquad (2.4)$$

Where: P is precipitation, I is irrigation, R is runoff, Dr is deep drainage below the rooting depth (0.6 m), and ΔQ 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 ΔQ indicates a gain in soil water storage. ΔQ 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:

$$IUE = \text{Forage yield}/I \tag{2.5}$$

$$WUE = \text{Forage yield}/ET \tag{2.6}$$

$$NUE = (\text{Forage yield from fertilised treatment} - \text{Forage yield from } N_0)/\text{Applied N} \tag{2.7}$$

2.2.4 Statistical analysis

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 $P < 0.05$.

2.3 RESULTS and DISCUSSION

2.3.1 Forage yield and quality

In 2007, maximum forage yields were obtained with N_{60} while the optimum quality was for the N_{30} treatment (Table 2.4). 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 2.5). In both years, there were no significant differences in forage yield between treatments in the first two growth cycles (Tables 2.4 and 2.5). 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 2.1). The significantly lower 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 2.1).

Table 2.4 Forage yield (t ha^{-1}), crude protein (CP: g kg^{-1} DM), total N application rates (kg ha^{-1}), fertiliser N use efficiency (NUE: kg DM kg^{-1} N), 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 rate (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) treatments in 2007

Treatment		Forage yield									CP	N rate	NUE	I	ET	IUE	WUE
		07 May 1[§]	11 June 2	11 July 3	08 Aug 4	04 Sep 5	27 Sep 6	24 Oct 7	20 Nov 8	Total							
N_0		2.06a[β]	1.71a	1.16b	0.90c	0.61c	0.65b	0.53c	0.61c	8.23c	172c	0	-	435b	701b	18.8b	12.5b
N_{30}		2.06a	1.72a	1.46a	1.23b	1.76b	1.77a	1.87b	1.35b	13.21b	224b	280	20.8	529a	779a	26.9a	18.3a
N_{60}		2.09a	1.79a	1.58a	1.66a	2.35a	1.98a	2.35a	1.81a	15.61a	265a	460	15.4	565a	816a	29.2a	20.6a
Source of variation	df[φ]	Mean squares															
Treatment	2	0.001	0.006	0.140	0.005	2.324	1.542	2.664	1.095	42.54	6332	-	-	7686	10920	98.20	52.39
Error	4	0.006	0.013	0.004	0.443	0.016	0.007	0.006	0.003	0.048	39.33	-	-	342.1	1016	2.602	0.795
Significance		ns	ns	**	**	**	**	**	**	**	**	-	-	**	**	**	**

[§] Number of growth cycles. [β] Values followed by the same letter within a column are not significantly different.

[φ] Degrees of freedom. ns non-significant and ** significant at the 0.01 probability level.

Table 2.5 Forage yield (t ha^{-1}) and crude protein (CP: g kg^{-1} DM) of annual ryegrass under a range of 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	Yield (t ha^{-1})								CP
	28 May 1§	01 July 2	07 Aug 3	05 Sep 4	01 Oct 5	24 Oct 6	16 Nov 7	Total	
N_0	1.10a$^{\beta}$	1.91a	0.95d	0.76c	0.41c	0.46c	0.41c	5.9c	143d
N_{20}	1.08a	1.96a	1.54c	1.44b	1.34b	1.54b	1.10b	10.0b	175c
N_{40}	1.04a	2.02a	2.10a	2.08a	1.95a	1.97a	1.82a	13.0a	221b
N_{60}	1.09a	2.03a	2.14a	2.16a	2.28a	2.06a	2.05a	13.8a	272a
N_{MB}	1.12a	1.97a (0)‡	1.97ab (38)	1.96a (46)	2.05a (47)	1.81ab (43)	1.80a (41)	12.7a	217b
N_{soil}	1.05a	2.07a (0)	1.91ab (20)	2.02a (50)	2.20a (50)	1.92a (50)	1.95a (50)	13.1a	228b
N_{water}	1.16a	1.98a (0)	1.84b (40)	2.01a (47)	2.17a (40)	1.94a (39)	1.92a (39)	13.0a	219b

Source of variation	df$^{\varphi}$	Mean squares								
Treatment	6	0.005	0.007	0.520	0.770	1.376	0.935	1.093	23.00	5038.10
Error	12	0.004	0.017	0.008	0.029	0.014	0.012	0.021	0.182	24.81
Significance		ns	ns	**	**	**	**	**	**	**

[§] Number of growth cycles.

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

[‡] Values in brackets are fertiliser N application rates (kg N ha^{-1} cycle^{-1}).

[φ] Degrees of freedom.

ns non-significant and ** significant at the 0.01 probability level.

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 2.5).

2.3.2 Nitrogen rates and nitrogen 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 2.6). 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 2.6).

Generally, fertiliser use efficiencies (NUE) were higher in 2008 than 2007 (Tables 2.4 and 2.6), 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 managements showed significantly higher NUE compared to the fixed rate of $N_{60.}$

Table 2.6 Total N application rates (kg ha^{-1}), fertiliser N use efficiency (NUE: kg DM kg^{-1} N), 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 and soil solution nitrate concentrations (mg L^{-1}) under a range of 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		N rate	NUE	I	ET	IUE	WUE	Nitrate$^{\beta}$
N_0		0	-	343c	493d	17.5d	12.2c	13.1c
N_{20}		120	33.4a§	382ab	547bc	26.2c	18.3b	13.3c
N_{40}		240	29.1ab	384ab	564ab	33.9ab	23.0a	64.5b
N_{60}		360	21.7b	408a	571a	33.9ab	24.2a	101.6a
N_{MB}		216	30.9a	411a	563ab	30.9b	22.5a	21.8c
N_{soil}		220	32.4a	396ab	561ab	33.1ab	23.4a	23.8c
N_{water}		205	34.1a	367bc	529c	35.5a	24.6a	27.4c
Source of variation	df$^{\varphi}$	Mean squares						
Treatment	6	-	62.38	1721.19	2304.43	120.34	60.25	3279.2
Error	12	-	7.41	133.06	69.78	1.180	0.728	72.1
Significance		-	**	**	**	**	**	**

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

$^{\beta}$Mean nitrates collected from WFDs installed at 0.45 m soil depth.

$^{\varphi}$Degrees of freedom. ns non-significant and ** significant at the 0.01 probability level.

2.3.3 Water use efficiency

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 2.4). 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.

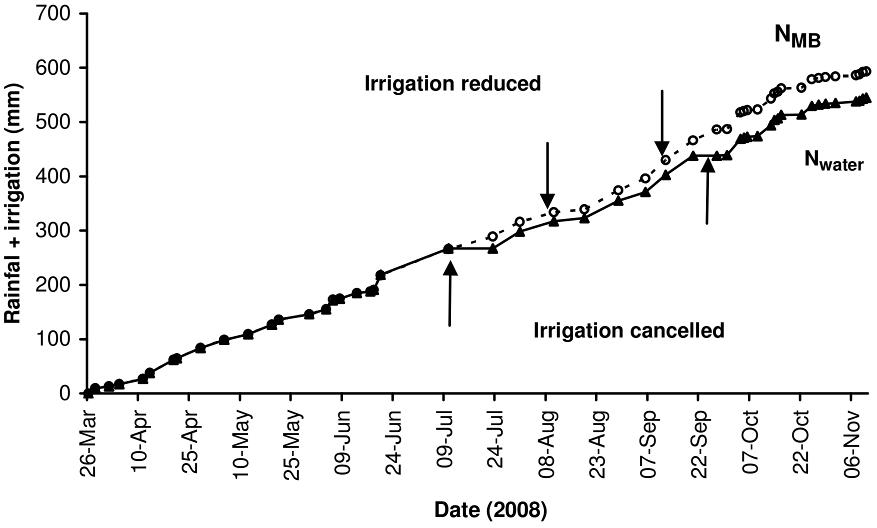

Figure 2.4 Rainfall plus irrigation for N mass balance (N_{MB}) and adaptive water (N_{water}) treatments in 2008 (upward arrows show cancellation of irrigation events and downward arrows reduced irrigation amount)

There were significant differences in irrigation applied and water use between treatments in 2007 (Table 2.4) and 2008 (Table 2.6). 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. Seasonal irrigation use efficiency of N_{water} was significantly higher than that of N_{MB}.

2.3.4 Potential leaching

Soil NO_3 concentrations from WFDs (Figure 2.5) and soil coring (Figure 2.6) 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 2.5), where there was high initial inorganic N and mineralised organic N after tillage (Figure 2.1). 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 2.6).

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 2.6). 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 2.6). 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.

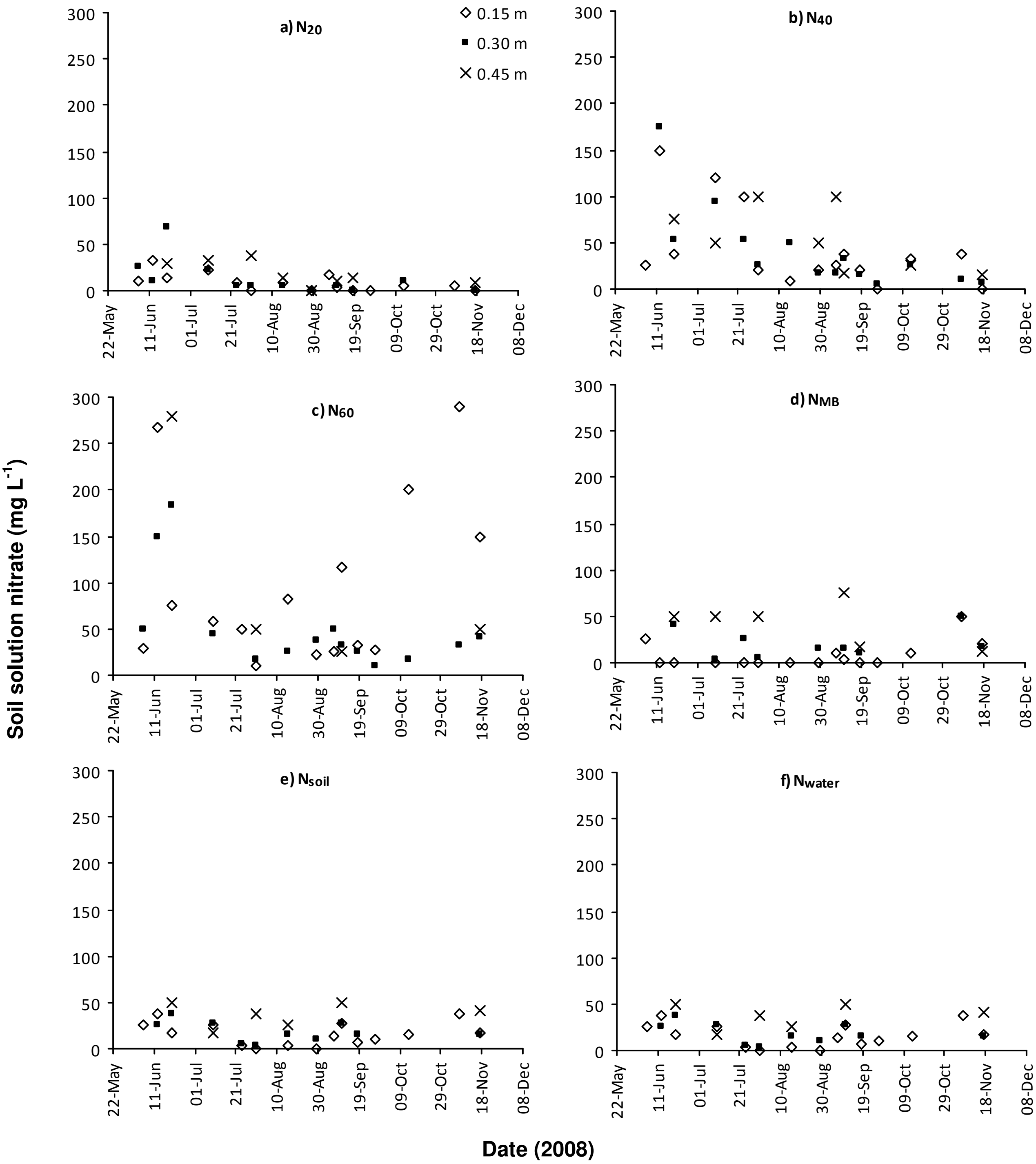

Figure 2.5 Soil solution nitrate concentrations collected from 0.15 (◊), 0.30 (■) and 0.45 (x) m deep wetting front detectors installed in the a) 20 kg ha^{-1} cycle^{-1} (N_{20}), b) 40 kg ha^{-1} cycle^{-1} (N_{40}), c) 60 kg ha^{-1} cycle^{-1} (N_{60}), d) N mass balance (N_{MB}), e) adaptive N (N_{soil}) and f) adaptive water (N_{water}) treatments in 2008

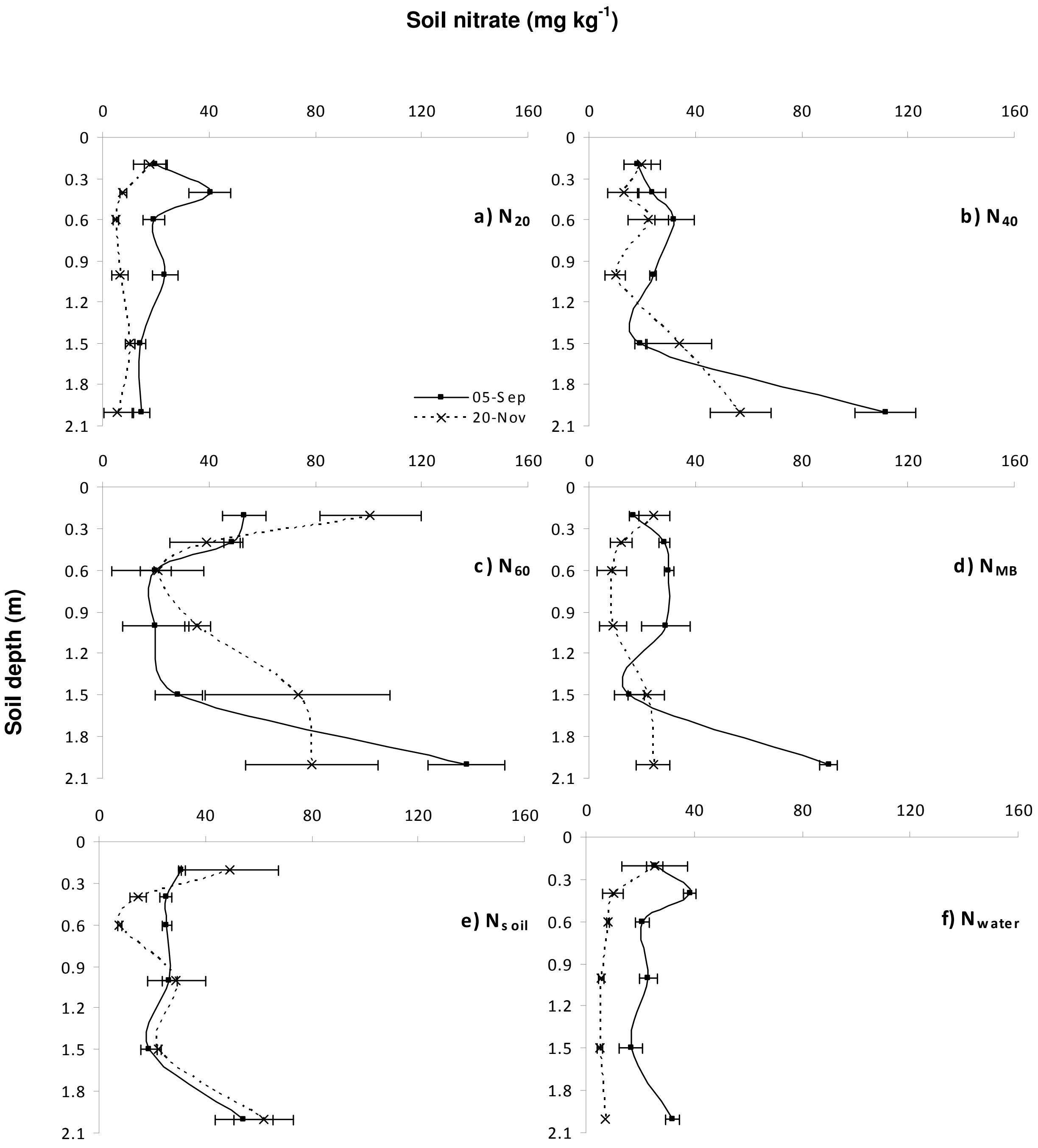

Figure 2.6 Soil nitrate concentrations (mg kg^{-1}) collected from soil cores in September (solid line) and November (dotted line) for the a) 20 kg ha^{-1} cycle^{-1} (N$_{20}$), b) 40 kg ha^{-1} cycle^{-1} (N$_{40}$), c) 60 kg ha^{-1} cycle^{-1} (N$_{60}$), d) N mass balance (N$_{MB}$), e) adaptive N (N$_{soil}$) and f) adaptive water (N$_{water}$) treatments in 2008

2.4 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.

Some may also argue that the use of simple thresholds is little more than an environmental management strategy (EMS), such as those promoted by the international standard organisation (ISO). However, farmers are subjective 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. A good adaptive manager is expected to improve these thresholds as more experience is gained. For example, lower threshold values than 25 mg L^{-1} could be selected or the two adaptive treatments could be combined to seek alternative strategies.

CHAPTER 3

NITROGEN APPLICATION AND CRITICAL NITRATE SOIL SOLUTION CONCENTRATIONS FOR YIELD AND QUALITY OF ANNUAL RYEGRASS

3.1 INTRODUCTION

Annual ryegrass is one of the most widely grown irrigated winter pastures in South Africa in the high rainfall areas particularly in the Natal Midlands, the Eastern Highveld, the Eastern Cape and in winter rainfall areas of South Africa (Dickinson *et al*., 2004). It has high nutritional qualities, palatability, digestible energy, protein and mineral contents (Theron and Snyman, 2004) and plays an essential role in supplying good quality grazing between winter and summer (Eckard *et al.,* 1994).

Nitrogen fertiliser is a major input influencing yield and quality of irrigated annual ryegrass in South Africa. Current N recommendations are based on empirical relationships with forage yield, with little focus on pasture quality or losses of N to the atmosphere and groundwater. The high rates of N applied to ensure a maximum forage yield (Eckard *et al.,* 1995), often results in high crude protein (CP) concentration, which is associated with an increase in non-protein N (Reeves *et al*., 1996), nitrate toxicity, imbalances in mineral metabolism and metabolic disorders (Coombe and Hood, 1980; de Villiers and van Ryssen, 2001). It can also reduce non-structural carbohydrates content, forage 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.

There is high potential for N losses in pasture fed dairy production, through the process of ammonia release and leaching of nitrates, with urinary N output accounting for about 65% of N intake for dairy cows feeding on highly fertilised pasture (Peyraud *et al*., 1997). One way to reduce N losses is to reduce CP intake by reducing forage CP concentration, which can be achieved either through reduced N fertilisation or increasing energy intake to balance for ingested CP (Tamminga, 1992;

Hoekstra *et al*., 2007). For indoor ration based dairy production, feed composition can be balanced by mixing diets of herbage with supplements. However, due to the lower cost of inputs in the pasture based systems than a mixed ration system (Gertenbach, 2006), milk production is mainly dependent on pastures. Manipulation of forage quality of the grazing pasture is complex, because high N applications are common for achieving maximum forage yield, while high N application can reduce forage quality and energy value. For example, Nash *et al.* (2008) reported higher energy yield with an application rate of 30 kg N ha^{-1} $cycle^{-1}$ even though the highest biomass yield was obtained at 60 kg ha^{-1} per $cycle^{-1}$.

In Chapter two, results showed how N fertiliser applications could be reduced using various adaptive strategies based on regular monitoring of soil nitrate using a passive lysimeter. This Chapter extends the work of Chapter two by investigating the nexus between fertiliser, biomass production and quality in more detail. Specifically the objectives of this research are to determine 1) response of annual ryegrass to forage yield and quality to N fertilizer application, 2) critical soil nitrate concentrations for yield and quality and 3) the nature of the trade-off between biomass and quality parameters.

3.2 MATERIALS AND METHODS

3.2.1 Site description and crop management

The experiment was conducted at Cedara, a Department of Agriculture experimental site (altitude 1076 m, 29^{o}32'S; 30^{o}17'E) in 2007 and 2008. The site is located in the midlands of KwaZulu-Natal, one of the main milk producing areas of South Africa. It has a mean annual rainfall of 876 mm and a reference evapotranspiration of 1511 mm (Table 1). Total precipitation over the growing period (March to November) at the study site was 557 mm in 2007 and 441 mm in 2008 (Figure 3.1). Both 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.

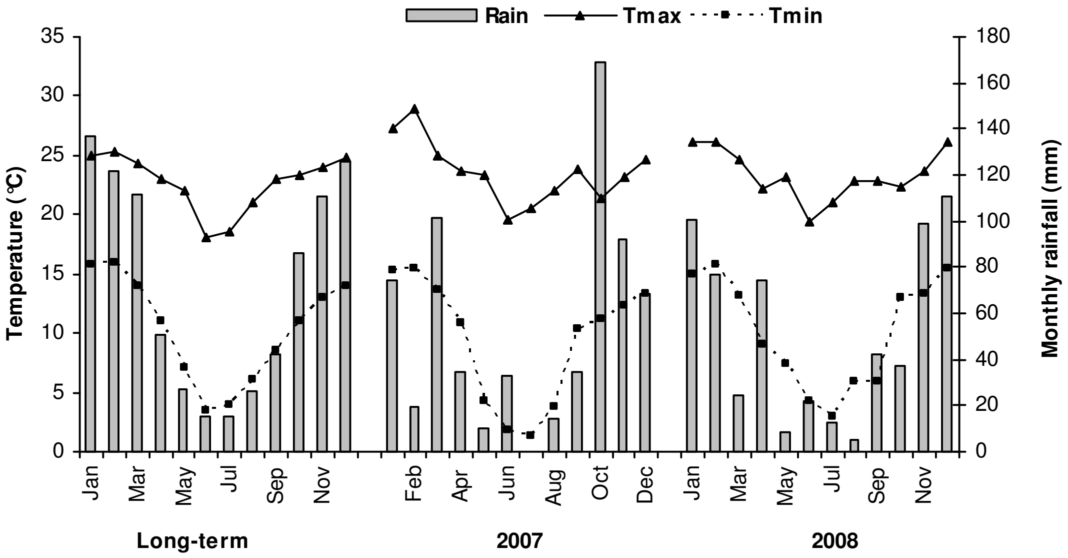

Figure 3.1 Long-term (85 years), 2007 and 2008 total monthly rainfall and mean maximum and minimum temperatures for Cedara

The experimental site has a deep, red, kaolinitic Hutton soil (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. In both years, soil core samples were collected to a depth of 1 m at the beginning of the seasons. Soil fertility status was determined prior to planting. Ammonium acetate was used for K, Ca and Mg extraction. Organic carbon and N were estimated by mid-infrared spectroscopy (Ben-Dor and Banin). P measured with Bray I. Nitrate and ammonium N were analysed using 1 M KCl extraction. The soil test results of both years were similar and are presented in Table 2.2. Based on soil fertility status 20 kg P ha^{-1} (super phosphate - 10.5%) was incorporated at planting. Both N (limestone ammonium nitrate - 28%) and K (KCl - 50%) were top-dressed within two days after 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 cultivar (*Lolium multiflorum*) "Agriton" was planted on the 6th March in 2007 and 25th March 2008 at a seeding rate of 30 kg ha^{-1} and a spacing of 15 mm between rows. A Cambridge roller was used to facilitate good contact between the seed and soil. 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.

A dragline sprinkler irrigation system with a delivery rate of 4.0 mm h^{-1} and a spacing between sprinklers of 12 m was used. Plots were 12 m wide and 36 m long with a border spacing between plots of 12 m. Each plot had its own sprinkler lines and was irrigated independently by determining the deficit to field capacity using the Diviner-2000 capacitance probe (Sentek®, Australia) to a depth of 0.6 m. 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 some room was left for rain.

3.2.2 Treatments

Experiments were conducted with three levels of N application rates: 0 (N_0), 30 (N_{30}) and 60 kg N ha^{-1} (N_{60}) in 2007. Four fixed rates of N: 0 (N_0), 20 (N_{20}), 40 (N_{40}) and 60 (N_{60}) kg of N ha^{-1} were applied in 2008. The reason for including four application rates in 2008 was to ensure that the yield plateau was determined because from the 2007 data biophysical optimum yield was between 30 and 60 Kg of N ha^{-1}. For all treatments, N was applied at the beginning of each growth cycle except for the first growth cycle in 2008 when no fertiliser N was applied. In both years, treatments were assigned in a complete randomized block design with three replications.

3.2.3 Plant sampling and quality analysis

The pasture was defoliated at the two to three leaf stages. For yield and quality 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: t ha^{-1}) was determined by oven drying the samples at 70 °C to constant mass. Samples were milled to pass through a 0.1 mm sieve and were kept in air tight 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 (NRC, 2001). True protein (TP) was determined using the trichloroacetic acid (TCA) precipitation method. Non-true protein (NTP, i.e. peptides, free amino acid, nucleic acids, amines, nitrate and ammonia) was calculated by dividing the difference between crude and true protein by 6.25 (NRC, 2001). Neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentrations were determined according to Van Soest *et al.* (1991) method. Metabolisable energy (ME: MJ kg^{-1} DM) content was estimated from CP, NDF and ADF using a relationship developed by Fulkerson *et al.* (1998) using:

$$ME = 16.4 - 0.012\ ADF * NDF + 0.0084\ NDF * CP - 0.315\ CP + 0.01\ (ADF)^2 \qquad (3.1)$$

3.2.4 Soil nitrate sampling and analyses

Wetting front detectors were used to collect soil solution for determining the concentration of nitrate at different depths. They were installed at depths of 0.15, 0.30 and 0.45 m in each plot. Solution sampling from WFDs was conducted a day after an irrigation or a rainfall event. Solutions were kept in a cooler box and nitrate content was estimated using paper colour nitrate test strips (Merck KGaA, Germany). Only nitrate is considered because it is the dominant form of inorganic N (Appendix B1).

3.2.5 Calculations and statistical analysis

Growing degree days (GDD) were calculated by subtracting a base temperature of 4°C from daily average temperature [(maximum + minimum)/2] according to Akmal and Janssens, (2004). Days after emergence, the length of growth cycles in terms of days and GDD are presented in Appendix B2. In pastures, the first week is the most important period in terms of N application (Collins and

Allinson, 2004), and fertiliser is applied at the beginning of each cycle or immediately after each cut. Therefore, measuring soil N during the first week can give a good estimate of N required for the full growth cycle. Mean soil nitrate solution concentrations of all depths from all replications in the first week were used to calculate the critical nitrate levels for various measured and calculated pasture parameters. Biophysical optimum forage yield was expressed relative to the lowest yield that was not statistically significant from the maximum plateau yield for each growth cycle. In case of no plateau, relative yield was calculated using the maximum yield. Therefore, it was easier to compare yields between growth cycles and seasons.

Data were analysed using SAS (SAS, 2002). Forage yield and quality parameters were analysed separately for each growth cycle. Where applicable, significantly different means were separated using Tukey's test at the 95% confidence level. Analyses of variance and regression were performed for yield, N nutrition and crude protein concentration using SAS Proc NLIN (SAS, 2002). Critical levels for biophysical optimum forage yield, optimum (CP_{opt} = 17%) and maximum (CP_{max} = 22%) forage crude protein concentrations (Peyraud and Astigarraga, 1998) were determined using the Cate-Nelson response plateau (CN) model. Error percentages and r^2 were used to show the ability of CN model to express the data (Cate and Nelson, 1971). According to De Jager (1994), for accurate model predictions, error should be less than 20%.

3.3 RESULTS AND DISCUSSION

3.3.1 Forage yield

Forage yield was higher in 2007 than 2008 (Figure 3.2). This was due to early planting and late ending of the 2007 season with longer growing season and greater accumulation of growing degree days (Appendix B1). Forage biomass produced was between 5.9 t ha^{-1} (N_0) and 15.6 t ha^{-1} (N_{60}) (Figure 3.3). 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}.

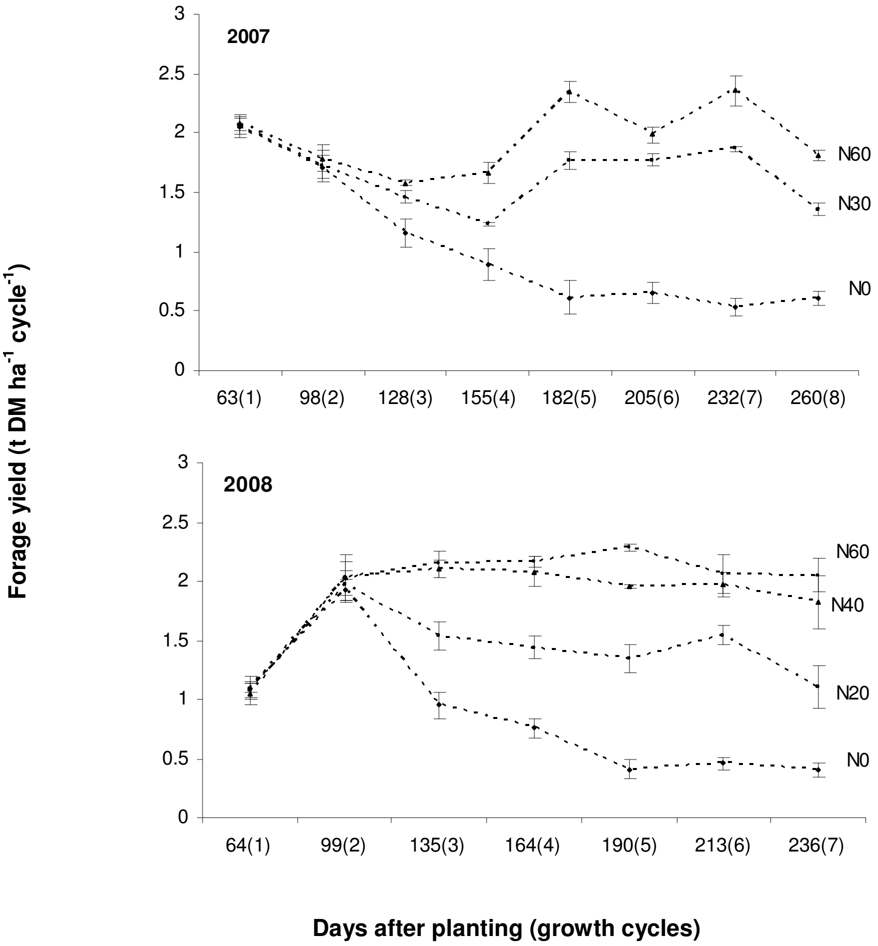

Figure 3.2 Forage yield of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})

Biophysical optimum forage yields (the lowest yield that is not statistically significant from the maximum yield) were observed between N_{30} and N_{60} in 2007 and between N_{40} and N_{60} in 2008 (Figure 3.2 and Figure 3.3). Nitrogen fertiliser application was not effective in the first 2 - 3 growth cycles. This could be due to high initial soil inorganic N and high rates of N mineralisation after tillage in autumn and in spring. This suggests over-fertilisation for the first 2-3 growth cycles, because farmers usually apply equal amount of N (i.e. 50 kg ha^{-1} cyle^{-1}) for all growth cycles.

Reduction of N fertiliser for these growth cycles could help increase profitability and reduce risk of N loss.

