WATER USE AND CROP PARAMETERS OF PASTURES FOR LIVESTOCK GRAZING MANAGEMENT

Report to the

WATER RESEARCH COMMISSION

Compiled by

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EXECUTIVE SUMMARY

1. BACKGROUND AND MOTIVATION

Irrigated agriculture is facing fierce competition for a substantial share of water as the water demand for industrial, domestic, municipal and other activities are increasing rapidly. The increasing shortage of irrigation water in addition to the increasing cost of fertiliser creates a great need to improve the practices of irrigation through better understanding of crop water requirements and ultimately better irrigation scheduling.

Cultivated pastures form the base of feed for many livestock production enterprises in South Africa, comprising more than one sixth of the country's total irrigated land, making it one of South Africa's highest value crops. To ensure sustainable pasture production to produce sufficient pasture to supply the protein demand more efficiently for a growing population, innovations will be required to increase the efficiency of water and nitrogen use in such pasture production systems used in the livestock industry.

To save on nitrogen fertilizers costs, much attention has been given to self-nitrogen fixating legume hay crops and mixed grass-legume grazed pastures. These pasture management practices are not always very economical from both a quantitative and qualitative perspective, but are becoming more economical especially in the light of sustainability. Lucerne which is regarded as the most important legume hay crop, has for many years been the pasture crop most frequently irrigated. Lucerne however is known for its high water usage compared to other pastures. The current irrigation guideline for lucerne is a very rigid and for mixed legume-grass pastures non-existent.

From literature it is evident that there are knowledge gaps regarding the pasture crop growth responses to management practices in relation to the amount of water used. There also exists a lack of data and reliable information pertaining to water requirements of valuable pasture legumes. Methods to address these gaps, therefore, need to be devised and applied

in order to increase water use efficiency of important irrigated pasture crops at farm level.

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

Currently, satellite-based remote sensing is showing promising results in estimating irrigation requirements of many crops. In the near future, this technology could become a more affordable tool for managing irrigations of pastures. The accuracy of the technology for pasture management will hereby be assessed. This can therefore inform any potential future use of this technology for real time irrigation scheduling for pasture management.

2. PROJECT OBJECTIVE AND AIMS

The objective of this research is to address the abovementioned challenges and to find answers to the knowledge gaps identified in literature.

Specific project aims include:

- To measure water use of selected irrigated pastures (subtropical grass/temperate grass mixture, temperate grass/temperate legume mixtures and monospecific Lucerne stands) at representative sites of the major irrigated pasture growing areas.

- To generate information on growth analysis, crop model parameters and water balance studies for selected irrigated pastures in the major growing regions (winter and summer rainfall areas).
- To develop, verify and validate the most appropriate crop growth/pasture model(s) for selected irrigated pastures.
- To determine water requirement of selected irrigated pastures using the validated model(s).
- Extrapolate irrigation requirement estimates of selected irrigated pastures to pasture growing areas as far as possible.
- To test remote sensing technology for a possible future use for irrigation management of pastures.

In order to address the set objective and aims, this project focussed on synthesizing fragmented data that exists on various aspects of irrigated pasture production nationally and where applicable internationally. Pasture production systems are very dynamic due to the influence of climatic factors, species differences and different management systems. To provide the best possible guideline for such systems it was imperative to synthesize collated fragmented historical data with data collected from this project. Data collected represents different locations (summer and winter rainfall regions) in addition to different management systems (mechanically defoliated or grazed) used in South Africa.

3. PASTURE EVALUATION TRIALS: EXPERIMENTAL STATION

To establish the water requirements of different mixed pasture systems, it was imperative to understand the monospecific pasture water requirements. To further understand the water requirements of mixed pastures, the water used by selected irrigated pasture mixtures (subtropical grass/temperate grass mixture, temperate grass/temperate legume mixtures and monospecific pasture stands) in the summer rainfall and winter rainfall region was measured. Furthermore, a simple irrigation scheduling method based on canopy cover was evaluated as a potentially effective method for pasture production. The on-station research trials were also imperative to generate information on growth analyses, crop model parameters and water and nitrogen balance studies for selected irrigated pastures.

Study areas

Summer rainfall region: Hatfield Experimental Farm, University of Pretoria, Pretoria South Africa.

Winter & Summer rainfall region: Outeniqua Experimental Farm, Western Cape Department of Agriculture, George.

These region's growing season for subtropical species extended from September-May, and for temperate species March-November.
Thirteen different grass and legume pasture treatments were planted as pure stands and in mixtures.

Measurements

Field measurements related to crop development and the soil water balance (soil water content, rainfall, irrigation and evapotranspiration) were obtained in both study areas. Growth (e.g. canopy cover, leaf area index, destructively sampled biomass, yield and crude protein) was measured at approximate monthly intervals. Water balance measurements were made continuously or at weekly intervals.

Crop coefficients for each pasture treatment were calculated, compared and synthesized with published crop coefficients, as described in literature and especially following the methods used in FAO 56.

4. ON FARM PASTURE MONITORING SITES

To get an understanding of the on-farm level of water management in a lucerne production and mixed pasture grazing systems, the following sites were selected to obtain the necessary data to verify and align with modelling outcomes. The objective of these trials was to measure the water use and growth rate of commercially planted lucerne and commonly grazed mixed pastures under irrigated conditions. A further objective was to provide in field monitoring tools and feedback to the farmer on irrigation practices and data collection.

Study areas

Lucerne production system: Brits / Thabazimbi, North West Province.

Mixed kikuyu / perennial ryegrass pasture grazing system: Cedara region. KwaZulu-Natal.

Measurements

Field measurements related to crop development and the soil water balance (soil water content, rainfall, irrigation and evapotranspiration) were obtained in both study areas. Growth (e.g. canopy cover, leaf area index, destructively sampled biomass, yield and crude protein) was measured at approximate monthly intervals. Water balance measurements were made continuously or at weekly intervals.

The crop coefficients for each pasture treatment were calculated, compared and synthesized with published crop coefficients, as described in literature and especially following the methods used in FAO 56.

5. UNDERSTANDING THE WATER REQUIREMENT OF MONSOSPECIFIC AND MIXED PASTURES

In evaluating various pasture treatments and production systems, it was important to assess a few critical plant growth parameters to understand the effects of irrigation and defoliation on pasture water use and production. To further understand the value of individual species in mixed pastures, the understanding of the growth potential of these monospecific pastures is imperative. Using the Rising Plate Meter (RPM) to estimate the yield of pastures is a practical tool many farmers use and was included during the evaluation of pastures.

Botanical composition is an important parameter to measure, indicating how management and growth conditions contribute to the species adaptability. Botanical composition changes during the growing season which is ascribed to management, specifically the intensity of defoliation which favours some species more than others in a mixture. This complexity affects the consistent measuring of such pastures. It is expected that the more dominant species in the mixture are responsible for the majority of the water use. With the changing botanical composition of mixed pasture systems, it was hypothesized that there would be a strong correlation between canopy cover, irrespective of botanical composition, with the leaf area index (LAI) and the fractional interception through photosynthetically active radiation (PAR) of the plant canopy.

Crop water use and growth can be simulated relatively simply, using crop coefficients for various growth stages. The crop coefficients for each pasture treatment are calculated, compared and synthesized with published crop coefficients, as described in literature and especially following the methods used in FAO 56.

To understand the water use and efficiency of pastures, it is important to establish the crop growth and soil water balance fluxes and storage using weather, soil and crop units. This can easily be achieved using crop growth models. Besides knowing the water content of the soil, it will also be useful for farmers to understand the movement of the wetting front when irrigating their pastures.

6. MODELLING THE WATER USE OF PASTURES

Irrigation recommendations are typically developed from field experiments conducted for a few years. 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. 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. These models can be used to extrapolate research findings (irrigation and other pasture management requirements) to pasture growing areas. Models can also be helpful in selecting best management practices for specific sites and environmental conditions. However, models need to be parameterised, calibrated and tested with measured data. In recent years, a wide range of soil-plant-atmosphere type numerical models with different degrees of complexity have been developed. In general, complex models have a wide range of input parameters and hence intensive data sets are needed to run them accurately.

Soil-plant-atmosphere continuum type models were selected for this project. Based on the scope, input data requirements, adoption by farmers and consultants, and accessibility, the DairyMod and SWB crop/pasture models were selected. In this project, these two models were parameterised, tested and validated.

7. POTENTIAL OF DETERMINING WATER USE OF PASTURES USING REMOTE SENSING

Satellite-based remote sensing (SEBAL) is showing promising results in estimating irrigation requirements. The accuracy of the technology for pasture management will hereby be assessed. This can therefore inform any potential future use of this technology for real time irrigation scheduling for pasture management. The main benefits which a technology that uses satellite data and a physically based algorithm like SEBAL brings to agricultural and water management, is the fact that (a) data can be represented spatially and (b) it is quantitative. Hence these spatial, quantitative data products can be used to evaluate farms and fields and to detect problems (anomalies) which can then be investigated further. Farmers can subsequently be advised in terms of, for example, better water management, based on trends in the data over space and time.

8. CAPACITY BUILDING AND TECHNOLOGY EXCHANGE

Students

Seven students from the University of Pretoria have been involved formally in this project: one PhD, five MSc and one BSc Hons.

One information dissemination workshop was held with farmers and consultants to align research findings with practical expectations and queries.

One in-field demonstration was conducted as part of this project, to expose farmers to the field technologies used to estimate water used and applied to pasture crops.

Researchers

The researchers were exposed to different data sets, technologies and models through the project in working with the available data sets.

9. PROJECT CONCLUSIONS AND RECOMMENDATIONS

Conclusions that have been reached are related to the extent to which the objectives have been met.

This project has focussed on synthesizing on-station and on-farm data together with fragmented historical data and the use of empirical models to provide a better understanding of the behaviour of different pasture systems and to identify and develop tools and general guidelines in order to increase water use efficiency at farm level.

In evaluating various pasture treatments and production systems, it was imperative to assess a few important plant growth parameters to understand the effects of irrigation and defoliation on pasture production.

Most monospecific and mixed pastures are predominantly perennial production systems with a lifespan of more than 5 years, resulting in successional regrowth cycles after defoliation. A regrowth cycle of 6-8 weeks until the pasture reaches a physiologically optimal defoliation stage, has variable moisture requirements and losses.

Botanical composition is an important parameter to measure, as it indicates how the mixed pasture is changing due to either management and/or changing growth conditions. It is clear from the study that the mixed pastures botanical composition changed during the growing season due to management. These results have pre-concluded that monitoring the canopy cover of a mixed pasture might be more valuable than understanding individual species in the mixture due to the change in botanical composition over time due to management.

It is concluded that the more dominant species in a mixed pasture in its specific growing season is responsible for the majority of the water use.

To establish the rate and availability of pasture in field (on-farm), the RPM method is well adopted. This is a quick tool to assess the dry matter availability, and this study confirmed strong correlations between Rising Plate Meter (RPM) readings and DM yield measurements obtained for mixed pastures. This was obviously due to the good growth interaction of species with the more dominant species being supported by the less dominant species.

It is concluded that mixed pastures have a better canopy density and resistance throughout the year resulting in a good yield estimate with a Rising Plate Meter (RPM).

The RPM method is accepted as an easy, quick and accurate method of establishing the amount of available pasture, irrespective of the amount of water used.

The research concluded that there is a potentially good correlation between RPM reading and a pastures water use. This research however, will require further investigation.

The data collected for monospecific pastures illustrate the different water requirements per week, which relates to the physiological growth stage (maturity) of the pasture at a specific period after defoliation. In this time the evaporation factor is at its highest since there is a small canopy present to cover the soil surface and only enough water should be applied for pasture growth. It is evident that less water than the current guideline (25 $mm.week^{-1}$) needs to be applied to a pasture in the first two weeks after defoliation. Once the pasture canopy develops, less water is evaporated and more water is available for pasture growth.

It is concluded that after defoliation occurs less water than the current guideline (25 $mm.week^{-1}$) is required for initial regrowth since more moisture is lost through evaporation. An increase in canopy size, results in an increase in water use efficiency if not under/over irrigated.

Some pastures are more water use efficient in their known growing seasons and as soon as growth conditions become less suitable, too cold or too hot, shorter or longer day lengths, they require more or less water to survive these periods.

It is concluded that when a grazing or cutting cycle is too long and a pasture reaches a mature and reproductive stage, canopy cover is large and WU high, but DM and quality will start to decrease and so will water use efficiency decrease.

The WU of grazed kikuyu/lucerne mixed pastures and kikuyu oversown with perennial ryegrass or cocksfoot had a relatively strong, positive relationship with PAR and LAI. The research found that with an in increase in canopy cover, WU also increased. After the pasture was grazed and the canopy cover was small (PAR and LAI low), WU was also at its lowest point and started to increase as the canopy grew larger. It is recommended that this research be further investigated.

This research concludes that when a fixed irrigation rate (e.g. 25 mm.week^{-1}) is used for a pasture at an earlier stage of regrowth (small canopy), there is higher percentage moisture lost as a result of evaporation than the later stages of canopy development. With the same fixed rate while the canopy is fully developed and species enters a mature and reproductive stage, then a higher percentage of water is lost to drainage in dormant seasons resulting in a lower WUE.

It is important to observe that some species can become dominant in the mixture and this is a function of the species growth habit (strongly rhizomatous and stoloniferous) which can also become extremely vigorous due to intensive defoliation practices, i.e. mechanical harvesting. It is therefore important that if a mixed pasture is considered, that the species selected to be planted together, have the same growth habit as far as possible, or that the more vigorous species are planted in lower proportions, giving the less competitive species an opportunity to grow.

Using calculated crop coefficients which are defined as the ratio of ET determined from researched pastures and their soil surfaces to reference ET as defined by weather data, can assist in establishing pasture irrigation requirements.

Examples of estimated pasture water requirement ranges per annum (Winter / Summer):

1. Kikuyu (*Pennisetum clandestinum*) (Gauteng)
   17-30 mm.week^{-1}

2. Tall fescue (*Festuca arundinacea*) (Gauteng)
   14-30 mm.week^{-1}

3. Lucerne (*Medicago sativa*) (Gauteng)
   15-30.5 mm.week^{-1}

4. White clover (*Trifolium repens*) (Gauteng)
   18-29 mm.week^{-1}

5. Kikuyu / Lucerne mixed pasture (Gauteng)
   15-34 mm.week^{-1}

6. Tall fescue / Lucerne mixed pasture (Gauteng)
   15.5-28 mm.week^{-1}

7. Tall fescue / White clover mixed pasture (Gauteng)
   16.5-30 mm.week^{-1}

8. Lucerne (*Medicago sativa*) (North West)
   12.5-44 mm.week^{-1}

9. Kikuyu / Perennial ryegrass (Grazing) mixed pasture (KZN)
   9.5-29.5 mm.week^{-1}

10. Kikuyu / Lucerne (Grazing) mixed pasture (Western Cape)
16-28 mm.week^{-1}

11. Kikuyu / Perennial ryegrass (Grazing) mixed pasture (Western Cape)
12-28 mm.week^{-1}

12. Kikuyu / Cocksfoot (Grazing) mixed pasture (Western Cape)
9.3-28 mm.week^{-1}

Modelling is an extremely important and powerful tool, and was successfully used to focus on the integration of the soil, plant and livestock factors (data) to obtain a better understanding of how the entire pasture production system functions. The international model, DairyMod was successfully evaluated and tested and has shown its ability to incorporate local weather data and to adjust specific parameters related to the soil, pasture growth and livestock management factors. This model has been specifically used to test mixed pastures.

This project assisted in parameterizing SWB to estimate real-time crop water requirements and recommend the irrigation amount and date, based on the current crop water usage and set user preferences for lucerne. If farmers do not have access to irrigation monitoring tools, SWB can be used to develop site-specific irrigation calendars. The calendar, which recommends irrigation dates and amounts, can be printed out and used as a guide to manage irrigations.

It was concluded that the water use of lucerne and mixed pastures estimated using remote sensing is similar to the water use estimated using SWB model, eddy covariance and field water balance measurements. From the results of water use, the remote sensing technology looks promising and could be used as a tool for irrigation scheduling of pastures. It is recommended that more dedicated remote sensing research be conducted on irrigated pasture production systems in the livestock industry.

Finally, it can be concluded that the water (irrigation) requirements of mixed and monospecific pastures can be determined by the following approach:

Step 1: Determine the pasture components (which species) of the mixture and their expected growth cycles according to production system (grazing intensity or harvesting period)
Step 2: Derive / use available crop coefficients (K_C)
Step 3: Determine and use the areas ET_o together with crop coefficients to calculate ET_C
Step 4: Obtain RPM readings (Calibration important)
Step 5: Measure the canopy cover (PAR and LAI) – if possible
Step 6: Run DairyMod or SWB (generate irrigation calendars) with available resource parameters including ET_o

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11. PUBLICATIONS

Knowledge generation in this project by researchers, farmers and other stakeholders were an important part of this project. This information was shared through presentations at conferences, published proceedings and popular articles, dissertations and scientific articles published.

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CONTENTS

LIST OF DEFINITIONS

1. **Soil water balance**: It is the difference between inputs and losses that reflect a change in soil water storage

2. **ET_o (Reference crop evapotranspiration):** The evapotranspiration rate from a reference surface (Calculated using grass as a reference crop). The reference surface is a hypothetical grass reference crop with specific characteristics was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. The reference evapotranspiration as determined by the Penman-Monteith approach considers an imaginative crop with fixed parameters and resistance coefficients.

3. **ET_r (reference evapotranspiration):** ET_r is defined as the rate at which water would be removed from the soil and plant surfaces expressed as the rate of latent heat transfer per unit area, or as a depth of water per unit time evaporated and transpired from a reference crop. The use of ET_r for a specified crop surface has largely replaced the use of the more general potential crop ET. This is calculated using alfalfa as the reference crop.

4. **Soil water (moisture) deficit:** this is the amount of rain needed to bring the **soil** moisture content back to field capacity.

5. **Adaptive management:** A learning process through which a farmer is able to adopt practices that make sense for his specific conditions to increase profits and reduce environmental impacts at the same time.

6. **Water use efficiency:** A quantitative measurement of how much biomass or yield is produced over a growing season, normalised with the amount of water used up in the process. It also refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration.

7. **Monospecific pastures:** are pastures comprising of a single species of grass or legume.

8. **Mixed pastures:** are pastures comprising of different grasses or grass/legume combinations growing together.

9. **Overseeding:** The process by which a seed is broadcast in to existing vegetation irrespective of whether the existing vegetation is a pasture, a standing crop or stubble**.**

10. **Crop coefficient:** the crop coefficient is defined as the ratio of ET from any specific crop or soil surface to some reference ET as defined by weather data.

11. **Crop coefficients** are properties of plants used in predicting evapotranspiration (ET). The most basic crop coefficient, K_c, is simply the ratio of ET observed for the crop studied over that observed for the well calibrated reference crop under the same conditions.

12. **Photosynthetic Active Radiation (PAR):** designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.

13. **Leaf Are Index (LAI)**: is a dimensionless quantity that characterizes plant canopies. It is defined as the one-sided green leaf area per unit ground surface area (LAI = leaf area / ground area, m2 / m2) in broadleaf canopies.

LIST OF TABLES

LIST OF FIGURES

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CHAPTER 1 – INTRODUCTION

By Wayne Truter, Omphile Sehoole and Malissa Murphy

1.1 BACKGROUND

Currently, 60% of South Africa's surface and ground water resources are used for irrigation (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. Considering the increasing shortage of irrigation water, increased cost of N fertilisers and associated concerns, the need to improve current irrigation and fertilisation guidelines is accentuated (Truter et al. 2012; 2015). 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. 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. Sustainable pasture production requires the best fertiliser and water management possible, in order to attain high biomass yield with minimum inputs, which maximises profit whilst the impact on the environment. Thus, farmers are under pressure to decrease their share of water and fertiliser usage, whilst at the same time, produce sufficient pasture to supply the protein demand of a growing population more efficiently. Therefore, innovations are needed to increase the efficiency of water and nitrogen use (Truter et al. 2012).

Irrigation water, nutrients and electricity are considered to be the main limiting resources for pasture production in South Africa. These resources can be optimised by selecting the appropriate irrigation type and scheduling technique and pasture (i.e. N fixing legumes and/or crops with high water use efficiency). According to the pasture and livestock budgets of 2009/2010 N and K fertilisers stands for more than 50% of the total input. Fertiliser is the other major input which is directly linked with irrigation water because managing one is also directly or indirectly managing the other. The most appropriate and cost effective management strategy would therefore be to integrate irrigation and nutrient (especially N) inputs, since nitrogen and water cannot be managed independently. This projects focus is to integrate both irrigation and nitrogen management in order to improve the efficiency of both resources (Truter et al. 2012).

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. The most common irrigated pastures are ryegrass, kikuyu and lucerne. Irrigated ryegrass and dryland kikuyu with supplemental irrigation are the primary sources of feed in the pasture based dairy industry and are mostly grown in the relatively higher rainfall areas (Tainton 2000; Truter et al. 2012; 2015).