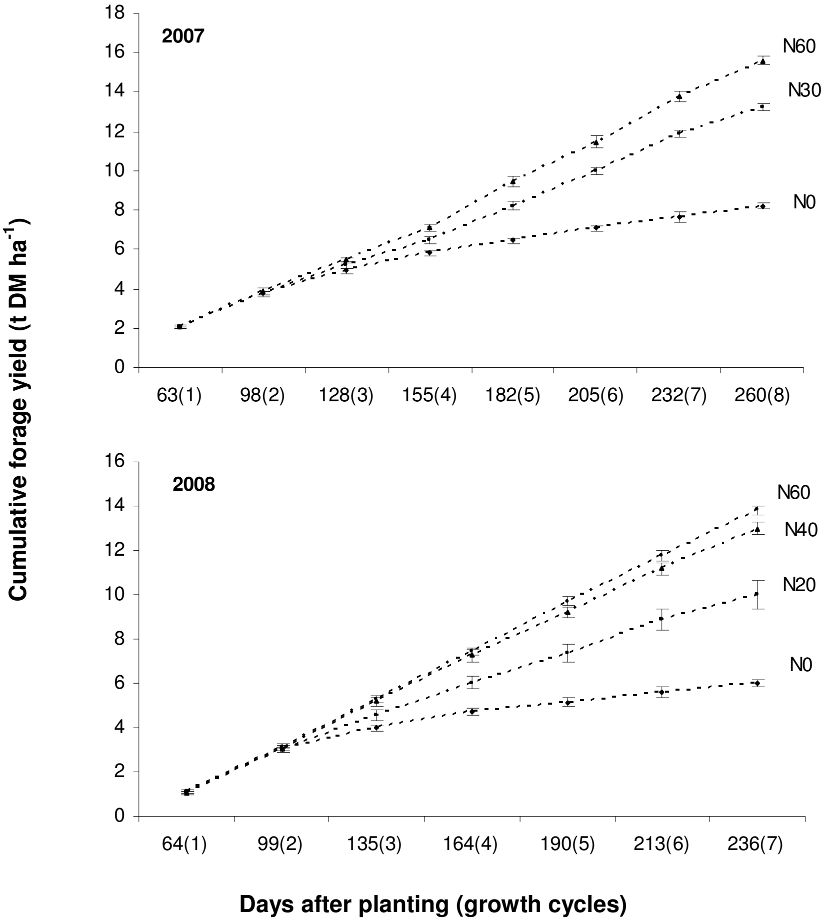

Figure 3.3 Cumulative forage yield of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})

3.3.2 Forage quality

3.3.2.1 Crude protein, true protein and non-true protein

In both years, CP concentrations of N_{60} treatment were above the CP_{max} for all growth cycles (Figure 3.4). CP_{opt} was attained only in few cycles for N_0 and N_{30} in 2007, and in N_0 and N_{20} in 2008. At the biophysical optimum forage growth, CP concentrations exceed the recommended concentrations for reasonable levels of milk production (NRC, 2001). In general, although the CP was dependent on the soil N availability, N applications between 30-40 kg ha^{-1} cycle^{-1} generally produce CP concentrations between CP_{opt} and CP_{max}. However, N applications above 40 kg ha^{-1} cycle^{-1} will most likely produce CP concentrations above the maximum limit of 22%.

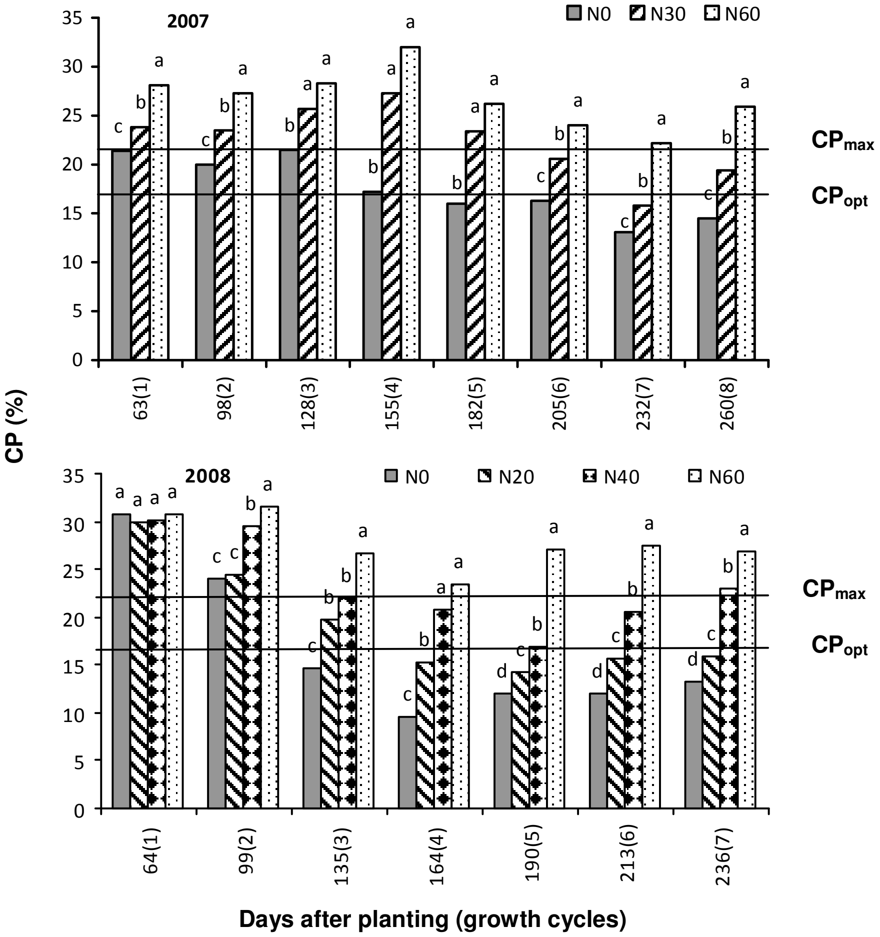

Figure 3.4 Crude protein (CP) concentrations of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})

Nitrogen fertilisation has a direct effect on proportion of protein (true or non-true protein). At high N levels the percentage of TP to CP decreased significantly in most of the growth cycles (Appendix B2), which reduces the proportion of true protein while increasing the non-true protein portion (Figure 3.5).

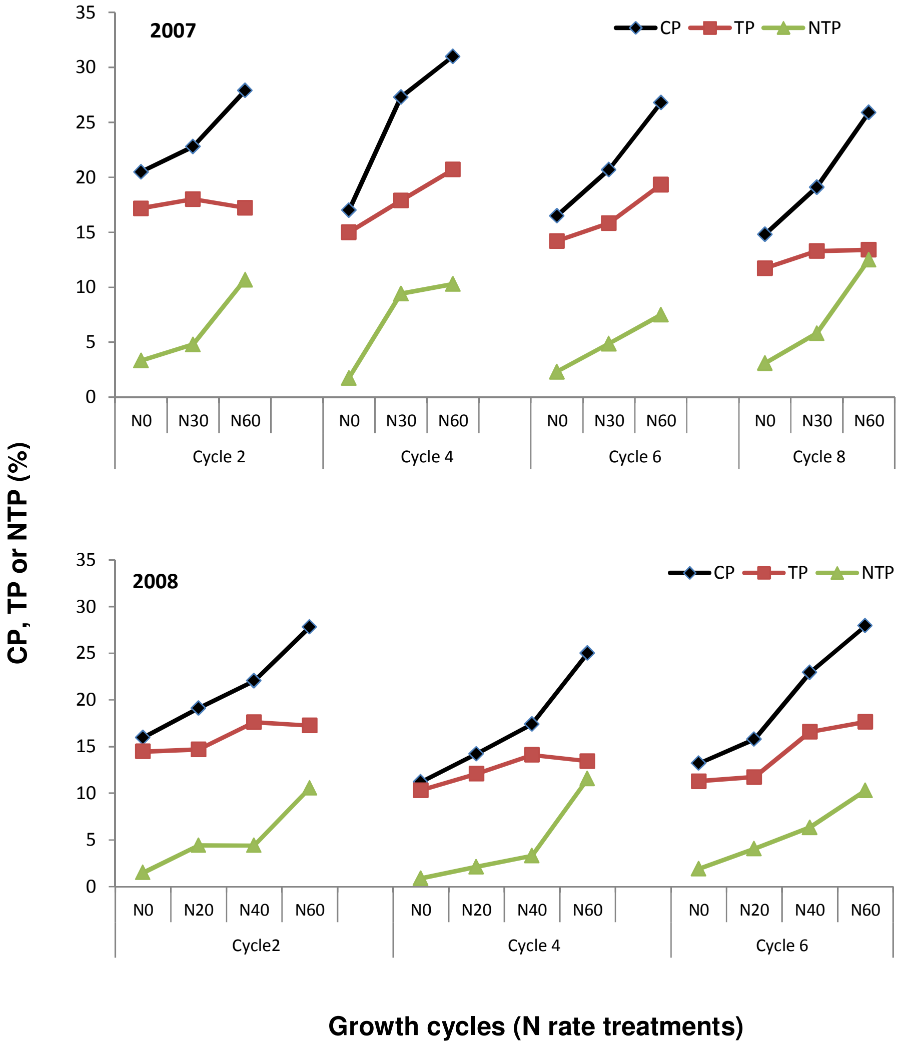

Figure 3.5 Crude protein (CP), true protein (TP) and non-true protein (NTP) concentrations of annual ryegrass under a range of N application rates for four growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and three growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})

The majority of true protein and non-true protein entering the rumen is broken down to ammonia, which bacteria require for synthesising their own body protein. Ammonia, in excess of that used by the micro-organisms, is absorbed through the rumen wall into the blood, carried to the liver and converted to urea, in which the greater part is excreted in the urine (only small portion is lost by belching). An increase in non-true protein usually leads to nitrate accumulation in the plant, where in the rumen the nitrate is converted to nitrite and then to ammonia. Generally, when N application exceeds the pasture requirement (20-22% CP), the increase in CP was mostly in the form of non-true protein, with a negligible increase in true protein. True protein only increases up to certain level (20-22% CP optimum for growth), however, above this CP is stored in non-true protein (largely in the form of peptides, free amino acid and nitrates) form (Van Soest, 1994; Marais *et al.,* 2003). Animal performance and milk production may, however, significantly be affected when the CP concentrations significantly drop below the minimum requirement of 8 -11% (Hoekstra *et al.*, 2007).

3.3.2.2 Fibre

Expressing the fibre requirement as NDF is superior to ADF because it measures most of the structural components of the plant cell (i.e. cellulose, hemicellulose and lignin) while NDF does not include hemicellulose (NRC, 2011). Therefore, in this study only NDF (Figure 3.6) is discussed but ADF values are also presented in Appendix B3. Neutral detergent fibre is closely associated to rumen fill or intake (Allen, 1996). The slow digestion of the NDF in the herbage may have a large influence on passage rate and therefore the NDF fraction is believed to have a direct effect on rumen fill. Increased NDF reduces digestibility and intake by increasing the residence time of the course material in the rumen and therefore, reduce the nutritional status of a high producing dairy cow.

Neutral detergent fibre was the least affected quality parameters (Figure 3.6). It was more affected by the plant growth stage of maturity than by N fertiliser (Peyraud and Astigarraga, 1998). In general, the NDF values were higher than the minimum requirements for dairy cows of 25-28% (NRC, 2001). Lower values of NDF usually correspond to high nutritive value, however, excessively low NDF values than the recommended requirement can cause digestive problems due to fast passage through the rumen (Redfearn *et al.*, 2002). Towards the end of the season, the NDFs were high and may show a reduced intake (Hopkins *et al.,* 2002).

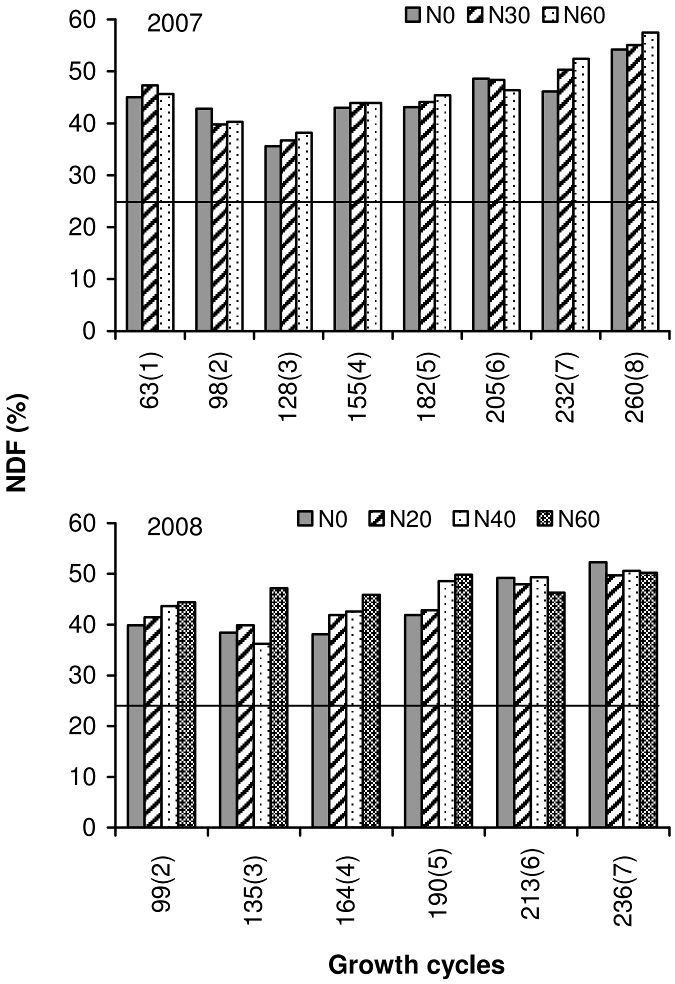

Figure 3.6 Neutral detergent fibre (NDF) of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60}). Horizontal line is minimum NDF requirement for dairy cows

3.3.2.3 Metabolisable energy

Metabolisable energy was calculated from NDF, ADF and CP concentrations using an empirical relationship developed by Fulkerson *et al.* (1998). The calculated ME values are in the range of typical annual ryegrass reported in literature (Fulkerson *et al.,* 1998; Meeske *et al.*, 2006). In most cases (Figure 3.7), ME contents of all N rate treatments were within the acceptable rages of 10 - 12 MJ kg^{-1} DM (Fulkerson *et al.,* 1998), except end of the season when the NDF values were high.

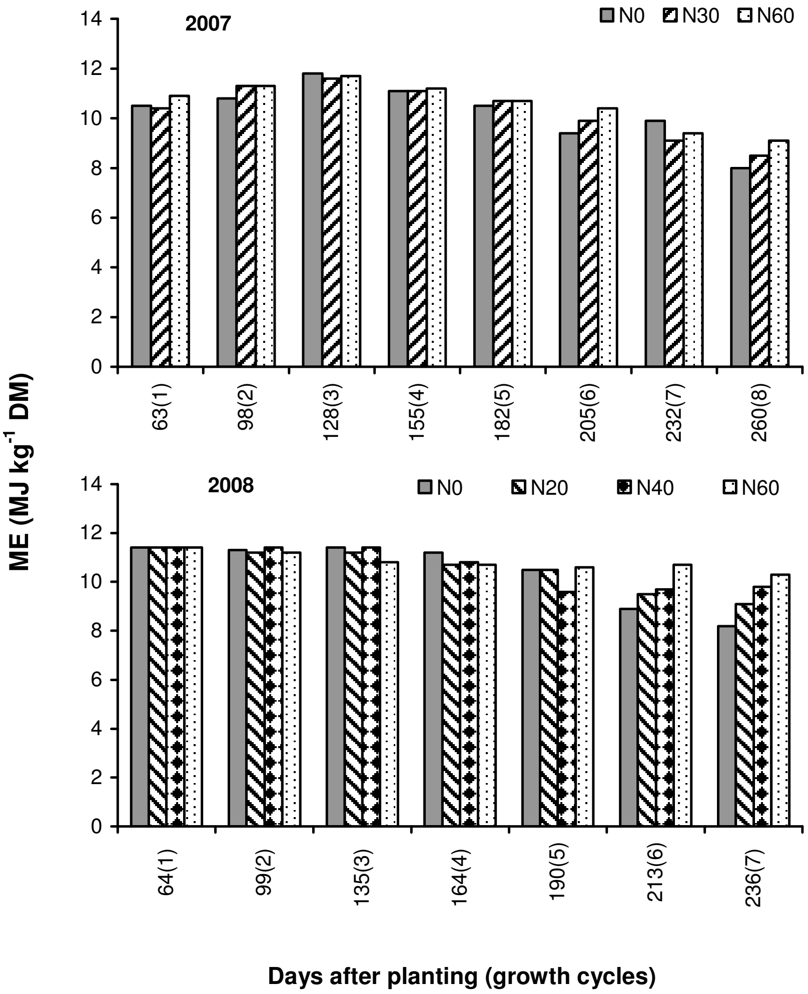

Figure 3.7 Metabolisable energy (ME) content of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})

ME values were similar for the first five growth cycles for different N rate treatments (Figure 3.7). However, high N rate treatment tends to produce higher ME towards end of the season. This could be due to the depletion of N in the low rate fertiliser treatments which leads to low CP than the N required for pasture growth. Generally, N application rate has no effect on ME content (Figure 3.7). This implies that at the high N rate treatment milk production is likely to be reduced due consumption of high CP. The decrease in milk production would be due to a higher energy required for metabolising the excess CP.

3.3.3 Critical soil nitrate concentrations for yield and quality

The critical soil solution concentration is a concept widely accepted for interpreting soil nitrate for optimum growth/yield/quality (Cate and Nelson, 1971). Values lower than the critical concentrations indicate a high potential response in growth to N application. Above the critical value, the biomass response to an increase in the availability of N is negligible and the forage quality may be reduced. In all Cate-Nelson (CN) figures, the vertical line which intersects the x axis indicates the critical soil solution nitrate concentration for yield or quality parameters (Van Biljon *et al.,* 2008). The CN partitions the data into four groups. Horizontal and vertical lines are plotted to maximise points in the upper right (non-responsive) and lower left (responsive) and minimise points at the upper left (over-prediction) and lower right (under-prediction) quadrants (Cate and Nelson, 1971).

In Chapter 2, the thresholds for the adaptive management treatments were somewhat arbitrarily selected in the knowledge that they would be improved with experience. In this study, optimum soil solution nitrate concentration ranges for yield and quality were developed using statistical models. Critical mean nitrate concentration was 28 mg L^{-1} for biophysical optimum forage yield, 20 mg L^{-1} for CP_{opt} and 41 mg L^{-1} for CP_{max} (Figure 3.8). These ranges can be used by trading of forage yield with a good forage quality, whilst also minimising N leaching. All the relationships between soil nitrate solution measured at the first week and crop parameters were significant at 99% level of confidence and the total error was within an acceptable range (De Jager, 1994). In the Cate-Nelson model, error I showed that the parameters reached optimum while the soil solution nitrates were below optimum value which may result in yield/quality reduction because no N fertiliser application is required. On the other hand, error II showed that the critical nitrate level reached optimum but the crop N was in deficit, in which case N would have been applied and would lead to leaching.

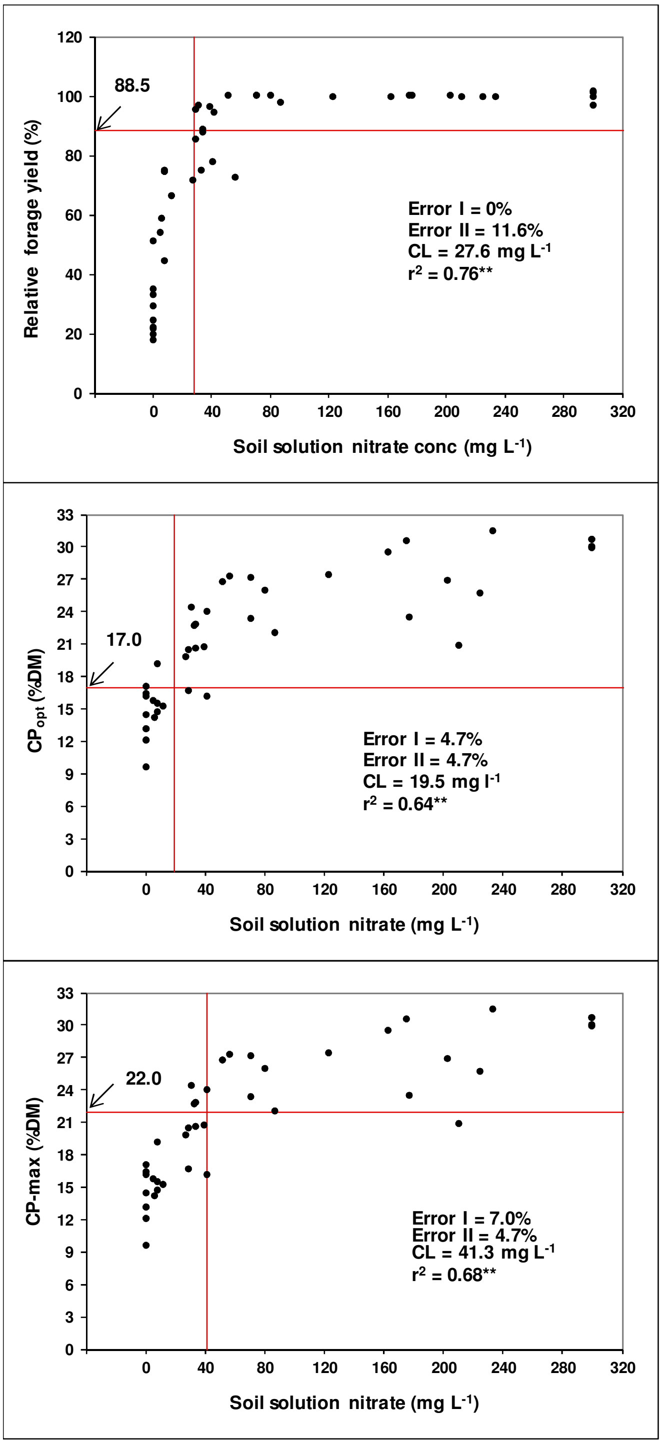

Figure 3.8 Critical soil solution nitrate concentration for biophysical optimum forage yield, optimum (CP_{opt}) and maximum (CP_{max}) crude protein concentrations using Cate-Nelson model. Critical soil solution nitrate concentration (CL), coefficient of determination (r^2), number of observations (n = 43), error I upper left side of the quadrant (I) and error II lower right side of the quadrant (II)

In Chapter 2 (Fessehazion *et al.,* 2011), 50 mg L^{-1} (mean of all WFD that responded) was used. In this study, the values are slightly lower than the 50 mg L^{-1} (when critical levels were determined statistically). However, considering the variability of the pooled data, growth cycles and averages of nitrate from the WFDs, a range of critical mean nitrate concentration between 20 and 41 mg L^{-1} could be used as better estimates of the critical nitrate soil solution concentration. However, since the nitrate test strips used in the experiment were in a range of 0, 10, 25, 50, 100, 250 and 500 mg L^{-1}, a range of soil nitrates between 25 to 50 ppm would be an appropriate value for yield and quality whilst also minimising N leaching.

Critical soil nitrate levels developed in this study can be used in the following strategies. First, to apply part of the recommended N at the beginning of the growth cycle and supplement the rest as necessary based on the WFD nitrate concentration. This can be more practical in winter when intervals of the growth cycles are 35 to 60 days and there is enough time to apply N fertiliser once or twice especially for farmers who fertigate their pasture where a small amount of N can be applied. Secondly, critical soil nitrate is a guide for how much N to apply for the next growth cycle based on nitrate soil solution from the last irrigation of the previous growth cycle. This would be more suitable during the short growth cycle intervals and/or when tractors are used for fertiliser application. In autumn, spring and early summer when the growth cycles are between 21 and 28 days, there may not be enough time to apply N based on the nitrate levels from the same growth cycle. Therefore, soil solution nitrate concentrations from the last irrigation of the previous growth cycle can be used as a guide for the next growth cycle (as reported in Chapter 2). Finally, critical soil nitrate values can be used for integrated adaptive N and irrigation management because the WFD shows the depth the wetting front has passed and the concentration of nutrients at that particular soil depth.

There was a significant exponential relationship between N application rate and soil solution nitrate concentrations collected from the WFDs (Figure 3.9). The reciprocal of the graph would give some indication on the amount of N required to reach a target soil solution nitrate concentration for yield or quality. For example, N application of 35 - 48 kg ha^{-1} cycle^{-1} is required to reach mean nitrate concentrations of 25 to 50 mg L^{-1}. To attain critical mean nitrate concentration of 28 mg L^{-1} (biophysical optimum forage yield), 20 mg L^{-1} (CP$_{opt}$) and 41 mg L^{-1} (CP$_{max}$), N application rates of 31, 37 and 43 kg ha^{-1} cycle are required, respectively. Because the data are averaged across sampling dates over two years and the solutions are affected by plant uptake, rate of mineralisation and initial soil inorganic concentrations, the relationship (in Figure 3.9) may not hold for all growth cycles and years.

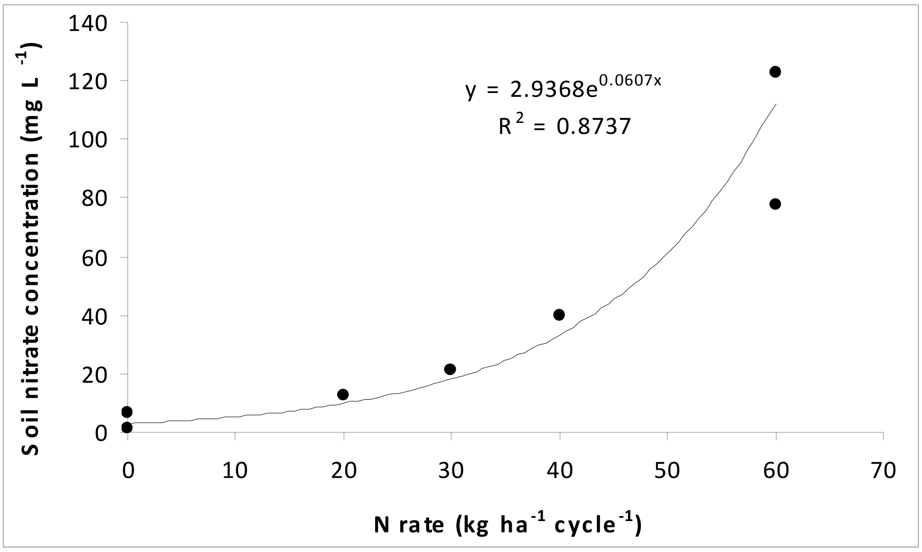

Figure 3.9 Exponential equation used to show the relationship between N application rates and mean soil solution nitrate concentrations. Data pooled from range of N application rates in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N$_0$, N$_{30}$, N$_{60}$) and in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N$_0$, N$_{20}$, N$_{40}$, N$_{60}$)

3.3.4 Nature of the trade-off between yield and quality parameters

Neutral detergent fibre and ME were the least affected quality parameters by N application rate treatments. As a result, CP was used for balancing forage biomass yield and to determine the nature of trade-off between yield and quality. This was because CP represents the overall forage quality and is also the most affected quality parameter. Forage CP (or N) is the most important forage quality parameter that can be easily analysed. It can also be used as a good indicator for other quality parameters which can be affected directly or indirectly by N application.

Both metabolisable energy yield (MJ ha^{-1}) for individual growth cycles (Appendix B4) and seasonal cumulative (Figure 3.10) showed similar trends to forage yield. Similar to forage yield, though not always significant, the highest ME yields were observed from the highest N rate treatment. As a result optimum ME yield was obtained at N rate between N_{30} to N_{60} in 2007 and at N_{40} in 2008 (Figure 3.10).

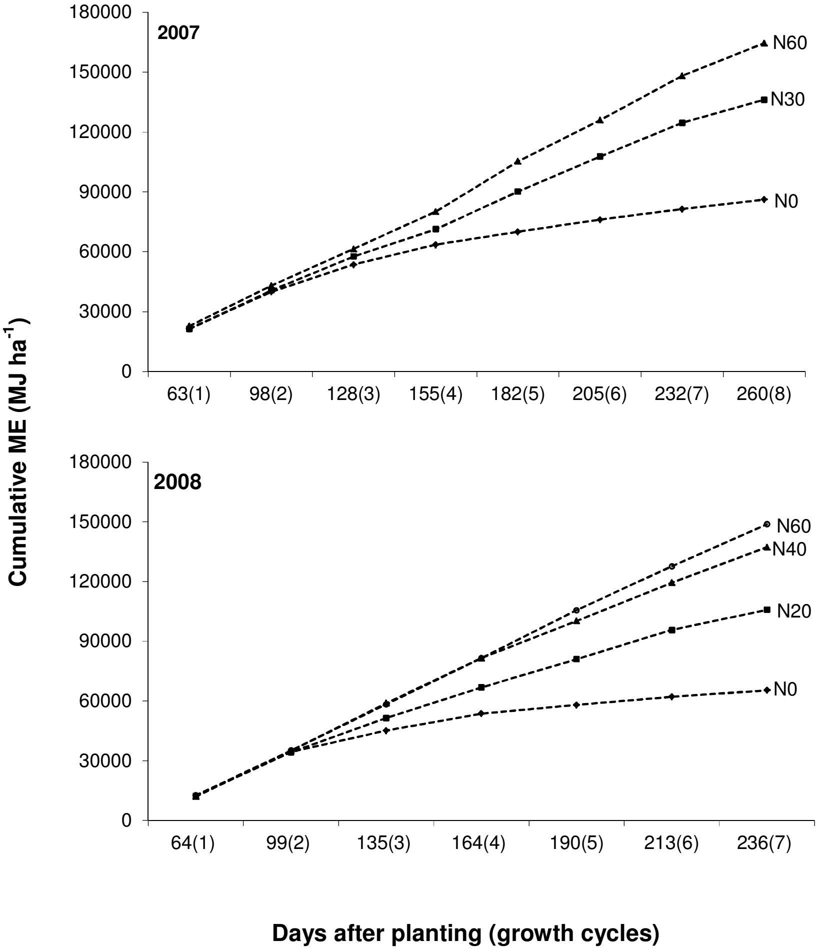

Figure 3.10 Cumulative metabolisable energy (ME) of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} $cycle^{-1}$ for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} $cycle^{-1}$ for N_0, N_{20}, N_{40}, N_{60})

Critical CP concentrations required for biophysical optimum relative yields (which are also similar for ME yield) developed using the Cate-Nelson model was 18.1% (Figure 3.11). This value is slightly higher than the optimum CP (CP_{opt}) concentration of 17% but lower than the maximum CP (CP_{max}) of 22%. Nitrogen fertiliser required for achieving a maximum forage yield/ME yield and CP varies amongst growth cycles (Appendix B5) depending on soil N availability. As a result, N fertiliser application for the first two to three cycles not only reduced forage quality (high CP) but also did not improve forage and ME yields.

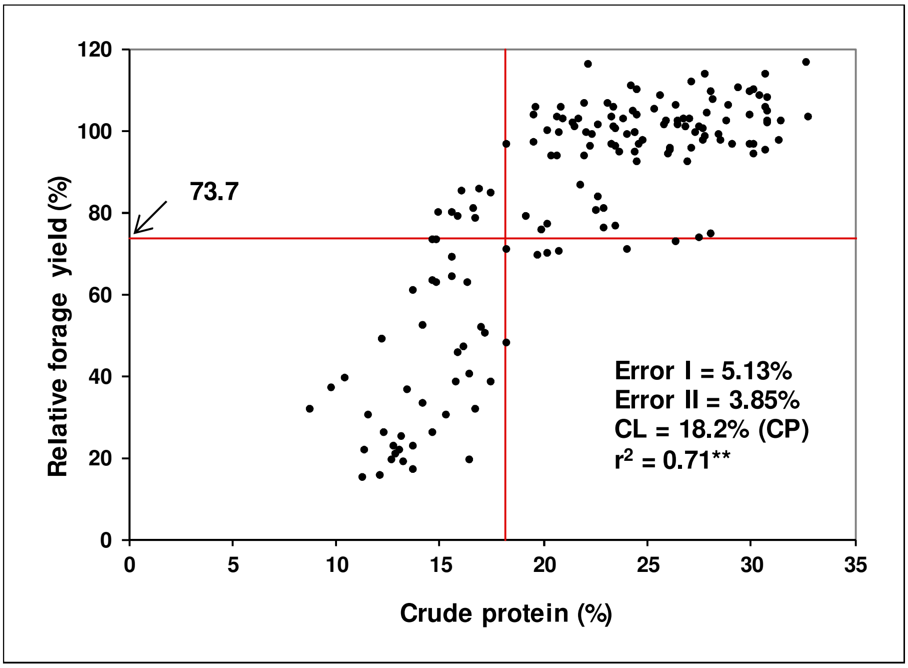

Figure 3.11 Critical crude protein concentration (%) for biophysical optimum relative forage yield (%) using Cate-Nelson model. Critical crude protein concentration (CL), coefficient of determination (r^2), number of observations, error I upper left side of the quadrant (I) and error II lower right side of the quadrant (II)

Generally, the current study showed that the biophysical optimum N application per cycle (the highest non- significant forage and ME yields) was between 30-60 kg N ha^{-1} in 2007 and 40 kg N ha^{-1} in 2008. Hence, N application rate of around 30-40 kg N ha^{-1} per growth cycle could be biophysical optimum yield to slightly lower forage and ME yield, but with CP concentrations ranging between CP_{opt} and CP_{max}. This may not be applicable for the first 2-3 growth cycles, where there is excessive CP concentrations, however, this can be managed by considering soil N (as presented in Chapter 2).

3.4 CONCLUSIONS

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. The amount of N fertiliser required for achieving a maximum forage yield and optimum quality varies widely among growth cycles depending on soil N availability. As a result, N fertiliser application for the first two to three cycles did not improve forage yield (and the N nutrition) but reduced quality (high CP). Consequently, the current farmers' recommendation (fixed N application rate of 50 kg ha^{-1} per growth cycle) based on target yield may give the highest biomass but not optimal quality and hence may not improve animal performance (for all growth cycles). It could also increase N leaching as a result of high CP which most likely will result in high urinary excretion. Therefore, 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. However, farmers who use a pasture based system have only limited options for managing N by integrating both yield and quality whilst minimising leaching, because balancing rations for pasture based dairy production is difficult.

Generally, the current study showed that the optimum N application per cycle (the highest non-significant forage and ME yields) was between 30-60 kg N ha^{-1} in 2007 and 40 kg N ha^{-1} in 2008. Hence, N application rate of around 30-40 kg N ha^{-1} per growth cycle could give biophysical optimum forage yield (or slightly lower) and ME yield and but with CP concentrations with the boundaries of CP_{opt} and CP_{max}. This may not be applicable for the first 2-3 growth cycles, where there is excessive CP concentrations, however, this can be managed by considering soil N (as presented in Chapter 2).

The trade-off between yield and quality will depend on the management of pasture, whether for pasture based systems or indoor ration based dairy production (feed composition can be balanced by mixing diets of herbage with supplements). For pasture based systems due to difficulty in manipulation of all parameters of pasture quality, trading-off forage yield for better forage quality may be required. However, for indoor ration based dairy production, targeting maximum biomass yield would be better because the feed can be supplemented with low-cost roughages.

CHAPTER 4

IMPROVING WATER MANAGEMENT OF IRRIGATED ANNUAL RYEGRASS USING THE SWB-PRO MODEL

4.1 INTRODUCTION

Water availability is considered to be the main factor limiting pasture production in South Africa (Aucamp, 2000). About 62% of South Africa's surface and ground water resources (at 98% assurances) are used for irrigation (DWAF, 2004). This substantial amount of water assigned to irrigated agriculture is facing fierce competition as the water demand of industrial, domestic and other activities increase. Thus, farmers are facing pressures to decrease their share of water usage, while at the same time producing sufficient pasture to supply the milk demand of the growing population. Clearly, therefore, innovations are needed to increase the efficiency of irrigation and water use.

Unfortunately, knowing how much water to apply through irrigation and how often is no trivial matter. In addition, nutrient management, especially N, is inextricably linked to water management, as over-irrigation leaches valuable nitrates from the profile out of reach of the growing pasture. As energy, fertiliser and water costs increase and profit margins narrow, farmers are realising the necessity of improved irrigation scheduling to obtain maximum yields for the lowest financial investment. Ideal pasture management is the production of economically optimum forage yield and quality without compromising the environment. Accurate irrigation scheduling plays an important role in deciding the income of a dairy enterprise by affecting yield and quality; irrigation input and energy usage; and environmental pollution. Improved knowledge of irrigation timing and amount can also be of great value in scheduling other cultural operations.

Annual ryegrass is one of the most widely grown irrigated winter pastures in South Africa. It has high nutritional quality, is very palatable, and is high in digestible energy, protein and minerals

(Dickinson *et al.,* 2004; Theron and Snyman, 2004). Annual ryegrass plays an essential role in supplying good quality grazing between the winter and summer seasons, thereby dramatically improving fodder flow options (Eckard *et al*., 1995). However, it is a high user of water and its performance is less than optimum under drought or adverse environmental and/or management conditions (Theron and Snyman, 2004).

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. 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, 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 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; Beletse *et al.,* 2008; Singels *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 current irrigation guidelines 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. Once satisfied with the model's water requirement prediction capability, the model can be used to develop site specific irrigation calendars for major ryegrass growing regions of South Africa.

4.2 MODEL DESCRIPTION

SWB model 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 (Oliver 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; Beletse *et al.,* 2008; Geremew *et al.,* 2008; Jovanovic *et al*., 1999; Singels *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.

4.3 MATERIALS AND METHODS

4.3.1 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 Experimental Farm of the Department of Agriculture Research Station (altitude 1076 m, 29°32’S; 30°17’E) in the Midlands of KwaZulu-Natal. The rainout shelter experiment was conducted at the Hatfield Experimental Farm (altitude 1327 m, 25°45’S; 28°16’E) 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. At planting 20 kg P ha^{-1} was applied 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.

4.3.2 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 conditions. The data were used for model calibration and validation.

4.3.2.1 Irrigation strategies

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 4.1). For the first three growth cycles, plots were irrigated 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**).

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 4.1). In both sites and years, treatments were replicated three times and were assigned in a randomised complete block design.

Table 4.1 Treatments used for calibration and validation of the SWB model

Site	Year	Planting date	Treatments	Defoliation	Growth cycles	Modelling objective
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
Hatfield	2007	05/06/2007	W1 W2 W3	28 days	4	Validation
	2008	23/04/2008	W1 W2 W3	28 days	4	Validation

4.3.2.2 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 *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 $\varepsilon = \arctan v/u$ 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 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 (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.

4.3.3 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℃ to constant mass.

4.3.4 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).

4.3.5 Model application

Four major milk producing areas of South Africa including the KwaZulu-Natal Midlands (Cedara), Eastern Highveld (Ermelo), Eastern Cape (Queenstown) and Southern Cape (George) were selected. Long-term (50 years: 1950 to 2000) rainfall and reference evapotranspiration (ETo) of the selected sites are presented in Figure 4.1. The sites showed seasonal variations in rainfall and ETo which clearly motivate the need to develop site specific irrigation calendars.

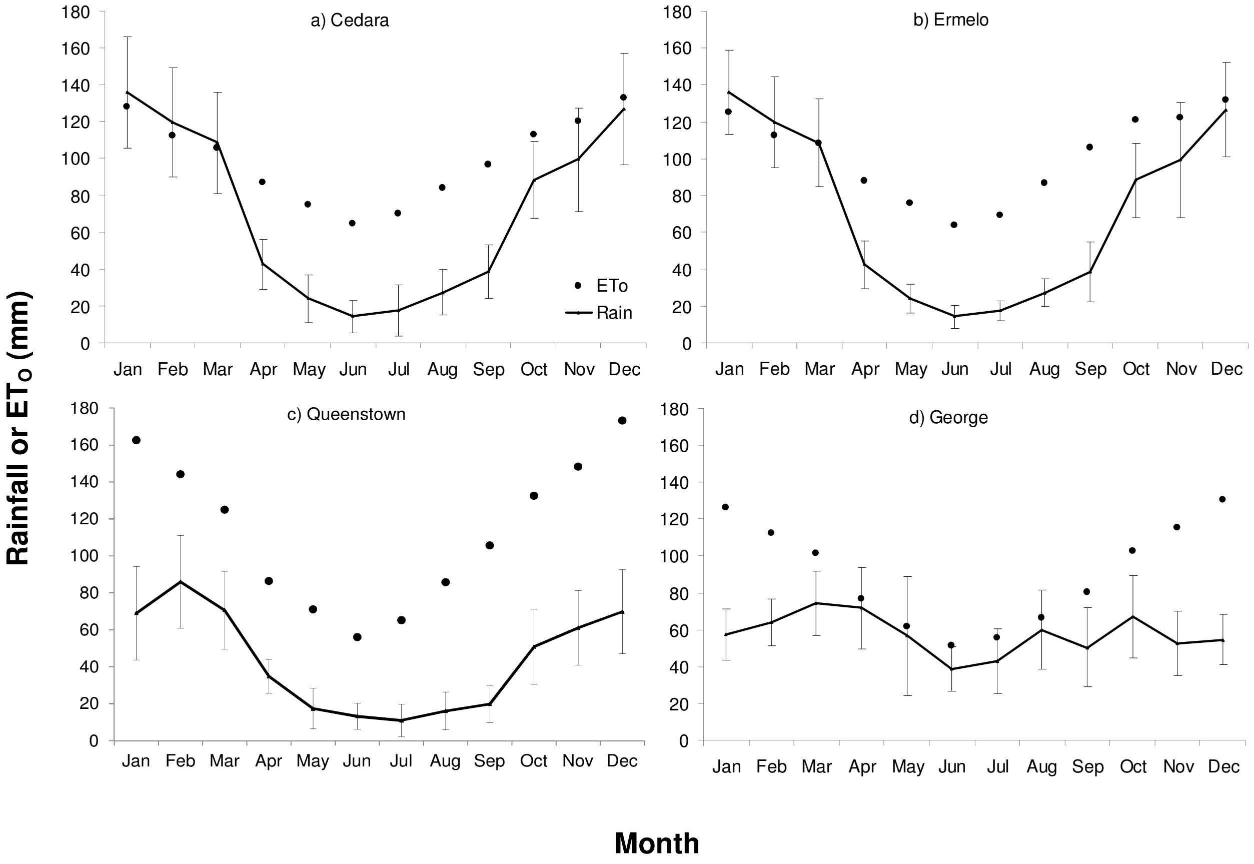

Figure 4.1 Monthly long-term means (1950-2000) of reference evapotranspiration (ETo) and precipitation in four ryegrass growing areas (vertical bars are standard deviation)

Long-term historical weather data (1950 to 2000) including minimum and maximum temperatures of representative sites were used for estimating water requirements and irrigation calendars of annual ryegrass. Water requirements were estimated for 50 years while calendars were developed using the daily mean of the long-term weather data. 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 4.1).

Irrigation calendars are simple guidelines or charts that indicate when and how much to irrigate. Site specific and monthly irrigation calendars were developed by excluding rain as examples, to illustrate how farmers can develop their own crop and site specific calendars. Site specific irrigation calendars were developed for four major milk producing areas of South Africa for a sandy (low water holding capacity), sandy loam (medium water holding capacity) and clay (high water holding capacity) soil textural classes. The pasture was irrigated when 50% of the plant available water was depleted which was equivalent to 16 mm for sandy, 21 mm for sandy loam and 28 mm for clay loam. Monthly general irrigation calendars were also developed for a deep, well drained and fertilised, medium textured soil using a common “recipe” of 25 mm per irrigation event, but scheduling the timing according to long-term water requirement.

4.4 RESULTS AND DISCUSSION

4.4.1 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 4.2) 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 4.2 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	℃	Akmal and Janssens (2004)
Temperature for optimum light limited growth	15	℃	Annandale *et al.* (1999)
Cut off temperature	25	℃	Annandale *et al.* (1999)
Emergence day degrees	50	d ℃	Measured
Day degrees at the end of vegetative growth	3000	d ℃	Adjusted with calibration
Day degrees for maturity	3500	d ℃	Adjusted with calibration
Transition period day degrees	300	d ℃	Annandale *et al.* (1999)
Day degrees for leaf senescence	600	d ℃	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 4.2 to 4.7, 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 4.2). 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 4.3).

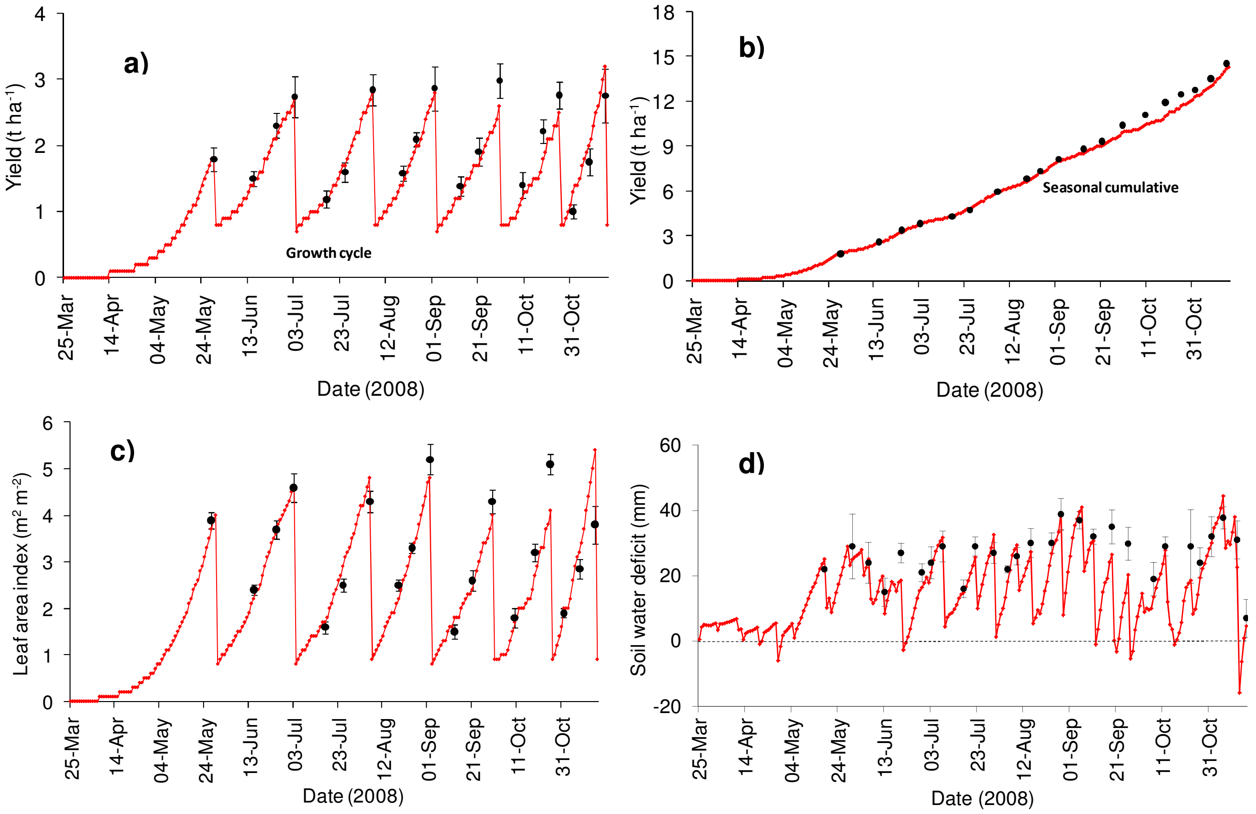

Figure 4.2 Simulated (lines) and measured data (symbols) of above ground dry matter for a) growth cycles and b) from whole season, c) leaf area index and d) soil water deficit to field capacity for model calibration of ryegrass at Cedara during the 2008 growing season (Vertical bars are the standard 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 4.2). 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 4.3). 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 4.3).

Table 4.3 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	8.99
Forage yield (cumulative)	21	0.99	0.99	3.80
Leaf area index	21	0.81	0.95	10.89
Soil water deficit	33	0.79	0.96	16.25

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

4.4.2 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 4.4.

Table 4.4 Statistical evaluation between observed and predicted values of forage yield and leaf area index during model validation in 2007 and 2008 seasons

Parameter	N 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

4.4.2.1 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 4.3 for individual growth cycles and in Figure 4.4 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 4.3).

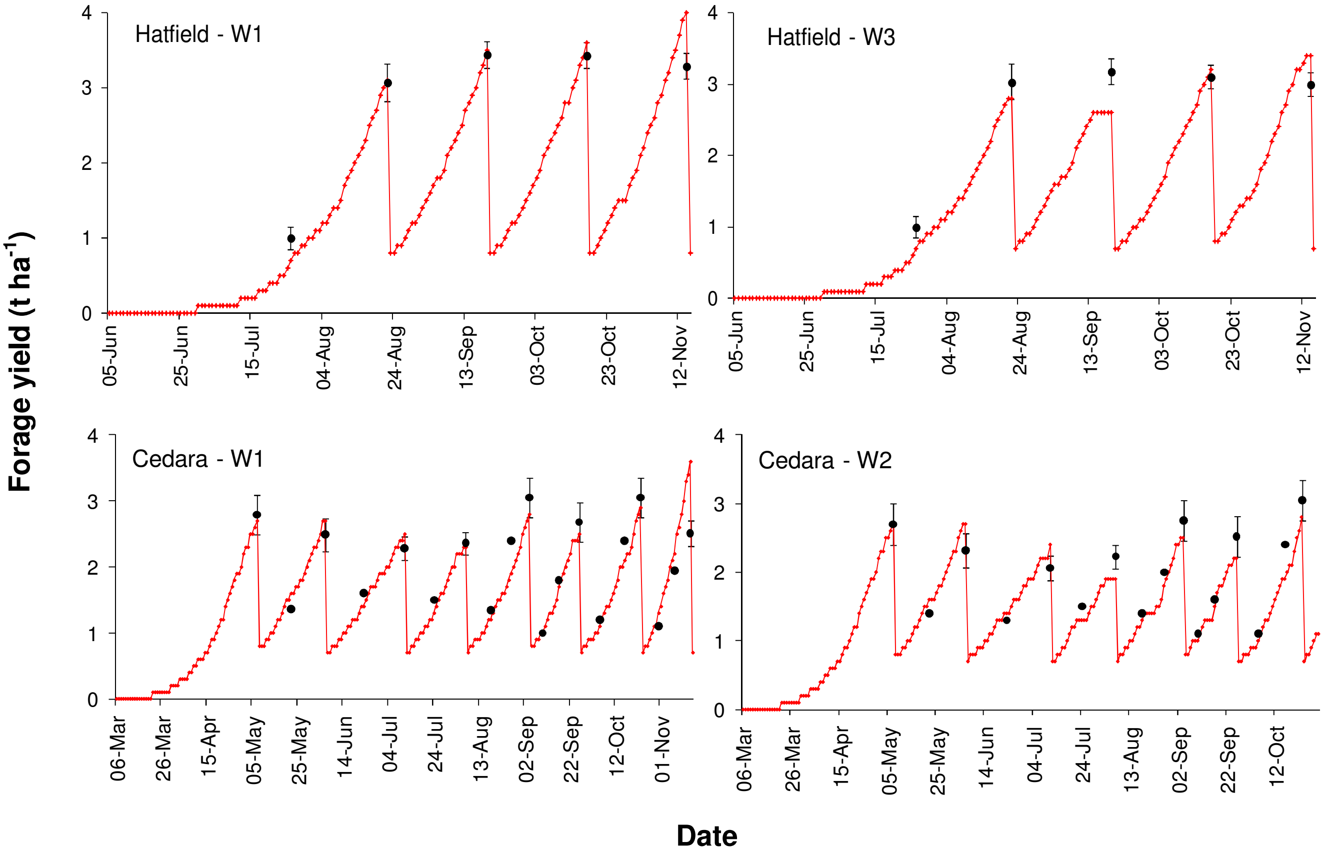

Figure 4.3 Simulated (solid lines) and measured (symbols) forage yield for individual growth cycles for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 growing season

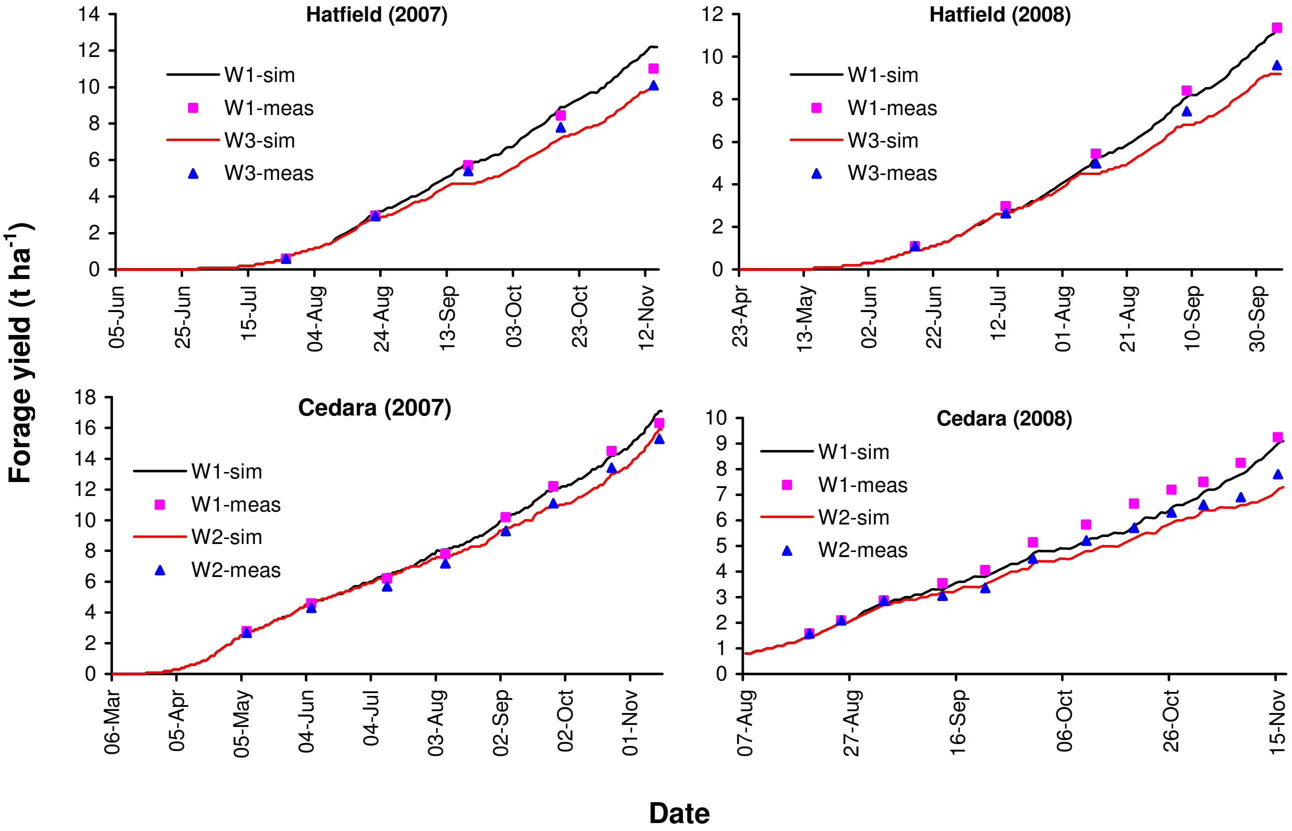

Figure 4.4 Simulated (solid lines) and measured (symbols) seasonal cumulative forage yield for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 and 2008 growing seasons

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 4.4), 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 4.5).

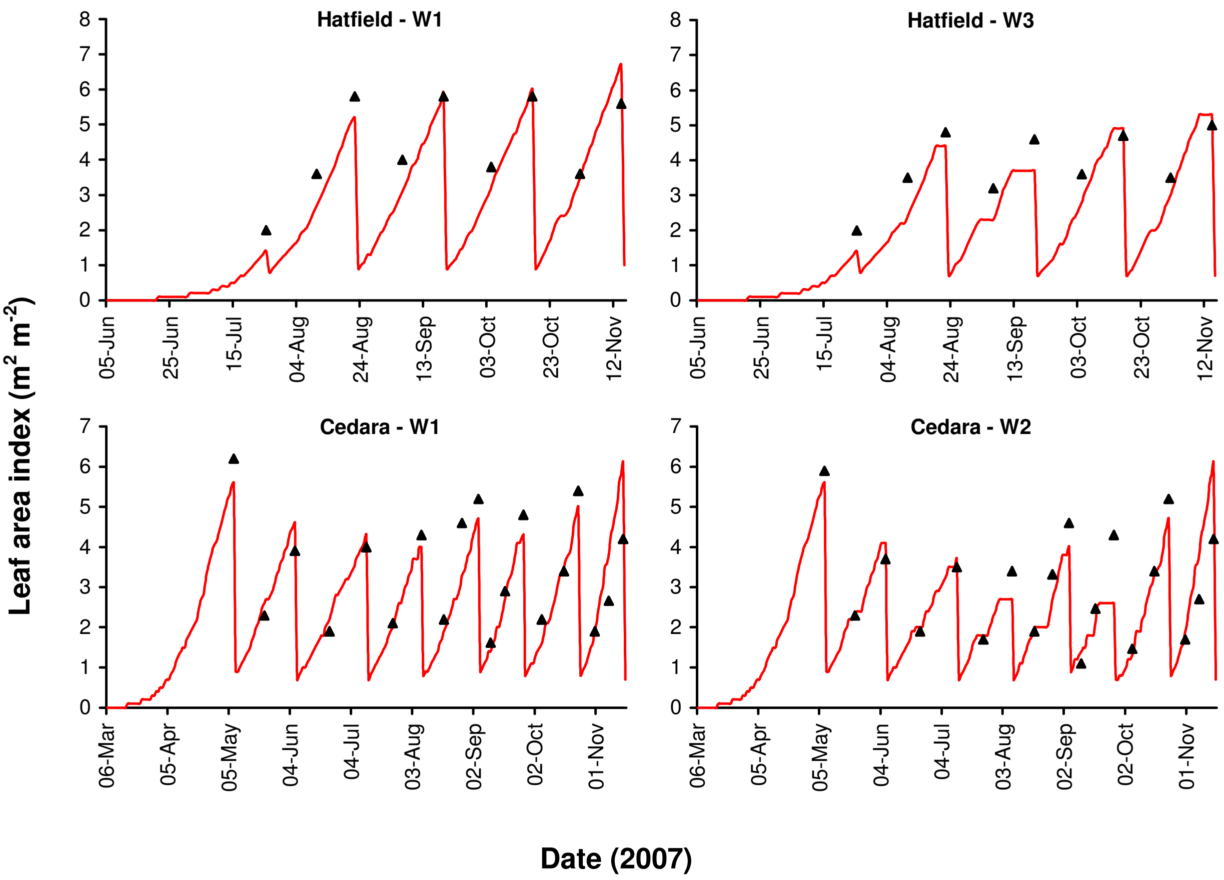

Figure 4.5 Simulated (solid lines) and measured (Symbols) leaf area index for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 growing season

4.4.2.2 Soil water deficit

Soil water deficit to field capacity (FC) predictions were less accurate (r^2: 0.30 - 0.75; D: 0.73 - 0.89; MAE: 14.19-22.64%) compared to other simulated parameters (Table 4.5), but still with reasonable agreement between measured and simulated values, especially for well-watered treatment (Figure 4.6). 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.

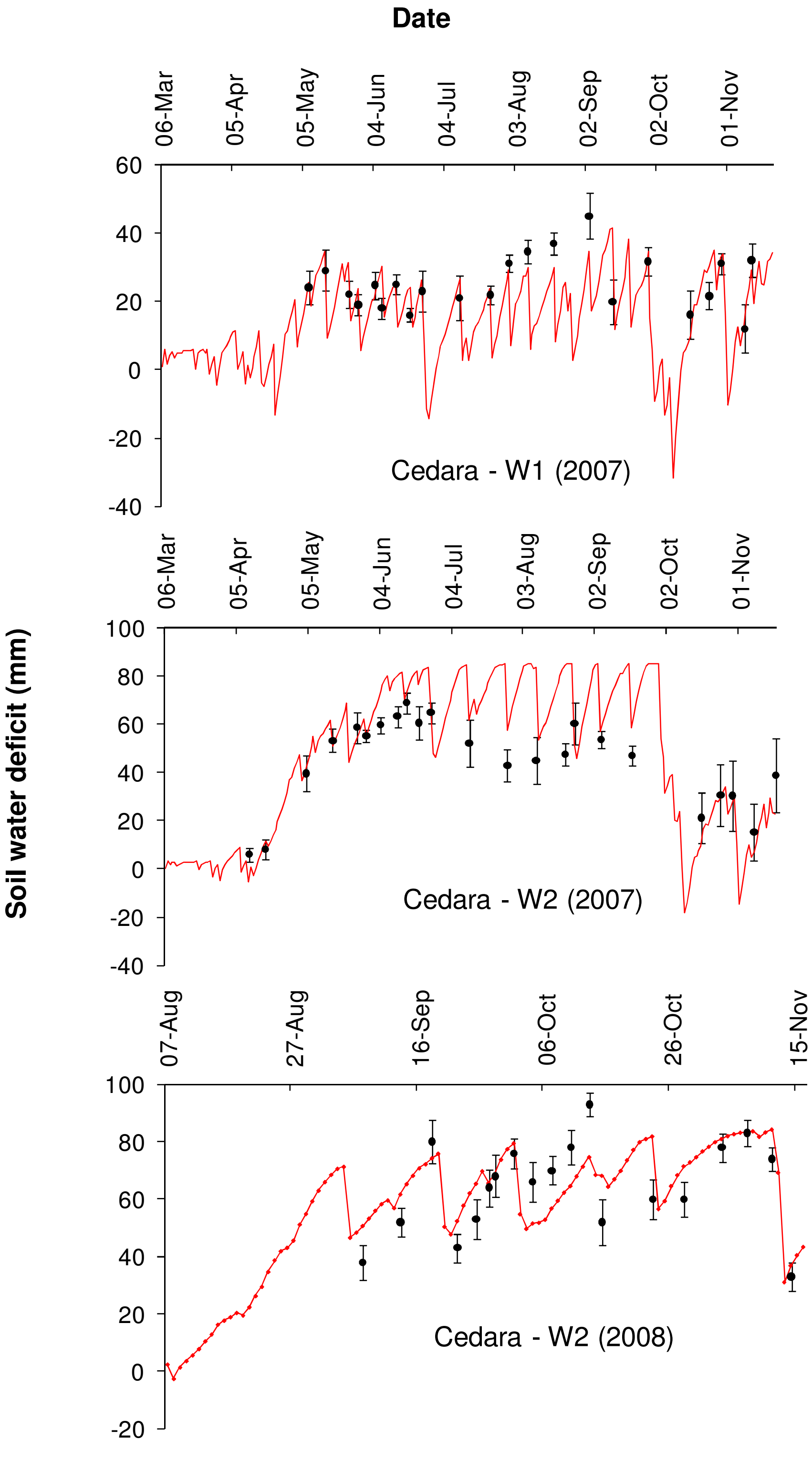

Figure 4.6 Simulated (solid lines) and measured (symbols) of the soil water deficit for the well watered (W1) and water stressed (W2) treatments for Cedara during the 2007 and 2008 growing seasons

Table 4.5 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	22.64
		W2-2007	0.75	0.89	21.55
		W2-2008	0.52	0.83	14.19
Evapotranspiration	Cedara 2008	Well-watered	0.69	0.98	25.83

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

4.4.2.3 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 4.7). 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 4.5).

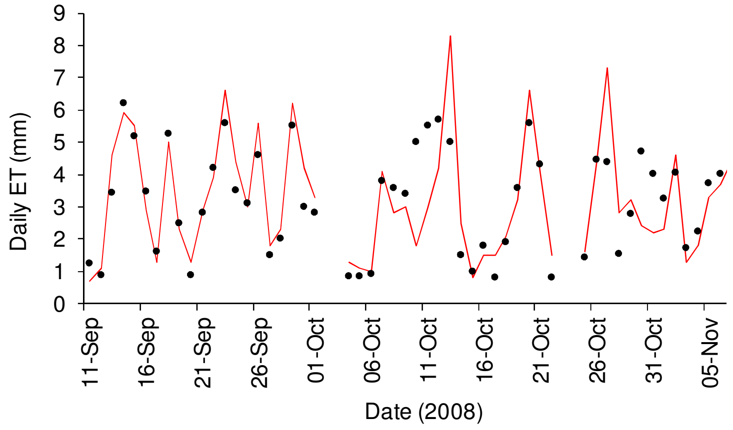

Figure 4.7 Simulated (lines) and measured (symbols) evapotranspiration of ryegrass for the Cedara site during the 2008 growing season for well watered conditions

4.4.3 Model application

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 with different irrigation scheduling strategies.

4.4.3.1 Water requirement

Model simulations showed variation in water use of ryegrass between years (Figure 4.8). 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.