The Water Research Commission initiated and funded a 5-year project to study the irrigation management of ryegrass/kikuyu pasture under different pasture management conditions (WRC K5/1650) (Fessehazion et al. 2012). From this project, irrigation guidelines of ryegrass including calendars for the major pasture growing areas of South Africa were developed. In addition, a simple irrigation scheduling model has been parameterised and tested and is now available to be used by farmers for their own specific conditions. However, only limited research was conducted on kikuyu and kikuyu/ryegrass mixtures. Hence, in this project, the research focuses on the irrigation of mixed pastures in conjunction with important legumes such as clovers and lucerne and relevant mixtures thereof.

The use of mixed grass/legume pastures is becoming integral in pasture based grazing systems. This will reduce nitrogen inputs, which is the most limiting resource in pasture production after water. It also balances forage nitrogen content, causing less bloat than pure legume pastures and is therefore safe to graze by livestock. Due to the high cost of N fertiliser, some South African farmers have started planting temperate legume/tropical grass- and temperate legume/grass mixtures in the Southern Cape coast (Van Heerden 1986; Labuschagne 2005), KwaZulu-Natal and Eastern Cape (le Roux 1991; Eckard 1994). Therefore, in this project, this promising practice of temperate legume with tropical grass or temperate grass mixture and the most commonly practised grazing mixture of kikuyu/ryegrass were researched.

With respect to pure legume pastures, lucerne is regarded as the most important pasture legume produced in the drier parts of South Africa for its high quality roughage (hay). This roughage is extensively used in many animal production systems, including feedlots, dairy systems, the animal feed industry and the wildlife industry, to correct for poor quality natural veld especially in winter. Lucerne is planted on 240 000 to 300,000 ha (Gronum et al. 2000; National Lucerne Organization 2011), about 80% of which is irrigated. It is mostly used for making hay, and selective grazing for cattle, sheep, ostriches and other livestock in the game industry. It provides high yields with excellent forage quality (high protein) compared to other legumes and tropical grasses. Its versatility in utilisation and adaptation to a wide range of climatic and soil conditions, its capability of soil improvement and symbiotic N_2 fixation makes it the preferable choice for intensive forage production systems (Truter et al. 2012).

Despite the above benefits, however, lucerne is known for its high water usage compared to other pastures. Annual water requirements of 1100-1200 mm are quoted by the pasture handbook (Dickinson et al. 2004), and various Provincial Departments of Agriculture and various seed companies. According to Green (1985), water requirement ranges between 1200-2100 mm per year depending on weather conditions. The current guideline of irrigation amount for lucerne is a very rigid 150 mm per cutting cycle, applied in two equal applications of 75 mm, with the first applied after hay making and the subsequent application 14 days later (Dickinson et al. 2004). Due to complications with the harvesting, raking and baling processes, the second irrigation has to supply sufficient water for the cutting cycle under consideration and the initial stages of the following growth cycle, because normally the first irrigation will only take place 5-7 days after cutting (depending on the time required for harvesting, raking, baling and bale removal).

In addition, the rate of lucerne stand mortality may increase as a result of disease (e.g. scald) when irrigated immediately after harvest (especially when the temperature is high). Lucerne is also very sensitive to over- irrigation during establishment and early growth may be affected through damage to the tap root, which may turn to excessive yield reduction in subsequent years. There is a need, therefore, to study irrigation management of lucerne, by addressing crucial management practices (such as type of irrigation system and irrigation scheduling technique), which may have a direct or indirect effect on water use of lucerne.

There is a close link between biomass production and water use of lucerne as studied in South Africa by Landsberg (1967), De Kock (1978), Beukes and Weber (1981) and Beukes and Barnard (1985). Reductions in lucerne transpiration due to water deficits were associated with decreases in biomass production. Hence, it seems there is little opportunity to reduce its water consumption without affecting yield. According to Tanner and Sinclair (1983), there is a direct relationship between biomass production and transpiration when corrected for vapour pressure deficit. The need therefore exists to study more efficient ways to increase yield and possibly improve quality of lucerne with less water, so as to ensure more efficient use of, and higher returns from, each unit of water. Since lucerne is a perennial pasture, it is possible to avoid or reduce its production when there is excessive evaporative demand. Imposing stress during different growth stages or using rainfall strategically to optimise yield and quality in a period of water scarcity could also be an option. Therefore, a basic understanding of the effects water stress on the physiology and dormancy of lucerne production is prerequisite for the development of sound water management strategies.

From the challenges listed above, despite the latest fertiliser and irrigation application equipment and scientific guidelines, it can be seen that there are knowledge gaps between research and lucerne farming practices. There is lack of data and reliable information pertaining to water requirements of this valuable pasture legume. Methods to address these gaps, therefore, need to be devised and applied in order to increase water use efficiency at farm level.

Therefore, water use of kikuyu/ryegrass, tall fescue/clover, tall fescue/lucerne mixtures and lucerne was monitored at research stations representing summer rainfall and winter rainfall areas and commercial farms within the selected regions. Detailed studies will focus the water use and the efficiency of kikuyu and lucerne studying the soil water balance, some micro-meteorological or remote sensing methods. Data collected from controlled research sites and compared field measurements were used to develop practical on-farm strategies for monitoring irrigated pasture performance. Pasture systems are highly temporal and spatially complex, as they involve interactions amongst crop growth, nutrient dynamics between soil, plant and animal and pasture management systems. Hence, it is difficult to evaluate the whole system with short-term monitoring experiments. Development of site-specific pasture and irrigation management practices requires costly long-term trials. It is expensive and impractical to test multiple irrigation and other pasture management strategies in all pasture growing areas.

Models can be used to extrapolate research findings (irrigation and other pasture management requirements) to pasture growing areas. Models can also be helpful in selecting best management practices for specific sites and environmental conditions. However, models need to be parameterised, calibrated and tested with measured data. In recent years, a wide range of soil-plant-atmosphere type numerical models with different degrees of complexity have been developed. In general, complex models have a wide range of input parameters and hence intensive data sets are needed to run them accurately (Fessehazion et al. 2012). A thorough survey of the current soil-plant-atmosphere continuum type models was conducted during the previous WRC Pasture Project (WRC K5/1650). Based on scope, input data requirements, adoption by farmers and consultant, and accessibility, the SWB and the DairyMod crop/pasture models were selected. In this project, these two models were parameterised, tested and validated.

Currently, satellite-based remote sensing is showing promising results in estimating irrigation requirements of fruit trees in the Western Cape. In the near future, this technology could become a more affordable tool for managing irrigations of pastures. This study will take opportunity of an on-going remote sensing satellite-based crop water use measurement project funded by the WRC (K5/2079/4). The accuracy of the technology for pasture management will hereby be assessed. This can therefore inform any potential future use of this technology for real time irrigation scheduling for pasture management.

The studies conducted under controlled environments and at representative research stations and commercial farms were to: 1) determine water use and irrigation requirement of most common farming practices including kikuyu/ryegrass, tall fescue/clover, tall fescue/lucerne mixtures and lucerne; 2) conduct detailed physiological studies of selected species and 4) parameterise, test and validate selected crop growth/pasture model(s). As end products, databases of irrigation requirements of kikuyu/ryegrass, tall fescue/clover, tall fescue/lucerne mixtures and lucerne under different pasture management practices were developed. The validity and practicality of irrigation tools developed will finally be assessed in conjunction with pasture production stakeholders.

1.2 PROBLEM STATEMENT

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. However, availability of irrigation water cost of fertilisers and energy 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.

In these regions, however, there are still limitations to pasture based systems due to irrigation water availability. Despite the latest fertiliser and irrigation application equipment and scientific guidelines, it can be seen that there are knowledge gaps between research and livestock and pasture farming practices. There is lack of data and reliable information pertaining to water requirements of valuable pasture legumes, such as lucerne and clover species which are often used in mixed pastures. Methods to address these gaps, therefore, need to be devised and applied in order to increase water use efficiency at farm level.

Irrigation technologies may be adapted by commercial and emerging rural farmers for more-effective and wiser use of limited water supplies. Knowing how much water to apply through irrigation and how often is no trivial matter. Irrigation scheduling is the main component of water management by which irrigators decide when and how much water to apply. 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. However, some of the tools required are relatively expensive and complicated making the implementation of irrigation scheduling for the average farmer difficult. 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.

Nutrient management, especially nitrogen, 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.

Nitrogen fertiliser continues to be a major input influencing yield and quality of irrigated pastures 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. According to the Food and Agriculture Organisation (FAO), N fertiliser use has increased by 7-fold from 1960 to 2000. Commercial fertilisers are normally used as sources of nitrogen in pasture production, but because of increasing energy costs and international demand, N prices continue to escalate. Therefore, new ways for reducing N applications in order to have sustainable and economical forage and animal production are required.

To date, leguminous pastures have been used with great success, often to exclude the cost of N to provide high quality and not necessary high quantity forage. These leguminous pastures had also been included in mixtures with other grasses, so as to benefit from this biological N fixation process legume species are responsible for. This pasture management practice was not always very economical from both a quantitative and qualitative perspective, but is becoming more economical especially in the light of sustainability. Not only is there a free source of N being produced, but this is often responsible by a more palatable, digestible and more nutritional pasture species than grass species. The management of these species, especially in a mixture, is however more intensive and challenging. The challenge however, it remains to establish how much N is available under different irrigation scenarios in a mixed pasture of grass and legumes.

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 is a prerequisite for the development of sound 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 irrigation management practices requires costly long-term trials. Since it is expensive and impractical to test multiple irrigation 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.

1.3 PROJECT AIMS

- To measure water use of selected irrigated pastures (subtropical grass/temperate grass mixture, temperate grass/temperate legume mixtures and monospecific Lucerne stands) at representative sites of the major irrigated pasture growing areas.
- To generate information on growth analysis, crop model parameters and water balance studies for selected irrigated pastures in the major growing regions (winter and summer rainfall areas).
- To develop, verify and validate the most appropriate crop growth/pasture model(s) for selected irrigated pastures.
- To determine water requirement of selected irrigated pastures using the validated model(s).
- Extrapolate irrigation requirement estimates of selected irrigated pastures to pasture growing areas as far as possible.
- To test remote sensing technology for a possible future use for irrigation management of pastures.

1.4 SPECIES EVALUATED

Figure 1.1 Lucerne (*Medicago sativa*)

Figure 1.2 Tall fescue (*Festuca arundinaceae*)

Figure 1.3 White clover (*Trifolium repens*)

Figure 1.4 Kikuyu (*Pennisetum clandestinum*)

Figure 1.5 Mixture 1 – Lucerne / kikuyu

Figure 1.6 Mixture 2 – Tall fescue / Lucerne

Figure 1.7 Mixture 3 – Tall fescue / White clover

1.5 RESEARCH SITES AND DATA COLLECTION

This project has focussed on synthesizing fragmented data that exists on various aspects of irrigated pasture production nationally and where applicable internationally. This information / data will also be collated with data collected in various locations in the country (Figure 1.8). Two designed experimental trials Hatfield Experimental Station (Pretoria – Gauteng) and Outeniqua Experimental Station (George – Western Cape) which represent two different climatic zones **(Red squares)** were used to parameterise the proposed crop models. Additionally, data measured on-farm in two locations (Brits/Thabazimbi – North West Province and Cedara region – KwaZulu Natal) in the country was used in this project to align experimental work with practical situations **(Yellow squares)**. Data collected on another WRC project using remote sensing (Douglas, Northern Cape) was included in this project to illustrate the potential of using remote sensing data to determine water use of pastures **(Blue square)**.

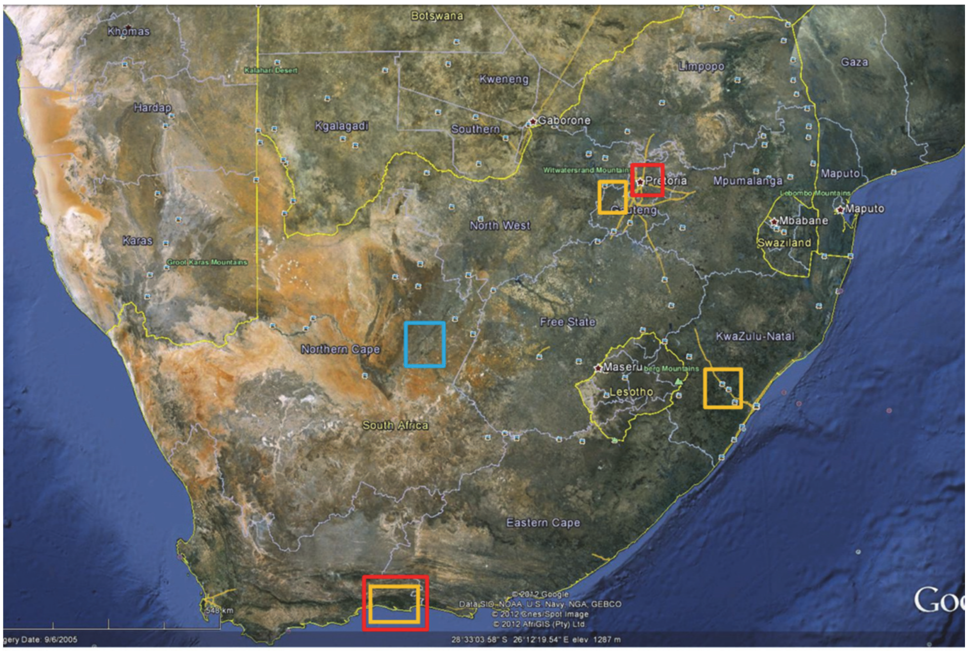


Figure 1.8 Different locations assessed and monitored in the study.

Pasture production systems are very dynamic due to the influence of climatic factors, species differences and different management systems. This was the rationale for collecting data from different locations. These different site management systems include the following:

- **Mechanically defoliated mixed pasture system** – which where predominantly temperate grasses evaluated under an irrigated system in a mild subtropical region with minimal threat of winter rain, which did not complicate soil water balance monitoring. Kikuyu was however the only sub-tropical grass used to represent the oversown pasture systems with kikuyu as a base.
- **Grazed mixed pasture system –** which was a mixture of temperate grasses (Perennial ryegrass, Cocksfoot) and legume (Lucerne) mixtures with a summer kikuyu base grazed by a commercial dairy herd.
- **Mechanically harvested lucerne hay production system –** which consisted of only a temperate legume species.
- **Mechanically harvested mixed pasture production system** – which consisted of a subtropical grass (kikuyu) based system oversown with perennial ryegrass.

These different systems represent the most common irrigated pasture production systems in the country and the world. Very little integrated data exists on mixed or combined pastures in South Africa, and this project has attempted to consolidate and integrate available data for optimal water management in pasture production systems nationally.

Note: Chapter 2 will provide insight into the methodology used to collect all field data (On-station and On-farm). The data contribution from the other WRC remote sensing project is discussed separately in Chapter 6.

CHAPTER 2 – PASTURE EVALUATION TRIALS: EXPERIMENTAL STATION

Wayne Truter, Omphile Sehoole, Malissa Murphy, Melake Fessehazion and John Annandale

2.1 MECHANICALLY DEFOLIATED PASTURE AND MIXED PASTURE SYSTEM

Figure 2.1 Hatfield Experimental Farm (University of Pretoria).

2.1.1 Objectives

- To measure water use of selected irrigated pastures (subtropical grass/temperate grass mixture, temperate grass/temperate legume mixtures and monospecific pasture stands) in the summer rainfall region.
- To test whether a simple irrigation scheduling method based on canopy cover is effective for pasture production.
- To generate information on growth analyses, crop model parameters and water and nitrogen balance studies for selected irrigated pastures.

2.1.2 Methodology

2.1.2.1 Site description

The Hatfield Experimental farm is geographically located at 25^o 44'30" S, 28^o 15'30" E (Figure 2.1). The area has an elevation of 1327 m above sea level, with an average annual rainfall of 674 mm (Annandale *et al*. 1999). The soil of the experimental site characterized by deep red soil classified as silt clay loam of the Hutton form that belongs to the Suurbekom family with clay content of 26-37% (Soil Classification Working Group 1991). The climate of the experimental farm is sub-tropical, with warm and wet conditions in summer; and dry and cold conditions in winter (Annandale *et al*. 1999).

2.1.2.2 Experimental design and layout

The land was prepared by a conventional plough and disc to be ready for planting. Different grass and legume pastures were planted as pure stands and in mixtures (Table 2.1). The sub-tropical perennial pasture (i.e. kikuyu) was planted from vegetative material in December 2012 to serve as a base for the inter-seeded temperate species. Other species were seeded into a scarified kikuyu base in February/March 2013 and a Cambridge Roller was used to facilitate good contact between the seed and soil.

Table 2.1 Description and grouping of pasture species at Hatfield Experimental farm

	Species name (treatment)	**Growth Form**	**Cultivar**	**Abbreviations**
1.	Perennial ryegrass (*Lolium perenne*)	Tufted	Bronsyn	PR
2.	Annual ryegrass (*Lolium multiforum*)	Tufted	Agriton	AR
3.	Kikuyu (*Pennisetum clandestinum*)	Creeping	------	K
4.	White clover (*Trifolium repens*)	Creeping	Haifa	C
5.	Tall fescue (*Festuca arundinacea*)	Tufted	Fuego	TF
6.	Cocksfoot (*Dactylis glomerata*)	Tufted	Hera	CF
7.	Lucerne (*Medicago sativa*)	Tufted	SA Standard	L
8.	Kikuyu / Annual ryegrass/Lucerne	------	-----	K/AR/L
9.	Kikuyu / Annual ryegrass / White clover	-----	-----	K/PR/C
10.	Tall fescue / White clover	-----	-----	TF/C
11.	Tall fescue / Cocksfoot	-----	------	TF/CF
12.	Tall fescue/ Cocksfoot / White clover	-----	-----	TF/CF/C
13	Lucerne/Kikuyu	-----	-----	L/K

Each plot was 5 m x 5 m with 2 m border spacing between the experimental plots. A total of 12 treatments (6 pure stands and 7 mixtures) were assigned in a complete randomized block design (Figure 2.2). Each treatment was replicated three times. This design was selected to minimise any experimental error. All measured, calculated and estimated parameters was statistically analysed using SAS (SAS 2001).

<u>*2.1.2.2.1 Irrigation system and layout*</u>

At the Hatfield experimental farm irrigation was applied using a drip irrigation system. Irrigation was applied once every week to field capacity by measuring the cumulative water deficit of the 1.0 m soil profile. In each plot, a neutron probe access tube was installed and the soil water content was calculated. The amount of water required to replenish each plot will then be converted to irrigation run time. In summer a soil deficit of about 15 mm was left after irrigation to provide a buffer for storing rainfall and minimizing leaching.

2.1.2.2.2 Irrigation scheduling

The neutron probe water metre was calibrated for the specific site. For monitoring soil water content three access tubes were installed to a depth of 1 m for each cultivar. Soil water measurements are taken at 0.2 m intervals down the 1.0 m soil depth. Irrigation was applied based on the soil water content measurements. Plots were filled to field capacity on a weekly interval by estimating the deficit using neutron probe water metre.

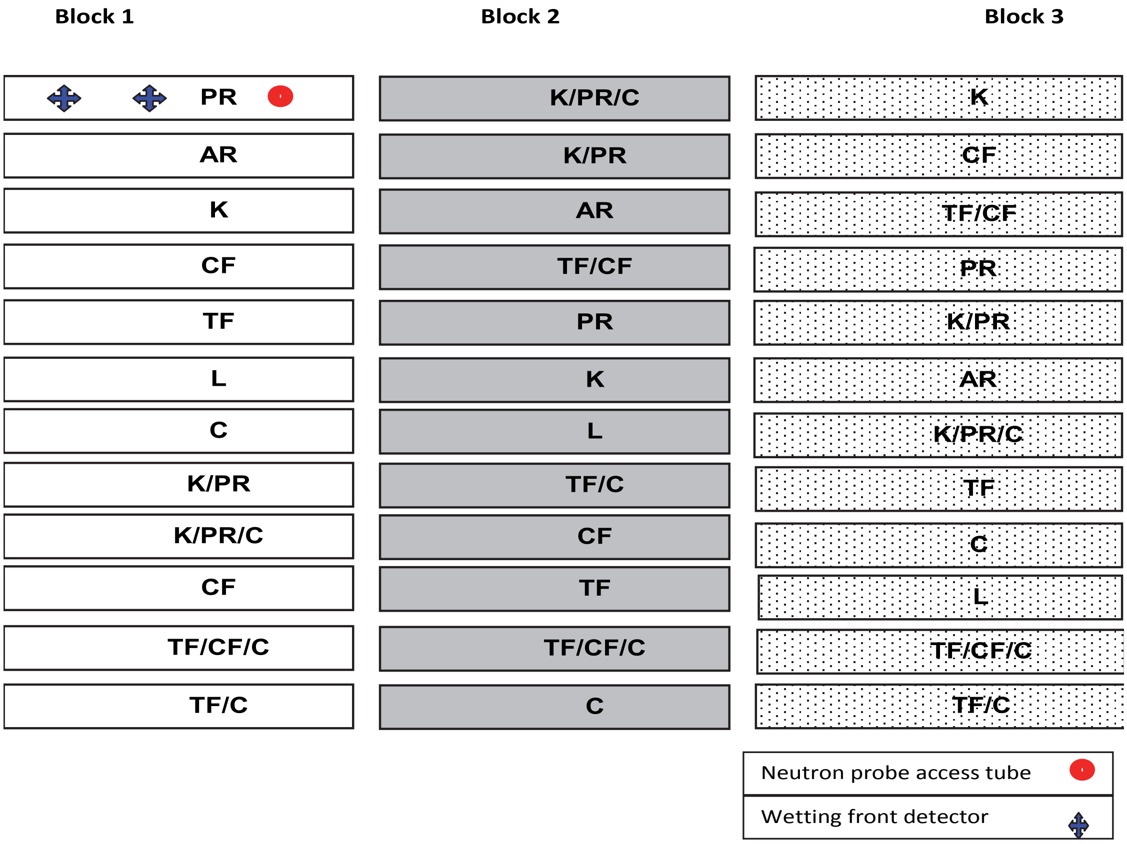


Figure 2.2 Experimental layout of the Hatfield experimental site

Figure 2.3 Plot and irrigation system layout

2.1.3 Management

2.1.3.1 Adaptive water management

Besides knowing the water content of the soil, it will also be useful for farmers to understand the movement of the wetting front when irrigating their pastures. A wetting front detector (WFD) (Figure 2.4) indicates how deep the wetting front has moved. The WFD is buried in the soil and pops up an indicator flag when a wetting front reaches at certain depth. The WFD comprises a specially shaped funnel, a filter and a mechanical float mechanism. The funnel is buried in the soil within the root zone of the plants. When rain falls or after irrigation, water moves downwards through the root zone. The infiltrating water converges inside the funnel and the soil at the base becomes so wet that water seeps out of it, passes through a filter and is collected in a reservoir. This water in the reservoir activates a float, which in turn operates an indicator flag above the soil surface.