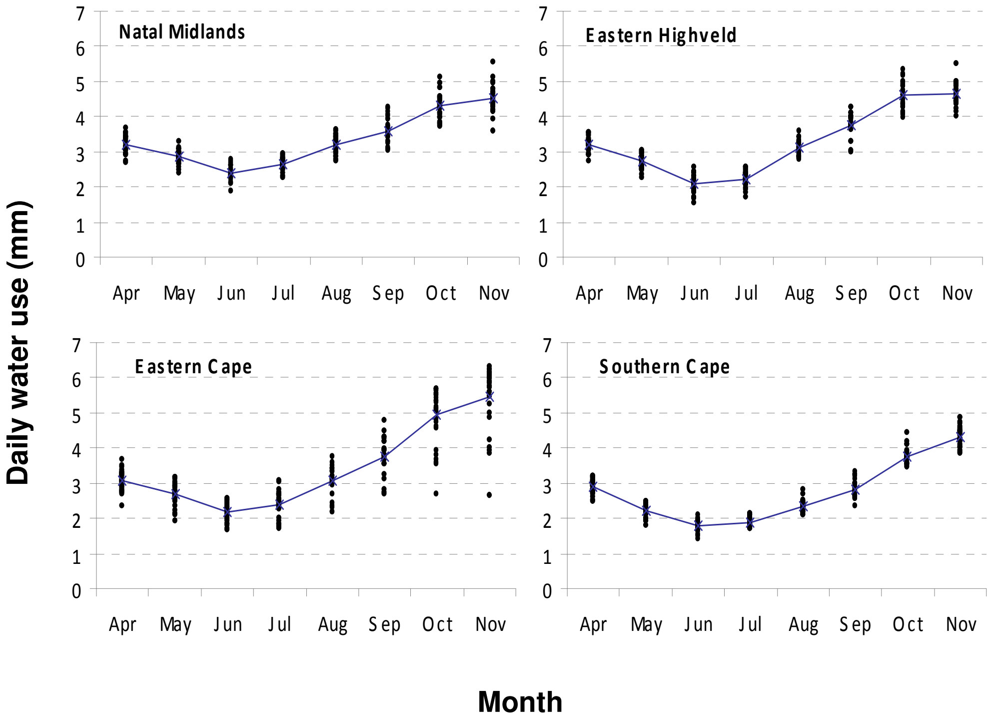

Figure 4.8 Simulated mean long-term daily water use of ryegrass for major milk producing areas of South Africa (points show individual season simulated water use)

There were variations in forage yields, irrigation requirements and irrigation use efficiency of ryegrass simulated using the SWB growth model (Table 4.6). In spite of the lowest irrigation applications (581 mm), simulated forage yields were highest in the Southern Cape, which lead to the highest irrigation use efficiency (Table 4.6). 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 4.6 Seasonal forage yield, irrigation application and irrigation use efficiency (IUE) for the long-term simulation for four major milk producing areas of South Africa

	Yield	**Irrigation (mm)**		**IUE (kg ha^{-1} mm^{-1})**	
	(t ha^{-1})	**FC**	**Farmer**	**FC**	**Farmer**
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 4.6). 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 (Figure 4.9).

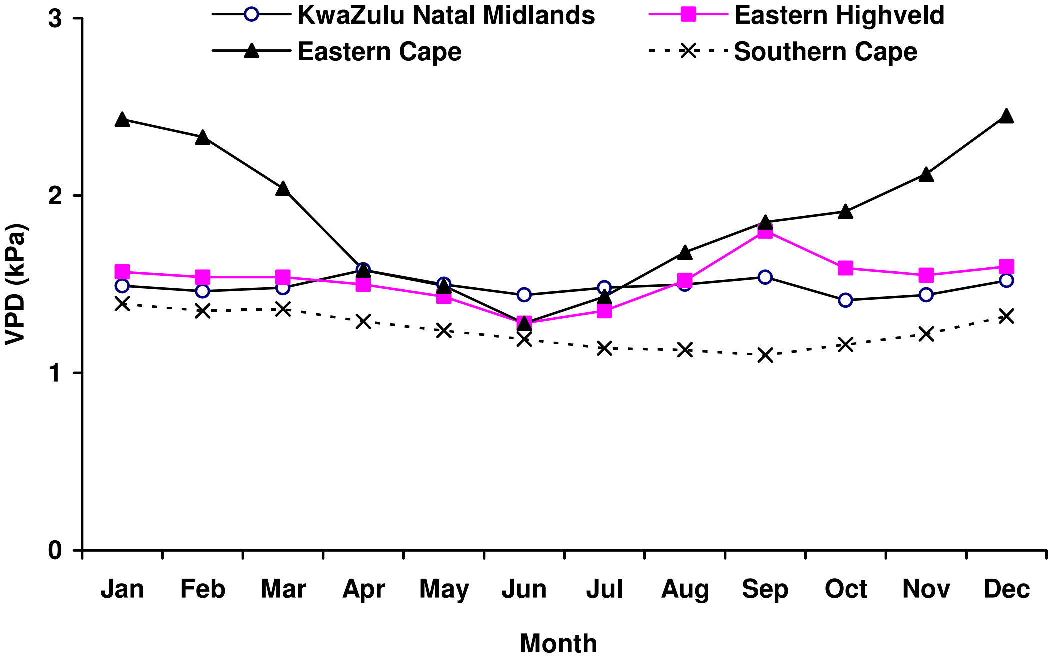

Figure 4.9 Mean monthly vapour pressure deficit (VPD) for long-term (1950-2000) for major milk producing areas of South Africa

4.4.3.2 Irrigation calendars

Site specific irrigation calendars developed for four major milk producing areas of South Africa including the KwaZulu-Natal Midlands, Eastern Highveld, Eastern Cape and Southern Cape using three soil textural classes are presented in Tables 4.7 to 4.9. These calendars were developed as examples by excluding rainfall. For more specific cases, irrigators can develop their own site and crop specific calendars using the user friendly SWB model.

Table 4.7 Simulated site specific irrigation calendars for a sandy soil for four major ryegrass growing areas of South Africa

Events	**KwaZulu Natal Midlands**		**Eastern Highveld**		**Eastern Cape**		**Southern Cape**	
	Date	mm	Date	mm	Date	mm	Date	mm
1	03-Apr	13	04-Apr	13	04-Apr	12	05-Apr	16
2	09-Apr	16	10-Apr	15	11-Apr	16	11-Apr	16
3	14-Apr	17	15-Apr	17	16-Apr	16	17-Apr	18
4	19-Apr	18	20-Apr	18	21-Apr	17	23-Apr	18
5	24-Apr	18	25-Apr	18	26-Apr	17	29-Apr	18
6	29-Apr	18	30-Apr	17	01-May	16	07-May	16
7	05-May	16	07-May	15	10-May	16	15-May	17
8	12-May	17	13-May	16	16-May	16	22-May	17
9	18-May	18	19-May	17	22-May	17	29-May	17
10	23-May	16	25-May	18	28-May	16	07-Jun	15
11	28-May	16	31-May	18	05-Jun	16	17-Jun	16
12	03-Jun	17	10-Jun	16	15-Jun	16	25-Jun	16
13	12-Jun	17	18-Jun	16	23-Jun	16	03-Jul	15
14	19-Jun	17	25-Jun	16	01-Jul	17	14-Jul	16
15	25-Jun	17	02-Jul	16	13-Jul	16	22-Jul	16
16	01-Jul	17	13-Jul	16	21-Jul	16	29-Jul	17
17	11-Jul	17	21-Jul	17	28-Jul	17	07-Aug	16
18	18-Jul	17	27-Jul	16	04-Aug	16	15-Aug	16
19	24-Jul	18	01-Aug	15	13-Aug	17	21-Aug	16
20	29-Jul	16	10-Aug	17	19-Aug	17	27-Aug	17
21	03-Aug	16	16-Aug	17	25-Aug	18	02-Sep	17
22	10-Aug	16	21-Aug	17	30-Aug	17	10-Sep	17
23	15-Aug	16	26-Aug	19	05-Sep	16	16-Sep	18
24	20-Aug	18	30-Aug	16	11-Sep	17	21-Sep	18
25	25-Aug	18	04-Sep	16	15-Sep	16	27-Sep	17
26	30-Aug	19	10-Sep	18	19-Sep	17	03-Oct	18
27	04-Sep	16	14-Sep	17	23-Sep	18	07-Oct	16
28	10-Sep	17	18-Sep	18	29-Sep	16	11-Oct	16
29	14-Sep	16	22-Sep	19	03-Oct	16	15-Oct	16
30	18-Sep	17	27-Sep	16	07-Oct	18	21-Oct	17
31	22-Sep	18	02-Oct	18	11-Oct	19	26-Oct	18
32	27-Sep	15	06-Oct	18	15-Oct	20	30-Oct	17
33	02-Oct	17	10-Oct	20	20-Oct	17		
34	06-Oct	17	14-Oct	20	24-Oct	17		
35	10-Oct	19	18-Oct	17	28-Oct	19		
36	14-Oct	18	23-Oct	17	31-Oct	17		
37	18-Oct	17	27-Oct	18				
38	23-Oct	16	31-Oct	20				
39	27-Oct	18						
40	31-Oct	19						

Table 4.8 Simulated site specific irrigation calendars for a sandy loam soil for four major ryegrass growing areas of South Africa

Events	**KwaZulu Natal Midlands**		**Eastern Highveld**		**Eastern Cape**		**Southern Cape**	
	Date	mm	Date	mm	Date	mm	Date	mm
1	07-Apr	23	08-Apr	23	07-Apr	19	07-Apr	22
2	14-Apr	23	15-Apr	23	15-Apr	22	15-Apr	23
3	20-Apr	22	22-Apr	25	22-Apr	24	23-Apr	24
4	27-Apr	25	29-Apr	24	29-Apr	24	01-May	23
5	04-May	22	09-May	23	10-May	23	14-May	23
6	13-May	22	17-May	22	19-May	23	24-May	23
7	21-May	24	25-May	24	28-May	24	03-Jun	22
8	29-May	24	02-Jun	23	10-Jun	22	18-Jun	23
9	09-Jun	22	15-Jun	22	23-Jun	23	29-Jun	22
10	19-Jun	23	26-Jun	23	05-Jul	22	15-Jul	22
11	27-Jun	22	09-Jul	23	19-Jul	23	26-Jul	23
12	08-Jul	23	21-Jul	23	29-Jul	23	06-Aug	22
13	18-Jul	23	30-Jul	24	10-Aug	22	17-Aug	23
14	26-Jul	24	10-Aug	23	19-Aug	23	25-Aug	22
15	02-Aug	23	18-Aug	23	27-Aug	25	02-Sep	22
16	12-Aug	23	25-Aug	25	03-Sep	23	12-Sep	23
17	19-Aug	23	31-Aug	23	11-Sep	22	19-Sep	23
18	26-Aug	25	09-Sep	24	17-Sep	24	26-Sep	22
19	01-Sep	22	15-Sep	24	22-Sep	22	04-Oct	24
20	10-Sep	24	20-Sep	23	30-Sep	23	10-Oct	24
21	16-Sep	24	25-Sep	22	06-Oct	25	16-Oct	24
22	22-Sep	26	02-Oct	24	11-Oct	23	24-Oct	23
23	30-Sep	23	07-Oct	24	16-Oct	24	30-Oct	25
24	06-Oct	25	12-Oct	25	23-Oct	23		
25	11-Oct	23	17-Oct	24	28-Oct	25		
26	16-Oct	23	24-Oct	24	01-Nov	22		
27	23-Oct	22	29-Oct	24				
28	28-Oct	23						

Table 4.9 Simulated site specific irrigation calendars for a clay soil for four major ryegrass growing areas of South Africa

Events	**KwaZulu Natal Midlands**		**Eastern Highveld**		**Eastern Cape**		**Southern Cape**	
	Date	mm	Date	mm	Date	mm	Date	mm
1	09-Apr	29	10-Apr	29	11-Apr	28	09-Apr	29
2	18-Apr	31	19-Apr	31	20-Apr	29	19-Apr	30
3	26-Apr	29	28-Apr	31	29-Apr	30	29-Apr	29
4	05-May	28	10-May	30	13-May	30	14-May	29
5	16-May	29	20-May	29	24-May	30	27-May	30
6	26-May	31	30-May	29	07-Jun	29	13-Jun	29
7	06-Jun	28	15-Jun	28	23-Jun	29	28-Jun	29
8	19-Jun	29	28-Jun	28	10-Jul	29	17-Jul	29
9	30-Jun	31	15-Jul	29	25-Jul	30	30-Jul	29
10	15-Jul	29	27-Jul	28	08-Aug	29	15-Aug	29
11	25-Jul	29	08-Aug	28	20-Aug	31	26-Aug	30
12	03-Aug	28	18-Aug	28	29-Aug	29	06-Sep	28
13	15-Aug	30	26-Aug	29	09-Sep	29	16-Sep	29
14	24-Aug	32	03-Sep	30	17-Sep	31	24-Sep	28
15	01-Sep	29	12-Sep	29	24-Sep	30	04-Oct	29
16	11-Sep	29	19-Sep	30	03-Oct	30	12-Oct	32
17	18-Sep	29	26-Sep	30	10-Oct	32	20-Oct	29
18	25-Sep	30	04-Oct	31	16-Oct	28	28-Oct	30
19	04-Oct	31	10-Oct	29	24-Oct	29		
20	11-Oct	31	16-Oct	28	30-Oct	32		
21	18-Oct	32	25-Oct	30				
22	26-Oct	30	31-Oct	30				
23	02-Nov	33						

Monthly irrigation calendars developed for a deep, well drained, medium textured soil (using the current guideline application rate of 25 mm irrigation event) for major milk producing areas of South Africa are presented in Figure 4.10. These monthly calendars are general (because they are same for all soil types and only weather is considered) but simple and can be used in the absence of site specific irrigation calendars.

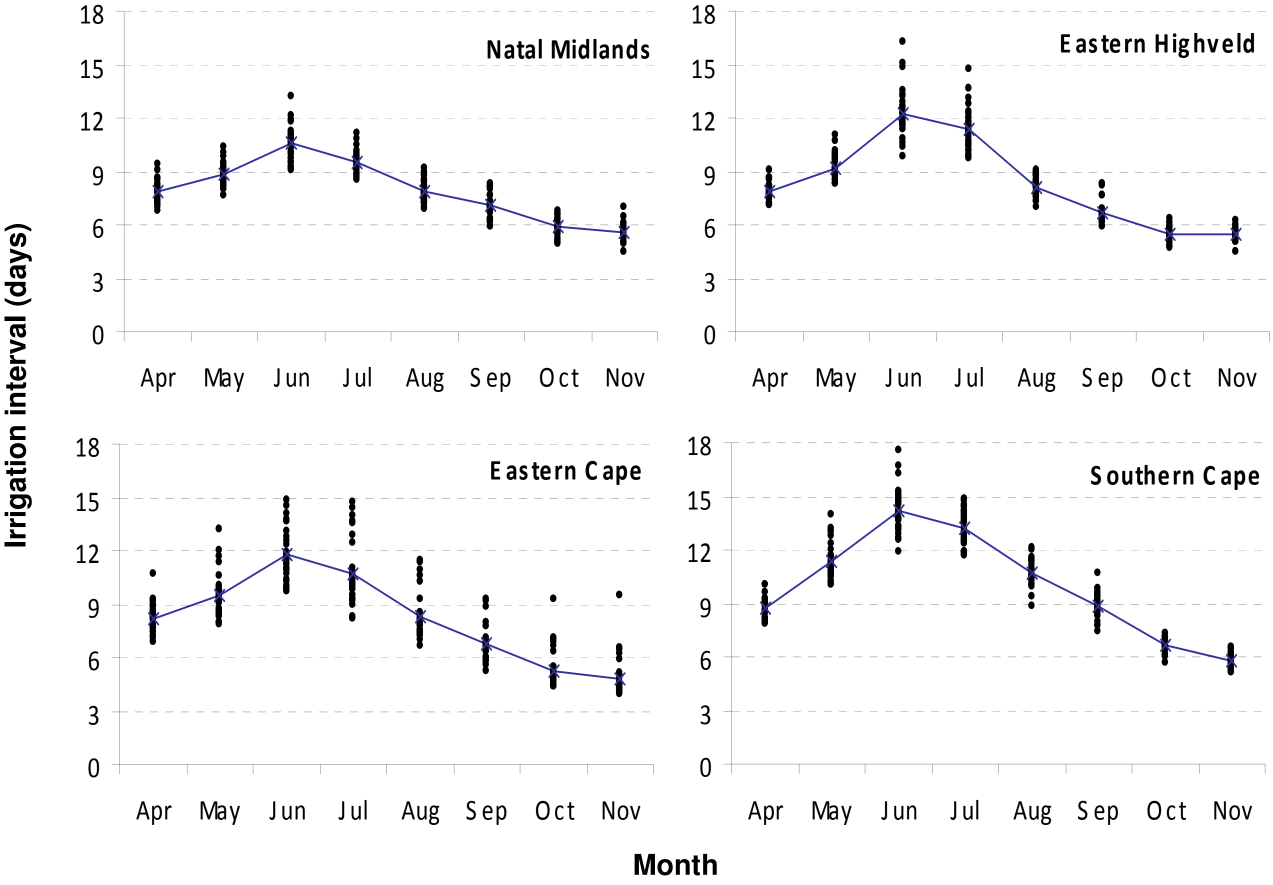

Figure 4.10 Example monthly recommended irrigation intervals (25 mm per event) for milk producing areas of South Africa (points show long-term irrigation intervals)

The model can be used by farmers or consultants to develop their own calendars with relatively few and simple inputs. The minimum inputs required for developing calendars are: 1) Weather data including location of the farm and long-term weather data including minimum and maximum of nearest weather station; 2) soil root depth and textural class (i.e. sand, sandy clay loam, clay loam) and 3) irrigation management including irrigation system, timing and refill options. A range of irrigation systems can be selected including farrow, sprinkler, pivot, micro, drip and subsurface drip. Irrigation timing can be based on three strategies; namely to irrigate at a fixed time interval, when a fixed amount is depleted or when a certain depletion level has been reached. For example: a) Farmers who receive water allocations on specific days (such as those participating in irrigation schemes), usually follow a fixed time interval (eg. every 7 days). b) Farmers use a fixed irrigation amount due to practical on-farm limitations (such as the limited capability of the irrigation system, storage capacity of reservoirs, etc) and usually initiate irrigation when soil deficit reaches a fixed threshold. c) Farmers could also prefer variable timing and amount to avoid crop water stress (depletion level strategy whenever a certain predetermined percentage of plant available water is depleted from the root zone). Refill options can be to field capacity, deficit, leave room for rain or use leaching fractions. Therefore, irrigators can follow different strategies for making a decision on when and how much to irrigate depending on particular situations.

4.5 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 well with observed values. The model was used for predicting water requirement and developing irrigation calendars using 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.

The model can be used for managing irrigation scheduling, predicting yields and estimating water requirements of ryegrass under different climatic conditions. If available, accurate site specific measurements using soil water sensors that represent the whole field could be preferable over model predicted irrigation requirements. In the absence of such measuring devices, farmers or consultants can develop site specific calendars using the model without considering rainfall. These calendars can also be modified by farmers when rain falls by subtracting rainfall from the recommended irrigation requirement. These calendars can also be supported with the help of some simple irrigation scheduling tools such as the wetting front detector (WFD). A WFD informs the irrigator when the required wetting front has been reached but it does not tell when to irrigate (Stirzaker, 2003; Geremew *et al.,* 2008). Therefore, combining the calendars (when to irrigate) and using a WFD (how much) can be more beneficial than using calendars developed using a model alone. However, these calendars are clearly superior to the common ‘recipe’ of 25 mm per week.

CHAPTER 5

SIMULATING WATER AND NITROGEN BALANCES OF ANNUAL RYEGRASS WITH THE SWB-SCI MODEL

5.1 INTRODUCTION

The increasing food production target requires intensive use of fertilisers and water in agriculture which leads to a higher cost of production and greater risk of environmental pollution. Irrigated pasture production in the dairy industry of South Africa represents one of the most intensive agricultural activities in terms of water and fertiliser inputs, especially N (Theron *et al*., 2002; Eckard *et al.,* 1995). Despite the latest N and irrigation application equipment and scientifically based fertilisation and water application guidelines, N and water use efficiency are generally still very low (Monaghan *et al.,* 2007).

Sustainable pasture production requires optimal fertiliser and water management practices in order to attain high biomass yield with minimum inputs to maximise profit. As a result, a basic understanding of the effects of N and water stress in pasture production are a prerequisite for the development of sound N and water management strategies. However, pasture systems are highly complex involving interactions between crop growth, soil and plant nutrient dynamics, and animal and pasture management systems. Considering temporal and spatial complexity, it is difficult to evaluate the whole system with short-term monitoring experiments. Development of site specific optimal N and irrigation management practices requires costly long-term trials. Since it is expensive and impractical to test multiple irrigation and N application strategies, the use of models can provide great insight and better understanding of the behaviour of the pasture system. Models can also be helpful in selecting best management practices for specific sites and environmental conditions.

Over the last few decades many mathematical computer models have been developed with varying levels of complexity, ranging from simple empirical models to mechanistic process based models (Godwin and Jones, 1991). The Soil Water Balance (SWB-Sci) model is a mechanistic, real time, generic, crop growth, soil water, nutrient and salt balance model (Annandale *et al.,* 1999; Van der Laan *et al.,* 2011) which can be used for irrigation, nutrient and salt management. The Soil Water Balance model was parameterised and tested for a wide range of crops including cereals, vegetables and pasture (Annandale *et al.,* 2000; Jovanovic and Annandale, 2000; Beletse *et al.*, 2008). The simple water balance model (without the nutrient sub-module) was intensively tested under different pasture management practices using annual ryegrass in Chapter 4. The N sub-module was validated for a range of sludge loading rates for dry land and irrigated agronomic crops as well as for dry land pasture (Tesfamariam, 2009), and a range of inorganic N fertiliser treatments under agronomic cropping systems (Van der Laan, 2009; Van der Laan *et al.,* 2011). Performance of the model for irrigated pasture with different N management strategies had not previously been tested. Therefore, the objectives of this study were to parameterise, calibrate and evaluate the performance the SWB-Sci model under varying N levels and irrigation regimes for annual ryegrass pasture.

5.2 MODEL DESCRIPTION

The simple irrigation scheduling version of the model is called SWB-Pro and was described in Chapter 4. The scientific version of the SWB model (SWB-Sci) includes salt balance, 2-D above-ground radiation interception and finite difference water balance routines (Singels *et al.,* 2010). Recently, N and P modelling subroutines have been incorporated into the SWB-Sci model (Van der Laan, 2009). Weather, soil and crop parameters are the same for both versions (SWB-Pro and SWB-Sci) and are described in Chapter 4. Hence, in this Chapter, the focus will be only on the N sub-module.

The main N processes (Figure 5.1) of the N sub-model including N transformations (mineralisation, nitrification, denitrification and ammonium volatilisation), N fixation, crop N demand and crop N uptake (Van der Laan, 2009) are presented below briefly:

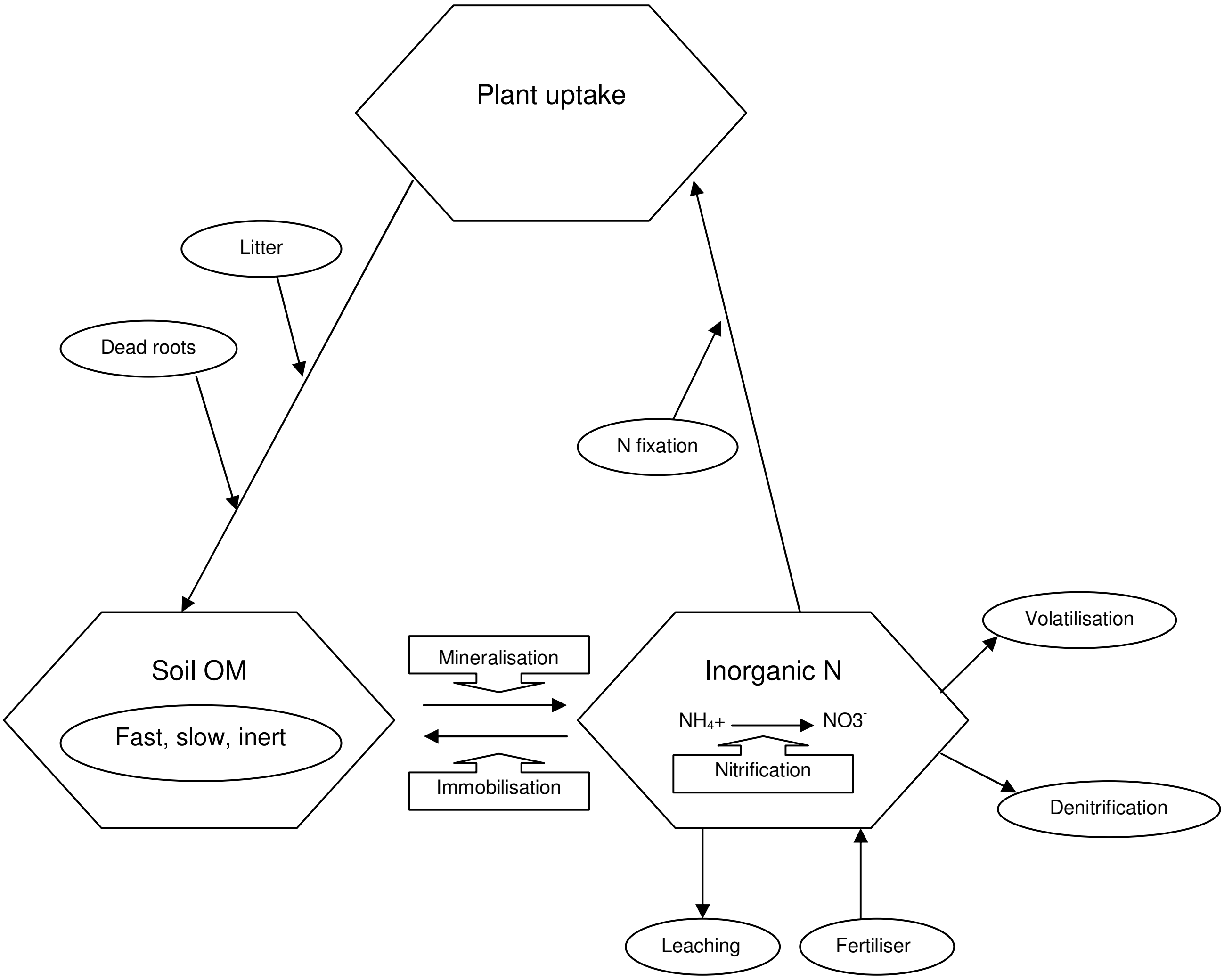

Figure 5.1 Schematic representation of the organic matter and inorganic N dynamics

5.2.1 Crop nitrogen uptake

For estimating N demand and potential uptake, SWB-Sci follows similar approach to that of CropSyst (Godwin and Jones, 1991; Stöckle *et al*., 2003). Crop N demand is calculated from crop input parameters of plant N concentration. While it is known that N concentrations of crops are different, the dilution curves are grouped only for C3 and C4 plants. Therefore, plant N concentrations for critical, minimum and optimum crop growth for C3 or C4 plants are available in the model. N limited growth is estimated to occur when above ground biomass N concentration is between the critical and minimum concentration (Stöckle *et al.*, 2003). Below the minimum N concentration crop growth stops, although there may be translocation of resources between plant organs.

5.2.2 Organic matter turnover

Both mineralisation of soil organic matter and turnover of crop residues modelling follow similar principles as the CropSyst (Stöckle *et al.*, 2003). Residues need to be parameterised for the fraction and half-life of the three pools (active, slow and inert) (Figure 5.1). It is also important to determine the C:N ratio of the residues (Van der Laan, 2009; Tesfamariam, 2009). The C:N ratio is a key parameter that is used in the estimation of N mineralisation or immobilisation. The model first calculates net N mineralisation, while immobilisation is considered if the net mineralisation is less than zero (Van der Laan, 2009; Tesfamariam, 2009).

5.2.3 Inorganic nitrogen transformations

Ammonia volatilisation is simulated from inorganic and organic fertilisers as a function of weather, method of N application (broadcasted or incorporated), soil pH and cation exchange capacity (CEC). The value is further modified by a turbulent transfer coefficient estimated from wind speed and leaf area index. Nitrification is influenced by soil water and texture (indirectly estimate of soil aeration), soil temperature and soil pH and usually it takes place when the climatic and soil conditions are favourable. In the model, denitrification is the conversion of nitrate to nitrous oxide, and N gas to the atmosphere is simulated. Denitrification is simulated as function of soil temperature, soil water and soil porosity (Van der Laan, 2009; Tesfamariam, 2009).

The movement of solutes in the soil profile is based on incomplete solute mixing (Corwin *et al.*, 1991) using the coefficient of mobility which represents the percentage of solute to be displaced and cascaded to the next layer (Van der Laan *et al.,* 2010). The water and N budgets interact to produce a simulation of N transport within the soil profile (Van der Laan *et al.,* 2010). Crop growth can be limited by water, radiation and/or nitrogen. A N nutrition index is used to account for N deficiency and accumulation of biomass (Van der Laan 2009; Van der Laan *et al.,* 2010).

5.3 MATERIALS AND METHODS

5.3.1 Site description and crop management

Data sets for model evaluation were collected from experiments carried-out under a rainout shelter (Hatfield) and in an open field (Cedara) in the 2007 and 2008 growing seasons. The open field experiment was conducted at the Cedara Experimental Farm of the Department of Agriculture (1076 m asl, 29°32'S; 30°17'E) in the Midlands of KwaZulu-Natal. The rainout shelter experiment was conducted at the Hatfield Experimental Farm (1327 m asl, 25°45'S; 28°16'E) of the University of Pretoria, Pretoria. At both sites, Italian ryegrass (*Lolium multiflorum*) cultivar 'Agriton' was planted at a seeding rate of 30 kg ha^{-1} with a row spacing of 0.15 m.

5.3.2 Treatments

A factorial design of irrigation levels and N rate treatment combinations were assigned in a completely randomized block design, with three replications (Table 5.1).

Table 5.1 Irrigation and N application rate treatments used for SWB-Sci model calibration and validation of annual ryegrass during 2007 and 2008 growing seasons

Site	Year	Growth cycles	Irrigation treatments	N Treatments (kg N ha^{-1})	
				Growth cycle^{-1}	Total
Cedara	2007	8	Non-stressed (W1) Mild-stress (W2)	N_0	0
				N_{30}	240
				N_{60}	480
	2008	7§		N_0	0
			Non-stressed (W1)	N_{20}	120
			Serve-stress (W2)	N_{40}	240
				N_{60}	360^β
Hatfield	2007-08	8	Non-stressed (W1)	N_0	0
			Mild-stress (W2)	N_{30}	120
			Serve-stress (W3)	N_{60}	240

[§] No N fertiliser was applied for all treatments for the first growth cycle.

5.3.2.1 Cedara

In 2007, the experiment included three different N rate applications of 0, 30 or 60 kg N ha^{-1} (N_0, N_{30} and N_{60}) over eight harvests applied at the beginning of each growth cycle. In 2008, treatments included four fixed N rates of 0, 20, 40 and 60 kg N ha^{-1} (N_0, N_{20}, N_{40} and N_{60}) applied after each cut (Chapter 2). In 2007, deficit (growth cycle one to three) and frequency (growth cycle four to eight) irrigation scheduling strategies were used. For the first three growth cycles, plots were irrigated to field capacity (**W1**) or 60% of W1 (**W2**) weekly. For the next five (four to eight) growth cycles, plots were irrigated every 7 days (**W1**) or 14 days (**W2**) to field capacity. In 2008, well watered treatment plots were irrigated once to field capacity weekly during autumn, spring and summer; and once every two weeks in winter (**W1**). Water stressed plots in 2008 were irrigated only at the start of growth cycles when N fertiliser was applied (**W2**).

5.3.2.2 Hatfield

In both years, N rates of 0 kg N ha^{-1}(N$_0$), 30 kg N ha^{-1} (N$_{30}$) and 60 kg N ha^{-1} (N$_{60}$) were applied for each growth cycle. Plots were irrigated to field capacity twice a week (**W1**); once a week (**W2**) or twice a month (**W3**).