Figure 2.4 Wetting front detectors

If the soil is dry before irrigation, the wetting front will not penetrate deeply because the dry soil absorbs most of the water. A long irrigation would be needed to activate a detector. However, if the soil is relatively wet before irrigation, it cannot store much more water, so the wetting front penetrates deeply. The detector retains a sample of water which can be extracted via a tube using a syringe. This can be analysed for its salt and nitrate concentration (Stirzaker 2003). FullStop WFD's are installed at depths of 0.20 and 0.40 m at each treatment.

2.1.4 Instrumentation and measurements

2.1.4.1 Climatic data

Weather readings were collected from an automatic weather station located near the experimental site (Figure 2.5). This station measures all necessary weather input parameters, i.e. solar radiation, temperature (maximum and minimum), wind speed and direction, rainfall and relative humidity (RH) and calculates evapotranspiration (ET_o). These parameters were used as inputs for the models to be tested.

Figure 2.5 The automatic weather station

2.1.4.2 Soil water balance

Soil water measurements are being monitored using a neutron water meter Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA) (Figure 2.6). Soil water deficit measurements were made twice a week to a depth of 1.0 m at 0.2 m intervals.

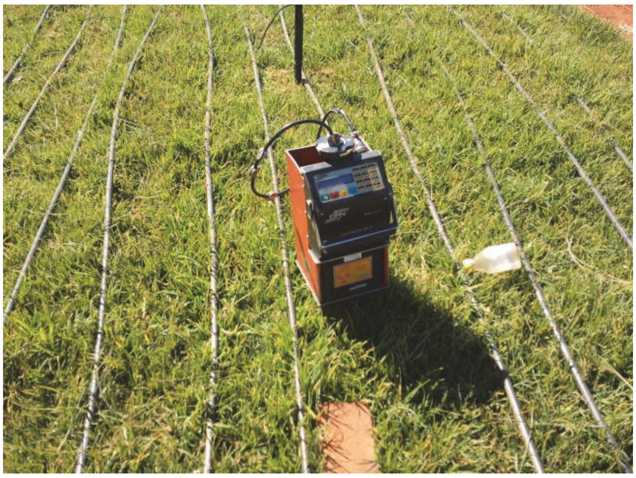


Figure 2.6 Neutron probe meter

Irrigation amount was measured using water flow meter. Irrigation amounts and efficiency were verified after each irrigation event by positioning two manual rain gauges in each experimental plot.

2.1.4.3 Measured pasture parameters

2.1.4.3.1 Growth analyses

Growth measurements were taken every 7 days starting at day 14 since very little measurable growth is expected in the first two weeks after each harvest. Five replicate quadrants of 0.09 m^2 were harvested in 25 m^2 plots to calibrate the pasture disc meter to correlate with forage yield. Harvested material was taken to the weighing room, oven dried and weighed to determine the **growth rate** and **yield** for that particular pasture (Figure 2.7). These samples were dried in an oven (70 °C) to obtain dry mass. **Leaf area index** was determined weekly using a belt driven Licor LAI-3100 (Figure 2.9).

Figure 2.7(a) Weighing of samples using a PGW ADAM Scale **(b)** Harvesting using a 0.9 m^2 quadrant

Fractional interception of photosynthetic active radiation (PAR) was measured at 12 pm on the day of measurement, by taking above and below canopy measurements using Decagon's AccuPAR model LP-80 PAR/LAI Ceptometer (Figure 2.8).

Figure 2.8 Decagon's AccuPAR model LP-80 PAR/LAI Ceptometer for measuring Fractional interception of photosynthetic active radiation

The collected data sets (LAI, canopy cover and maximum transpiration) were used as input parameters for testing the selected models.

Figure 2.9 Belt driven Licor LAI-3100 for measuring leaf area index

2.1.4.3.2 Forage yield and quality

Disk Pasture meter (Rising Plate Meter) method was used to determine growth and forage yield (Figure 2.10). This method works on the principle of relating plant height to yield by developing an equation which correlates pasture height (m) with biomass (kg m^{-2}). The pastures were harvested every 21-28 days (species specific) from 1 m^2 quadrant using a manual grass mower to 50 mm stubble height. A total of nine samples, three from each plot were collected from 11am-12pm time during the day, once the moisture on the leaf surface has evaporated. This was done not to overestimate the forage fresh mass and to reduce the variation on the forage quality that might result due to time of sampling. Forage fresh mass was determined immediately and for dry matter determination, samples were oven dried to a constant mass at 65 °C. At the end of each growth cycle, the material was separated into leaf and stem to determine the **leaf: stem ratio**. This is a method of subjectively observing the quality of the biomass produced. Crude protein (g.kg $forage^{-1}$) analyses were conducted seasonally.

Figure 2.10 Yield measurements using a Rising Plate Meter

2.1.4.4 Calculated parameters

2.1.4.4.1 Water use (WU)

Water Use (WU) is defined as the sum of water applied at the growing season and soil water deficit at the end of growth cycle. ***Water use (WU)*** or ***crop evapotranspiration (ET_c)*** of lucerne was calculated from soil water balance equation according to Allen et al. (1998) using equation:

$$ET_c = I + P - D - \Delta S - R \qquad (2.1)$$

Where:

P is precipitation
I is irrigation
R runoff
Δ**S** is change in soil water content measured with neutron probe
D deep drainage below the rooting depth (1 m)

All terms are expressed in mm. Run off was assumed to be negligible, because the field is relatively level and the amount of irrigation application rate was lower than rate of infiltration of the soil of the experimental site, and the maximum amount of irrigation was lower or equal to field capacity. Change in soil water content was calculated between the two irrigation intervals.

2.1.4.4.2 Crop coefficient

The crop coefficients for each pasture treatment were calculated, compared and synthesized with published crop coefficients, as described in literature and especially following the methods used in FAO 56. The following equation is used:

$$ET_c = K_c ET_o \qquad (2.2)$$

Where:

ET_c crop evapotranspiration [mm d^{-1}]
K_c crop coefficient [dimensionless]
ET_o reference crop evapotranspiration [mm d^{-1}]

2.1.4.4.3 Water use efficiency (WUE)

Water use efficiency (WUE) of each treatment was calculated from the total crop water use (ET calculated from the soil water balance equation) and DM yield for every season. It was calculated as follows:

$$Water\ use\ efficiency = \frac{DM\ Yield\ (kg\ DM\ ha^{-1})}{ET\ (mm)} \qquad (2.3)$$

2.2 GRAZED MIXED PASTURE

Figure 2.11 Outeniqua Experimental Farm (Western Cape Department of Agriculture).

2.2.1 Objectives

- To measure soil water balance for determining the water used by mixed pastures
- To measure canopy cover (canopy size and density)
- To correlate canopy cover with water use

2.2.2 Methodology

2.2.2.1 Site description

The study was conducted on two experimental sites (site A and site B) at the Outeniqua Research Farm, situated near George in the Western Cape Province of South Africa (Figure 2.11). The farm is located at 33°58’38’’S, 22°25’16’’E, and 201 metres above sea level.

2.2.2.1.1 Climatic data

The area has a temperate climate with minimum temperatures ranging between 7˚ and 15˚C in the winter and maximum temperatures of 18 to 25˚C in the summer (ARC-ISCW 2014). The area’s annual rainfall varies between 600-1000 mm with a long-term mean annual rainfall of 715 mm over the past 30 years (ARC-ISCW 2014).

2.2.2.1.2 Soil

Site A is characterised by a Witfontein soil form (cumulic hydromorphic) which is a podzol and Site B is characterised by a Katspruit soil form (Orthic) which is a gleyic soil (Soil Classification Working Group 1991).

2.2.2.2 Experimental layout and design

2.2.2.2.1 Treatments

The treatments consist of the following mixed pasture systems:

Site A:

- Kikuyu/ Lucerne (D2 WL357 GP)
- Kikuyu/ Lucerne (D5 WL711 GP)

Site B:

- Kikuyu/Cocksfoot (*Dactylis glomerata*)
- Kikuyu/Perennial Ryegrass (*Lolium perenne*)

These two pasture systems also include clover (*Trifolium*) species.

2.2.2.2.2 Experimental design

Site A:

The layout (Figure 2.12) is a randomised block design with two treatments, namely kikuyu/lucerne (D2 WL357 GP) and kikuyu/lucerne (D5 WL711 GP), and three blocks. This amounts to six experimental units in total. A research station consisting of two tensiometers, a neutron probe, two wetting front detectors and rain gauge, was assigned to each plot. The plot sizes are 12 m x 15 m. Readings were taken from these instruments during each grazing-cycle; therefore, each grazing-cycle is a "repeated measurement." There were 10 grazing-cycles and consequently 10 repeated measurements.

Site B:

The layout (Figure 2.13) is a randomized block design with two treatments, namely kikuyu/cocksfoot and kikuyu/ryegrass, and three blocks. This amounts to six experimental units in total. A research station consisting of two tensiometers, a neutron probe access tube, two wetting front detectors and rain gauge, is assigned to each plot. The plot sizes are 6 m x 7.5 m. Readings were taken from these instruments during each grazing-cycle; therefore, each grazing-cycle is a "repeated measurement." There were 10 grazing-cycles and consequently 10 repeated measurements.

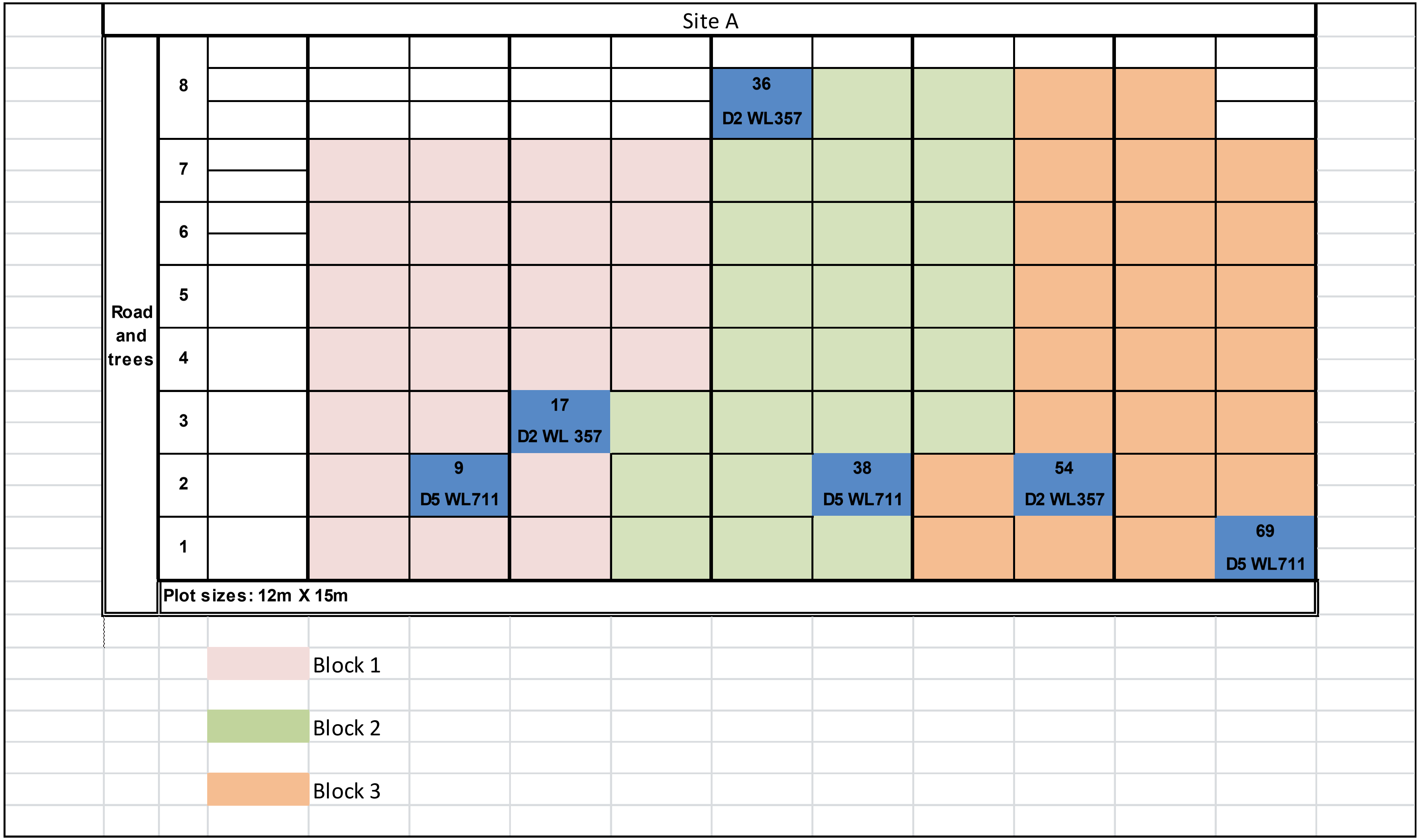


Figure 2.12 Site A experimental layout

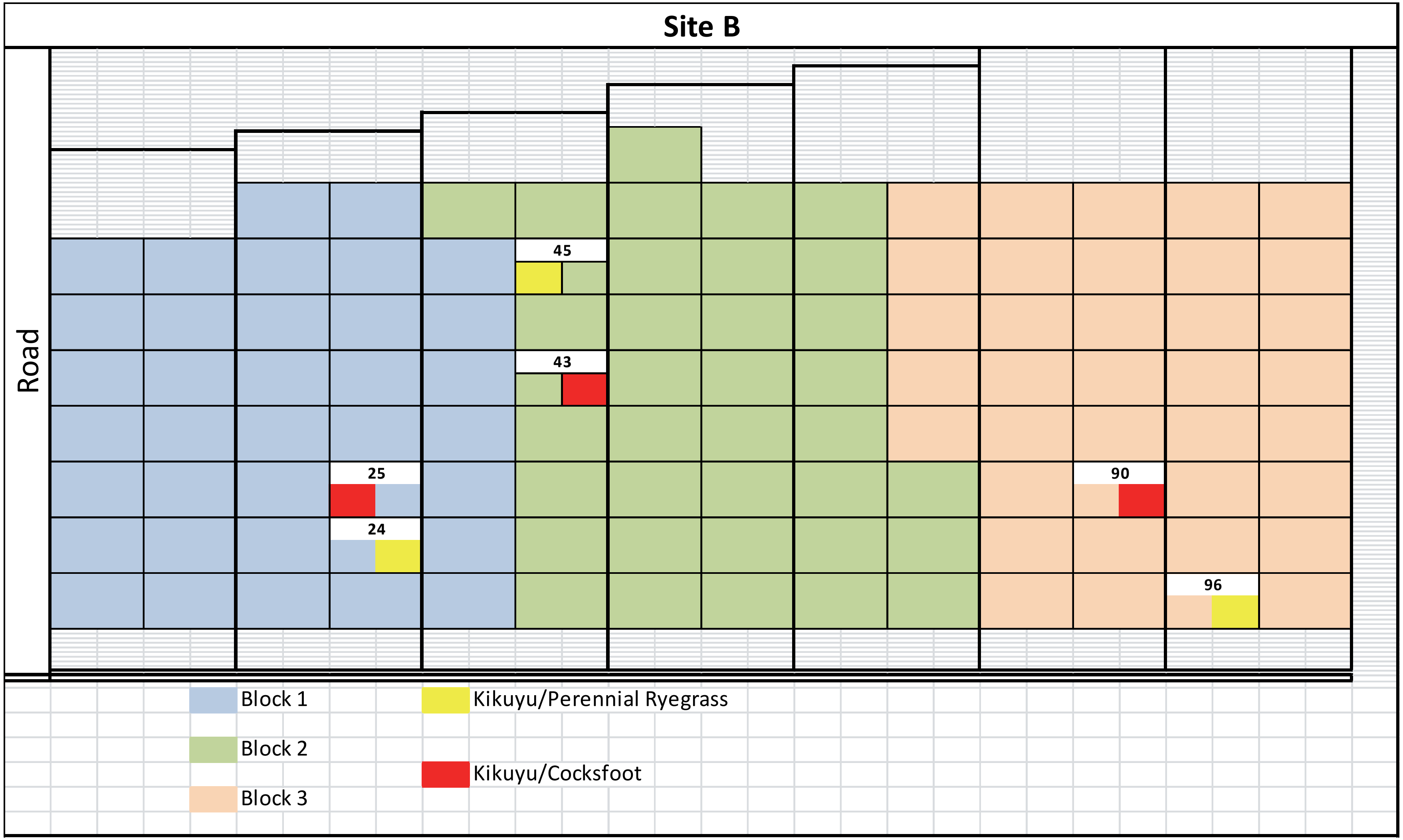


Figure 2.13 Site B experimental layout

2.2.3 Management

2.2.3.1 Grazing management

The kikuyu/lucerne as well as kikuyu/cocksfoot and kikuyu/perennial ryegrass were strip-grazed approximately every 35 days during winter and approximately every 28 days during summer (Durand 1993; Oberholzer et al. 1996) to a height of about 50 mm by a jersey herd. Pasture was allocated to cows according to disc pasture meter measurements done prior to grazing to determine the herbage available to cows. The mean grazing capacity of approximately 5.7 cows ha^{-1} was maintained (Swanepoel et al. 2014).

2.2.3.2 Irrigation scheduling

Both experimental sites consisted of a permanent sprinkler irrigation system placed in rows to allow for strip-grazing by cows. To avoid water stress, the pastures were irrigated when 15 cm deep tensiometer readings were at -25 kPa, which was considered as the allowable depletion level. In order to avoid over-irrigation, no irrigation was allowed above a tensiometer reading of -10 kPa, which was considered as field capacity. Thus, the soil water potential was maintained between -10 kPa and -25 kPa (Van der Colf et al. 2015). The tensiometers were read on a daily basis between 08:00 and 09:00.

Figure 2.14 Permanent sprinkler irrigation systems at the experimental sites

2.2.4 Instrumentation and measurements

(Refer to section 2.1.3 for visual presentation of instruments)

2.2.5.1 Soil Water Balance

The soil water balance equation was used to calculate evapotranspiration on a weekly basis for each experimental plot on both experimental sites (Jovanovic and Annandale 1999). Evapotranspiration was considered equal to crop water use and calculated as follows (Jovanovic and Annandale 1999):

$$ET = P + I - R - Dr - \Delta\theta \quad (2.1)$$

ET	=	Evapotranspiration (mm)
P	=	Precipitation (mm)
I	=	Irrigation (mm)
R	=	Runoff (mm)
Dr	=	Drainage (mm)
$\Delta\theta$	=	Difference in soil water content (mm)

Precipitation and irrigation was measured daily from a rain gauge placed in each plot. Runoff was assumed negligible because soil cover was 100% and the sites were relatively levelled. The infiltration rate of a similar pasture on the Outeniqua Research Farm was recorded to be 6.7 ± 1.6 mm h^{-1} (Swanepoel et al. 2013), which exceeds the rate of water application by sprinklers (approximately 5 mm h^{-1}) and thus runoff does not occur. Drainage was considered as the amount of water lost through deep percolation beyond the root zone, and was assumed negligibly small (Abraha et al. 2015). The difference in soil water content was calculated from weekly volumetric soil water content measurements made with a neutron probe (Campbell Pacific Nuclear, Martinez, CA, USA, model 503 DR CPN Hydroprobe).

Volumetric soil water content was calculated from pre-determined calibration equations which were determined by creating representative wet and dry spots for each experimental site. All four spots were created by clearing pasture from a surface area of 2 m x 2 m. Two access tubes were installed at depths of 60 cm in the middle of the cleared areas, each with an additional 10 cm of tube protruding from the soil surface. It was immensely difficult to install access tubes deeper than 60 cm, because of stony gravel and heavy clay in the deeper soil layers of site A and B respectively. The access tubes were installed by making holes with a soil auger that were slightly smaller than the tubes to ensure a tight fit. A can was placed over each tube to keep debris and water out when it was not in use. The wet spots were filled with water until the soil profiles were saturated. It was then covered with plastic sheeting to prevent evaporative losses, and allowed to drain for six days. The same procedure was followed for creating the dry spots except that it was not filled with water.

After six days, a profile hole was dug inside each of the cleared areas next to the access tubes to allow for soil sampling per increment. Two soil core samples were taken from the profile wall for every 20 cm increment by using a core sampler with a diameter of 7 mm and length of 7.5 mm (Blake 1965). The soil cores were carefully emptied into brown paper bags and sealed in plastic bags to prevent evaporation. At the laboratory, these samples were weighed and dried in an oven for 48 hours at 105°C.

Together with the soil sampling, a standard count was taken with the neutron probe by placing it on top of its protective case and taking numerous 16-second-long readings in the air. It was then placed on top of the access tubes and readings were taken at 20 cm intervals by lowering its radioactive source to the respective depths. These readings were divided by the average standard count to determine a count rate ratio.

After the soil core samples were dried, it was weighed again. The following equations were used to calculate gravimetric water content, soil bulk density, and consequently volumetric soil water content:

$$Gravimetric\ water\ content\ (w) = \left(\frac{wet\ mass - dry\ mass}{dry\ mass}\right) \quad (2.4)$$

$$Soil\ bulk\ density\ (\rho b) = \frac{dry\ soil\ mass}{volume} \quad (2.5)$$

$$Volumetric\ soil\ water\ content\ (\theta) = w\left(\frac{\rho b}{\rho w}\right) \quad (2.6)$$

where ρw is the density of water (1.0 Mg m^{-3})

Calibration regressions were drawn from the linear relationship between the count ratios and volumetric soil water content calculated from the wet and dry spots for each experimental site (Figure 2.15 and 2.16).

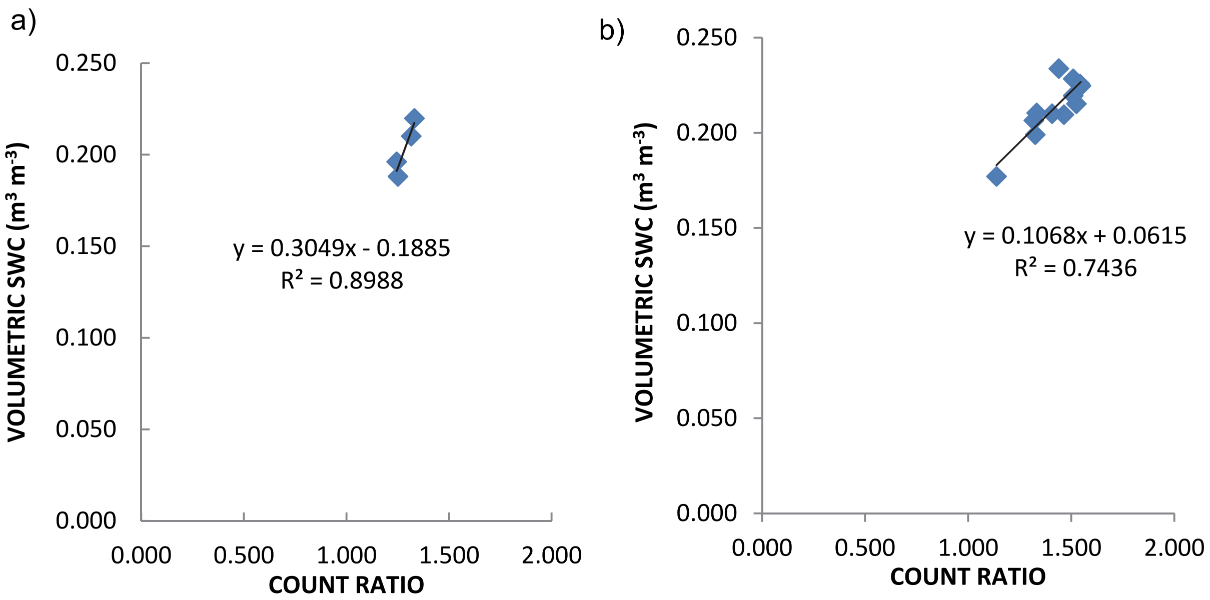


Figure 2.15 Relationship between volumetric soil water content (SWC) and count ratio in order to determine the calibration regression of neutron probe readings for a) 0 to 20 cm deep soil layer and b) 20 to 60 cm deep soil layer of kikuyu/lucerne pastures

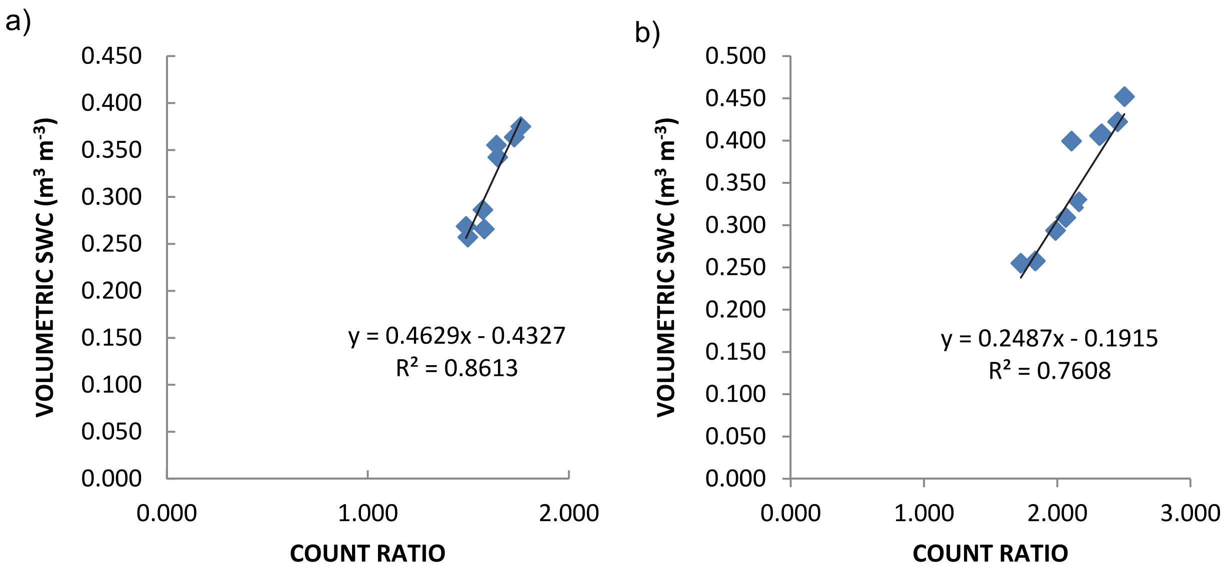


Figure 2.16 Relationship between volumetric soil water content (SWC) and count ratio in order to determine the calibration regression of neutron probe readings for a) 0 to 40 cm and b) 40 to 60 cm deep soil layers of kikuyu/perennial ryegrass and kikuyu/cocksfoot

2.2.5.1.1 Photosynthetic active radiation (PAR) and Leaf Area Index (LAI)

An AccuPAR (model LP-80) ceptometer was used to measure photosynthetically active radiation (PAR) on a weekly basis. This was done by taking approximately ten above and approximately ten below canopy measurements throughout each experimental unit. The ceptometer was able to invert PAR measurements to leaf area index (LAI). This data gave an indication of the size and density of a canopy.

2.2.5.1.2 Climatic data

Weather data was collected from an automatic weather station located on the Outeniqua Research Farm. It is the property of the ARC-ISCW (Agricultural Research Council – Institute for Soil, Climate and Weather) and they provided daily data records on a monthly basis. The station consists of a Stevenson screen with a CR200 logger. It measures temperatures (Vaisala), rainfall (Watchdog rain gauge), wind speed and direction (RM Young), solar radiation (Licor), relative humidity (Vaisala), relative evaporation, heat units, cold units, positive chilling units, saturated vapour pressure, and vapour pressure deficit.

Unfortunately, the weather station was out of order from November 2014 to February 2015, but luckily temperature and rainfall data could be retrieved from a manual weather station on the Outeniqua Research Farm. None of the nearby weather stations were able to record evapotranspiration data for that period. Therefore, evapotranspiration data, as measured by a weather station, were not discussed with the results of the study. Figure 2.17 illustrates the monthly mean minimum and maximum temperature, and total rainfall.

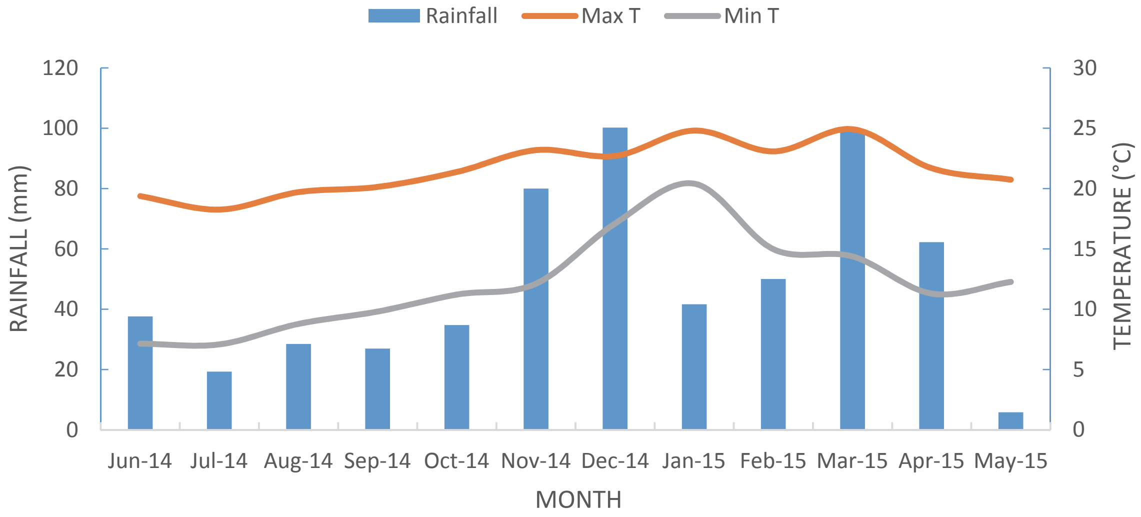


Figure 2.17 monthly mean minimum and maximum temperature and total rainfall recorded during the experimental trial period at the Outeniqua Research Farm, George, South Africa

2.2.5.1.3 Wetting Front Detectors

Wetting Front Detectors (WFDs) were installed at depths of 200 mm and 400 mm for each experimental unit for monitoring the depth of wetting. It gives an indication of how water moves through soil after irrigation. If the indicator is up, a wetting front had passed the buried funnel. If the indicator is down, it means that not enough water was applied to produce a wetting front which the WFD could detect.

2.2.5.2 Pasture growth measurements

2.2.5.2.1 Forage yield

Dry matter (DM) yield of the treatments were calculated before and after each grazing cycle. This was done by cutting the pasture to an approximate height of 50 mm above ground level from three randomly placed quadrats (0.25 m^2) within each experimental unit (Botha et al. 2008a). These three samples were weighed to determine its wet weight, where after it was pooled and thoroughly mixed. A subsample of approximately 500 g was pulled from each mixture, whilst the rest (approximately 1 kg) was kept for botanical fractioning. The subsample was used to determine DM content (Equation 2.7). Therefore, the subsample was weighed (wet weight), dried at 60^{0}C for 72 hours, and weighed (dry weight) again (Botha 2008). DM content was calculated as follows:

$$Dry\ matter\ content\ (DM\ \%) = \frac{wet\ weight}{dry\ weight}\ \text{x}\ 100 \qquad (2.7)$$

The wet weight of each sample (before it was pooled) in combination with its DM content was used to calculate DM yield (Equation 2.8) as follows:

$$Dry\ matter\ yield\ (kg\ DM\ ha^{-1}) = \left(\frac{wet\ weight\ of\ sample\ A \times DM\%}{100}\right) \div \left(\frac{0.25}{10000}\right) \quad (2.8)$$

2.2.5.2.2 Growth rate

The rate of plant growth was calculated as kg DM ha^{-1} day^{-1} by determining DM yield of three rings randomly placed in each plot. This was done before and after grazing.

2.2.5.2.3 Botanical composition

Botanical composition of each treatment was determined from the botanical fractioning of the remaining three pasture samples, done by hand. Kikuyu/lucerne treatments were fractioned into lucerne, kikuyu, clover, other grasses (such as naturally occurring *Bromus catharticus* and *Lolium* spp.), and weeds. Kikuyu/perennial ryegrass and kikuyu/cocksfoot were fractioned into kikuyu, sown grass (perennial ryegrass or cocksfoot), clover and weeds. The fractioned samples were weighed, dried at 60°C for 72 hours, and weighed again where after percentage contribution of each fraction was calculated on a DM basis (Botha 2008).

2.2.5.2.3 Water use efficiency (WUE)

Water use efficiency (WUE) of each treatment was calculated from the total crop water use (ET calculated from the soil water balance equation) and DM yield for every season. It was calculated as follows:

$$Water\ use\ efficiency = \frac{DM\ Yield\ (kg\ DM\ ha^{-1})}{ET\ (mm)} \quad (2.3)$$

CHAPTER 3 – ON FARM PASTURE MONITORING SITES

By Wayne Truter and Omphile Sehoole

To get an understanding of the on farm level of water management in a lucerne production and mixed pasture grazing systems the following sites were selected.

3.1 MECHANICALLY DEFOLIATED LUCERNE – Brits/Thabazimbi (North West Province)

The following site was selected to obtain the necessary data for on-farm water management in a lucerne production system to verify and align with modelling outcomes. The site was situated in the North West Province (Figure 3.1) on the Crocodile River Irrigation Scheme.

Figure 3.1 On-farm monitoring site in Brits/Thabazimbi (North West Province)

Figure 3.2 Fields monitored by research team in Brits/Thabazimbi area.

3.1.1 Objectives

- To measure the water use and growth rate of commercially planted lucerne under irrigated conditions.
- Provide in field monitoring tools and feedback to the farmer on irrigation practices and data collection.

3.1.2 Methodology

3.1.2.1 Site description

This commercial lucerne hay production system was approximately 40 ha planted to lucerne that was 1-4 years old, respectively. This land was a good representation of most of the lucerne lands irrigated out of the Crocodile river in this region. The land is located at 24°52'20.65" S, 27°30"09.94" E, and is 933 metres above sea level (Figure 3.2).

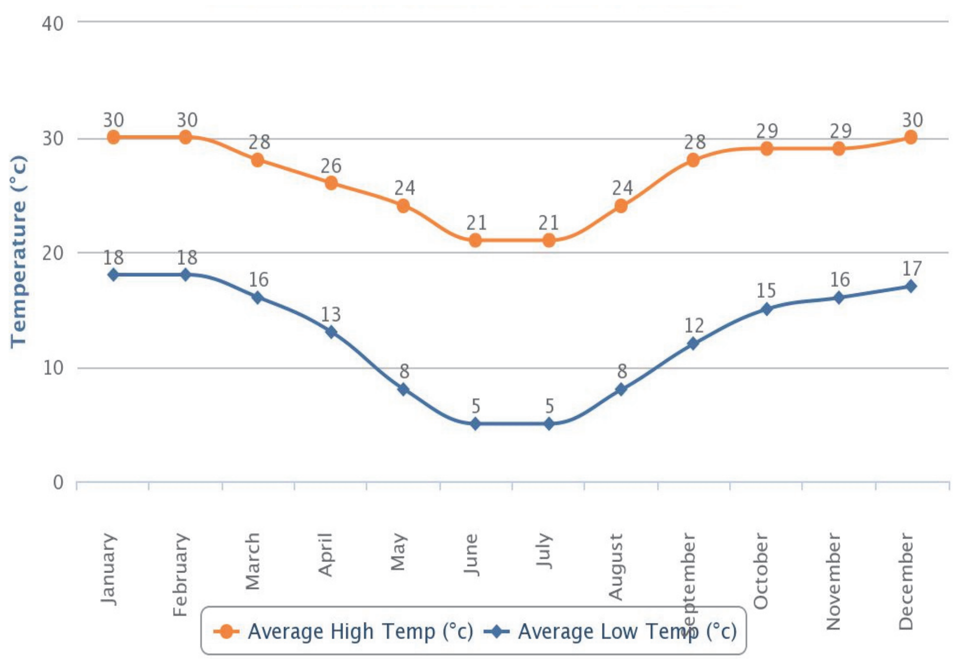


Figure 3.3a Average temperatures for Brits region (www.worldweatheronline.com)

The area receives a mean precipitation of 550 mm per annum. The soil of the monitoring site was characterized by a deep black soil classified as a Rensberg form and some areas with Hutton soils (Soil Classification Working Group 1991). The climate of the area is sub-tropical, with warm and wet conditions in summer and in winter it is dry, cold (sometimes below zero) and sunny.

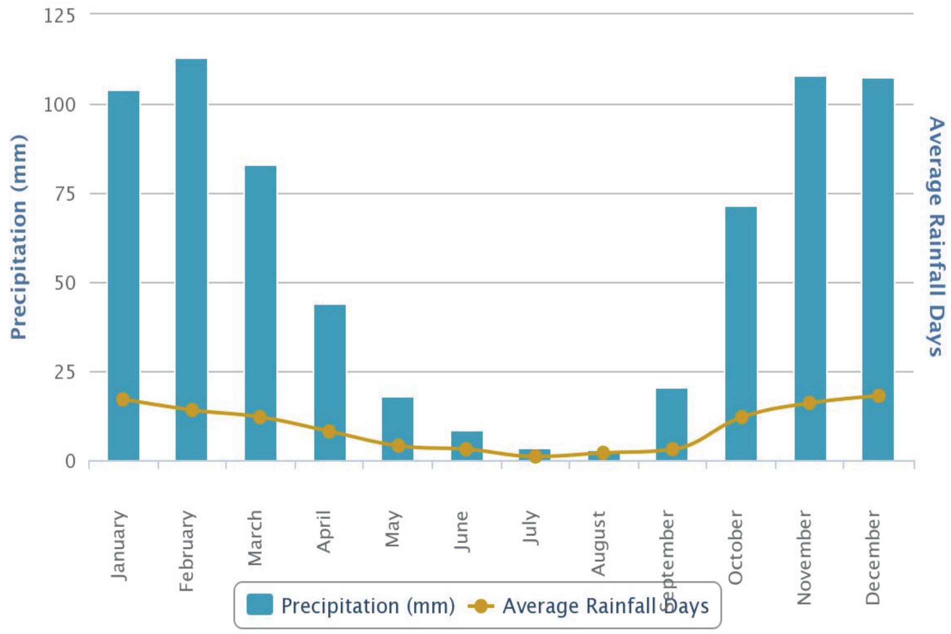


Figure 3.3b Average monthly rainfalls for Brits region (www.worldweatheronline.com)

3.1.3 Farm management system

3.1.3.1 Irrigation system and scheduling

An overhead sprinkler irrigation system and a centre pivot system were used to irrigate 20-25 mm a week when rainfall is limited. Rain-gauges were used to monitor the amount of water applied through irrigation.

(a) **(b)**

Figure 3.4 Two kinds of irrigation systems (a) pivot and (b) overhead sprinkler) used

3.1.3.2 Fertilisation practices

Fertilizer was applied when the deficiency symptoms are observed in the crop. Fertilizer was applied based on the soil recommendations. During establishment, fertilizer was applied based on the results of the soil analysis to boost the growth of the lucerne.

3.1.3.3 Harvesting procedure

Lucerne is generally harvested on a 5 week cycle in winter and a 6 week cycle in summer. The 10% blooming stage is used as a measure for when harvesting is conducted. Once 10% flower formation occurs, the pasture is cut to 70 mm.

3.1.4 Farm monitoring system

3.1.4.1 Climatic data

Weather readings were collected from an automatic weather station located near the monitoring site. Evapotranspiration (ET_o), solar radiation, relative humidity (RH), rainfall, maximum and minimum of temperature by the weather station every week.

Figure 3.5 Lucerne fields harvested every 5-6 weeks depending on blooming stage.

3.1.4.2 Measured pasture

A rising plate meter (RPM) was used to establish the amount of herbage every harvest cycle by measuring height and compressibility of the pasture. The RPM readings are calibrated to dry matter (DM) yield per unit area. This is done by recording the height and DM yield of three rings 0.098 m^2 randomly placed in each field. Yield is determined by cutting herbage within the border of the rings to a height of 0.05 m above ground level and by drying it at 60˚C for 72 hours.