5.3.3 Data collection

5.3.3.1 Weather

Meteorological data were recorded daily at both experimental sites. Fully automated weather stations were installed to measure solar radiation, minimum and maximum temperatures, wind speed and direction, rainfall and minimum and maximum relative humidities. Irrigation was recorded using water meters in Hatfield and manual raingauges at Cedara.

5.3.3.2 Soil analysis

Soil texture was determined to a depth of 1.0 m at the commencement of the trial in 2007. The sites have a deep, Hutton soil with a clay loam texture at Cedara and a sandy loam soil type at Hatfield (Soil Classification Working Group, 1991). Soil fertility was analysed in both years prior to planting by taking samples down to 1 m. These were analysed for N, P, K, pH, CEC, Mg, Ca and micro elements. Ammonium acetate was used for macro (K, Mg and Ca) and micro elements extraction (Table 2.2). Organic carbon and N were estimated by mid-infrared spectroscopy (Ben-Dor and Banin) and P was measured with the Bray I method. Nitrate and ammonium N were determined with an auto-analyzer after extraction using 1M KCl. To ensure maximum N utilization other elements were kept at optimum levels. Based on soil fertility analysis, no lime was required. K and P were applied based on South African Department of Agriculture recommendations of soil test analysis results by the Department of Agriculture. 20 kg P ha^{-1} was incorporated with the soil at the time of planting. The seasonal recommended K was divided into the number of expected regrowth cycles and 25 kg K ha^{-1} was broadcast at the beginning of each cycle.

5.3.3.3 Soil water content

Volumetric soil water content in the top 1.0 m soil profile was measured using a neutron probe (0.20 m intervals) at Hatfield and a Diviner 2000 Capacitance probe (0.10 m intervals) at Cedara. However, only the upper 0.60 m was used to calculate the deficit to field capacity and to use as the refill point during irrigation. This was because the majority of the annual ryegrass roots were in the top 0.60 m.

5.3.2.4 Crop growth, yield and nitrogen uptake

Plant samples were collected at 7 - 10 day intervals by harvesting plant material from an area of 0.0625 m^2 at Cedara and 0.09 m^2 at Hatfield to a height of 50 mm from the soil surface. Leaf area index (LAI) was determined using an LI3100 belt driven leaf area meter (LiCor, Lincoln, Nebraska, USA). For forage yield determination the grass was harvested at about the three leaf stage in Cedara and at 28 day intervals at Hatfield from 1.0 m^2 quadrants using a manual grass mower to 50 mm stubble height. At Cedara, biomass and leaf area index of the residual plant material after cutting (1 m^2) was determined. Forage yield and residual plant material were determined by oven drying the samples at 70 °C to constant mass. Forage N concentration was determined by Kjeldahl analysis (AOAC, 1991) and forage N uptake was calculated as forage DM yield multiplied by N concentration. For the Cedara site, forage yields and N concentrations are reported in Chapter 3.

5.3.3.5 Soil solution nitrate concentration

Wetting front detectors were used to collect soil solution samples for determining the soil nitrate concentration at different soil depths (Stirzaker, 2003). Solution sampling from WFDs was undertaken the day after irrigation or a rainfall event. This was done to standardise the sampling time and to allow redistribution within the profile. For each sample, nitrate content was analysed using a colour test strips (Merck KGaA, Germany).

5.3.4 Model parameterisation and testing

Crop growth parameters of annual ryegrass were generated using data collected from the field experiment (Table 4.2, Chapter 4). Some of the parameters which could not be determined from the collected data were obtained from literature and estimated by calibrating the model against measured field data (Table 5.2). Root N concentration of 0.015 kg N kg^{-1} DM^{-1} and increased root activity biomass of 0.50 were used. For starting the dilution curve for forage biomass and N concentration default values for typical C_3 crops (Van der Laan, 2009) were used. However, the slope of the dilution curve was increased with calibration to -0.40 from of -0.45. By-pass coefficients of 0.5 and 0.7 were used for clay loam (Cedara) and sandy loam (Hatfield) soils, respectively. The values were chosen after several runs of the model for optimally-growing annual ryegrass. Default values of soil initial C fractions for N mineralisation transformations were used. Average above ground measured biomass of (0.75 t ha^{-1}) and a leaf area index of 0.5 m^{2} m^{-2} were used to reinitialise the model after each cut.

Table 5.2 Specific crop input parameters of annual ryegrass used for SWB-Sci model for calibration and validation

	Parameter	Value	unit
Crop	N dilution slope	-0.40	-
	Increased root activity biomass	0.50	-
	Root N concentration	0.015	kg N kg^{-1} DM^{-1}
	Residual biomass after cut	0.75	t ha^{-1}
	Residual LAI after cut	0.50	m^2 m^{-2}
Soil	Initial C fraction to microbial biomass	default	-
	Initial C fraction to active labile SOM	default	-
	Initial C fraction to active metastable SOM	default	-
	Initial C fraction to passive SOM	default	-
	Bypass coefficient	0.5 - 0.7	-

Statistical parameters, including the coefficient of determination (r^2) to assess the degree of association, Wilmott (1982) index of agreement (D) to measure variability, and mean absolute error (MAE) to measure percentage of the relative difference between simulated and observed values were used to evaluate model performance. For accurate model predictions r^2 and D should be greater than 0.8, whilst MAE should be less than 20% (De Jager, 1994).

5.4 RESULTS AND DISCUSSION

5.4.1 Model calibration

Crop growth parameters from the SWB-Sci database (Table 4.2, Chapter 4) were used in conjunction with parameters developed from this study (Table 5.2) to run the model. Measured crop growth (forage yield and LAI), above-ground N uptake, soil water content and mobile soil solute concentrations were used to evaluate model accuracy.

Accuracy evaluation statistical parameters are presented in Table 5.3. The measured versus simulated values for the well-watered, nutrient non-limiting treatment (N_{60}) from Cedara for the 2008 growing season are presented in Figures 5.2 and 5.3. These parameters include forage yield, N uptake, LAI and profile soil water deficit (Figure 5.2) and mobile soil solution nitrate concentrations at four soil depths (Figure 5.3).

Table 5.3 Statistical parameters for SWB-Sci model calibration (r^2: coefficient of determination; D: Willmott index of agreement; MAE: mean absolute error) for optimally growing annual ryegrass

Treatment	r^2	D	MAE (%)
Forage yield (cycles)	0.90	0.97	8.3
Forage yield (cumulative)	0.99	0.99	7.5
LAI	0.84	0.94	13.0
Soil water content	0.78	0.81	19.2
N uptake (cycles)	0.37	0.59	10.4
N uptake (cumulative)	0.99	0.98	13.8
Mobile nitrate	0.64	0.58	58.9

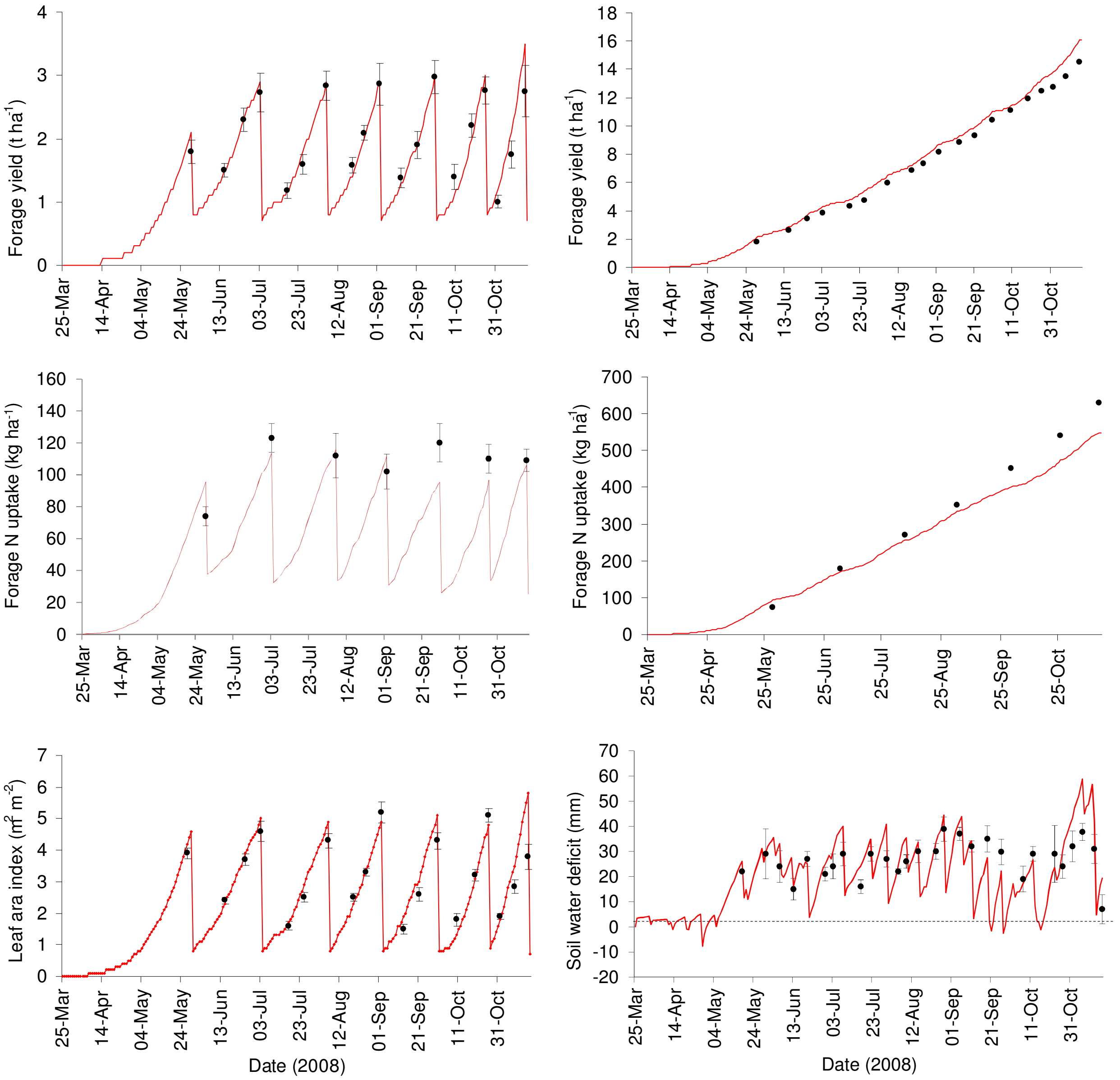

Figure 5.2 Simulated (solid lines) and measured (points) a) above ground forage biomass for growth cycles and b) the whole season, c) above ground forage N uptake for growth cycles and d) the whole season, e) leaf area index and f) soil water deficit to field capacity during model calibration under well watered (W1), N non-limiting (N_{60}) treatment at Cedara during 2008 (Vertical bars represent standard error)

The model predicted forage yield (per cycle and cumulative), LAI, cumulative above ground N uptake and soil water content accurately for all the statistical parameters within the prescribed range of r^2 and D > 0.80 and MAE < 20% (Table 5.3). Unlike cumulative N uptake, above-ground forage N uptake for individual growth cycles was simulated less accurately with $r^2 = 0.37$ and $D = 0.59$ (Table 5.3). Mobile nitrate soil solution concentration was, as can be expected, simulated with somehow lower accuracy ($r^2 = 0.64$ and $D = 0.58$). However, the model was able to predict trends of soil solution nitrate concentrations well (Figure 5.3). Considering the complexity of the N cycle, soil heterogeneity and the strong influence of water content, the model simulated soil solution nitrate concentration at different soil depths fairly accurate.

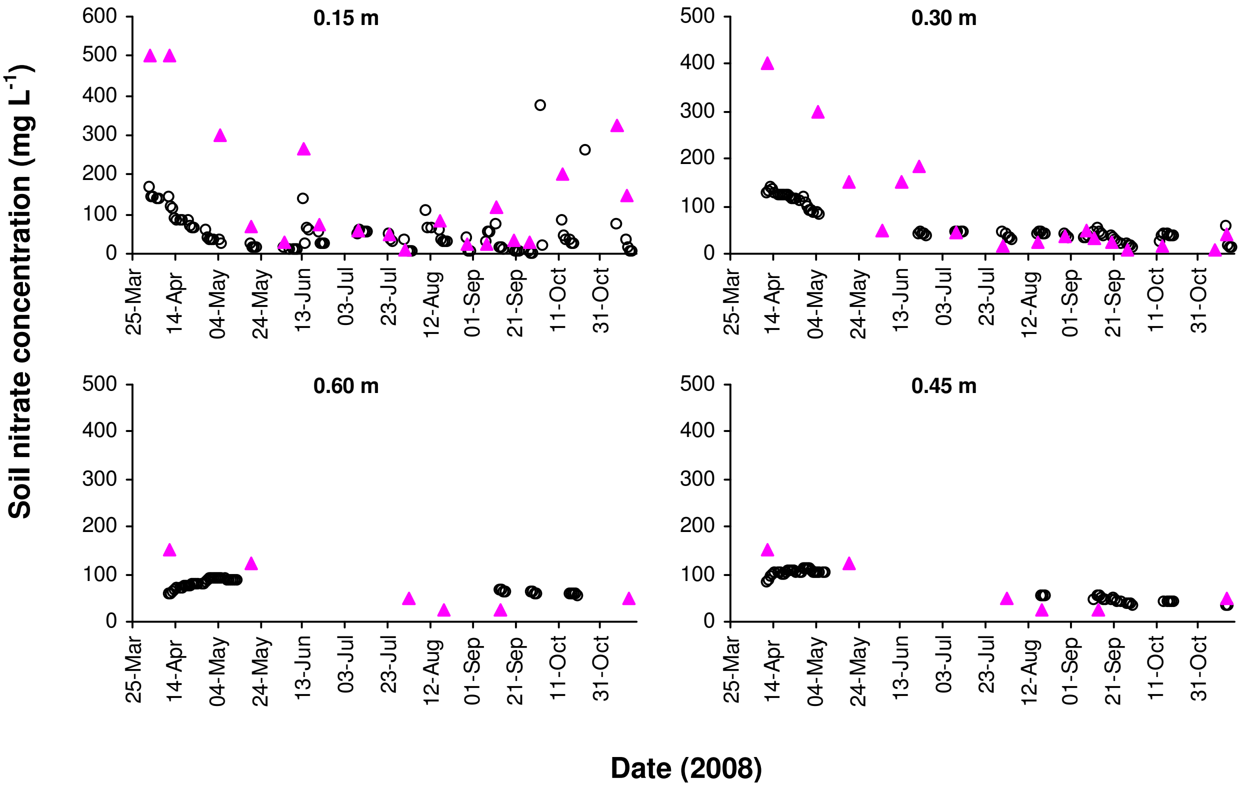

Figure 5.3 Simulated (O) and measured (▲) mobile soil solution nitrate concentrations for the well watered (W1), N non-limiting (N_{60}) treatment at Cedara site during 2008

5.4.2 Model validation

The model was validated using independent data for various irrigation and N treatment combinations. Parameters including forage yield, LAI, above-ground N uptake, soil water content and mobile soil solute concentrations were used to evaluate the performance of the model.

5.4.2.1 Forage yield

Simulated forage yield followed similar trends to the measured data for all years, sites and N rates for both growth cycle (Figure 5.4) and cumulative (Figure 5.5). As expected, yield simulations increased with increasing N rates under both water stressed and non-stressed conditions (Figure 5.5). Simulated and observed forage yield for growth cycles were in good agreement for all N rates under water stressed and non-stressed conditions except in N_0 with some statistical parameters marginally outside the acceptable ranges brought about by the model not simulating high forage yields in the late season (last growth cycle) (Table 5.4).

Generally, the model simulated forage yields well under well-watered and water stressed conditions. The model's predictive capability of cumulative forage yield was good for both Hatfield (Table 5.4) and Cedara (Table 5.5) with all statistical parameters within acceptable limits (r^2 and D > 0.80 and MAE < 20%). The model also predicted forage yield of individual growth cycles well for most treatments at Hatfield (Table 5.4) and with reasonable accuracy at Cedara (Table 5.5).

The residual forage biomass after cutting ranged between 0.5 to 1.0 t ha^{-1} for all sites and treatment combinations. However, no attempt was made to match biomass remaining after cutting, instead an average residual biomass value of 0.75 t ha^{-1} was used to run the model for all treatments and seasons. This could be the source of some variation in yield between modelled and measured forage yield of growth cycles. In spite of these variations, the measured and predicted yields agreed well for most treatment combinations.

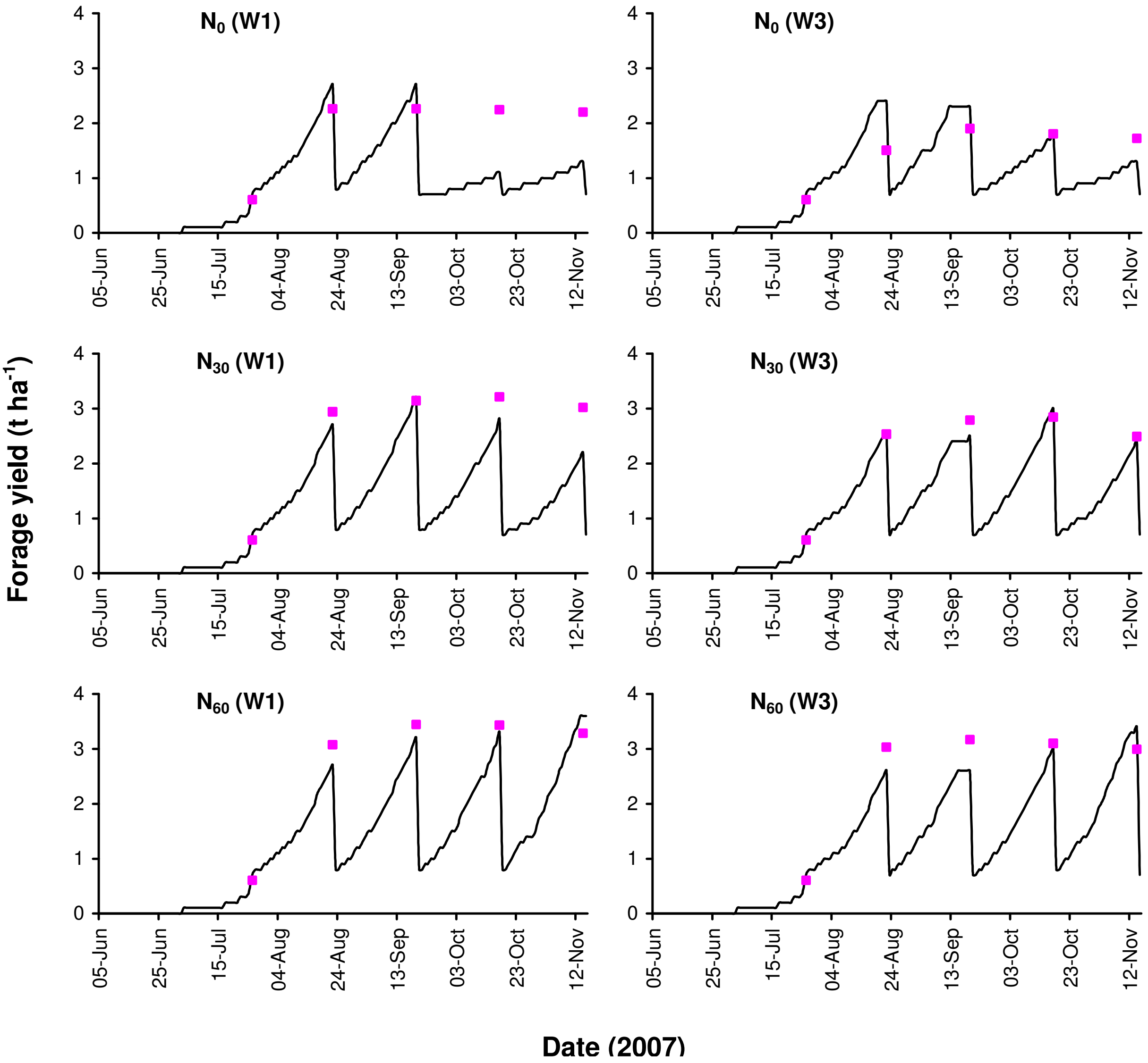

Figure 5.4 Simulated (solid lines) and measured (points) forage yield for growth cycles under a range of N rate (N_0: 0 kg N ha^{-1}; N_{30}: 30 kg N ha^{-1}; N_{60}: 60 kg N ha^{-1}) and water (W1: under well watered; W3: water stressed) treatments for Hatfield during the 2007 annual ryegrass growing season

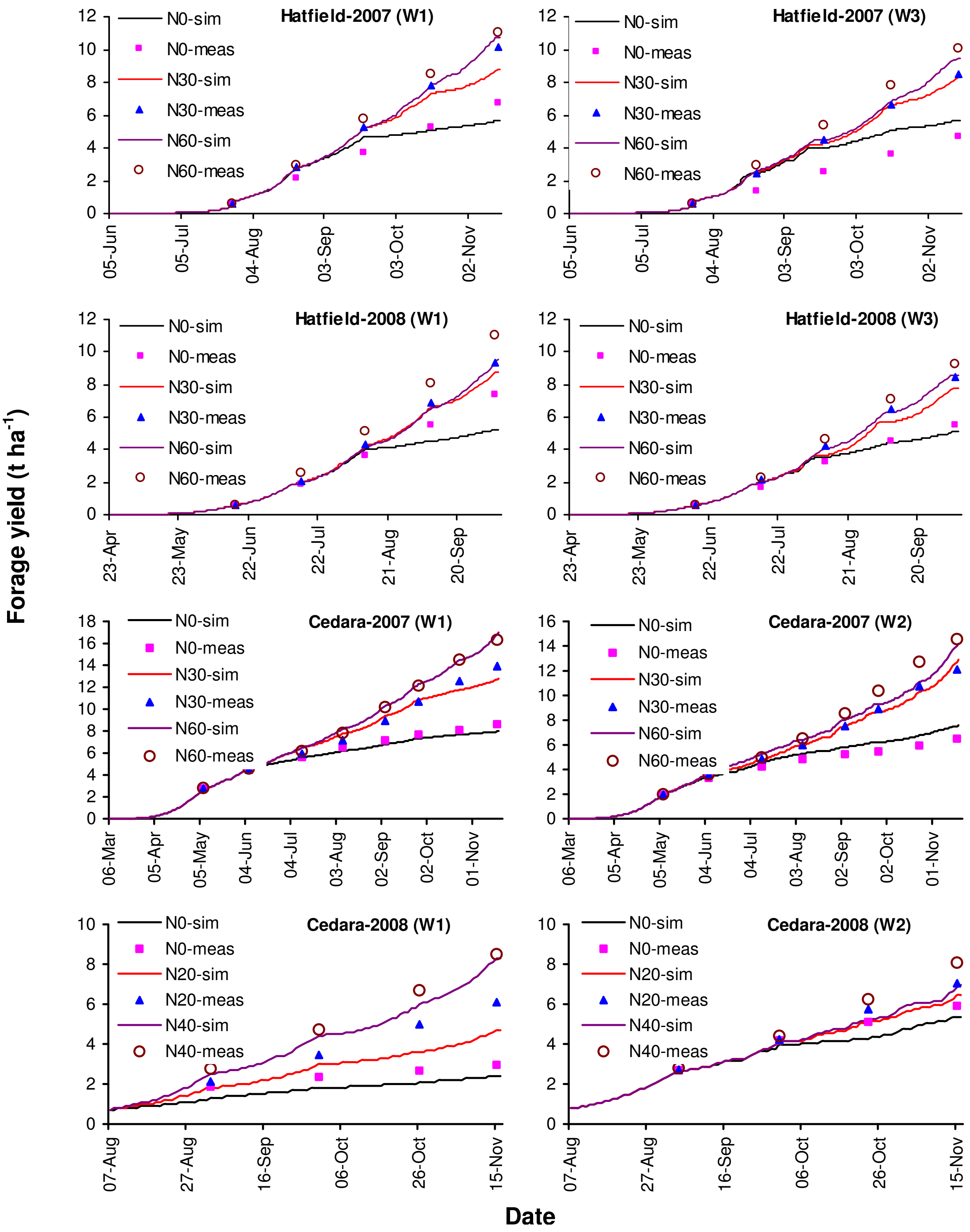

Figure 5.5 Simulated (solid lines) and measured (points) seasonal cumulative forage yield of ryegrass for well watered (W1) and water stressed (W2 and W3) under range of N application rate treatments for Cedara and Hatfield during 2007 and 2008 seasons

Table 5.4 Statistical evaluation between observed and predicted values of forage yield during model validation, Cedara 2007 and 2008 seasons

Field	Irrigation treatment	N treatment	Growth cycle yield			Cumulative yield		
			r^2	D	MAE (%)	r^2	D	MAE (%)
Cedara	Well watered (W1) 2007-2008	N_0	0.93	0.97	9.6	0.97	0.98	5.8
		N_{20}	0.40	0.70	15.0	0.98	0.99	7.6
		N_{30}	0.14	0.68	13.8	0.98	0.99	6.3
		N_{40}	0.48	0.82	9.9	0.97	0.99	4.2
		N_{60}	0.35	0.78	6.9	0.99	0.98	2.4
	Stressed (W2) 2007	N_0	0.83	0.92	12.7	0.99	0.96	5.4
		N_{30}	0.18	0.44	13.9	0.99	0.99	9.1
		N_{60}	0.17	0.36	20.0	0.98	0.98	12.9
	Water Stressed (W2) 2008	N_0	0.79	0.92	10.5	0.97	0.91	6.2
		N_{20}	0.70	0.88	8.6	0.98	0.94	5.2
		N_{40}	0.52	0.67	9.3	0.94	0.89	8.9
		N_{60}	0.60	0.68	9.9	0.96	0.93	9.7
Hatfield	Well watered (W1)	N_0	0.49	0.75	30.5	0.84	0.92	20.6
		N_{30}	0.97	0.97	8.9	0.99	0.99	11.3
		N_{60}	0.87	0.98	10.0	0.98	0.98	12.2
	Mild water stressed (W2)	N_0	0.46	0.81	26.7	0.86	0.96	17.1
		N_{30}	0.97	0.97	7.10	0.97	0.97	9.7
		N_{60}	0.94	0.98	8.40	0.98	0.99	8.8
	Severe water stressed (W3)	N_0	0.59	0.87	18.2	0.76	0.83	25.4
		N_{30}	0.95	0.98	6.8	0.96	0.98	11.8
		N_{60}	0.92	0.97	10.0	0.99	0.99	10.8

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

5.4.2.2 Leaf area index

In general, LAI simulations were similar to the measured values under varying irrigation and N fertiliser conditions (Table 5.5 and Figure 5.6). The model was able to predict LAI well under most irrigation and N fertiliser conditions, except N_0 (Table 5.6). For the unfertilised N_0 treatments, model predictions were poor regardless of irrigation treatment. For N_0, agreement between measured and simulated was low with most statistical parameters outside the acceptable range with r^2 = 0.12, D = 0.55 and MAE 45.2% (Table 5.5).

Table 5.5 Statistical evaluation between observed and predicted values of leaf area index during model validation, Hatfield 2007 and 2008 seasons

Parameter	N treatment	r^2	D	MAE (%)
Non-stressed (W1)	N_0	0.12	0.55	45.2
	N_{30}	0.82	0.82	24.7
	N_{60}	0.86	0.89	19.6
Mild- stressed (W2)	N_0	0.20	0.56	41.4
	N_{30}	0.89	0.93	15.3
	N_{60}	0.87	0.92	16.2
Severe-stressed (W3)	N_0	0.16	0.62	39.2
	N_{30}	0.83	0.92	15.6
	N_{60}	0.86	0.89	17.7

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

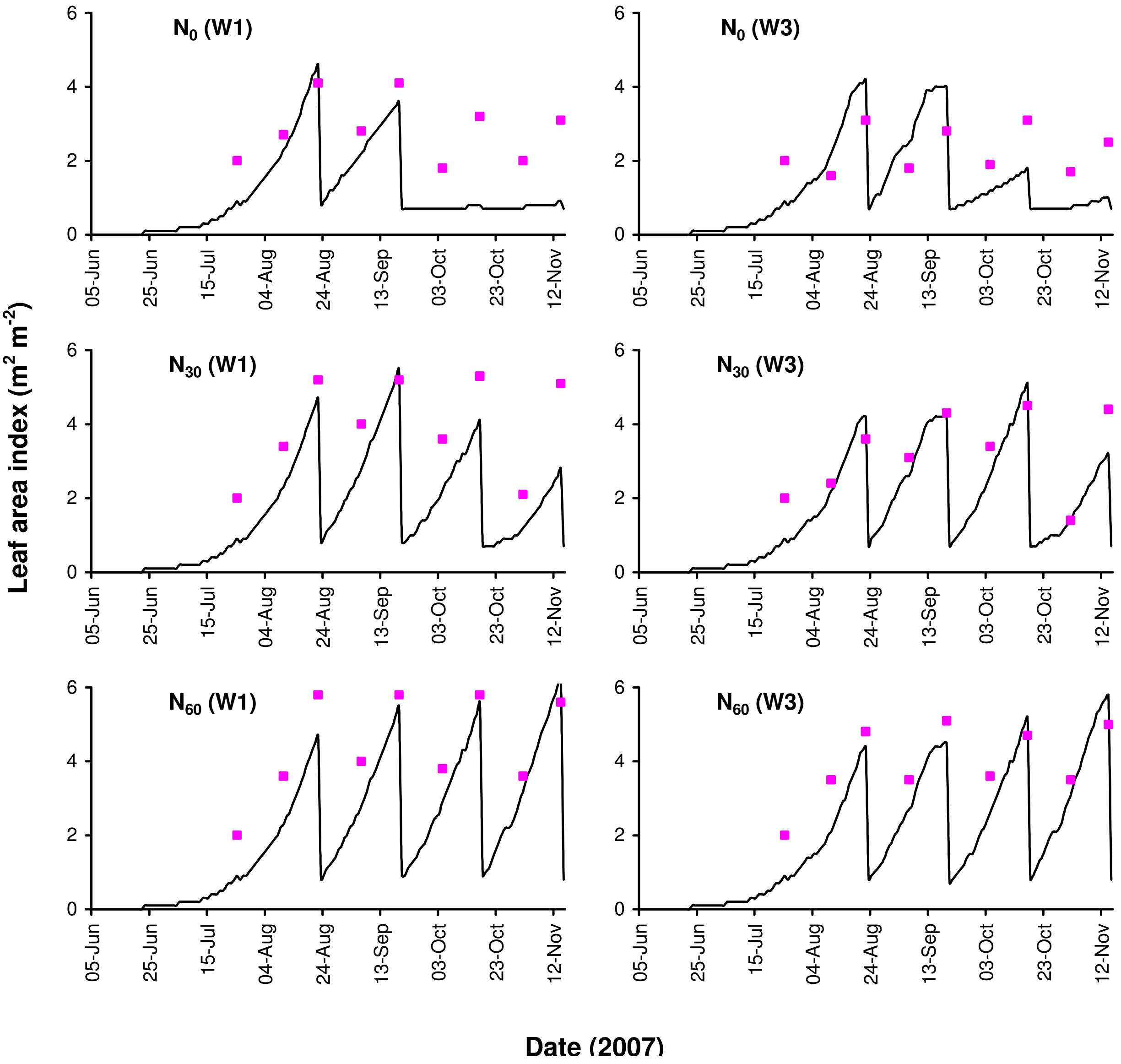

Figure 5.6 Simulated (solid lines) and measured (points) of leaf area index for a range of N rate treatments under well watered (W1) and water stressed (W3) treatments for Hatfield during the 2007 growing season

5.4.2.3 Forage N uptake

In most cases, the model overestimated N uptake of the individual growth cycles under-water stressed conditions (Figures 5.7), especially in 2008 (W2). As a result, the statistical parameters were outside the prescribed ranges (Table 5.6). However, simulated above-ground N uptake for growth cycles followed the pattern of measurements throughout the season (Figure 5.7), with modelled cumulative N uptake closely matching the observed data for most N rates and years (Figure 5.8).