A linear regression model using the following equations are used for calculating DM yield:

$$y = ax + b \tag{3.1}$$

Where:

y = dry matter yield (kg DM per ha)
a = gradient
x = recorded height of rising plate meter
b = intercept value

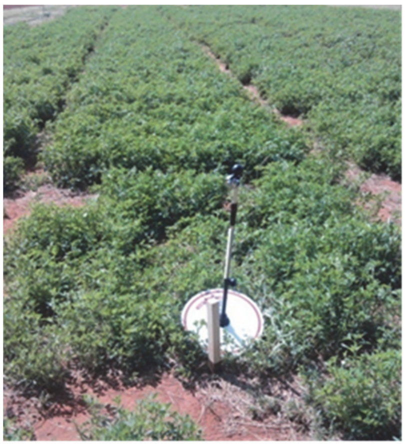


Figure 3.6 Rising plate meter used for evaluating the pastures

3.1.4.2 Forage quality

Data pertaining to forage quality analyses was provided by the farmer and only included crude protein (g CP kg DM^{-1}).

3.1.4.3 Calculated parameters

3.1.4.3.1 Water use (WU)

Water Use (WU) is defined as the sum of water applied at the growing season and soil water deficit at the end of growth cycle. ***Water use (WU)*** or ***crop evapotranspiration (ET_c)*** of lucerne was calculated using the crop coefficients as described in the FAO 56 (Allen et al. 2005):

$$ET_c = K_c ET_o \quad (3.2)$$

Where:
ET_c crop evapotranspiration [mm d^{-1}]
K_c crop coefficient [dimensionless]
ET_o reference crop evapotranspiration [mm d^{-1}]

3.1.4.3.2 Water use efficiency (WUE)

Water use efficiency (WUE, kg mm^{-1} ha^{-1}) was calculated using:

$$Water\ use\ efficiency = \frac{DM\ Yield\ (kg\ DM\ ha^{-1})}{ET\ (mm)} \quad (3.3)$$

3.2 MECHANICALLY DEFOLIATED MIXED PASTURES – (Cedara region) KwaZulu-Natal

The KwaZulu-Natal region is well known for the intensive dairy production systems that are dependent on a continuous supply of pasture throughout the year (Figure 3.7). This level of management requires the use of mixed pasture production systems, either oversown or interseeded pastures. This section provides insight into the value of using on farm data in conjunction with a parameterized model to predict water use and estimated production rates of pastures under varying climatic conditions.

Figure 3.7 On-farm research sites in KwaZulu-Natal, Cedara Region

3.2.1 Objectives

- Measure the water use and measure the growth rate of common mixed pastures planted under irrigated conditions.

Figure 3.8 Multiple fields monitored in Cedara region.

3.2.2 Methodology

3.2.2.1 Site description

The field data obtained for this region were part of a long term monitoring programme. The data collected represents a few fields with the same pasture production system. These lands represent a clayey soil. These lands are irrigated with overhead sprinkler systems. The land is located in and around 29°31 S, 30°15 E, and 1040 metres above sea level (Figure 3.8). The area receives a mean precipitation of 875 mm per annum. The soil of the monitored sites is characterized by deep red, kaolinitic soil classified predominantly as Hutton form (Soil Classification Working Group 1991). The climate is sub-tropical, with warm, humid and wet conditions in summer and in winter it is moist, cold and sunny.

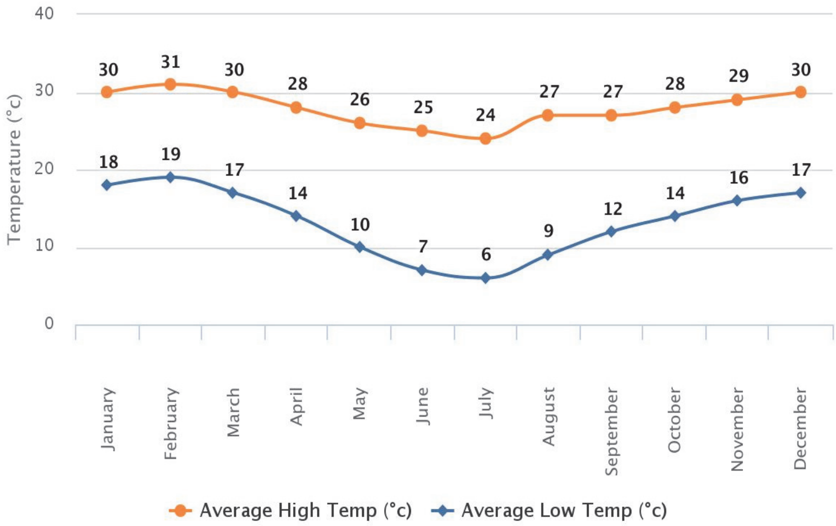


Figure 3.9 Average temperatures for Cedara region (www.worldweatheronline.com)

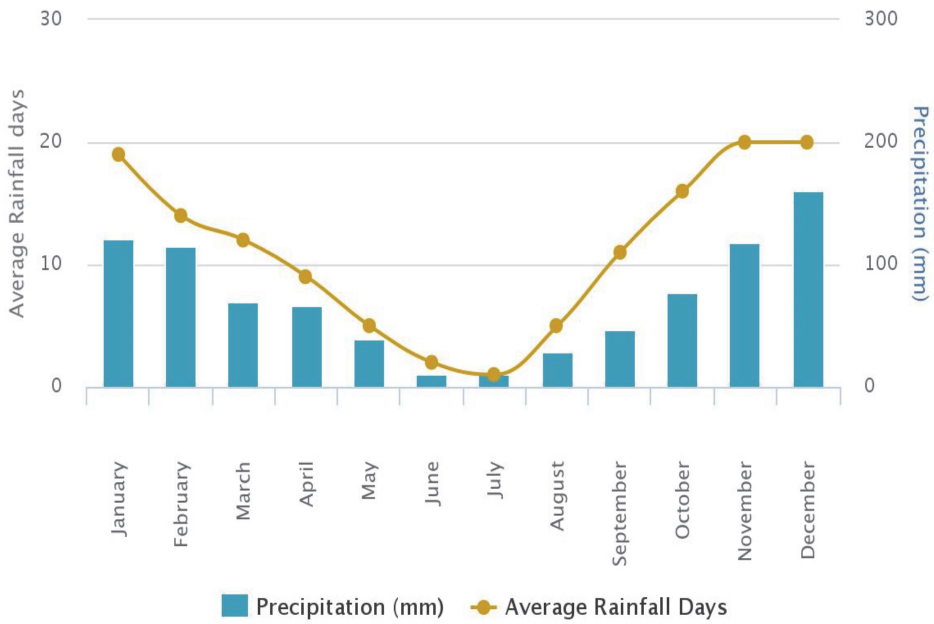


Figure 3.10 Average monthly rainfalls for Cedara region (www.worldweatheronline.com)

3.2.3 Farm management system

3.2.3.1 Irrigation system and scheduling

An overhead sprinkler irrigation system was used to irrigate approximately 25 mm a week when rainfall was limited. Rain-gauges were used to monitor the amount of water applied through irrigation.

Figure 3.11 Kikuyu oversown with perennial ryegrass

3.2.3.2 Fertilisation practices

Fertiliser was applied according to soil recommendations and was as high as 300 kg nitrogen per hectare. During establishment, baseline applications of P, K were applied according to soil analysis to ensure that these were not growth limiting nutrients. The pH of the soils was maintained at 6.5.

3.2.3.3 Harvesting procedure

The summer pastures were dominated by kikuyu and harvested every 3-4 weeks with a forage harvester. When the ryegrass component of the mixture is dominant in winter, the harvesting strategy was based on the 3-4 leaf stage of the ryegrass. The material harvested was used for silage and green feed purposes.

3.2.4 Farm monitoring system

3.2.4.1 Climatic data

Weather readings were collected from an automatic weather station located near Cedara Agricultural College. Evapotranspiration (ET_o) was calculated from solar radiation, relative humidity (RH), rainfall, maximum and minimum temperatures that were taken from the weather station every week.

3.2.4.2 Measured pasture

A rising plate meter (RPM) was used to establish the amount of herbage every week by measuring height and compressibility of the pasture. The RPM readings were calibrated to dry matter (DM) yield per unit area. This is done by recording the height and DM yield of three rings 0.098 m^2 randomly placed in each field. Yield is determined by cutting herbage within the border of the rings to a height of 0.05 m above ground level and by drying it at 60˚C for 72 hours. A linear regression model using the following equations are used for calculating DM yield:

$$y = ax + b \tag{3.1}$$

Where:

- **y** = dry matter yield (kg DM per ha)
- **a** = gradient
- **x** = recorded height of rising plate meter
- **b** = intercept value

3.2.4.2 Forage quality

Data pertaining to forage quality analyses was provided by the farmer and only included: crude protein (CP) g.kg.DM^{-1}.

3.2.4.3 Calculated parameters

3.2.4.3.1 Water use (WU)

Water use (WU) is defined as the sum of water applied at the growing season and soil water deficit at the end of growth cycle. ***Water use (WU)*** or ***crop evapotranspiration (ET_c)*** of kikuyu/ryegrass pastures was calculated using the crop coefficients as described in the FAO 56 (Allen et al. 2005):

$$ET_c = K_c ET_o \tag{3.2}$$

Where:

- ET_c crop evapotranspiration [mm d^{-1}]
- K_c crop coefficient [dimensionless]
- ET_o reference crop evapotranspiration [mm d^{-1}]

3.2.4.3.2 Water use efficiency (WUE)

Water use efficiency (WUE, kg mm^{-1} ha^{-1}) was calculated using:

$$Water\ use\ efficiency = \frac{DM\ Yield\ (kg\ DM\ ha^{-1})}{ET\ (mm)} \tag{3.3}$$

CHAPTER 4 – UNDERSTANDING THE WATER REQUIREMENT OF MONSOSPECIFIC AND MIXED PASTURES

By Wayne Truter, Omphile Sehoole and Malissa Murphy

4.1 MECHANICALLY DEFOLIATED PASTURE – Hatfield Research Station (Pretoria)

The intensive experimental trial was established to thirteen different pasture treatments. It is clearly noted from the data provided that climatic conditions did not favour the establishment and growth of some of the pasture treatments. Nevertheless, the remaining treatments assessed represented the various categories of pastures most commonly used in livestock production systems nationally.

4.1.1 Botanical composition

Botanical composition is an important parameter to measure, indicating how management and growth conditions are contributing to the species adaptability. It is clear for Figure 4.1a-c that the combined pastures botanical composition changes during the growing season due to management, specifically the intensity of defoliation which favoured some species more than others in a mixture. This complicates the consistent measuring of such pastures and it is expected that the more dominant species are responsible for the majority of the water use of the mixture.

It is evident form the data presented in Figure 4.1 a-c, that in certain climatic conditions and under certain management practices, some species are more responsive than others, resulting in more superior growth in certain seasons. It is as a result of poor establishment of half of the treatments that this chapter will only focus on the following treatments;

Monospecific pastures: Kikuyu, Tall Fescue, Lucerne and White Clover
Mixed pastures: Kikuyu / Lucerne, Tall Fescue/White Clover and Tall Fescue / Lucerne

4.1.2 Pasture growth

To understand the value of individual species in mixed pastures, the understanding of the growth potential of these monospecific pastures is important. Using the RPM to estimate the yield of pastures is a practical tool many farmers use. This study focussed on calibrating the RPM for different pastures, by correlating the RPM measurements to actual harvested yield, to ultimately determine whether the RPM would work for mixed pastures too.

4.1.2.1 Dry matter Yield (Measured and Estimated) – Mono specific pastures

With the multiple readings taken and the yield measurements obtained, promising correlations were obtained for the monospecific pastures (Figure 4.2-4.5). It can be noted that RPM readings can give a good estimate of the potential yield of the pasture, if the RPM is calibrated for the specific pasture. These calibrations become more accurate the more RPM readings are taken and correlated with yield data measurements. It is noted that there is a better correlation for species that do not have a distinctive leaf: stem ratio as lucerne does.

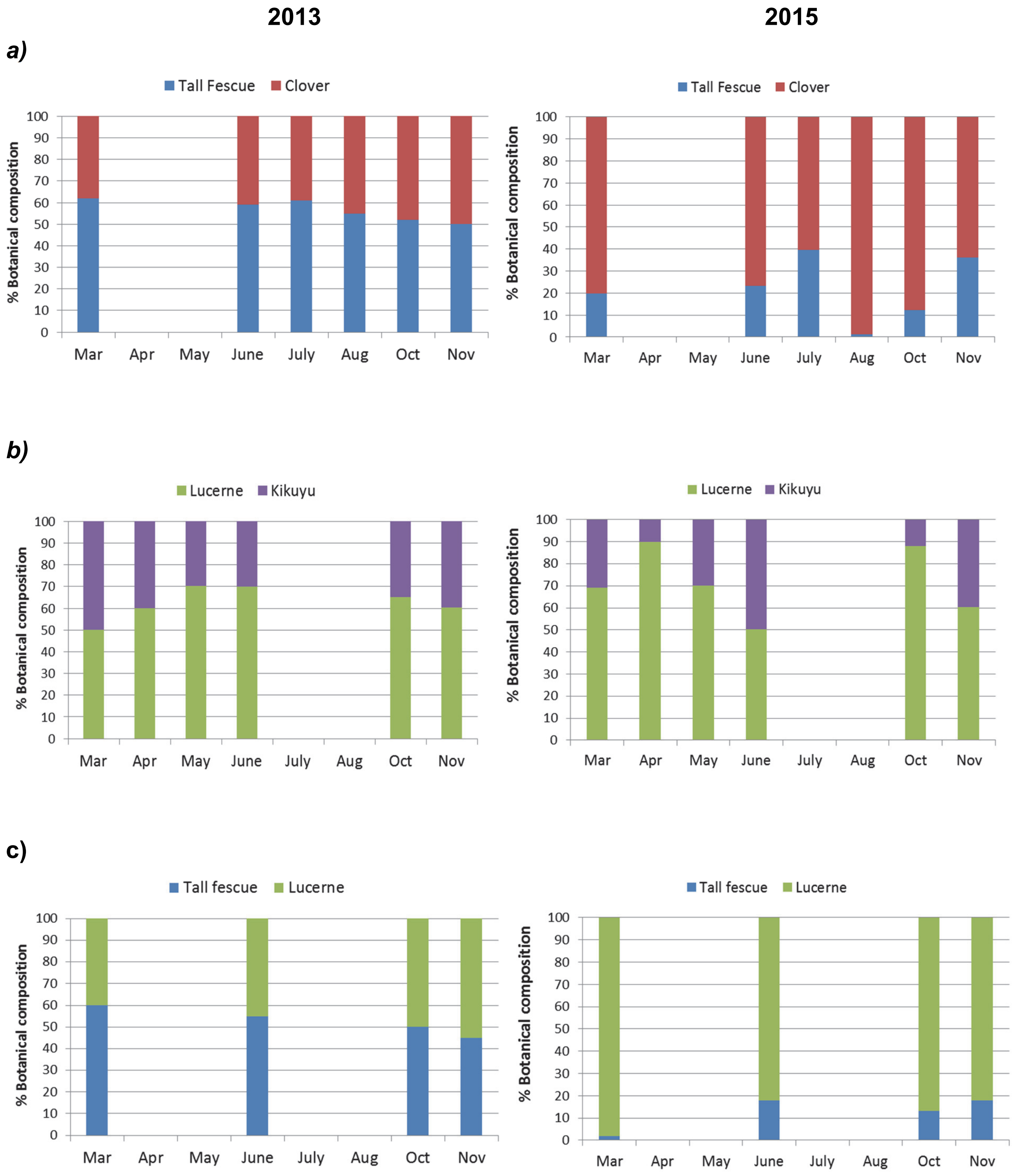


Figure 4.1 Changed botanical composition of a) Tall fescue / Clover from, b) Lucerne / Kikuyu, c) Tall Fescue