Table 5.6 Statistical evaluation between observed and predicted values of forage N uptake during model validation, Cedara 2007 and 2008 seasons

Parameter	N treatment	Growth cycle			Cumulative		
		r^2	D	MAE (%)	r^2	D	MAE (%)
Well watered (W1) 2007-2008	N_0	0.94	0.97	20.6	0.94	0.98	6.6
	N_{20}	0.92	0.89	31.0	0.99	0.98	4.0
	N_{30}	0.82	0.11	17.7	0.97	0.90	10.3
	N_{40}	0.88	0.94	5.7	0.98	0.96	13.7
	N_{60}	0.23	0.90	12.8	0.99	0.93	9.09
Water stressed (W2) 2007	N_0	0.88	0.84	54.3	0.87	0.83	22.1
	N_{30}	0.36	0.58	31.5	0.93	0.94	7.0
	N_{60}	0.17	0.22	18.9	0.98	0.95	4.8
Water stressed (W2) 2008	N_0	0.88	0.78	52.4	0.95	0.75	24.5
	N_{20}	0.73	0.67	33.5	0.96	0.88	20.8
	N_{40}	0.28	0.29	25.5	0.97	0.95	15.1
	N_{60}	0.21	0.20	22.8	0.99	0.96	16.5

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

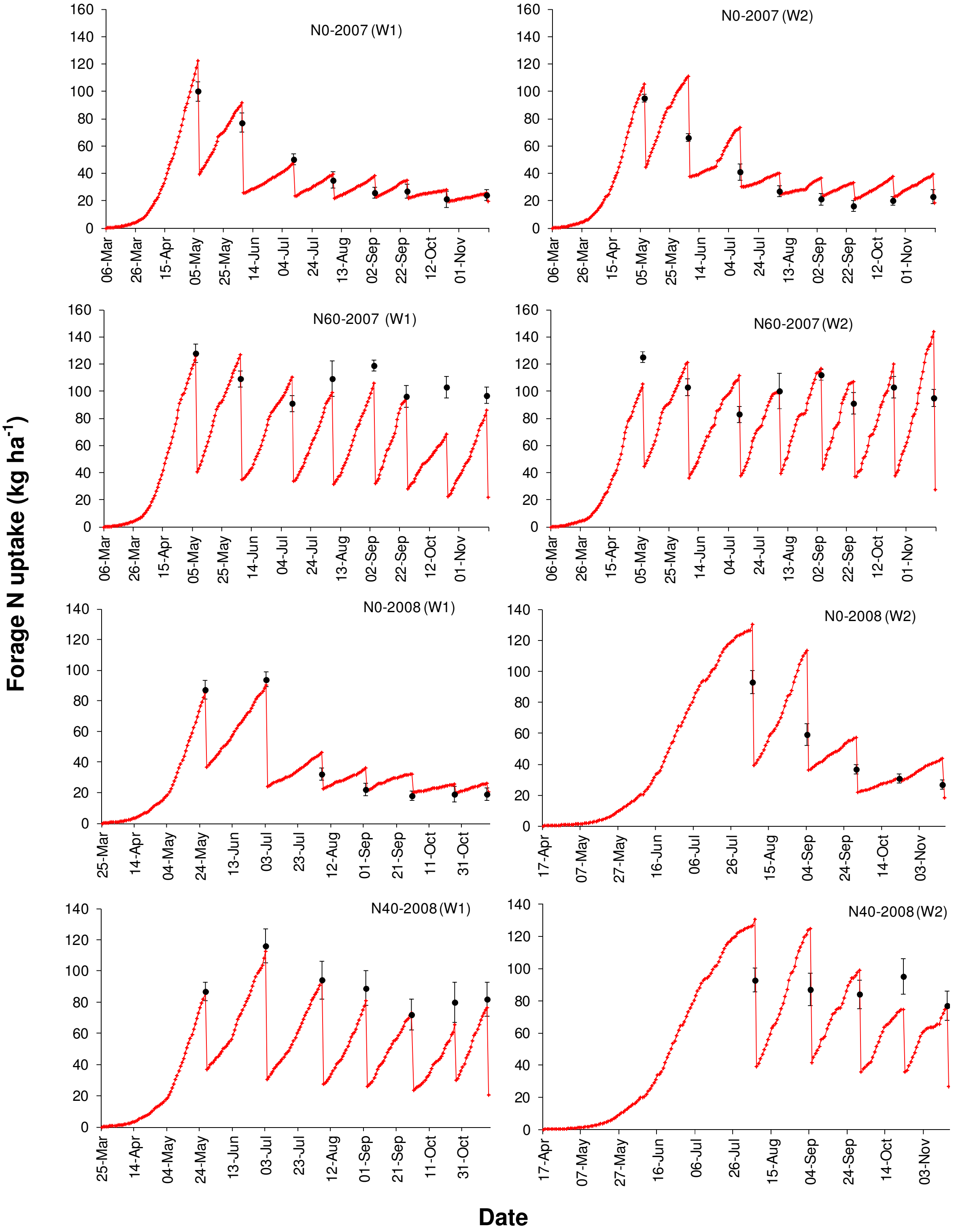

Figure 5.7 Simulated (solid lines) and measured (points) forage N uptake of growth cycles for range of N rate treatments under well watered (W1) and water stressed (W2) conditions for Cedara during 2007 and 2008 seasons

Measured and predicted cumulative above-ground N uptakes for the season were in a very good agreement (Table 5.6), with almost all parameters within the acceptable ranges ($r^2 > 0.80$, $D > 0.75$ and MAE < 25%). The model's better cumulative N uptake predicting capability as opposed to per growth cycle is most probably due to compensation of N uptakes between growth cycles. For planning N application strategies, overall seasonal N uptake simulations usually have more practical implication than individual growth cycles.

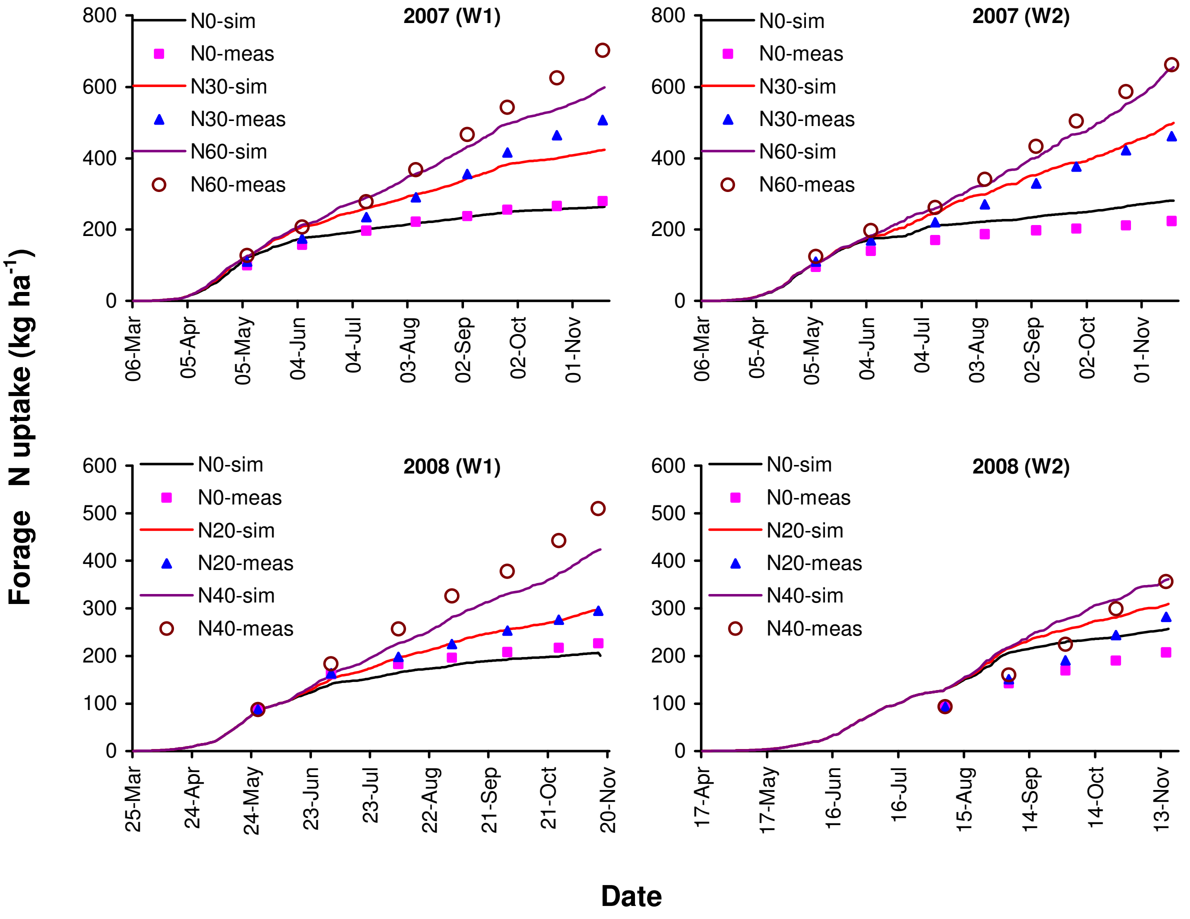

Figure 5.8 Simulated (solid lines) and measured (points) seasonal cumulative forage N uptake of annual ryegrass for range of N rate treatments under well watered (W1) and water stressed (W2) treatments for Cedara site during 2007 (N_0, N_{30} and N_{60}) and 2008 (N_0, N_{20} and N_{40}) seasons

The minimum and maximum biomass and N concentrations for starting dilution curves were set to default values of C_3. This was hardcoded in the model with slope set as an input parameter. The default slope for C_3 is -0.45 and for annual ryegrass this value was modified to -0.40 through calibration. Considering such generalised curves the model did well in predicting forage N uptakes.

5.4.2.4 Soil water content

Soil water deficit was under-estimated early in the season and over-estimated late in the season for the well watered treatments (Figure 5.9). The model simulated soil water content satisfactorily (D: 0.47-0.83 and MAE: 17-28%) for both Hatfield and Cedara (Table 5.7). Under water-stress conditions, soil water deficit predictions for Cedara were in good agreement with measurements at early and late in the season, but were overestimated in the mid-season (Figure 5.9). A notable difference between modelled and measured soil water contents were for the well watered zero N (W1-N_0) treatment at Hatfield where the modelled values were consistently higher than the measured ones (Figure 5.9).

It appears that the model did produce reliable estimates of the response of the soil to rain and crop water use. Generally the model predicted soil water content at Cedara better than at Hatfield under stress (water and N) conditions (Table 5.7). Although perfect simulations are impossible due to errors in measured data sets, sensor calibration and soil heterogeneity, the model can be still be improved by using a finite difference water balance approach as compared to the cascading approach used in the current simulation study. It is possible that while this alternative approach may improve simulations of soil water profiles only slightly, it may deal with movement of mobile nitrate concentration and N leaching more effectively. This, indirectly, can improve simulations of soil N availability, N uptake and crop growth.

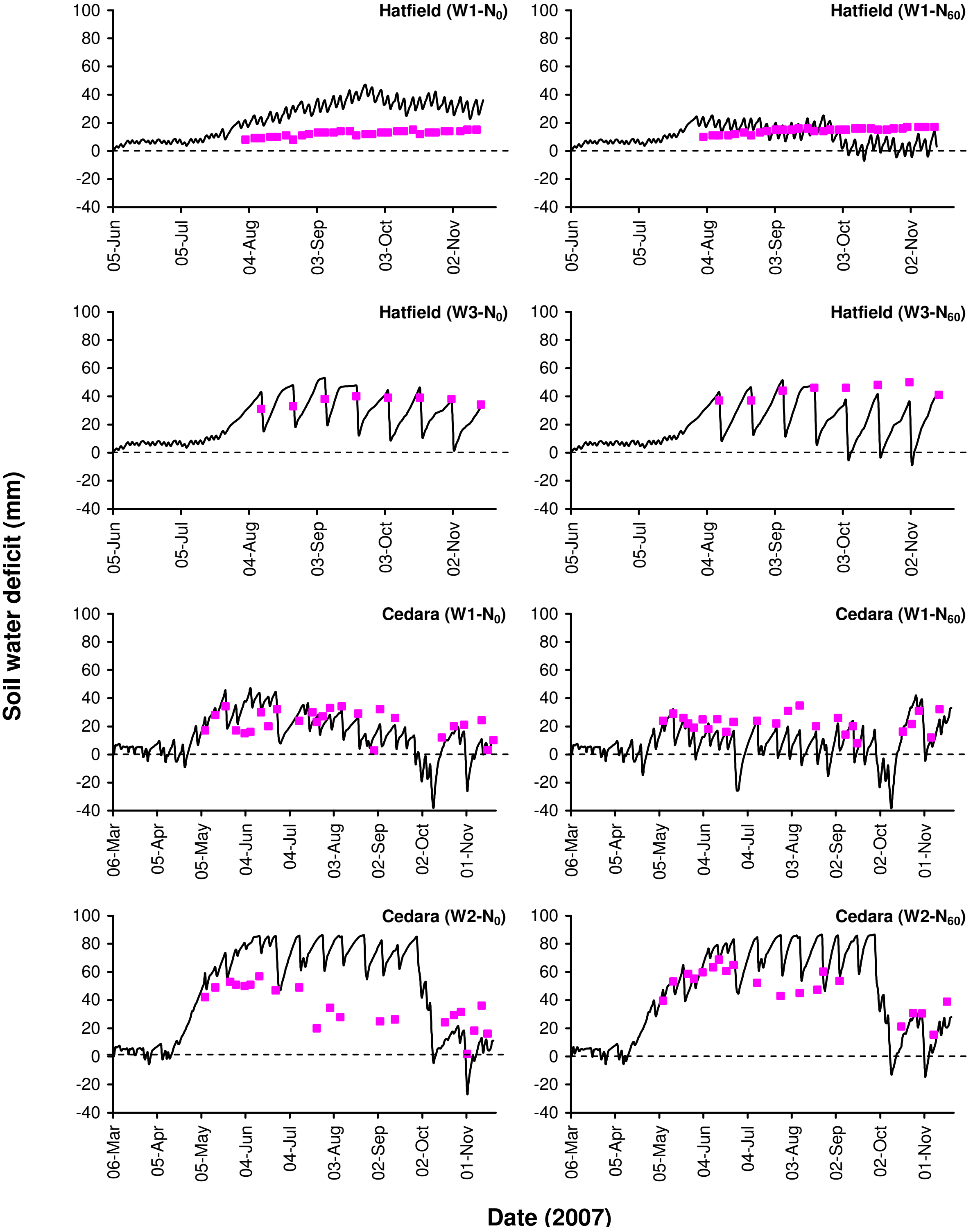

Figure 5.9 Simulated (solid lines) and measured (points) soil water deficit to field under a range of N rates and irrigation regimes data collected from Cedara during 2007 season

Table 5.7 Statistical evaluation between observed and predicted values of deficit water content to field capacity during model validation, Cedara 2007 and 2008 seasons

Water treatment	Hatfield				Cedara			
	N rates	r^2	D	MAE (%)	N rates	r^2	D	MAE (%)
Well watered	N_0	0.40	0.75	23.7	N_0	0.62	0.77	24.2
	N_{30}	0.37	0.84	8.9	N_{20}	0.23	0.47	28.2
	N_{60}	0.51	0.92	7.7	N_{40}	0.70	0.83	21.1
					N_{60}	0.46	0.68	18.7
Water stressed	N_0	0.29	0.28	26.4	N_0	0.52	0.68	21.9
	N_{30}	0.23	0.51	18.1	N_{20}	0.38	0.71	19.9
	N_{60}	0.28	0.55	15.4	N_{40}	0.53	0.74	22.3
					N_{60}	0.73	0.81	16.8

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

5.4.2.5 Soil nitrate concentrations

Generally, model prediction was close to the observed data of nitrate in the soil solution at all depths (Table 5.8) with r^2 (0.16 -0.84, mean 0.76), D (0.50 - 0.79, mean 0.71). In both years, measured nitrate concentrations were higher than model predicted values at the beginning of the season. In most cases, the greatest deviation occurred in the upper soil layers where significant under-estimation and over-estimation was evident (Figures 5.10 and 5.11). In 2008, there was a consistent under-prediction of soil solution nitrate concentrations in the top 0.15 m soil layer, particularly in the early period when simulated nitrate remained below 200 mg L^{-1} after planting, but observations reached 500 mg L^{-1}. High measured nitrate values at the beginning of the 2008 season could be a result of rapid mineralisation due to soil disturbance around the WFDs (Figure 5.11). But this could not be compared to 2007, because measurements of nitrates were started in the middle of the season (Figure 5.10). Nevertheless, the model was able to follow the patterns of observed values in most cases (Figures 5.10 and 5.11).

Table 5.8 Statistical evaluation between observed and predicted values of soil solution nitrate concentration during model validation, Cedara and Hatfield 2007 and 2008 seasons

N treatment	r^2	D	MAE (%)
N0 -2008	0.84	0.79	64.4
N20-2008	0.80	0.73	76.0
N30-2007	0.16	0.50	53.5
N40-2008	0.54	0.66	62.8
N60-2007	0.44	0.67	56.4
2007	0.52	0.64	57.8
2008	0.84	0.73	56.6
ALL	0.76	0.71	57.0

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

It is important to note that mobile nitrate concentrations are strongly dependent on soil water content and water applications. Hence, the differences between measured and simulated mobile nitrates could be as a result of complexities of N transformation processes, spatial soil variability, preferential paths of water and nitrate through the soil profile, non-uniform N fertiliser applications and crop N uptake. On the other hand, the trends of measured and predicted nitrates at different soil depths were similar (Figures 5.10 and 5.11). In general, considering the complexity of N cycle and heterogeneity of soil it can be said that the model showed good performance.

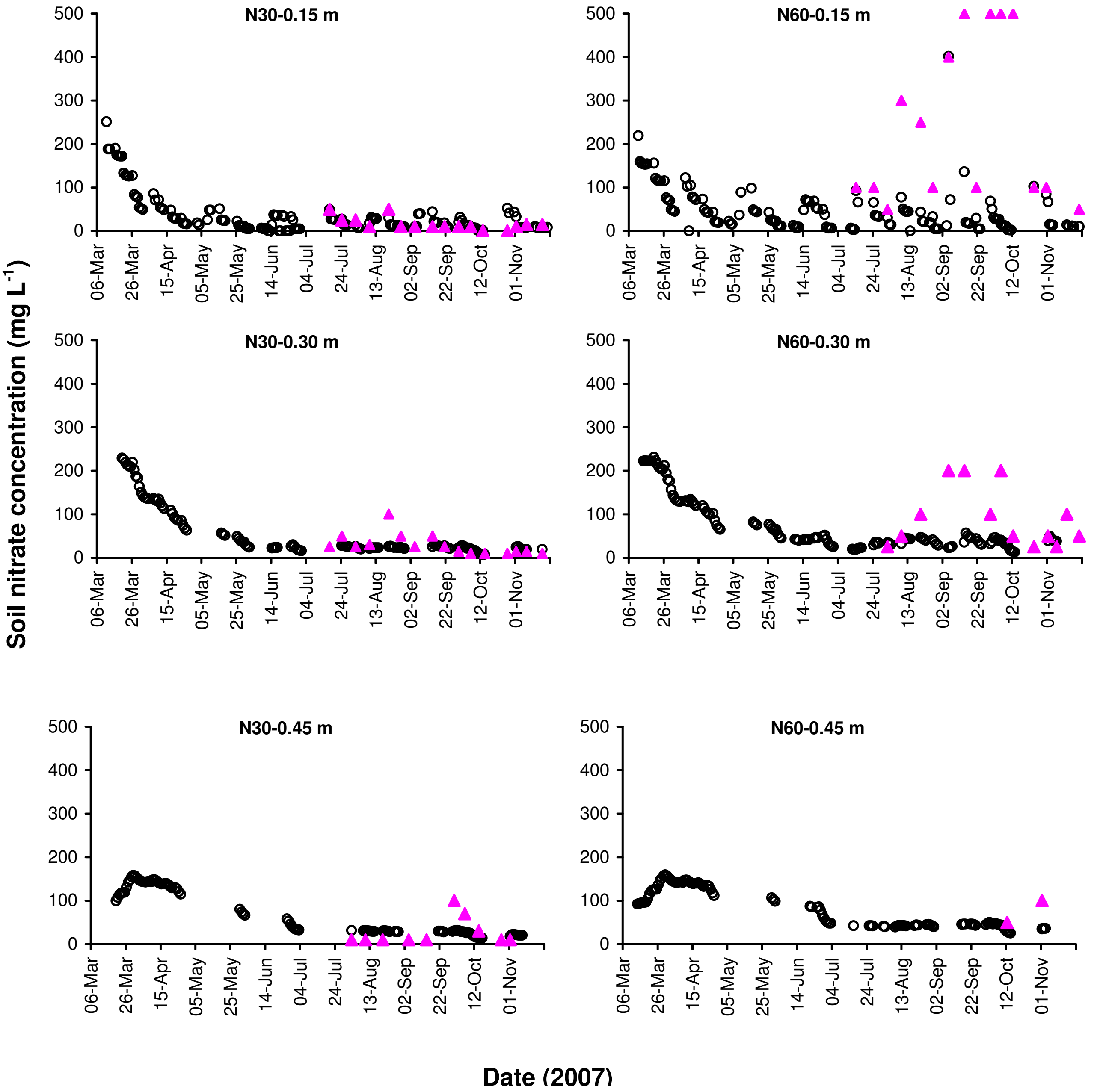

Figure 5.10 Simulated (O) and measured data (▲) soil nitrates concentrations at the depths of 0.15, 0.30, 0.45 m for well watered and range of N application treatments for Cedara site during 2007 season

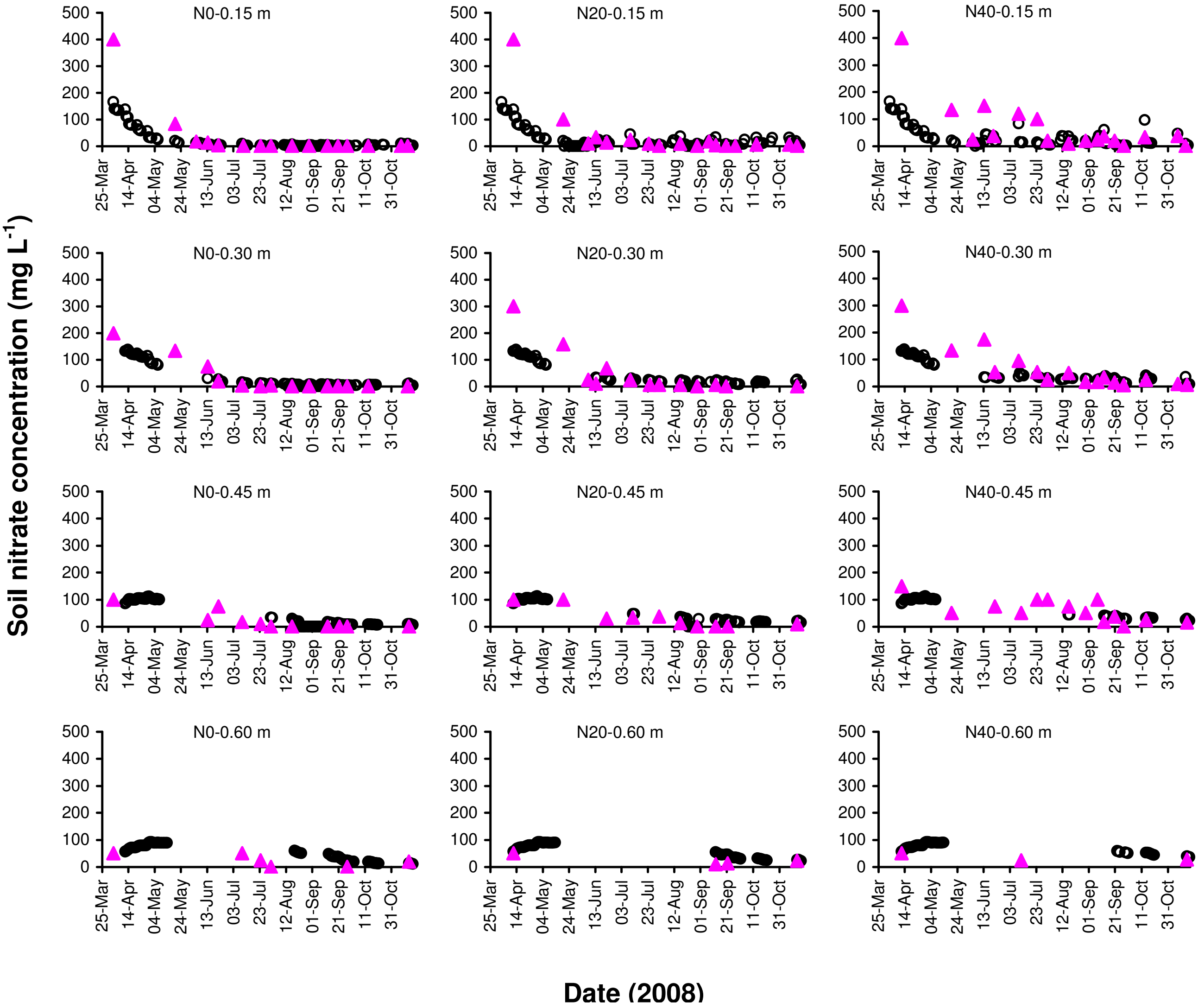

Figure 5.11 Simulated (O) and measured data (▲) soil nitrates concentrations at the depths of 0.15, 0.30, 0.45 and 0.60 m for well watered and range of N application treatments for Cedara site during 2008 season

5.5 CONCLUSIONS

In the current work, the SWB-Sci model was tested using different N fertiliser application rates and irrigation regimes at two sites. The model was sensitive to increased N application under water stressed and non stressed conditions as yield, LAI, above-ground forage N uptake and soil nitrates increased as levels of N increased. It predicted annual ryegrass growth, above-ground forage N uptake, soil water content and mobile soil nitrate reasonably well, as most of the statistical evaluation parameters were within acceptable ranges. Having gained confidence in modelling N and water interactions of pasture systems, the SWB-Sci model's simulation results can be used in conjunction with data collected from field experiments to better understand systems and extrapolate findings in time and space. Scenarios and conditions, including nutrient leaching and non-point source pollution, climate and soil variability, crop management, alternative irrigation and N management strategies can now be explored using the model. This can save money and time required for conducting long-term intensive field experiments for gathering information on potential pasture production.

CHAPTER 6

EXPLORING POTENTIAL IRRIGATION MANAGEMENT STRATEGIES FOR ANNUAL RYEGRASS USING THE SWB-SCI MODEL

6.1 INTRODUCTION

Cultivated pastures play an important role in livestock production by providing roughage throughout the year, improving fodder flow, carrying capacity of the farm and performance of individual animals. Input costs in the pasture based systems are much lower than with a total mixed ration system (Gertenbach, 2006). However, availability of irrigation water for producing pastures may limit the pasture based system. Hence, there has been a movement of milk producing enterprises from the central part of the country to the high rainfall areas of the KwaZulu-Natal Midlands, and the Southern, Eastern and Western Cape Coasts (Dickinson *et al.*, 2004). In these regions, however, there are still limitations to pasture based systems due to irrigation water availability (Gertenbach, 2006).

Annual ryegrass (*Lolium multiflorum*) pasture is one of the most widely utilised irrigated pastures in South Africa and is noted for its ability to provide winter grazing in the intensive dairy industry (Dickinson *et al.*, 2004). It is a high yielding pasture and possesses a high nutrient content under favourable environmental growing conditions (Theron *et al.*, 2002; Theron and Snyman, 2004). Its production requires intensive management of N fertiliser and irrigation to ensure maximum yield and optimum quality. However, irrigation water scarcity and increasing N fertiliser prices, concerns on excessive forage crude protein concentrations and environmental pollution necessitates prudent N and irrigation management in pasture production.

Most experiments conducted using annual ryegrass were to maximise forage yield per unit area by focusing on mainly N application with little consideration for irrigation water and environmental risk (Eckard *et al.,* 1995). Generally, for temperate grasses, including annual ryegrass, 25 mm of irrigation water per week is a common practice (Jones, 2006; Macdonald, 2006). However, evaporative demand differs between locations and over time for a specific location and crop requirements also change as crop canopy cover varies. Hence, the current irrigation practice of 25 mm per week may cause: a) forage yield and quality imbalances between harvests (Eckard, 1990; Eckard *et al.,* 1995), b) reduced water use efficiency by increasing unproductive water losses due to surface runoff and deep drainage (Chapter 4) and c) detrimental effects on soil and water resources due to nutrient leaching (Pervanchon *et al.,* 2005; Monaghan *et al.,* 2007). Overall, this will reduce profitability of the enterprise.

In the last few decades, several mathematical computer models have been developed to better understand nutrient and water dynamics of cropping systems. Models can supplement experimental data where long-term experiments are limited or not possible. Moreover, other alternative strategies can be explored under different conditions including soils, regions and irrigation and N management strategies. The scientific version of the Soil Water Balance (SWB-Sci) model, a locally developed mechanistic, crop growth, soil water and N balance irrigation-scheduling model, was calibrated and tested successfully for a range of irrigation regimes and N application rates of annual ryegrass at different sites (Chapter 5). This model can therefore be used with confidence to extrapolate irrigation and N requirements of annual ryegrass to other areas. It can also be used to improve N and irrigation water use efficiencies by assessing potential irrigation and fertilisation management strategies.

The objectives of this chapter are therefore, to test the hypotheses that an irrigation scheduling tool can 1) improve forage yield, 2) improve water use efficiency by decreasing unproductive water losses and 3) minimise nitrate leaching.

Hence, a range of irrigation management strategies including calendar based irrigation scheduling developed with the simple SWB-Pro model, deficit irrigation and “room for rain” were evaluated using the SWB-Sci model for major annual ryegrass growing areas of South Africa.

6.2 MATERIALS AND METHODS

6.2.1 Model description

SWB-Sci is a locally developed mechanistic crop growth, soil water and N balance, irrigation-scheduling model. Details of the sub-models of SWB-Sci are presented elsewhere (Annandale *et al.,* 1999, Annandale *et al*., 2004; Tesfamariam, 2009; Van der Laan, 2009).

6.2.2 Model modification

To adopt the model for long-term simulation, three commonly used defoliation practices were included into SWB-Sci. These are based on accumulated biomass, accumulated thermal time (growing degree days) and variable timing (user defined dates).

6.2.3 Model input parameters

The weather unit of SWB-Sci calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to FAO 56 recommendations (Allen *et al.,* 1998). Weather data including daily values of minimum and maximum air temperature and humidity, wind speed, incoming solar radiation and precipitation are used to run the model. For limited data the model can also calculate ET_O from minimum and maximum temperatures according to Annandale *et al.* (2002). Long-term weather data (1950-2000), including precipitation, minimum and maximum temperatures for major crop growing sites of South Africa are available in the SWB-Sci database.

Soil inputs of the model include parameters for runoff curve number, drainage factor, maximum drain rate of the soil profile, root depth limit, standing and surface biomass, cultivation depth and bypass coefficient. In each soil layer, input parameters including soil texture (sand and clay percentage), layer thickness, initial soil water content, water content at field capacity, water content at permanent wilting point, bulk density, soil cation exchange capacity, pH, organic carbon, inorganic N (ammonium and nitrate) and crop residue are required. Soil initial C fractions for N mineralisation transformation inputs can be categorised for the top cultivation layer (0.3 m) and deep sub-soil (below 0.3 m).

Crop input specific parameters representing different crops can be selected from the crop file database. Each crop has a database of crop parameters for phenology (thermal time requirements to reach specific growth stages and photoperiod), morphology (root depth, specific leaf area and other parameters defining canopy and root characteristics), growth (maximum transpiration, extinction coefficient for solar radiation, water use efficiency normalized by VPD, stress response parameters, etc.) and N parameters (defining crop N demand and root uptake).

The model has different N fertilisation application amounts, source (organic or inorganic), type (organic or inorganic) and method (broadcast or incorporated). Users can choose from a range of commercially available organic or inorganic N fertilisers with their respective N concentrations. In ‘tillage management”, users can select the depth and equipment used. The model has a database of different farm tillage equipment with their mixing and incorporation efficiencies from which a user can select. The model requires crop and type of residue (standing or surface) of the previous year, and relevant fractions (fast or slow cycling and lignified) of selected crop residue can be accessed from the database.

6.2.4 Model output parameters

The simulated output parameters from SWB-Sci include irrigation application, forage yield, water use, unproductive water loss (through soil evaporation, deep drainage and runoff), N uptake and N leaching.

6.2.5 Scenario simulation analyses

The model was used to determine how the crop reacts to different irrigation scheduling practices. Hence, to predict long-term pasture growth and yield, soil water balance and N loss (leaching) under different irrigation application strategies were simulated. Six irrigation management scenarios were tested (see Table 6.1 for full description). For the most common irrigation practice, rainfall of 3 mm and less was ignored (Macdonald, 2006). As a result for scenarios (2 and 3) small rainfall events (< 3 mm) were ignored for the site specific and general calendars. The seanrous

Table 6.1 Irrigation management scenarios tested in four major milk producing areas of South Africa

Irrigation strategies	Abbreviation	Detailed description
Field capacity	1. FC100	Common scientific practice - refill to field capacity when the soil water deficit to field capacity in the root zone exceeds 25 mm
Mild deficit irrigation	2. FC80	Irrigate 80% of FC20 (20 mm)
	3. FC60	Irrigate 60% of FC20 (15 mm)
Room for rain	4. RR20	Leaving 20 mm deficit to field capacity after irrigation as a buffer for rain (Pastures were irrigated when 60% plant available water was depleted)
common farmers' practice	5. WK25	The common farmers' practice of 25 mm irrigation per week (WK25) minus rainfall (> 3 mm) received within the week
General monthly calendar	6. Gen-cal	General monthly calendar guideline developed using the simple SWB-Pro model minus rainfall (> 3 mm) received from the last irrigation event
General monthly calendar	7. Site-cal	Site specific calendar developed using the simple SWB-Pro model minus rainfall (> 3 mm) received from the last irrigation event
Zero irrigation	8. I0	No irrigation or only rainfall scenario was included for calculating irrigation use efficiency

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-Sci 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 6.2). Measured long-term mean rainfall, minimum and maximum temperatures and vapour pressure deficit (estimated from temperature) of the sites are presented in Table 6.1.

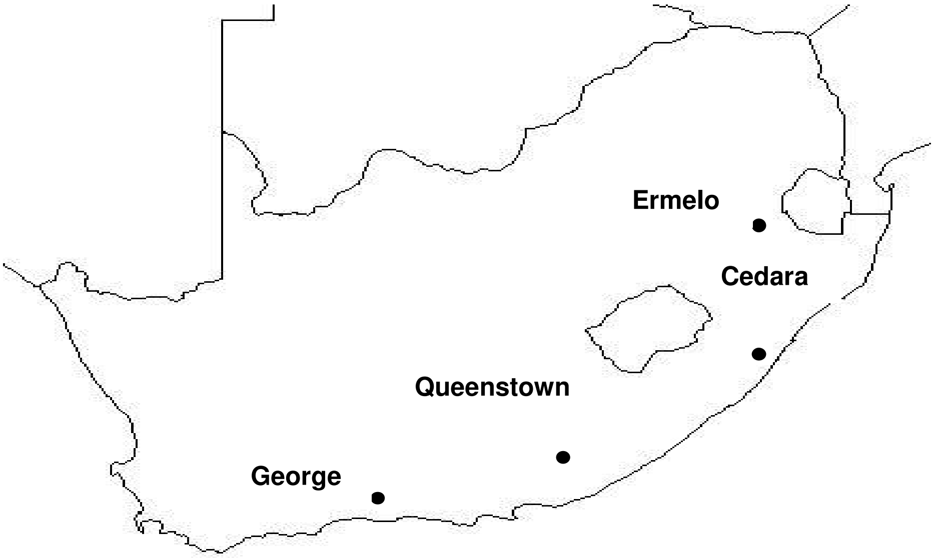

Figure 6.1 Main annual ryegrass growing areas of South Africa used to develop site specific and general irrigation calendars

Soil input parameters from the Cedara site described in Chapter 2 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 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 (Table 6.2).

Table 6.2 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} (℃)	24.6	22.9	21.0	19.0	19.5	20.7	22.4	22.4	23.4
	T_{min} (℃)	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} (℃)	23.6	21.5	19.2	16.5	17.0	19.5	22.7	23.2	23.4
	T_{min} (℃)	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} (℃)	26.8	22.5	20.2	17.5	18.6	20.9	23.6	24.4	26.8
	T_{min} (℃)	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} (℃)	23.7	21.6	20.4	19.3	18.6	18.4	19.1	20.0	21.6
	T_{min} (℃)	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

Common management and cultivation practices followed by farmers were simulated. Annual ryegrass planting date is between mid-February and mid-April, and the pasture grows until mid-October to mid-December each year. Annual ryegrass seedlings are very sensitive to heat and may die if sown too early during periods of high temperature, while forage yields in the winter may be reduced significantly if planting is too late. Long-term simulations were run for 30 years from 01 March to 06 November (eight harvests), with a fallow period between pastures. 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 and early summer.

Pasture growers usually split the annual recommended N equally into the number of growth cycles (cuts). Generally, a 50 kg N ha^{-1} per growth cycle is the recommend application rate used by farmers. The virtual N application rate used was, therefore, the same as that of the current farmers' guideline of 50 kg N ha^{-1} per cycle (400 kg N per year for eight growth cycles), applied one month after planting for the first harvest and immediately after each cut for the rest of the harvests.

Forage yield, unproductive water losses due to deep drainage plus runoff, and nitrate leaching below the root zone (0.6 m) were simulated. Water use efficiency (WUE) and marginal irrigation use efficiency (MIUE) were calculated according to Rawnsley *et al.* (2009) using:

$$\text{Water use efficiency (WUE)} = \text{Yield/ ET} \quad (6.1)$$

$$\text{MIUE} = (\text{Yield with irrigation} - \text{Yield without irrigation})/\text{Irrigation} \quad (6.2)$$

For all regions, simulated and calculated parameters were analysed using the Statistical Analysis System (SAS) program for Windows v9.2 (SAS, 2002) by considering irrigation strategies as treatments and years as replications. Where there was significance, means were separated using the least significant difference at the 5% confidence level.

6.3 RESULTS AND DISCUSSION

6.3.1 Forage yield and water use

In all regions there were significant yield differences among irrigation strategies (Table 6.3). The current common farmers' guideline of 25 mm a week (WK25) produced the lowest yields compared to the rest of the strategies except for the water stressed FC60. Calendar based irrigation scheduling Gen-cal and Site-cal simulated significantly higher yields than WK25. In all three regions except the Southern Cape, the lowest yields were obtained from the FC60 strategy. In the Southern Cape, yields between FC100 and the deficit irrigation strategies (FC80 and FC60) were not significantly different, while for the other three regions yields of FC60 differed significantly from FC100 and FC80. In the Southern Cape, the non-significant differences in yields between most irrigation strategies and FC60 were because of high mean annual rainfall (462 ± 109) during the growing seasons.

Table 6.3 Seasonal forage yield ($t\ ha^{-1}$) for the long-term simulation for seven irrigation strategies in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	13.7(1.3) [§]ab[β]	14.5(0.8)ab	13.2(1.5)a	13.7(2.1)b
FC80	14.0(1.1)a	13.9(0.6)bc	13.0(1.4)ab	14.7(2.1)ab
FC60	11.5(1.3)c	11.0(0.8)d	10.0(1.5)c	14.0(1.5)ab
RR20	14.3(1.3)a	14.9(0.6)a	13.8(1.4)a	15.0(1.7)a
WK25	12.6(1.7)bc	13.5(1.4)c	11.9(1.9)b	11.8(2.1)c
Gen-cal	13.8(1.7)a	14.3(1.1)ab	13.3(1.5)a	14.5(2.4)ab
Site-cal	14.0(1.9)a	14.5(0.9)ab	13.4(1.5)a	14.5(2.2)ab
I0	6.6(1.6)[NA]	5.6(1.0)[NA]	4.5(1.6)[NA]	10.0(2.3)[NA]

[§] Values in the brackets are standard deviations. [β] Values followed by the same letter within a column are not significantly different. [NA] is not applicable to the treatment.

In the Eastern Cape and KwaZulu-Natal Midlands the yield in the first growth cycle was lower compared to the Eastern Highveld and Southern Cape (Figure 6.2). Yield reduction could be due to higher deep drainage (Figure 6.4) which leads to nutrient leaching (Figure 6.5). In autumn and spring, the WK25 strategy produced similar yields to the highest yielding irrigation strategy. However, the yields were lower in the winter months of June and July (for the third and fourth growth cycles) when the WK25 strategy was used (Figure 6.2). This was due to lower growth rate and water use of annual ryegrass in winter as a result of unfavourable weather (Table 6.1) i.e. low minimum temperatures (from about 0°C in Eastern Highveld to 7.0 °C in Southern Cape).

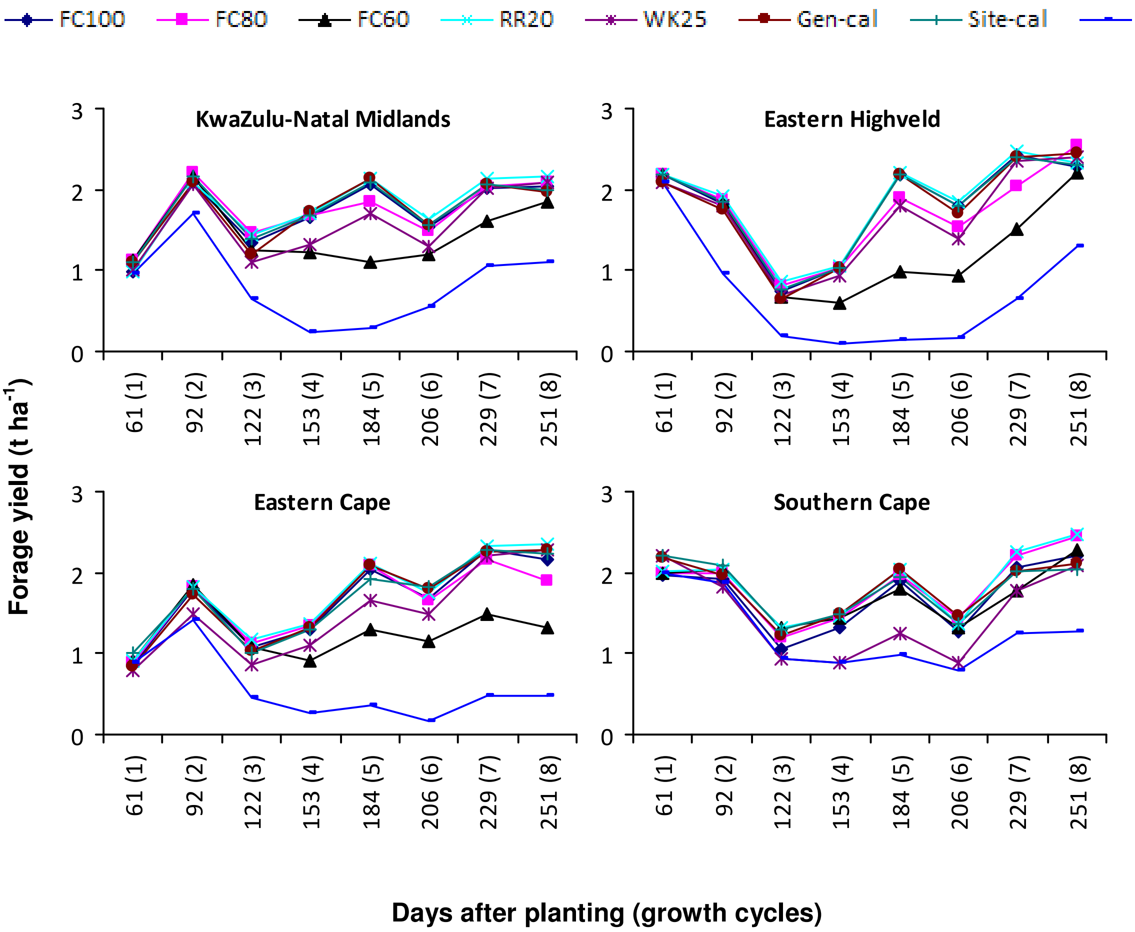

Figure 6.2 Growth cycle forage yield of annual ryegrass (average long-term simulation for seven irrigation strategies and dryland) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

There were variations in irrigation requirements (Figure 6.3) between different regions, years, irrigation strategies and growth cycles. As expected, for all irrigation strategies except WK25, in the summer rainfall areas (KwaZulu-Natal Midlands, Eastern Highveld and Eastern Cape) the highest irrigation applications were in late winter and late spring (70 - 90 mm per growth cycle), whilst in the winter rainfall area (Southern Cape) the highest irrigation applications were in autumn and early summer (60 -70 mm per growth cycle) (Figure 6.3). This was due to differences in rainfall distribution between the different sites (Table 6.1).

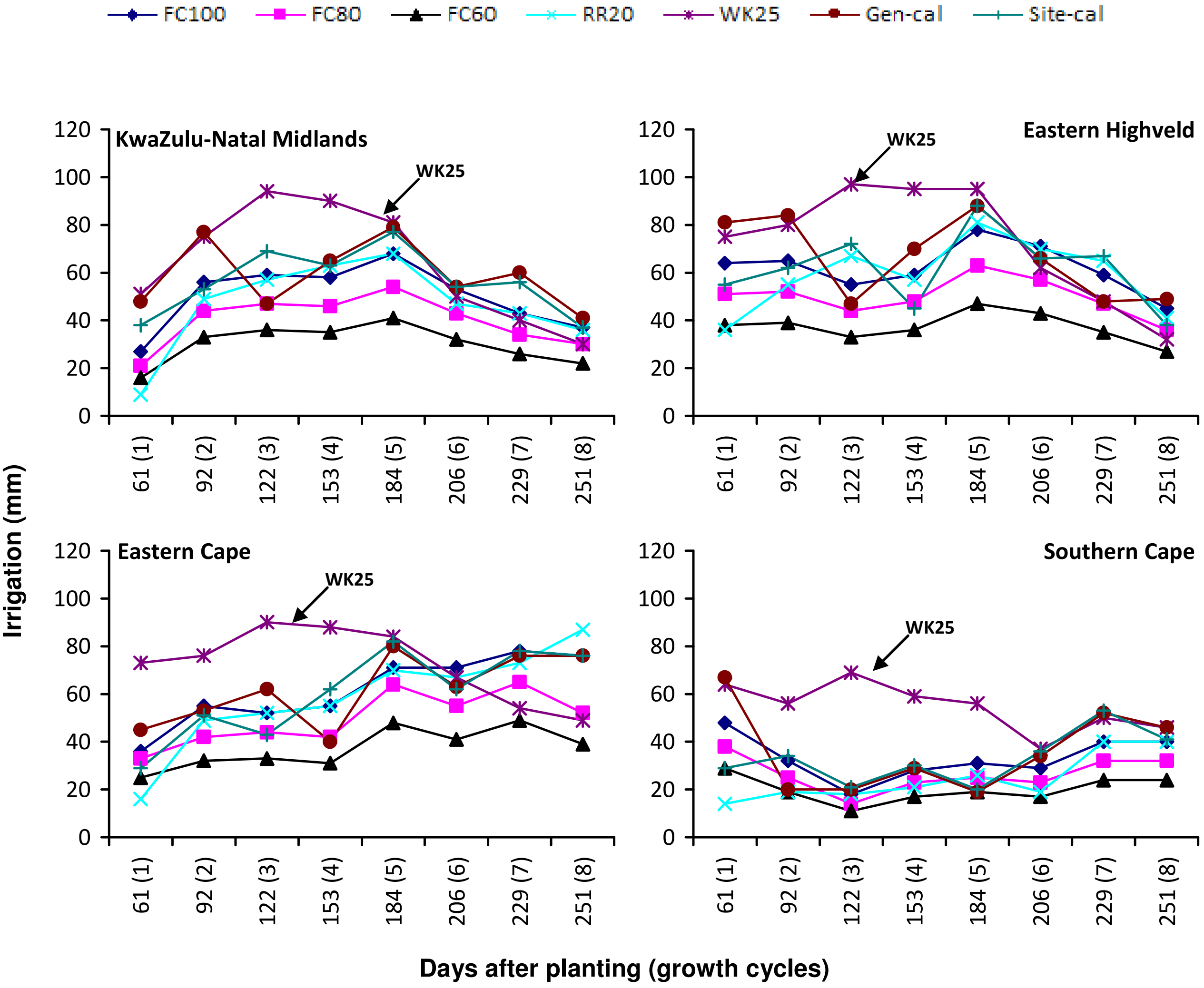

Figure 6.3 Growth cycle irrigation applications of annual ryegrass (long-term simulation for seven irrigation strategies) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

All regions with the exception of the Southern Cape showed similar irrigation requirements in each irrigation strategy (Table 6.4). Generally, irrigation applications for the WK25 strategy were significantly higher than the other strategies. In all regions, in spite of similar yields for the FC100 and RR20 strategies (Table 6.2), irrigation requirements of the “room for rain” (RR20) strategy were lower than the FC100 strategy. For example, in Southern Cape irrigation requirement of annual ryegrass using the RR20 (196 mm) was lower than the FC100 (266 mm) strategy by as much as 26%, where significant rainfall is experienced during the growth season (Table 6.4).

Table 6.4 Seasonal rainfall and irrigation application (long-term simulation for seven irrigation strategies) in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	401(60)§cβ	496(36)bc	495(77)b	266(70)b
FC80	321(48)e	397(29)d	396(62)c	213(56)bc
FC60	241(36)f	298(22)e	297(46)d	160(42)d
RR20	371(61)d	471(51)c	469(99)b	196(71)cd
WK25	511(42)a	581(29)a	580(41)a	434(37)a
Gen-cal	471(43)b	534(25)ab	497(51)b	290(35)b
Site-cal	450(40)b	493(30)bc	481(48)b	263(35)b
Rainfall	392(97)NA	265(62)NA	270(103)NA	462(109)NA

§Values in the brackets are standard deviations. βValues followed by the same letter within a column are not significantly different. NA is not applicable to the treatment.

To illustrate, the current irrigation guideline for annual ryegrass pasture in KwaZulu-Natal is 650 mm over a dry season of 26 weeks with an average of 25 mm per week (Jones, 2006). The total mean water application is 1042 mm (650 mm irrigation + 392 mm rain). This is higher than the model’s long-term mean estimated water application of 903 mm (511 mm irrigation + 392 mm rain) when the current farmers' practice of 25 mm per week strategy was used. This was due to inefficiencies in irrigation scheduling. There was over-irrigation in the cold winter and under irrigation during the warm spring and early summer seasons when WK25 was used (Figure 6.3). With good irrigation scheduling a mean irrigation amount of 191 mm (36%) for the KwaZulu-Natal Midlands, 110 mm (19%) for the Eastern Highveld, 184 mm (32%) for the Eastern Cape and 274 mm (61%) for the Southern Cape could have been saved as compared to the common farmers' practice, without significantly reducing the forage yield.

Deep drainage plus surface runoff losses showed differences among irrigation strategies (Table 6.5). Generally, the lowest losses were observed when the FC60 strategy (18 - 69 mm) was followed, however, for this strategy, yields were significantly reduced compared to other strategies (Table 6.2). In all regions, using calendar based irrigation scheduling (Gen-cal and Site-cal) and the RR20 (when 20 mm as room for rainfall was reserved in the profile) strategies, reduced water loss due to drainage and runoff by 40 - 70% compared to WK25 (Table 6.5), without significant yield reduction (Table 6.3).

Table 6.5 Seasonal water loss due to drainage plus runoff (mm) for the long-term simulation of seven irrigation strategies and dryland in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	89(61)[§]cd[β]	36(37)c	62(53)bc	106(80)b
FC80	64(57)d	21(24)c	45(40)bc	86(90)bc
FC60	61(56)d	18(18)c	42(38)c	69(85)c
RR20	73(68)d	28(26)c	46(43)bc	71(77)c
WK25	195(89)a	138(53)a	186(84)a	256(114)a
Gen-cal	127(92)b	69(53)b	73(56)b	113(108)b
Site-cal	116(91)b	40(47)c	63(66)bc	101(113)bc
I0	58 (57)[NA]	16 (17)[NA]	39 (77)[NA]	48(77) [NA]

[§] Values in the brackets are standard deviations. [β] Values followed by the same letter within a column are not significantly different. [NA] is not applicable to the treatment.

Generally, for all regions over 80% of the water loss (drainage plus runoff) was due to drainage (data not shown). In summer rainfall areas (especially in the KwaZulu-Natal Midlands and Eastern Cape) most of the deep drainage occurred in the first growth cycle (Figure 6.5). This was because planting was in late summer (March) when rainfall was in excess of plant requirements (Figure 6.1). There was also drainage and runoff in the I0 (no irrigation) strategy at the beginning of the season when canopy cover was sparse. In the winter rainfall area (Southern Cape), however, the highest drainage was observed in late winter and early spring when rainfall increased to over 70 mm per month.

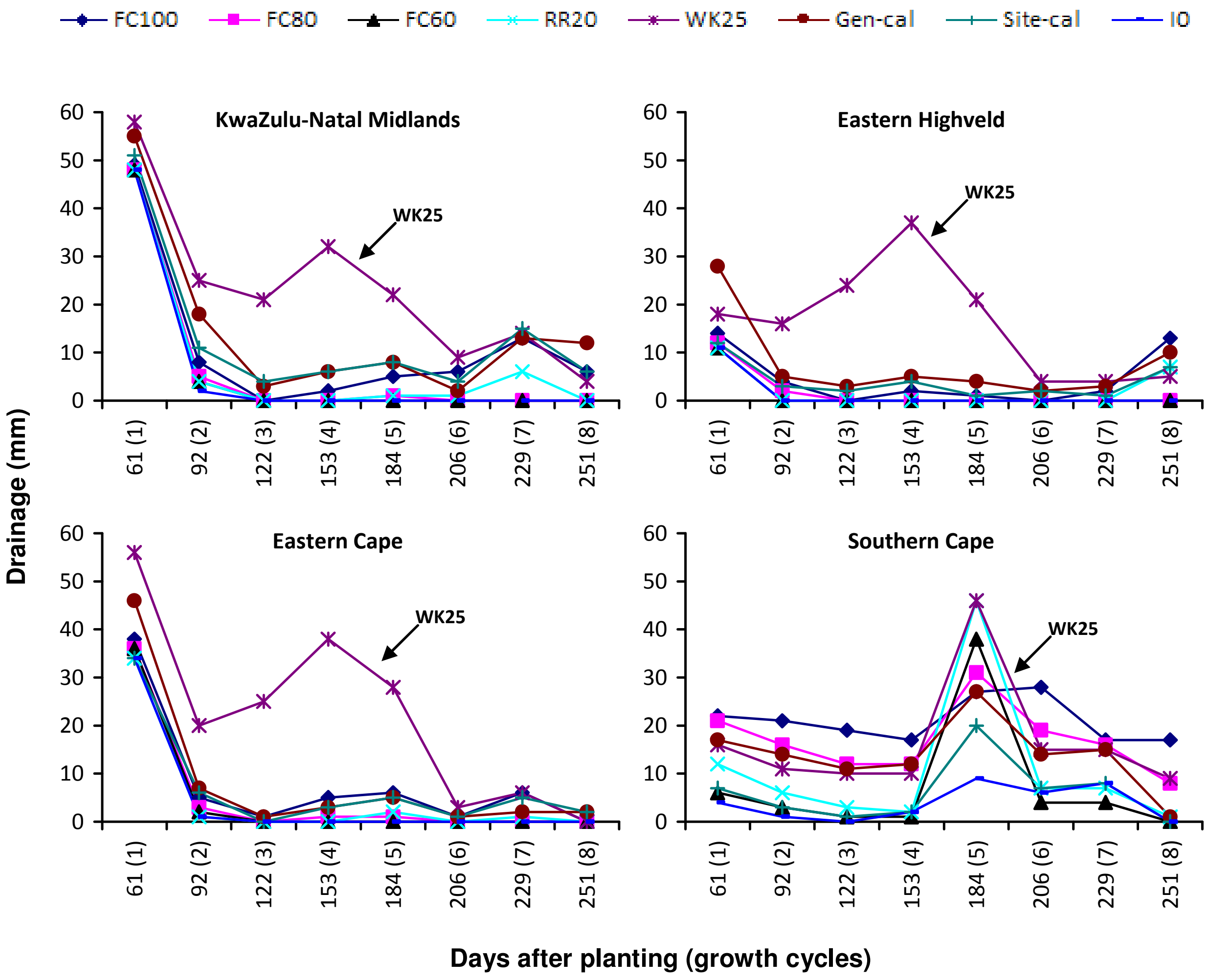

Figure 6.4 Deep percolation from annual ryegrass growth cycles (long-term simulation for seven irrigation strategies and dryland) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

6.3.2 Water and irrigation use efficiency

Generally for all irrigation scenarios, the lowest (mostly lower than 20 kg ha^{-1} mm^{-1}) water use efficiencies (WUEs) were observed in the Eastern Cape (Table 6.6). This could be due to higher vapour pressure deficits (VPD) resulting from higher maximum temperatures during autumn (March) and summer (November). For these months, VPD for Eastern Cape was greater than 2.0, however, for the other sites VPD ranged between 1.2 and 1.6 (Table 6.1). The RR20 strategy showed the highest WUEs compared to other irrigation strategies used. Site-cal also revealed similar results in all sites except in the Southern Cape. High WUEs were due to higher yields and reduced losses of water through drainage and possibly reduced leaching of nutrients. In most regions, all the irrigation scenarios with the exception of severe deficit (FC60) showed superior WUEs to the WK25 strategy. For example, in KwaZulu-Natal Midlands WUEs were greater than 20.0 kg ha^{-1} mm^{-1} for all strategies (except FC60) whilst for the WK25 strategy the WUE was 18.7 kg ha^{-1} mm^{-1}.

Table 6.6 Seasonal water use efficiency (WUE: kg ha^{-1} mm^{-1}) for a long-term simulation of seven irrigation strategies and dryland in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	21.3(1.8) §ab^{β}	21.6(0.7)ab	19.9(1.8)a	24.5(2.8)bc
FC80	21.3(1.5)a	21.3(0.9)ab	19.9(1.8)a	25.8(2.6)ab
FC60	19.6(1.6)cd	19.5(1.3)c	17.7(1.9)b	25.1(2.2)abc
RR20	21.7(1.8)a	21.9(0.8)a	20.4(1.9)a	26.6(2.3)a
WK25	18.7(2.2)d	19.6(1.1)c	17.4(2.3)b	19.8(2.8)d
Gen-cal	20.0(2.0)bcd	20.8(0.7)b	19.3(1.8)a	24.0(2.9)c
Site-cal	20.5(2.2)abc	21.3(1.8)ab	19.3(1.7)a	24.1(2.8)bc
I0	17.9(2.4)^{NA}	20.0(60)^{NA}	15.1(2.7)^{NA}	22.7(5.3)^{NA}

§Values in the brackets are standard deviations. ^{β}Values followed by the same letter within a column are not significantly different. ^{NA} is not applicable to the treatment.

Neal *et al.* (2011) reported ranges of WUEs similar to the current study for different annual temperate pastures using a range of deficit irrigation strategies. For the KwaZulu-Natal Midlands, the calculated WUE from the current farmers' irrigation practice (750 mm of irrigation) for the highest target yield (12 t ha^{-1}) of annual ryegrass is 16.0 kg ha^{-1} mm^{-1} which is lower than the ranges (18.7 to 21.7 kg ha^{-1} mm^{-1}) calculated from the irrigation strategies used in this study. Because evaporative demand changes throughout the season, it may be possible to limit or eliminate irrigation in the months of excessively high evaporative demand or VPD, and produce annual ryegrass only in periods of low evaporative demand. Simulations were conducted using a well-drained soil, therefore caution should be exercised in the selection of the correct soil type (water holding capacity) before using the deficit (FC80) and room for rain (RR20) strategies as choosing the wrong soil type could result in under-irrigation (especially sandy soil).

Marginal irrigation use efficiency (MIUE) explains the forage biomass produced per mm of irrigation application. WUE gives an indication of physiological capability of a particular species, whilst MIUE is more relevant in comparing the pros and cons of irrigation applied compared to dryland production (Rawnsley *et al.,* 2009). In all regions, the highest MIUEs were observed when deficit irrigation strategies were used (Table 6.7). In the Southern Cape, the highest MIUE (23.0 kg ha^{-1} mm^{-1}) was obtained using FC60, while for the other three regions FC80 showed the highest MIUEs (21.0 - 23.0 kg ha^{-1} mm^{-1}). In the Southern Cape, approximately 80 mm of water was saved when FC60 deficit irrigation strategy was used. When using FC80 strategy about 80 mm in the KwaZulu-Natal Midlands, 100 mm in the Eastern Highveld and 120 mm in the Eastern Cape water was saved. In all regions, the RR20 strategy also gave similar, but non-significant MIUEs compared to the most efficient irrigation strategies.

Table 6.7 Seasonal marginal irrigation use efficiency (MIUE: kg ha^{-1} mm^{-1}) for a long-term simulation of seven irrigation strategies in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	17.5(4.0)§bc^{β}	17.7(1.7)b	17.2(3.2)b	11.5(7.0)d
FC80	23.0(2.8)a	20.9(1.0)a	21.4(2.4)a	19.4(7.3)abc
FC60	20.5(2.6)ab	17.9(1.1)b	18.7(1.9)ab	23.0(3.8)a
RR20	21.5(3.6)ab	19.7(1.2)ab	19.8(2.4)ab	22.5(4.7)ab
WK25	11.6(4.3)d	13.4(3.0)c	12.5(4.5)c	13.9(7.3)e
Gen-cal	15.2(4.9)c	16.1(2.8)bc	17.5(3.8)b	15.0(9.9)cd
Site-cal	16.4(5.6)c	18.0(2.4)bc	18.2(4.3)b	16.7(9.8)bcd

§Values in the brackets are standard deviations. ^{β}Values followed by the same letter within a column are not significantly different.

6.3.3 N leaching

For all regions the greatest N leaching occurred in the WK25 strategy (Table 6.8). N leaching was highest in the Southern Cape and lowest in the Eastern Highveld. This was due to difference in the amount and distribution of rainfall between regions. Site specific (Site-cal) and general (Gen-cal) calendar based irrigation scheduling simulated less leaching than WK25, but similar to that of the FC100 simulation. Deficit (FC80) and room for rain (RR20) strategies gave the lowest leaching next to dryland (I0), without compromising yield (Table 6.3). For example, in KwaZulu-Natal Midlands N the use of site specific (Site-cal) and general (Gen-cal) calendar based irrigation scheduling reduced N leaching by up to 30-40% (90-103 kg N ha^{-1}) compared to the WK25 strategy (153 kg ha^{-1}).

Table 6.8 Seasonal N leaching (kg ha^{-1}) for long-term simulations of seven irrigation strategies and dryland in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	81(45)§b$^{\beta}$	34(39)bc	62(57)bc	94(65)b
FC80	46(39)c	11(21)cd	39(39)bcd	63(72)cd
FC60	43(38)c	7(16)d	36(39)d	49(69)d
RR20	53(47)c	15(21)cd	37(46)cd	51(63)d
WK25	153(52)a	104(44)a	148(64)a	176(51)a
Gen-cal	103(58)b	55(54)b	64(58)b	82(75)bc
Site-cal	90(61)b	30(43)cd	55(62)bcd	70(78)bcd
I0	7(4)^{NA}	9(15)^{NA}	33(39)^{NA}	29(61)^{NA}

§Values in the brackets are standard deviations. $^{\beta}$Values followed by the same letter within a column are not significantly different. ^{NA} is not applicable to the treatment.

In all regions, N leaching was highest at the beginning of the season (first growth cycle) during establishment. This was because there was high soil N mineralisation, N carryover from previous seasons, high rainfall, poorly established root systems and a sparse canopy cover. For example, for KwaZulu-Natal Midlands in the first growth cycle, all strategies including I0 (dryland) showed high N leaching (greater than 35.0 kg ha^{-1}) (Figure 6.5). In the remaining growth cycles, however, significant N leaching was observed only when the WK25 strategy was followed (Figure 6.5). When using WK25 strategy about 20.0 kg ha^{-1} was lost compared 0 - 10 kg ha^{-1} in the other irrigation strategies (Figure 6.5).