4.1.2.1.1 Kikuyu

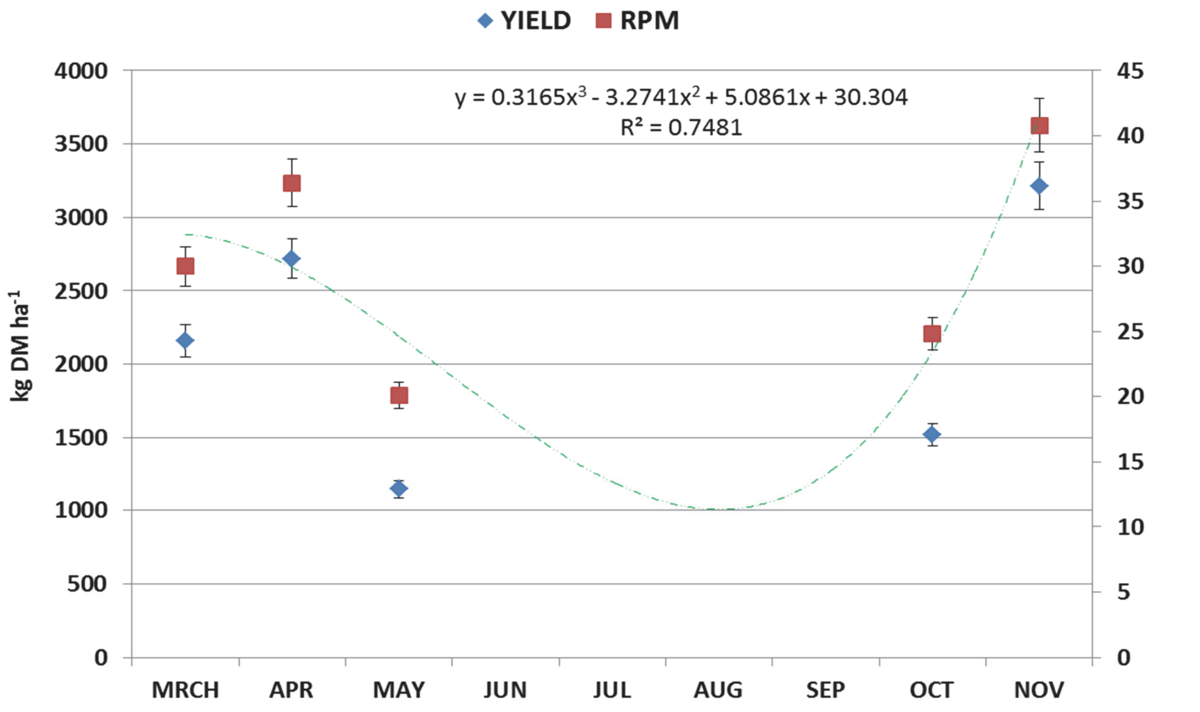


Figure 4.2 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for Kikuyu

4.1.2.1.2 Tall Fescue

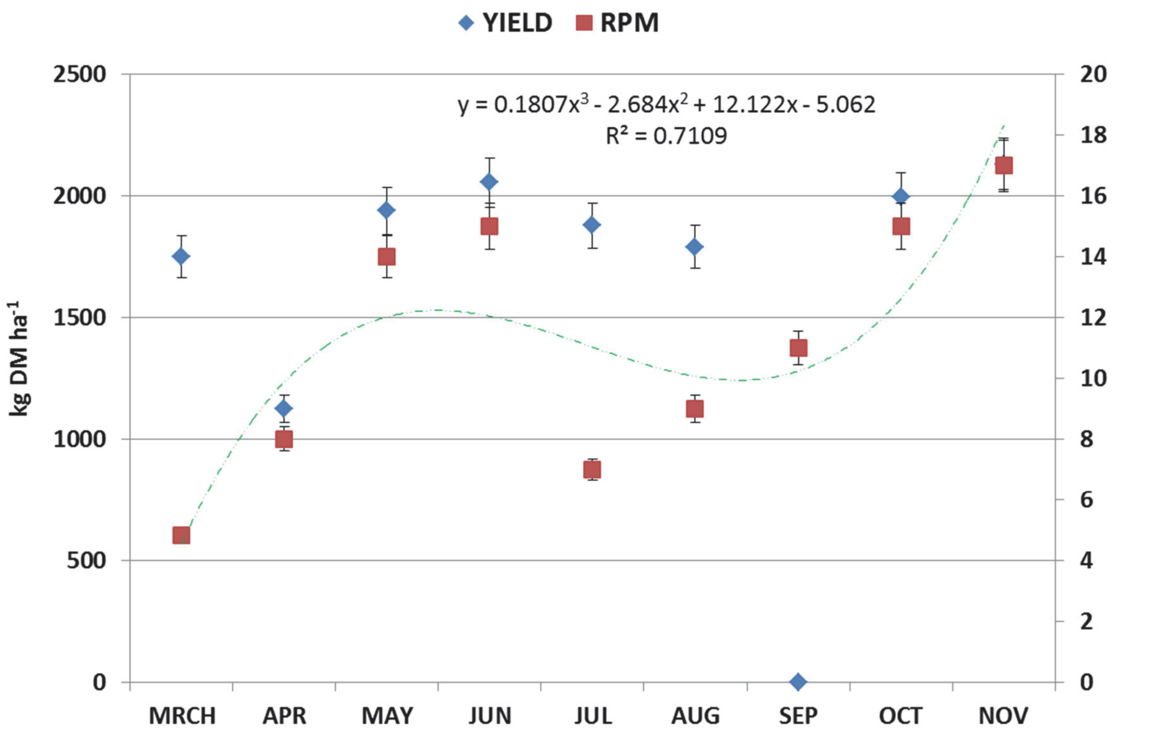


Figure 4.3 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for Tall fescue

4.1.2.1.3 Lucerne

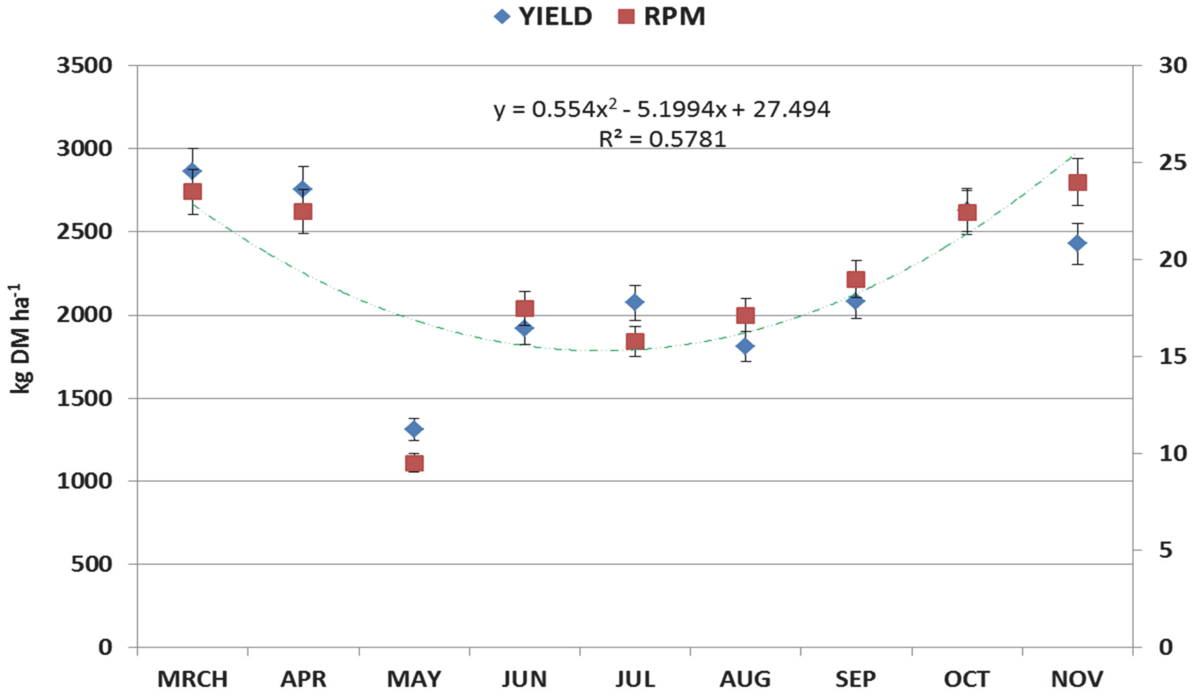


Figure 4.4 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for Lucerne

4.1.2.1.4 White Clover

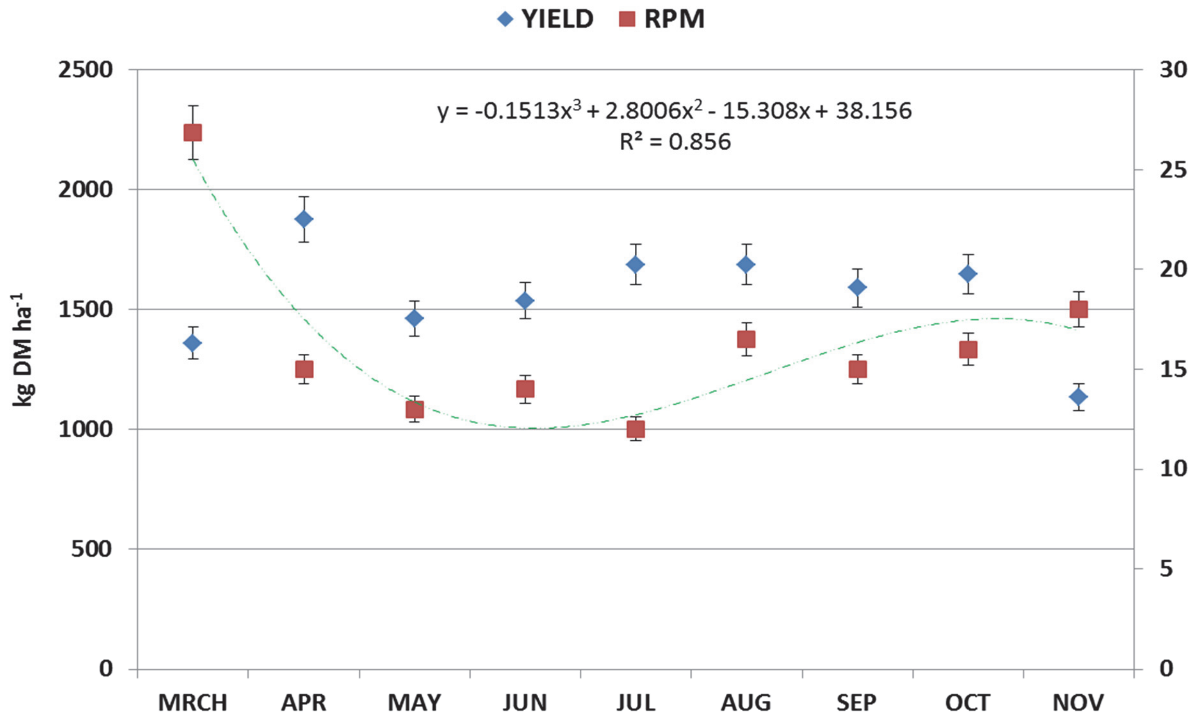


Figure 4.5 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for White clover

4.1.2.2 Dry matter Yield (Measured and Estimated) – Mixed pastures

It was interesting to note that stronger correlations between RPM readings and DM yield measurements were obtained for mixed pastures. This was obviously due to the good growth interaction of species with the more dominant species being supported by the less dominant species. This mixture therefore provides a better density and thus better resistance during the RPM measurement process.

4.1.2.2.1 Kikuyu / Lucerne mixed pasture

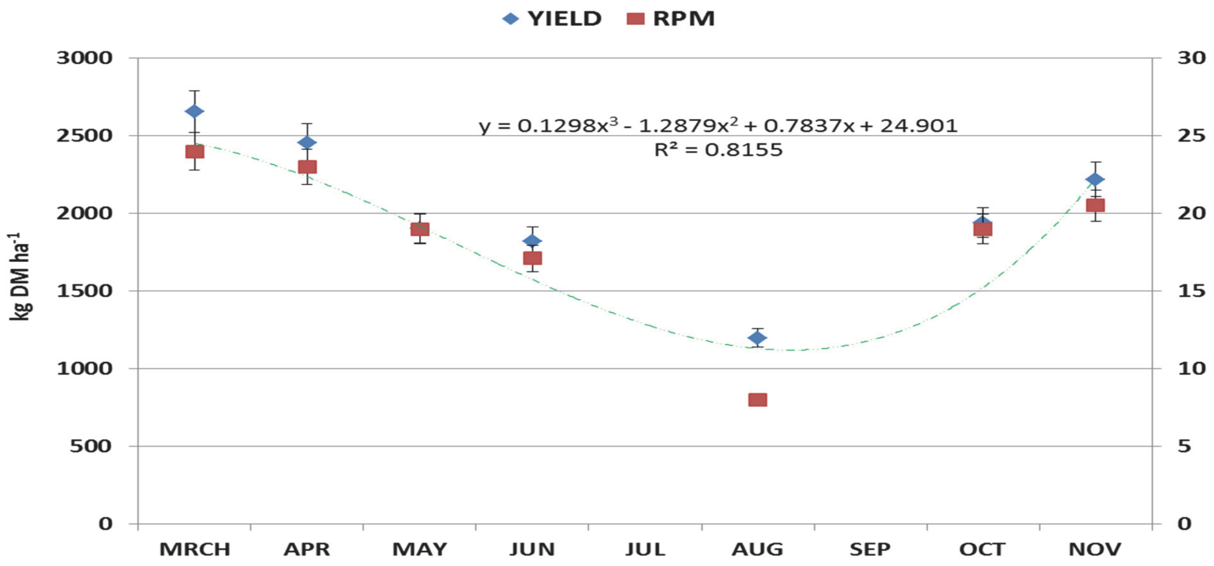


Figure 4.6 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for mixed pasture of kikuyu interseeded with Lucerne

4.1.2.2.2 Tall Fescue */ Clover mixed pasture*

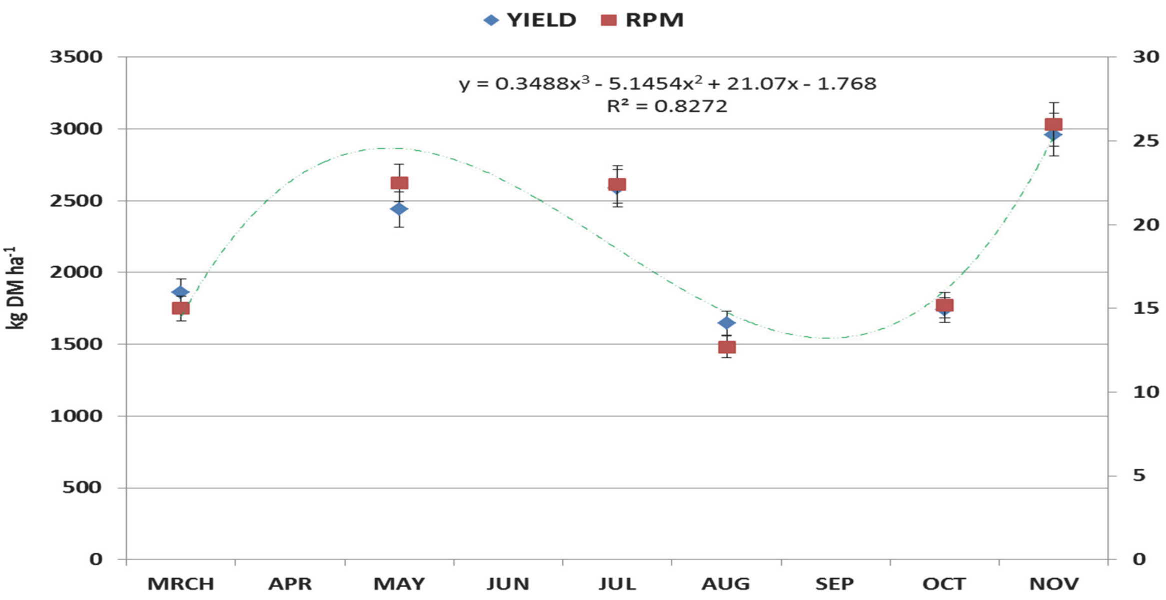


Figure 4.7 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for mixed Tall fescue / White clover pasture

4.1.2.2.3 Tall Fescue / Lucerne mixed pasture

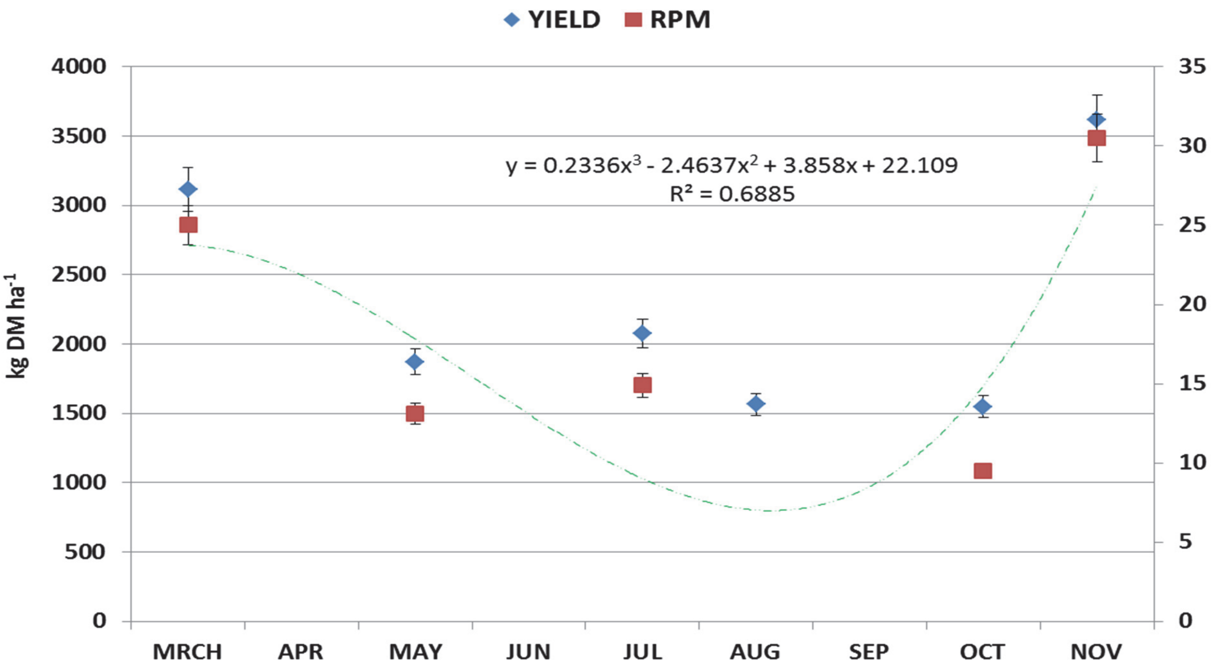


Figure 4.8 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for mixed Tall fescue / Lucerne pasture

4.1.3 Pasture crop water requirements and efficiencies – Mono specific pastures

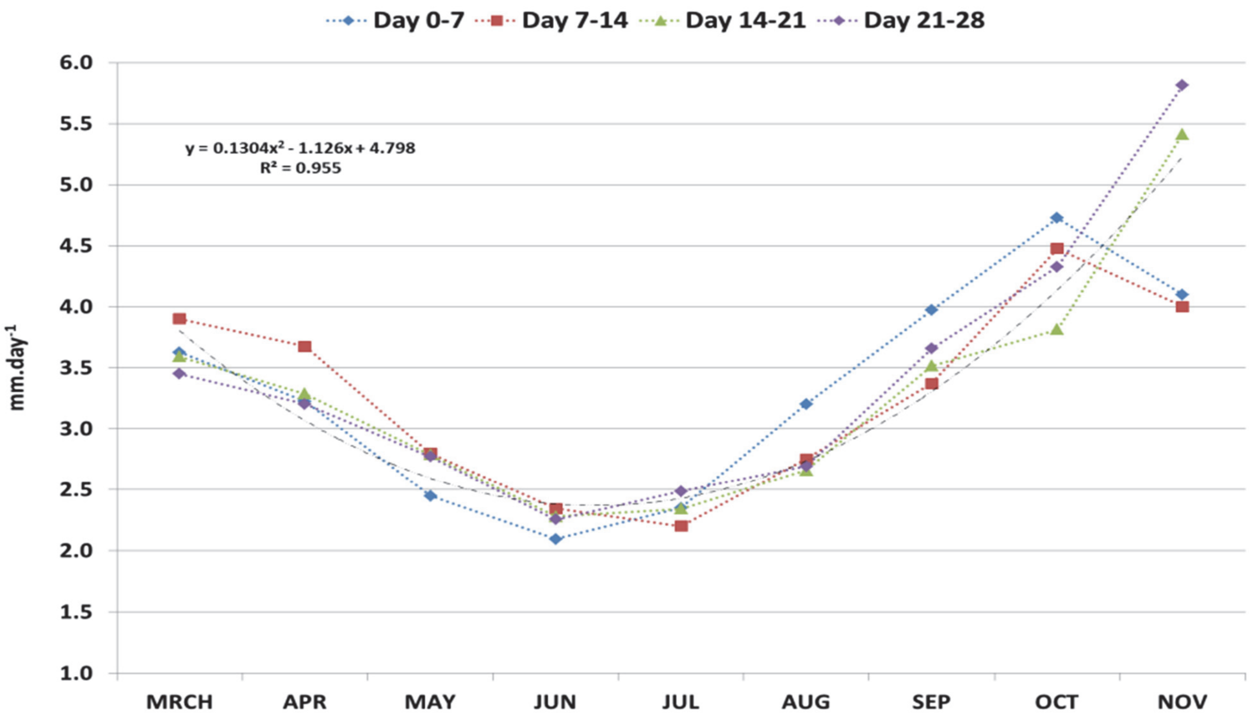


Figure 4.9 Monthly mean measured ET_o values for March to November for Hatfield Experimental farm

4.1.3.1 Kikuyu

Crop coefficients (K_c) (Table 4.1) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.10) using equation (2.2) in section 2.1.4.4.

Table 4.1 Monthly Crop coefficients (K_c) and crop water requirements for mono specific and mixed pasture crops

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o (mm.day^{-1})	3.4	3.2	2.8	2.3	2.5	2.7	3.7	4.3	5.8
Calculated Water Use (ET_c) (mm.day^{-1})	2.5	2.2	1.8	---	---	---	1.5	2.7	4.4
Calculated Water Use (ET_c) (mm.week^{-1})	17.6	15.7	12.6	---	---	---	10.2	18.8	30.5
Crop coefficient (K_c)	**0.8**	**0.7**	**0.7**	**---**	**---**	**---**	**0.4**	**0.6**	**0.8**

The data presented for monospecific pastures illustrates the different water requirements per week, which relates to the physiological growth stage (maturity) of the pasture at a specific period after defoliation. It is evident that less water needs to be applied to a pasture in the first two weeks after defoliation. In this time the evaporation factor is at its highest since there is a small canopy present to cover the soil surface. Once the pasture canopy develops more water is available for pasture growth. It is also interesting to note that some pasture species require less water once the pasture stand goes into a reproductive phase.

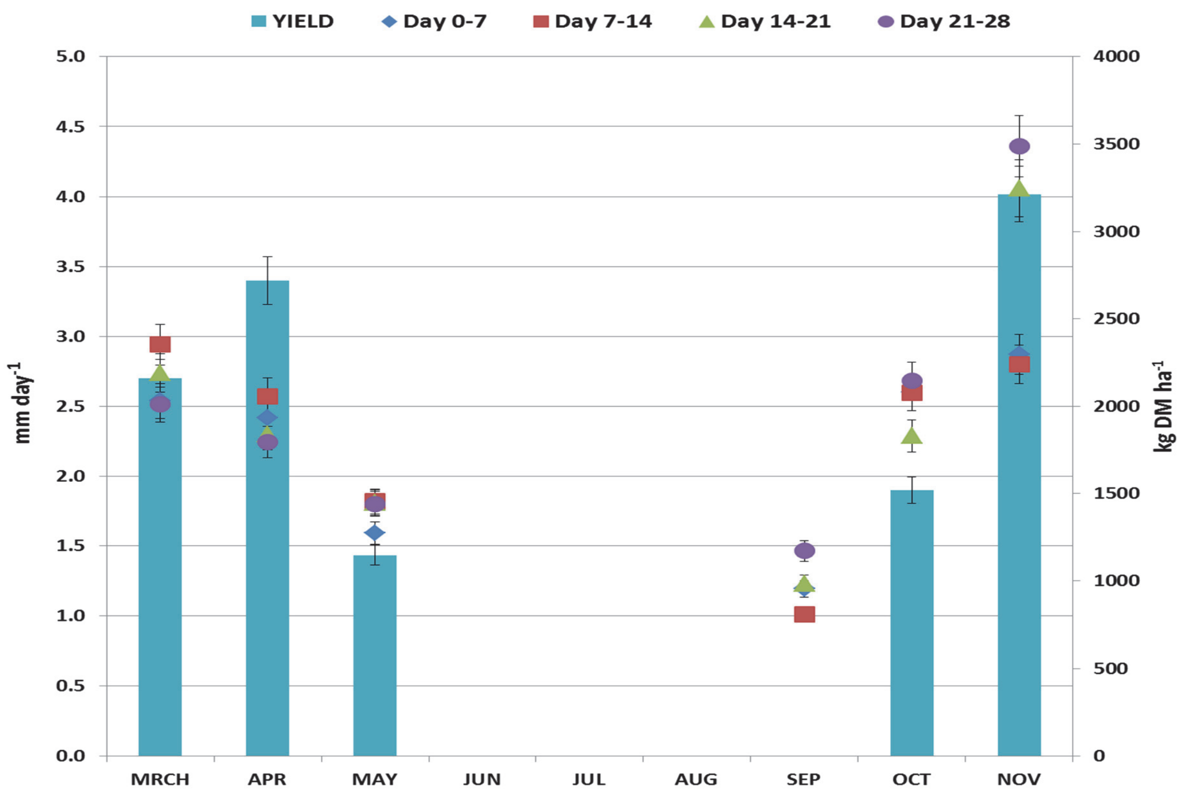


Figure 4.10 Relationship between kikuyu yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

To determine how well a pasture utilises the water being applied, it is essential to calculate the water use efficiency (WUE) in relation to the amount of dry matter (kg DM.ha^{-1}) and/or crude protein (kg CP.ha^{-1}) produced for these pastures. Notably some pastures are more water use efficient in the milder climatic conditions of their growing season.