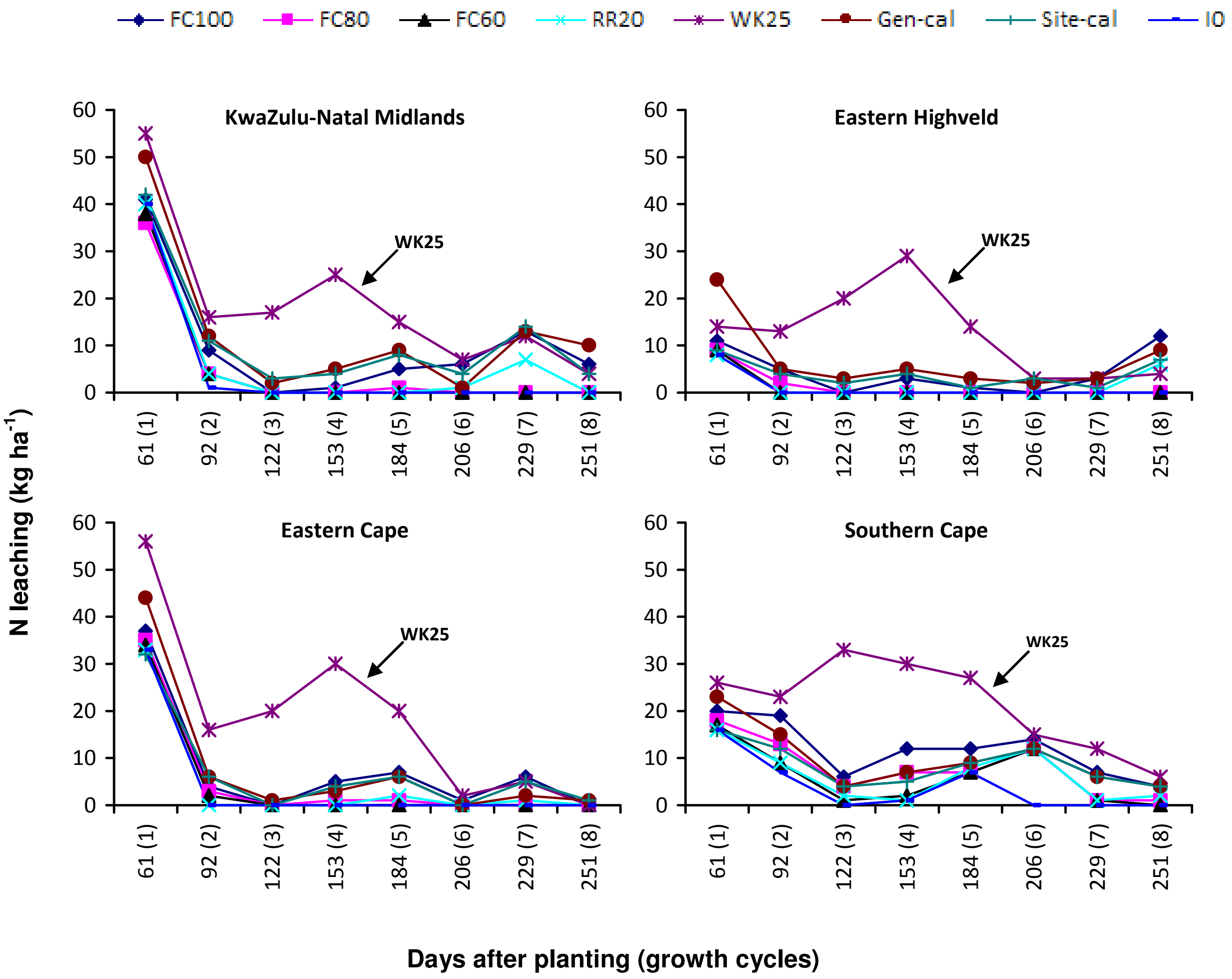

Figure 6.5 Growth cycle N leaching (kg ha^{-1}) below the active root zone (0.6 m) of annual ryegrass (long-term simulation of seven irrigation strategies and dryland) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

Model output trends for mobile soil nitrate concentrations in draining soil solutions during the long-term simulation were similar reaching a maximum of 200 mg L^{-1}. For example, during a ten year simulation exercises (1971-1980) for the KwaZulu-Natal Midlands (Figure 6.6), the occurrence of leaching events were less frequent when using a site specific calendar (Site-cal) compared to following the WK25, Gen-cal or FC100 strategies.

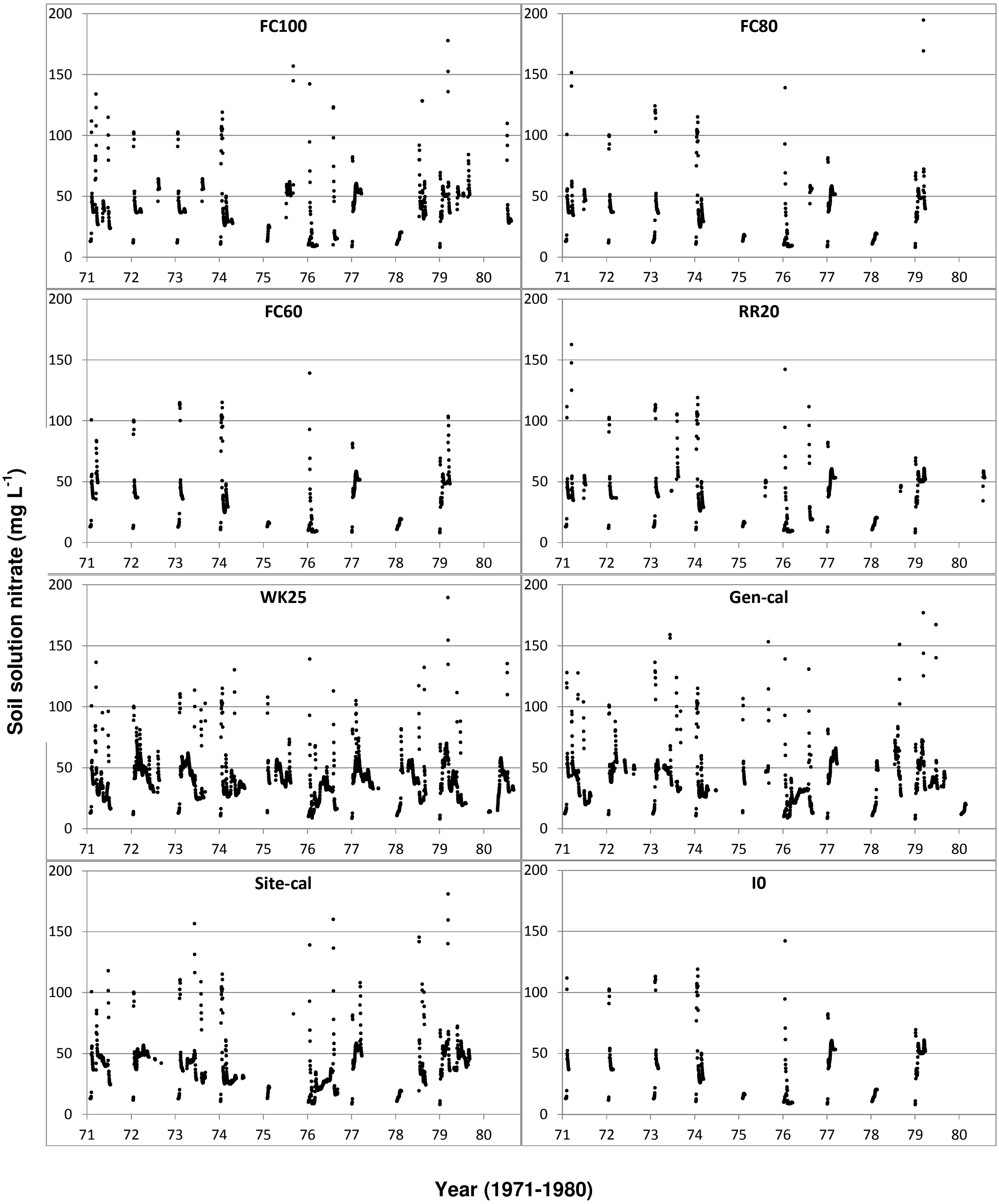

Figure 6.6 Leaching of mobile soil nitrate (mg L^{-1}) concentrations simulated using the model for a range of irrigation strategies for the KwaZulu-Natal Midlands

6.4 CONCLUSIONS

Intensive production of pastures such as annual ryegrass requires high inputs for land preparation, fertilisation and irrigation. Considering these costs, severe deficit irrigation (a deliberate reduction of irrigation) may not be cost-effective. Hence in this study, the main objective was to explore tactical irrigation (e.g. leave room for rain) scheduling and mild deficit irrigation options, where irrigation amount could be reduced without significantly affecting forage yield. The modelling exercise in this study showed that there may be opportunities to improve irrigation use efficiency of irrigated pastures by using rainfall strategically (RR20 or mild deficit of FC80). These strategies can have increased practical implications for medium to heavy soils (with relatively high water holding capacity) in the high rainfall areas of South Africa, especially in the Southern Cape and KwaZulu-Natal Midlands. Because evaporative demand changes throughout the season, it may be possible to limit or eliminate irrigation in months of high evaporative demand or VPD (towards the end of the growing season) and produce annual ryegrass only in periods of low evaporative demand.

Selecting an irrigation strategy depends on climate and availability, type and accuracy of irrigation scheduling equipment such automatic weather station, soil water monitoring probes, WFDs. However, in the absence of irrigation monitoring equipment, simple site specific irrigation calendars (developed using SWB-Pro in Chapter 4) can be used, as these give similar results to the common scientific (FC100) irrigation strategies. Most importantly, deficit irrigation or room for rain refill options can be employed while using calendar-based irrigation scheduling (e.g. by keeping the timing the same, but reducing the amount).

In 2010, of the total annual ryegrass production costs in South Africa, 25% was allocated to irrigation and 55% to fertilisers (Whitehead and Archer, 2009). Therefore, these strategies could also improve nutrient use efficiencies and protect the environment by reducing pollution (leaching of nutrients and chemicals) and soil erosion (surface runoff). Hence, using the cost savings made from reduced fertilisers, water and energy, pasture growers could expand their pastures and improve profits. This study demonstrated that the most appropriate management strategy for farmers is to integrate irrigation and N inputs, since N and water cannot be managed independently. In order to optimise yield and quality, and reduce N leaching, irrigation should be managed based on the wetness of the soil and nitrate concentration in the deep root zone, with the aid of tools such as the wetting front detectors (presented in Chapter 2).

CHAPTER 7

GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 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. This study was conducted to improve N and water use efficiencies using adaptive management and modelling approaches, using annual ryegrass for dairy production as the case study. Hence, field experiments were conducted for testing selected on-farm equipment (FullStop® wetting front detector) and the SWB model for managing N and irrigation.

7.2 BALANCING FORAGE YIELD AND QUALITY USING ADAPTIVE N AND WATER MANAGEMENT

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 N fertiliser and irrigation management (Chapter 2) 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 (Chapter 3). Hence, N application rate of 30-40 kg N ha^{-1} per growth cycle should give highest forage yields and ME yields with CP concentrations within the boundaries of CP_{opt} and CP_{max}. 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 (as presented in Chapter 2).

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.

7.3 ESTIMATING WATER REQUIREMENTS AND DEVELOPING IRRIGATION CALENDARS USING SIMPLE WEB-BASED SWB-PRO MODEL

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 cooler part of the season or under-irrigation in warmer part of the season. To use the model for determining irrigation requirements and developing irrigation calendars, the SWB-Pro model was validated at two sites for different irrigation treatment practices (Chapter 4). 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 model was satisfactory, site specific irrigation calendars were developed, for four major milk producing areas of South Africa (KwaZulu-Natal Midlands, Eastern Highveld, Eastern Cape and Southern Cape) using three different soil textural classes. Monthly irrigation calendars with variable intervals were also developed for a general deep, well drained and medium textured soil by replenishing the soil after 25 mm of soil water was depleted (similar to farmers’ recommendation but scheduling the timing according to the long-term water requirement). The simpler monthly irrigation calendars can be used in the absence the more accurate site specific calendars.

The SWB-Pro model can be used by farmers or consultants to develop their own calendars using the following simple inputs: 1) nearest weather station data; 2) soil textural class 3) planting date 4) rooting depth; and 4) irrigation system, timing and refill options. Irrigators can also follow different strategies for making decisions on when and how much to irrigate depending on particular situations.

In the absence of irrigation scheduling tools, irrigation calendars developed using a model would be far better than a rigid guideline of 25 mm a week. It needs to be stressed, however, that irrigation scheduling with the aid of real time modelling or measurements is better than calendars developed using the SWB-Pro model with long-term historical weather data. The model is available on the web and can be downloaded free of charge.

7.4 EXPLORING POTENTIAL N AND WATER MANAGEMENT STRATEGIES USING SWB-SCI MODEL

Sustainable pasture production requires best fertiliser and water management practice in order to attain high biomass yield with minimum inputs to maximise profit. However, pasture systems are highly complex, involving interactions between crop growth, soil and plant nutrient dynamics and animal and pasture management systems. To increase our basic understanding of the effects of N and water stress in pasture production, the SWB-Sci model was calibrated and validated using data sets collected from two sites under a range of N fertiliser and irrigation levels (Chapter 5). The model predicted annual ryegrass growth, biomass N uptake, soil water content and mobile soil nitrate reasonably well. The model was sensitive to N application under water stressed and non-stressed conditions as yield, LAI, biomass, N uptake and soil nitrates increased as levels of N increase.

The SWB-Sci model’s simulation results can be used in conjunction with data collected from field experiments to better understand systems and extrapolate findings in time and space. This can save money and time required for conducting long-term intensive field experiments for gathering information on potential pasture production with different resources management strategies.

Having gained confidence in modelling N and water interactions of pasture systems using SWB-Sci (Chapter 5), other scenarios and conditions, including nutrient leaching and non-point source pollution, climate and soil variability, crop management, alternative irrigation and N management strategies could now be explored using the this model. Therefore, SWB-Sci model was used to explore a range of irrigation management strategies (Chapter 6) including calendar based irrigation scheduling developed with the simple SWB-Pro model (Chapter 4), deficit irrigation and “room for rain” for the major annual ryegrass growing areas of South Africa.

The modelling exercise in this study showed that there are opportunities to improve irrigation use efficiency of irrigated pastures by using RR20 (20 mm room for rain) or mild deficit of FC80 (irrigation 80% of field capacity). These strategies have increased practical implications for medium to heavy soils (with relatively high water holding capacity) in the high rainfall areas of the Southern Cape and KwaZulu-Natal Midlands. Because evaporative demand changes throughout the season, it may be possible to limit or eliminate irrigation in months of high evaporative demand or VPD (towards the end of the growing season).

In 2010, of the total annual ryegrass production costs in South Africa, 25% was allocated to irrigation, and 55% to fertilisers (Whitehead and Archer, 2009). RR20 and FC80 strategies would improve nutrient use efficiencies and protect the environment by reducing pollution (leaching of nutrients and chemicals) and soil erosion (surface runoff). Using the cost savings made from reduced fertilisers, water and energy, a farmer could expand his pastures and improve his profits. This study demonstrated that the most appropriate management strategy for farmers is to integrate irrigation and N inputs, since N and water cannot be managed independently. In order to optimise yield and quality, and reduce N leaching, irrigation should be managed based on the wetness of the soil and nitrate concentration in the deeper part of root zone, with the aid of tools such as the wetting front detectors (presented in Chapter 2).

7.5 RECOMMENDATIONS

Farmers are subjective adaptive managers and the use of simple monitoring approaches and thresholds presents a way to structure their learning. However, the challenge is to find tools which allow effective implementation of adaptive management strategy. The wetting front detector is a robust, on-farm monitoring tool which is relatively simple, cost effective and readily adopted by farmers. It can be simultaneously used for managing irrigation water and observing N by monitoring depth of wetting and nitrate concentration of the passing wetting fronts. The thresholds obtained in the current study can be used as basis. Farmers are expected to improve these thresholds as more experience is gained.

Real-time monitoring is the best irrigation management approach. In the absence of such an approach, however, calendars developed using the SWB-Pro model with long-term historical weather data is better management option than the rigid guideline of 25 mm per week. SWB model could still be used for mixed pasture system in which ryegrass is the dominant species. However, the model needs to be evaluated for newly planted and already established annual and perennial pastures.

Scenario modelling demonstrated that the best management strategy of achieving maximum yield, low N leaching is by integrating N and water management. Thus, such integrated management can be achieved based on the wetness of the soil and nitrate concentration in the deep root zone using wetting front detectors. The model can be used to generate monitoring protocols such as depth of wetting front detectors placement and selecting N thresholds to be used adaptive management. Alternative integrated adaptive N and water management strategies need to be tested.

In pasture systems, N application is through surface broadcasting. This could result in increased N losses by surface runoff. Therefore, the inclusion of a runoff subroutine in SWB-Sci would most likely improve the accuracy of the simulation results.

The following areas are recommended for future studies:

1) Current field experiments were conducted under mechanical harvesting, therefore, studies need to be conducted under grazing conditions, especially for managing N.
2) Due to an increase in N fertiliser costs, other cheaper alternative N sources (e.g. mixed legume based) need to be assessed.
3) Real-time N and water management using remote sensing technology also needs to be tested for its applicability to pasture production.

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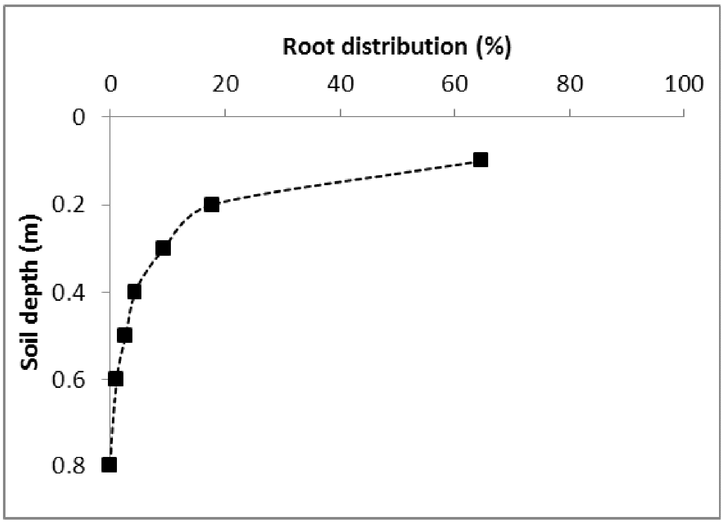
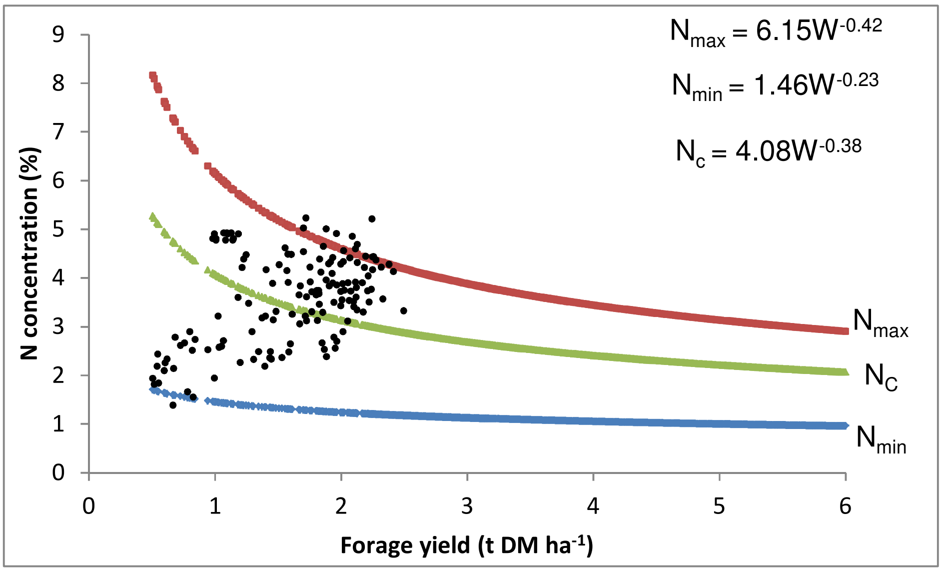
APPENDIX



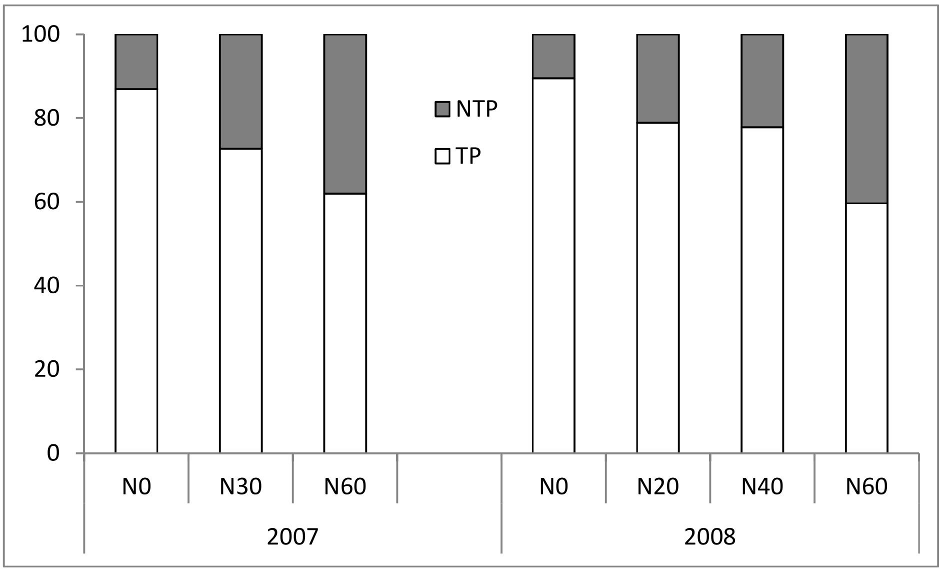
Appendix A1 Mean root biomass percentages of annual ryegrass for non N limiting well watered treatment



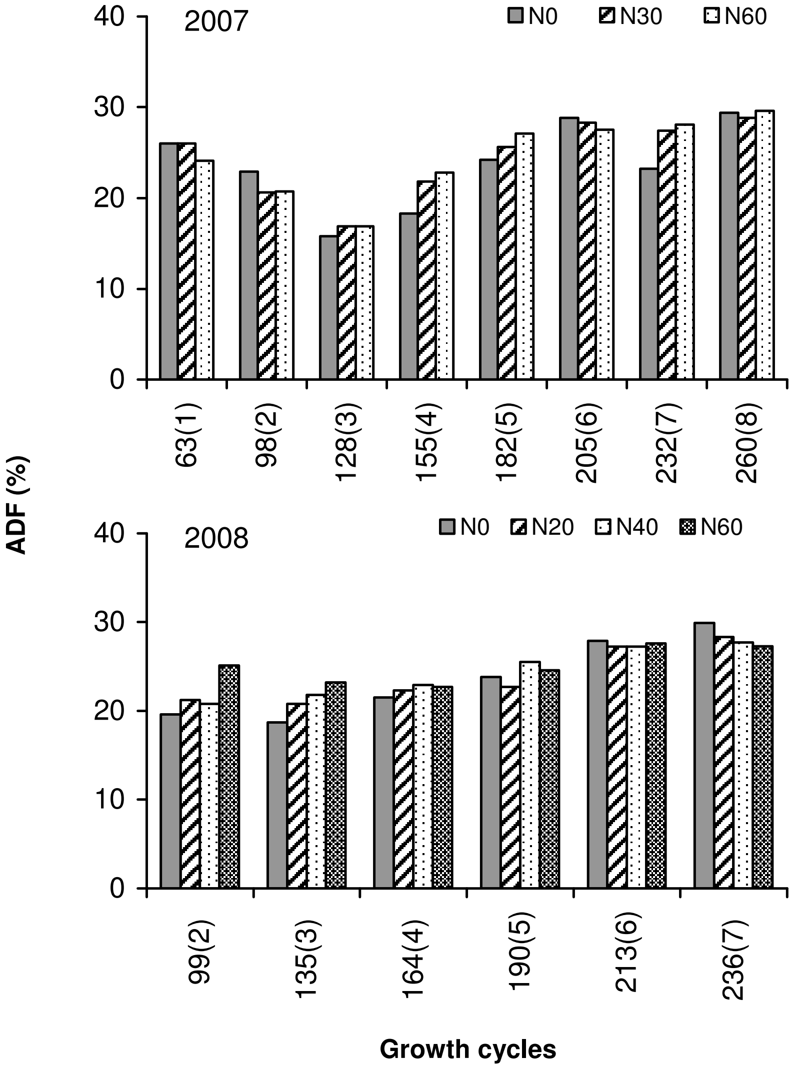
Appendix A2 Forage yield in relation to N concentration of annual ryegrass for data collected from a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60}). Maximum (N_{max}), minimum (N_{min}) and critical (N_c) forage N concentration developed using dilution curves of Marino *et al.* (2004).

Appendix B1 Days after planting (DAP) and growing day degrees (GDD) after planting for growth cycles in 2007 and 2008

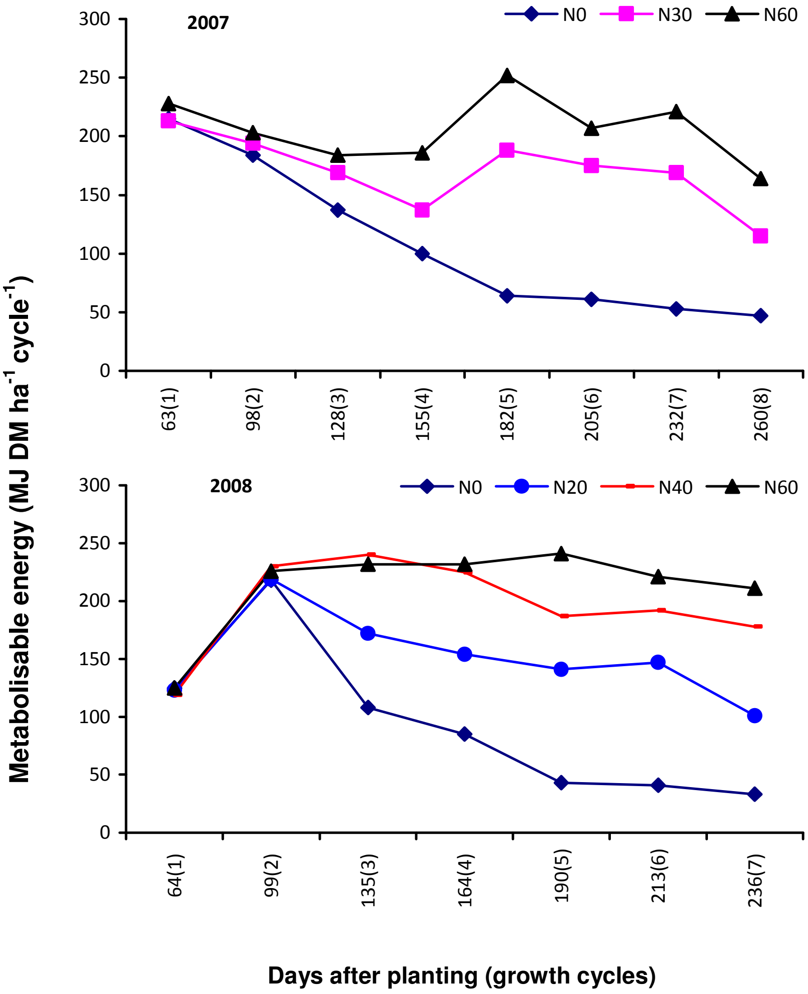
Growth cycle	DAP		Cumulative GDD		Days cycle^{-1}		GDD cycle^{-1}	
	2007	2008	2007	2008	2007	2008	2007	2008
1	63	64	780	735	63	64	780	735
2	98	99	1106	1023	35	35	326	288
3	128	135	1340	1333	30	36	234	310
4	155	164	1587	1645	27	29	247	312
5	182	190	1856	1943	27	26	269	298
6	205	213	2169	2235	23	23	313	292
7	232	236	2528	2555	27	23	359	320
8	259	-	2856	-	27	-	328	-



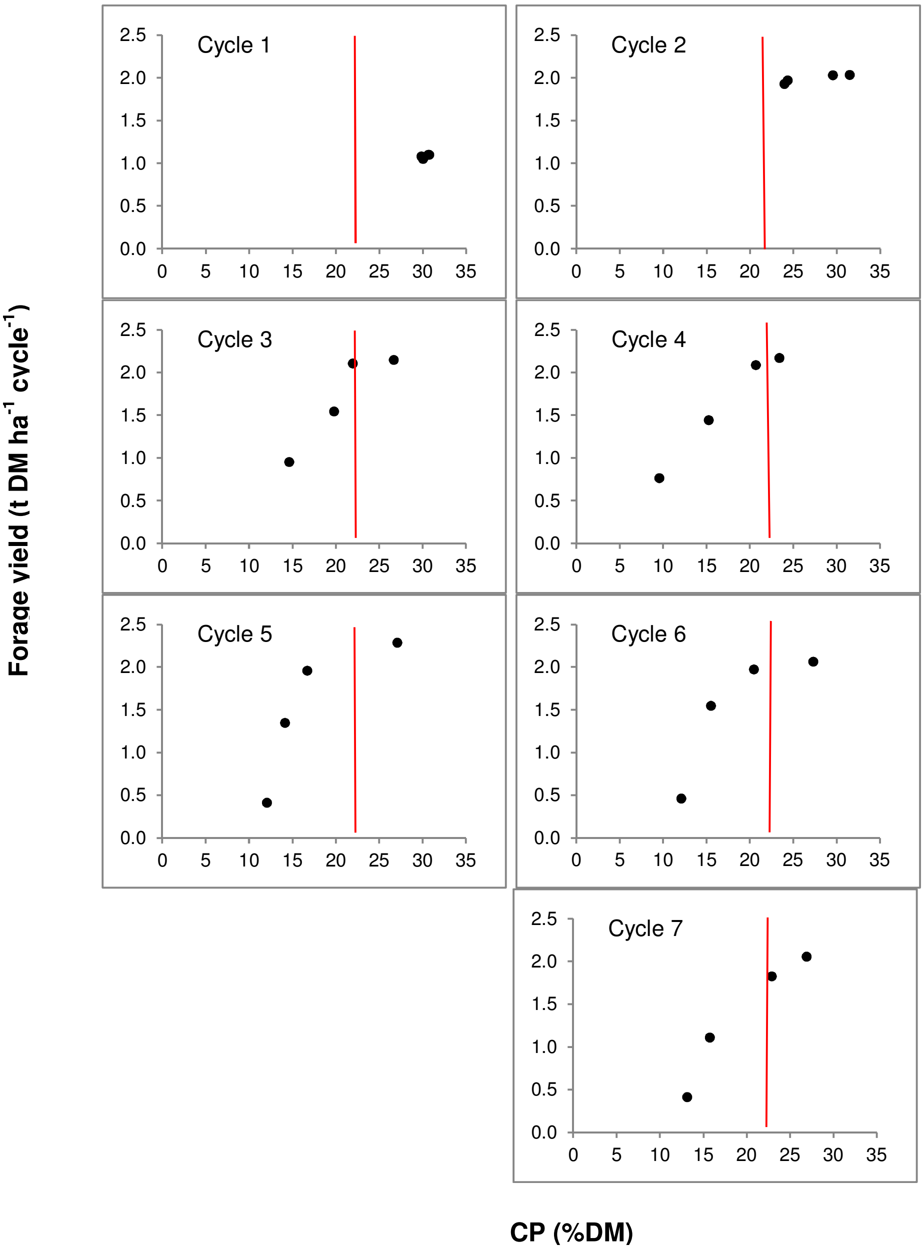
Appendix B2 Seasonal mean true protein (TP) and non-true protein (NTP) percentages of crude protein (CP) of annual ryegrass under a range of N application rates in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})



Appendix B3 Acid detergent fibre (ADF) of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})



Appendix B4 Metabolisable energy (ME) concentrations of annual ryegrass under a range of N application rates for eight growth cycles in 2007 (0, 30, 60 kg ha^{-1} cycle^{-1} for N_0, N_{30}, N_{60}) and seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1} for N_0, N_{20}, N_{40}, N_{60})



Appendix B5 Crude protein vs forage yield of annual ryegrass under a range of N application rates for seven growth cycles in 2008 (0, 20, 40 60 kg ha^{-1} cycle^{-1}). Vertical lines are maximum CP (22%)