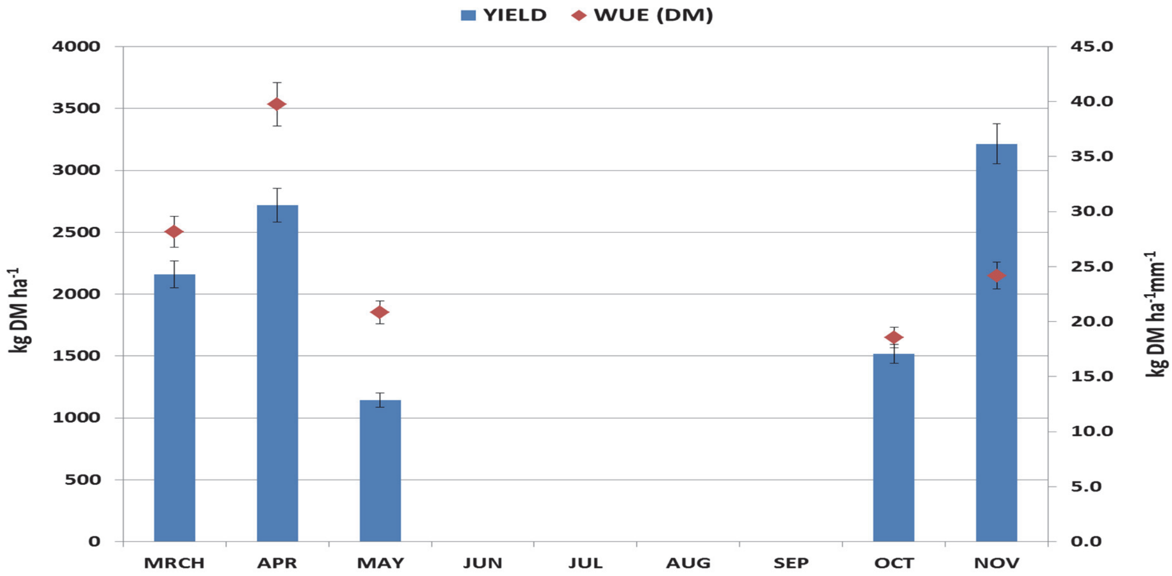


Figure 4.11 Water use efficiency (WUE – kg DM ha^{-1}mm^{-1}) of kikuyu pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

Data collected for the measurement period March-November for kikuyu (Figure 4.11-4.12), indicated that this pasture is most efficient in using water in the cooler months of autumn (March-May). Figure 4.11-4.12 illustrates that there is often a discrepancy between yield and quality in certain months.

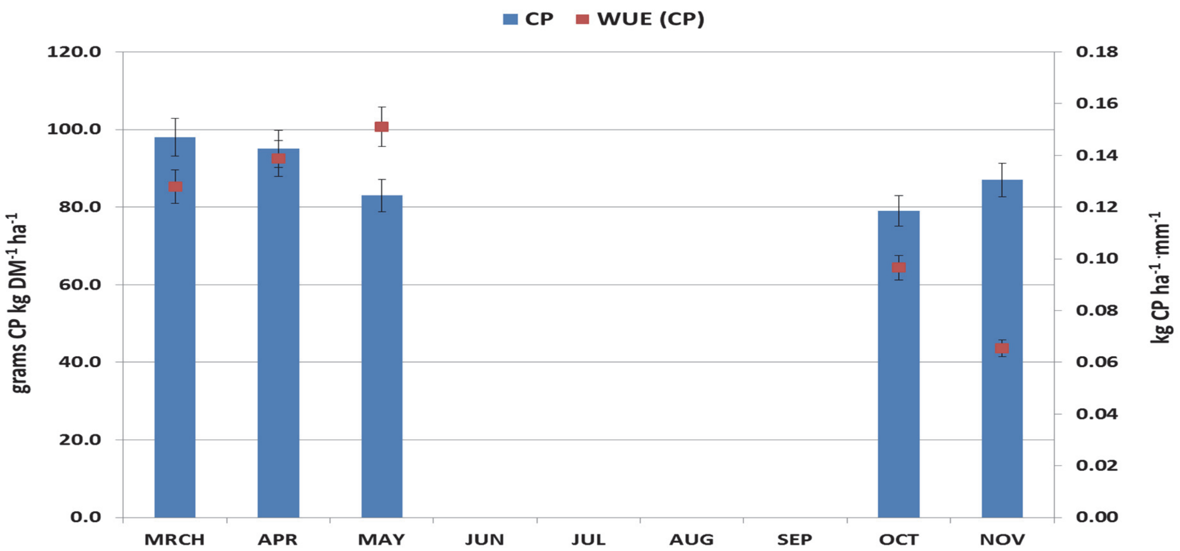


Figure 4.12 Water use efficiency (WUE – kg CP ha^{-1}mm^{-1}) of kikuyu pasture in terms of crude protein yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.3.2 Tall fescue

Crop coefficients (K_c) (Table 4.2) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.13) using equation (2) in section 2.1.4.4.

Table 4.2 Monthly Crop coefficients (K_c) and crop water requirements for mono specific and mixed pasture crops

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o (mm.day^{-1})	3.5	3.2	2.8	2.3	2.5	2.7	3.7	4.3	5.8
Calculated Water Use (ET_c) (mm.day^{-1})	2.1	2.6	2.6	2.2	1.2	1.9	2.6	3.0	5.3
Calculated Water Use (ET_c) (mm.week^{-1})	14.5	18.3	18.2	15.2	8.7	13.2	17.9	21.3	37.2
Crop coefficient (K_c)	**0.6**	**0.8**	**0.9**	**1.0**	**0.5**	**0.7**	**0.7**	**0.7**	**0.9**

It was interesting to observe that the perennial tufted and temperate tall fescue species had a relatively uniform water use from after the day of defoliation to the day of next defoliation. It was however evident that in the extreme warmer months (November), the pasture required more water once the canopy had developed at 21 days and went into bloom quicker than normal. The following week the plant used a significant amount of water to sustain the canopy developed.

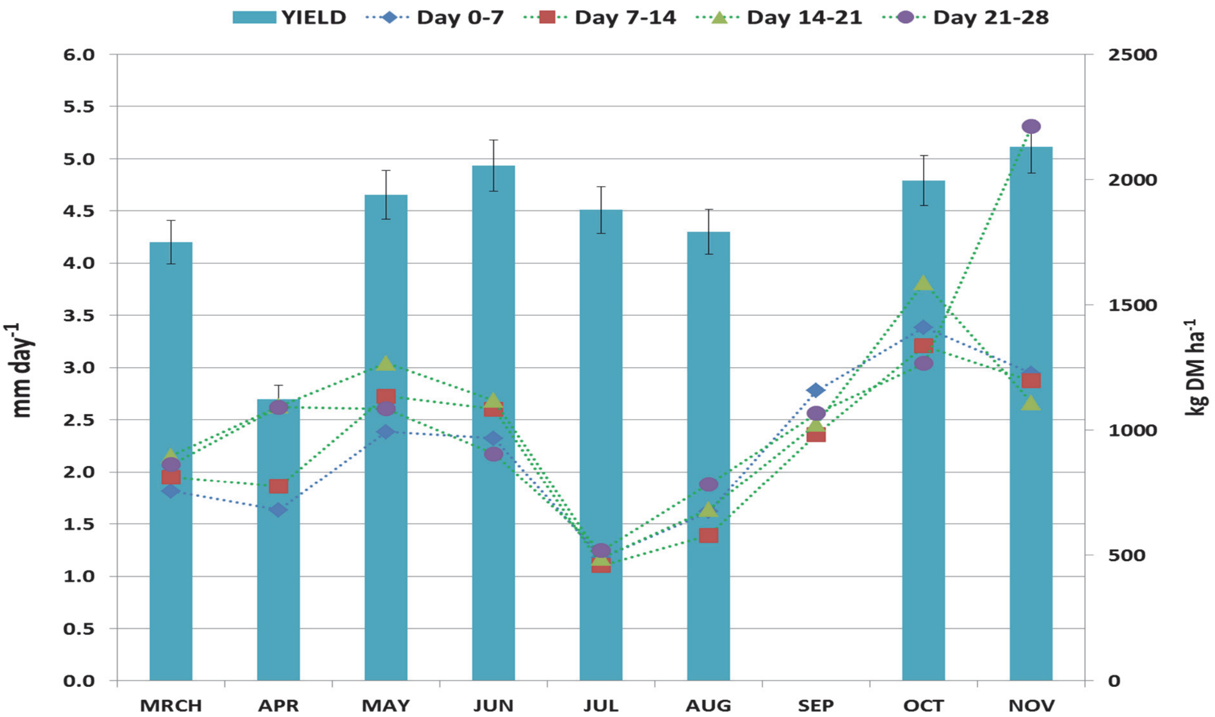


Figure 4.13 Relationship between Tall fescue yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

It is clear from the data that this temperate species suffered in the warmers months, irrespective of it receiving a sufficient amount of irrigation, and it is clear that the WUE's of this species declined severely for these months.

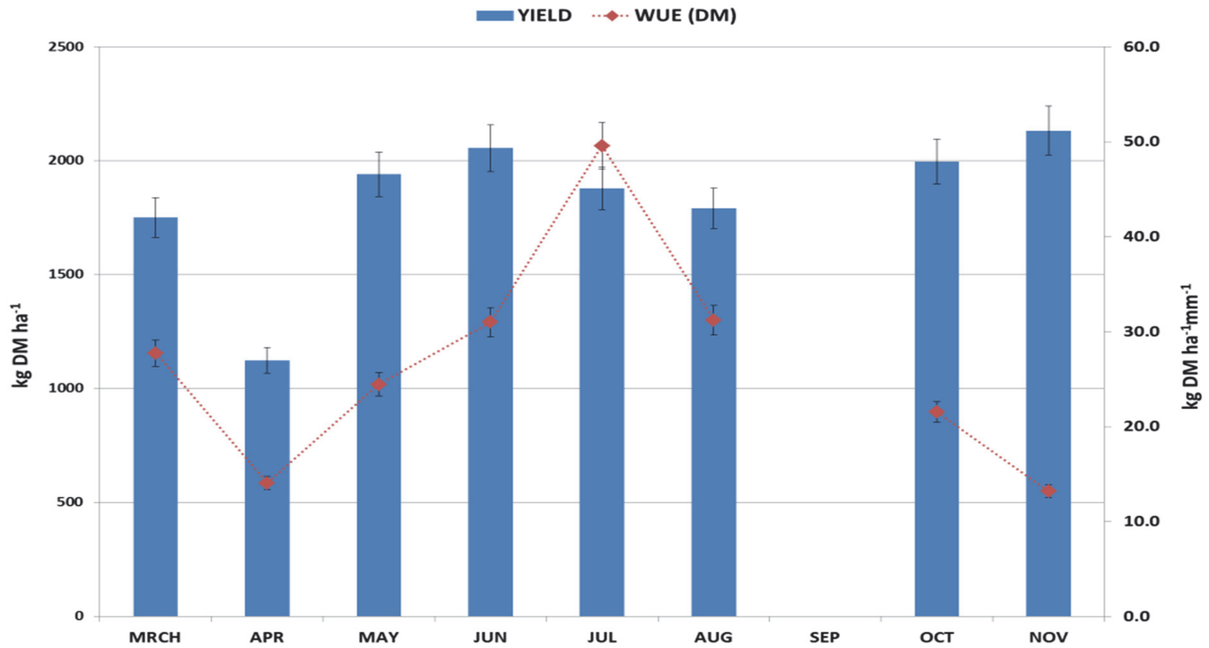


Figure 4.14 Water use efficiency (WUE – kg DM $ha^{-1}mm^{-1}$) of Tall fescue pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

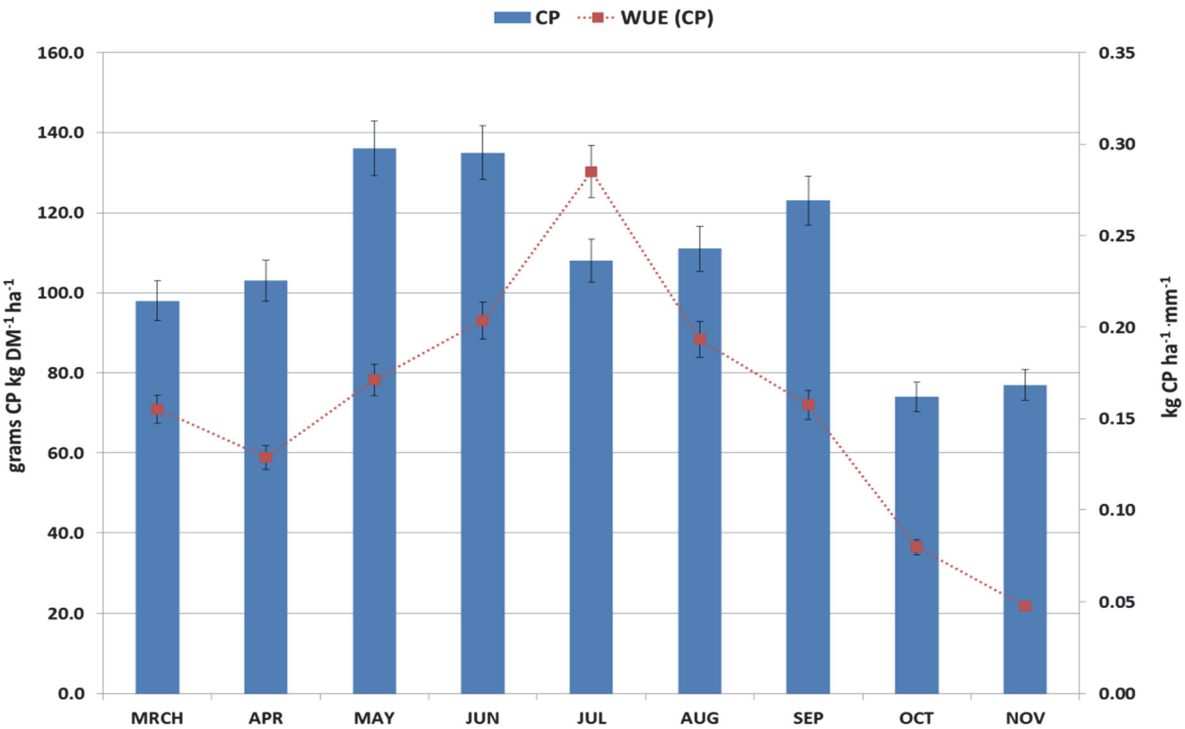


Figure 4.15 Water use efficiency (WUE – kg CP $ha^{-1}mm^{-1}$) of Tall fescue pasture in terms of crude protein yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.3.3 Lucerne

Crop coefficients (K_c) (Table 4.3) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.16) using equation (2.2) in section 2.1.4.4.

Table 4.3 Monthly Crop coefficients (K_c) and crop water requirements for lucerne (area without frost)

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o (mm.day^{-1})	4.0	2.7	2.3	1.9	2.5	2.7	3.7	4.3	5.8
Calculated Water Use (ET_c) (mm.day^{-1})	2.8	3.3	2.2	1.5	2.7	1.9	2.6	3.1	5.6
Calculated Water Use (ET_c) (mm.week^{-1})	19.8	23.3	15.5	10.4	18.6	13.2	17.9	21.9	39.2
Crop coefficient (K_c)	**0.7**	**1.2**	**1.0**	**0.8**	**1.1**	**0.7**	**0.7**	**0.7**	**1.0**

Similarly to tall fescue, lucerne enters into a reproductive phase quicker and experiences an increased water requirement in the last week of the harvest cycle in the extremely hot months. This increased water requirement is to sustain the canopy in the climatic conditions with a high evaporative demand.

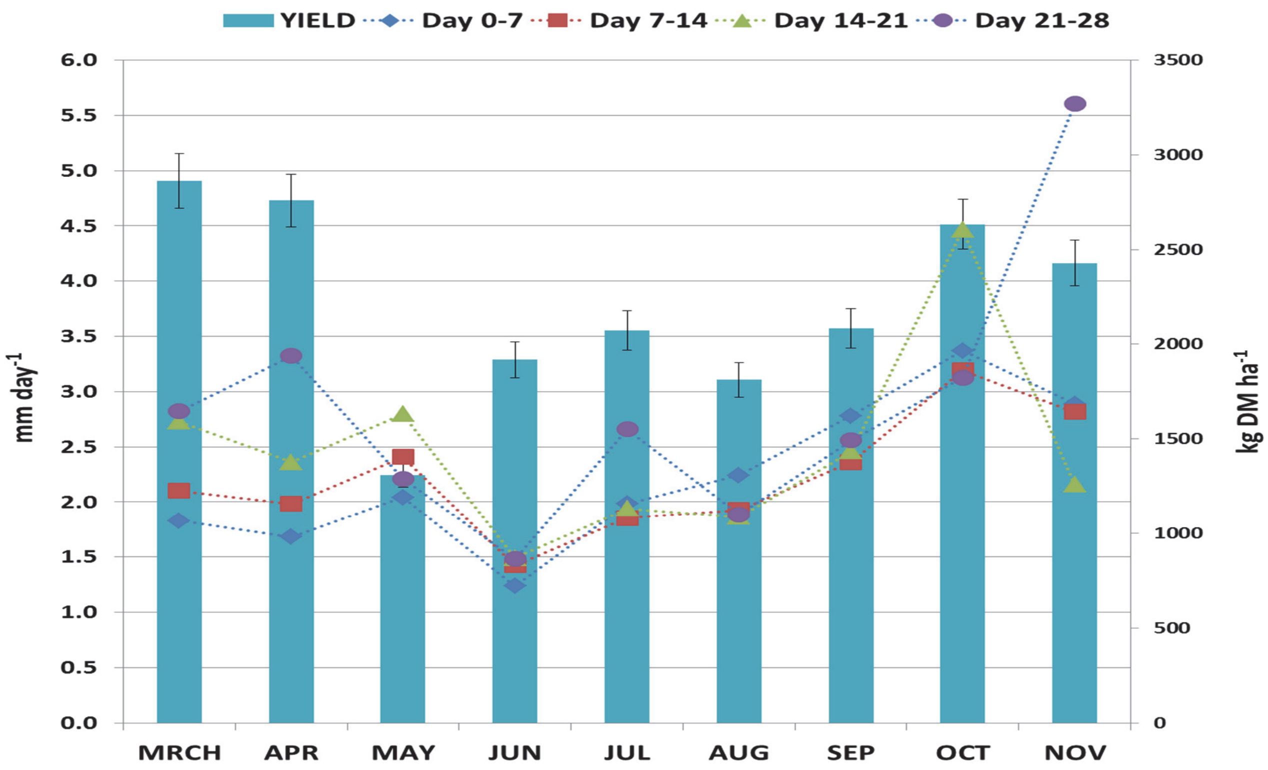


Figure 4.16 Relationship between Lucerne yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

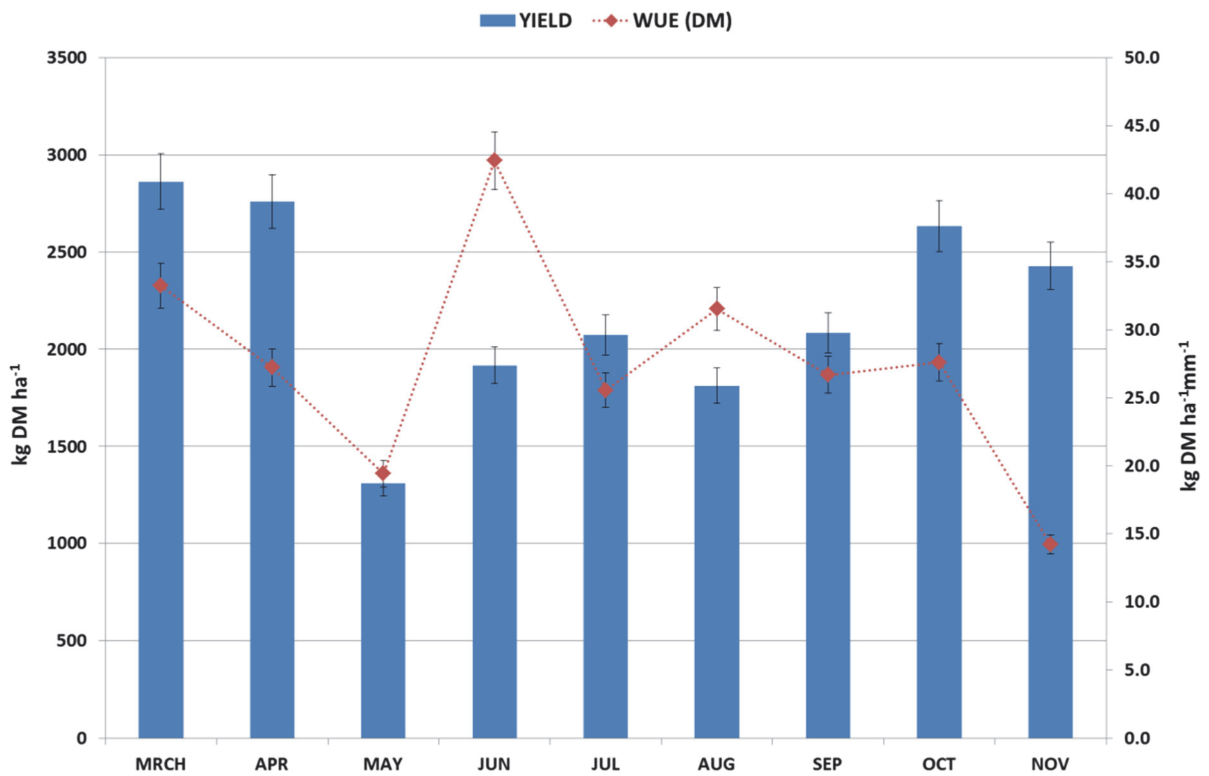


Figure 4.17 Water use efficiency (WUE – kg DM $ha^{-1}mm^{-1}$) of Lucerne pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

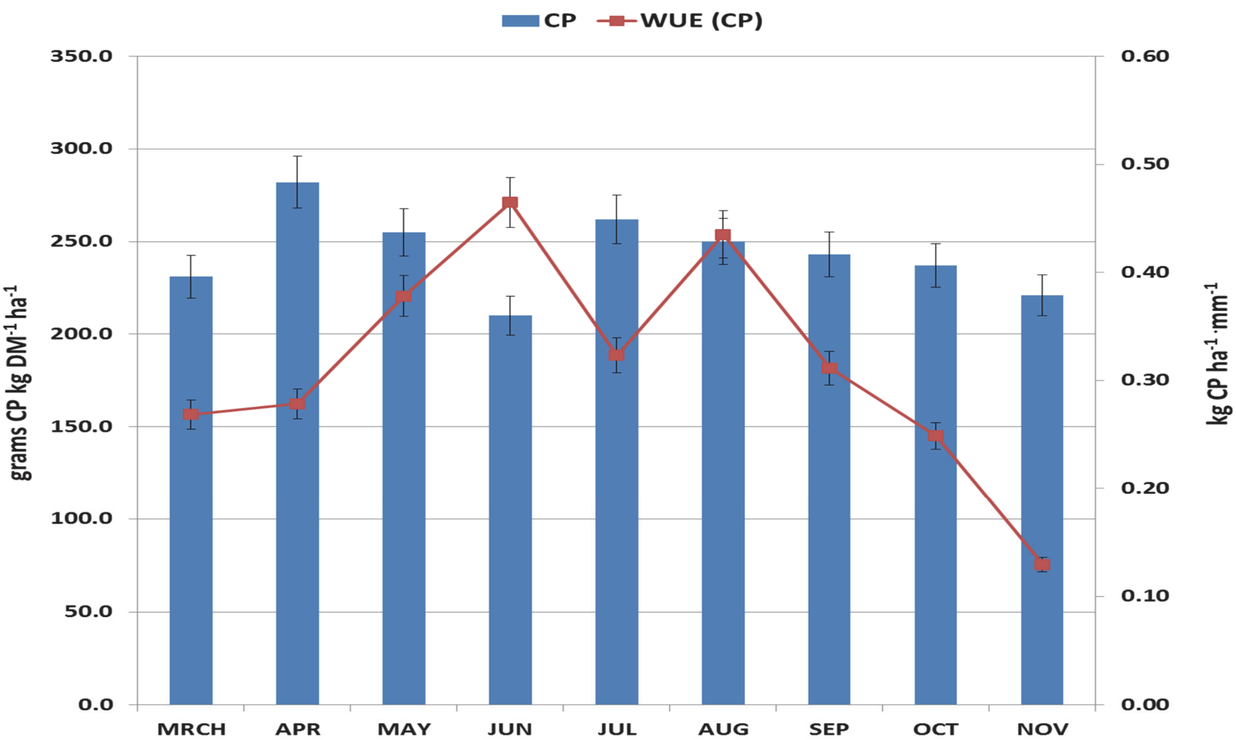


Figure 4.18 Water use efficiency (WUE – kg CP $ha^{-1}mm^{-1}$) of Lucerne pasture in terms of crude protein yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.3.4 White clover

Crop coefficients (K_c) (Table 4.4) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.19) using equation (2.2) in section 2.1.4.4.

Table 4.4: Monthly Crop coefficients (K_c) and crop water requirements for white clover pasture crop

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o (mm.day^{-1})	3.4	3.2	2.8	2.3	2.5	2.7	3.7	4.3	5.8
Calculated Water Use (ET_c) (mm.day^{-1})	2.2	4.3	3.9	2.1	1.6	2.9	2.7	3.3	5.1
Calculated Water Use (ET_c) (mm.week^{-1})	15.2	30.0	27.4	15.0	11.3	20.0	19.2	23.3	35.4
Crop coefficient (K_c)	**0.7**	**1.3**	**1.4**	**1.0**	**0.7**	**1.1**	**0.8**	**0.8**	**0.9**

White clover growth presented a similar response to climatic conditions as other temperate species. Interestingly, white clover required more water in the actively growing months, i.e. April, May and October. Similarly white clover had a more uniform water use during different weeks in the harvest cycle in the winter growing months.

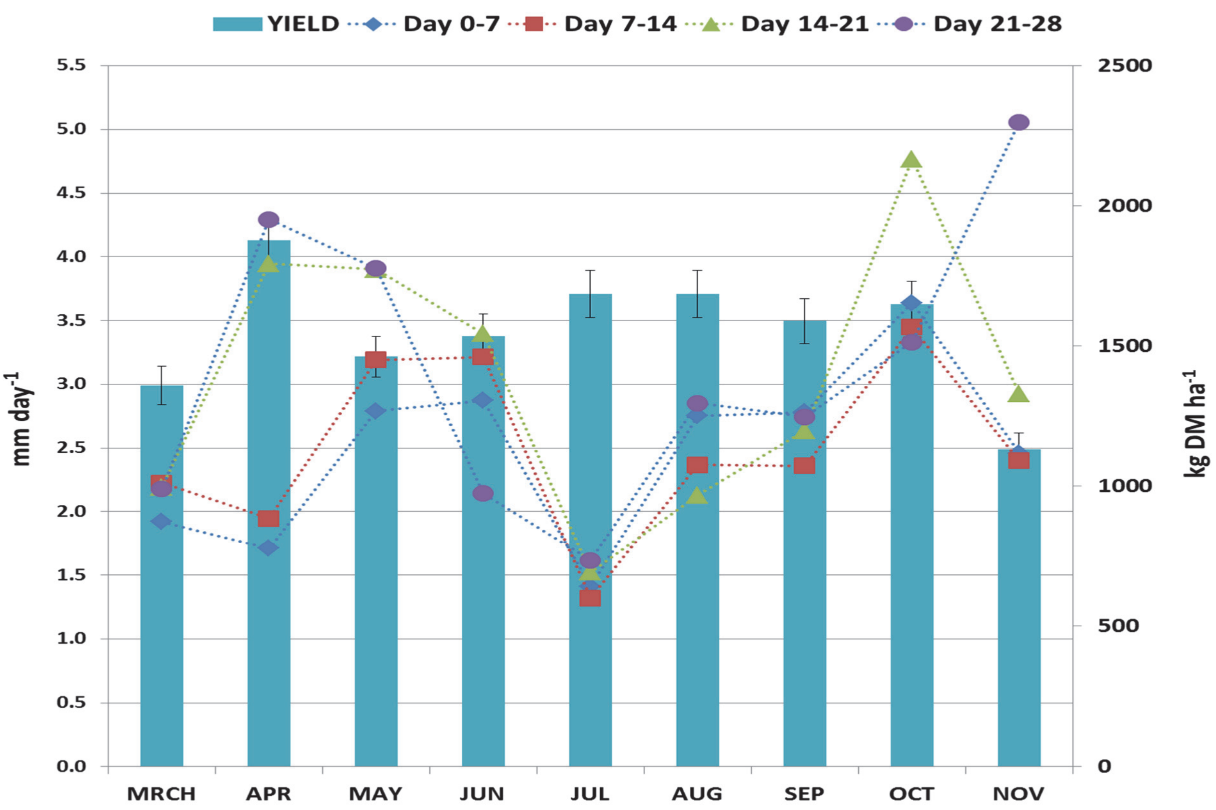


Figure 4.19 Relationship between White clover yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

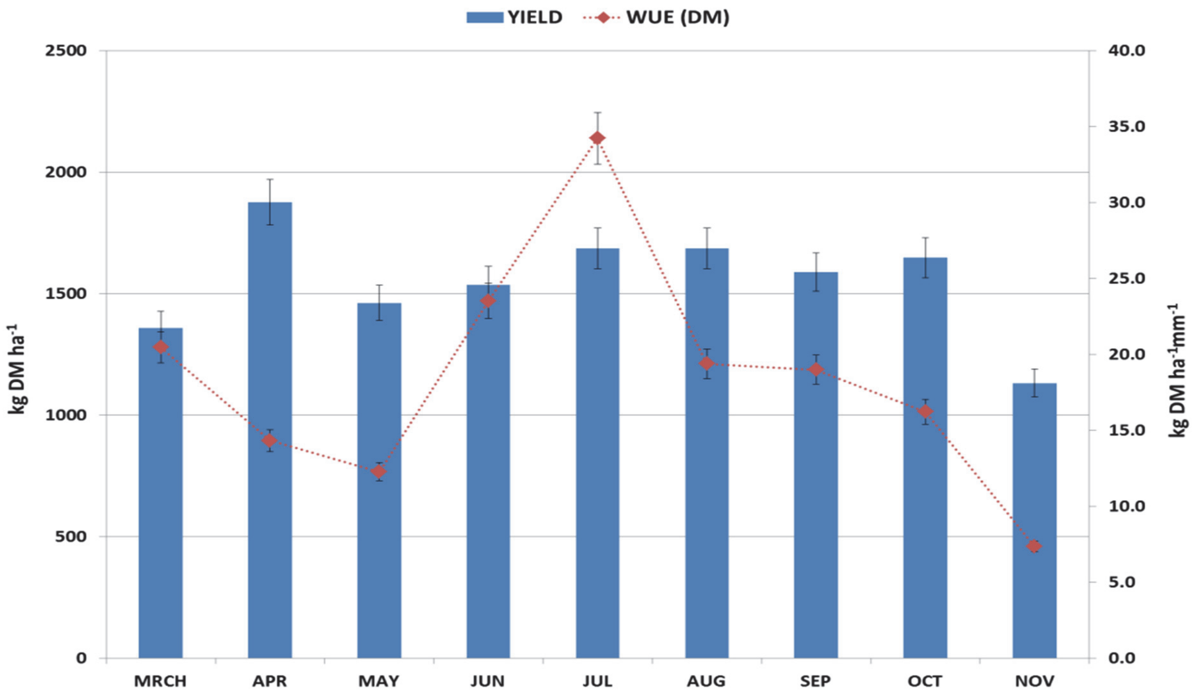


Figure 4.20 Water use efficiency (WUE – kg DM $ha^{-1}mm^{-1}$) of kikuyu pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

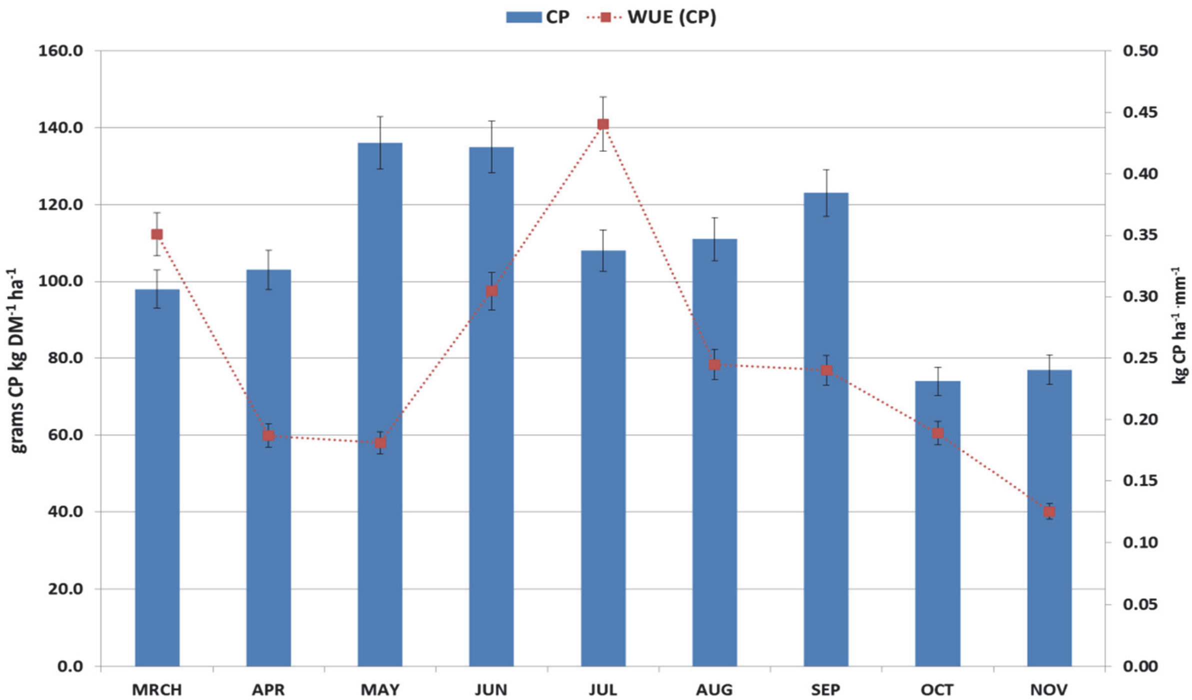


Figure 4.21 Water use efficiency (WUE – kg CP $ha^{-1}mm^{-1}$) of white clover pasture in terms of crude protein yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

These water requirements changes when the temperate species enter into a reproductive quicker in the warmer months due to heat stress. Once the canopy has fully developed and in the reproductive phase, a higher water requirement is evident.

4.1.4 Pasture crop water requirements – Mixed Pastures

The data presented for the mixed pastures clearly highlights the value of combined species from a water use perspective. It must be remembered that mixed pastures can mean the following: a) a perennial subtropical pasture oversown with an annual /perennial temperate species providing growth in both summer and winter months or b) two temperate species, either grass-grass or grass-legume mixtures with slow to no growth in summer months.

4.1.4.1 Kikuyu / Lucerne mixed pasture

Crop coefficients (K_c) (Table 4.5) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.22) using equation (2.2) in section 2.1.4.4.

Table 4.5: Monthly Crop coefficients (K_c) and crop water requirements for mixed kikuyu / lucerne pasture crops

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o (mm.day^{-1})	3.4	3.7	3.3	2.7	2.5	3.4	3.7	5.3	7.4
Calculated Water Use (ET_c) (mm.day^{-1})	2.3	3.3	2.6	2.3	1.6	2.2	2.4	3.7	5.9
Calculated Water Use (ET_c) (mm.week^{-1})	16.4	23.2	18.2	15.8	11.3	15.3	16.6	25.9	41.4
Crop coefficient (K_c)	0.7	0.9	0.8	0.9	0.7	0.7	0.7	0.7	0.8

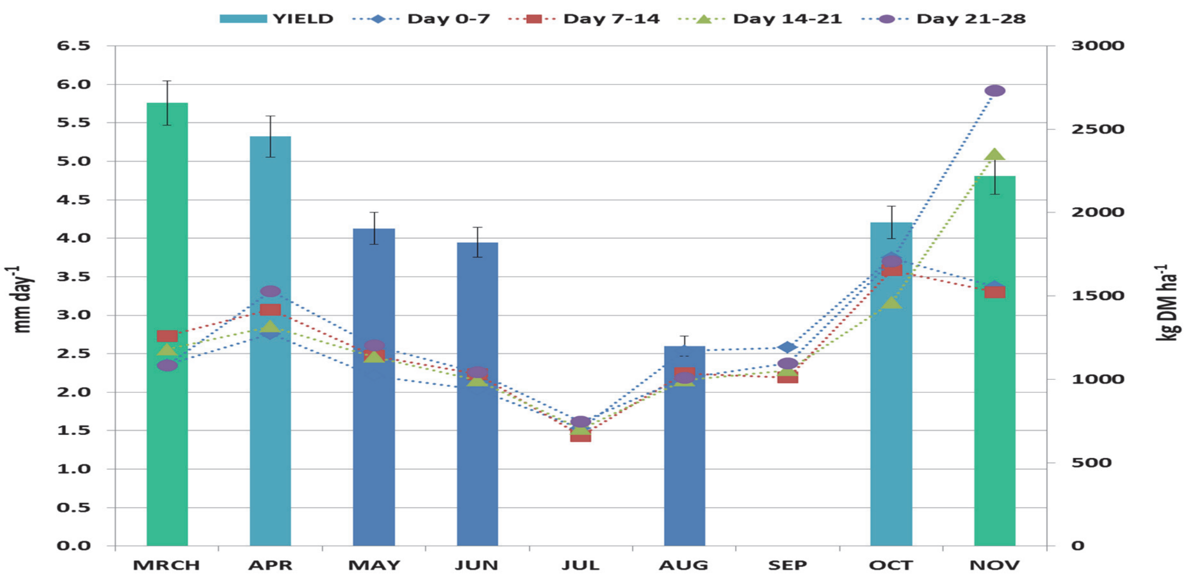


Figure 4.22 Relationship between mixed kikuyu / lucerne yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

It is always important to take note of the vigour of the individual species in the mixture, since certain individual species become more dominant than others, as influenced by either preferential climatic conditions or management intensity. The water requirement of a mixed pasture will depend on the dominant component of the mixture in that species specific growth season. This holds true for the subtropical / temperate species mixture, and very similar water use trends are noticeable for the different species in the mixture as seen for the monospecific pastures.

Water use efficiency did change for the mixture, and due to the competition between the subtropical and temperate components in the mixture, the water use efficiency declined in the warmer months. It was noted that the mixture's WUE was similar to kikuyu's water use efficiency and that of lucerne in May. This could potentially indicate the point at which the subtropical and temperate components switch dominance and determine the next growing seasons water requirements.

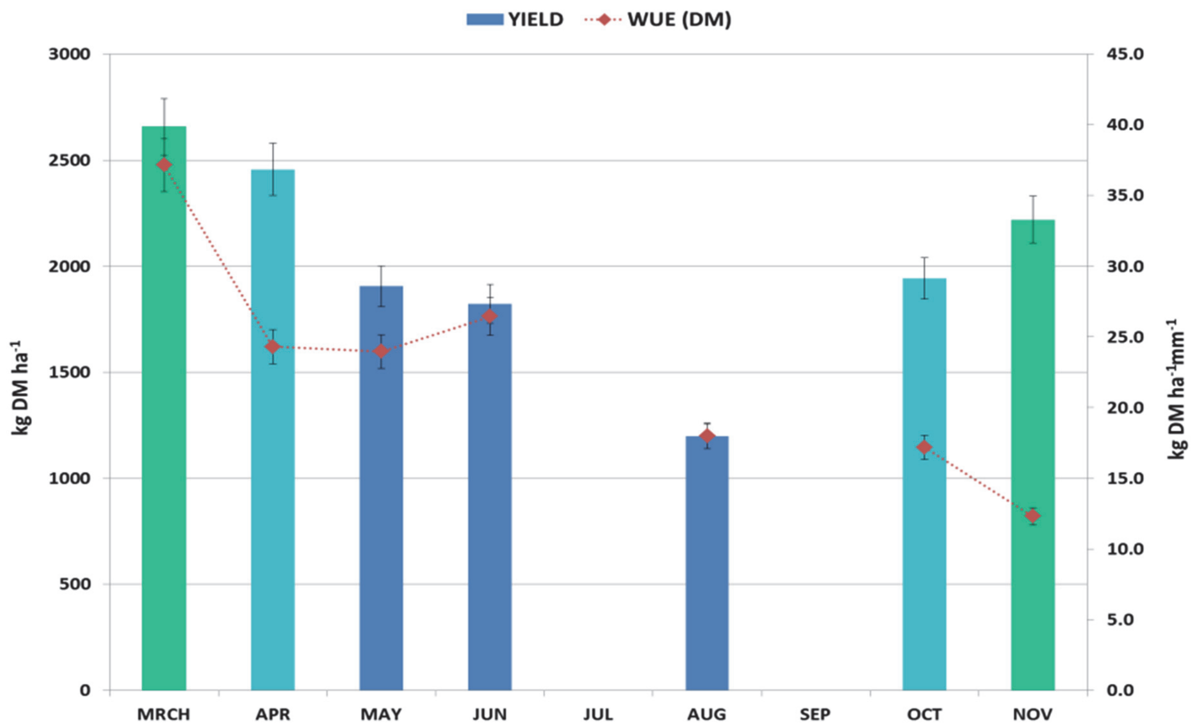


Figure 4.23 Water use efficiency (WUE – kg DM $ha^{-1}mm^{-1}$) of mixed kikuyu / lucerne pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

It was eminent to see that the kikuyu pasture component in the mixture performed more poorly that the monospecific kikuyu pasture. This highlights the importance of competition amongst species from different ecological groups (Temperate vs Subtropical). This data does not support combining these species from a water use perspective, but does however support the importance of eradicating the kikuyu before oversowing the temperate species into the suppressed subtropical component, which will then ensure better water use.

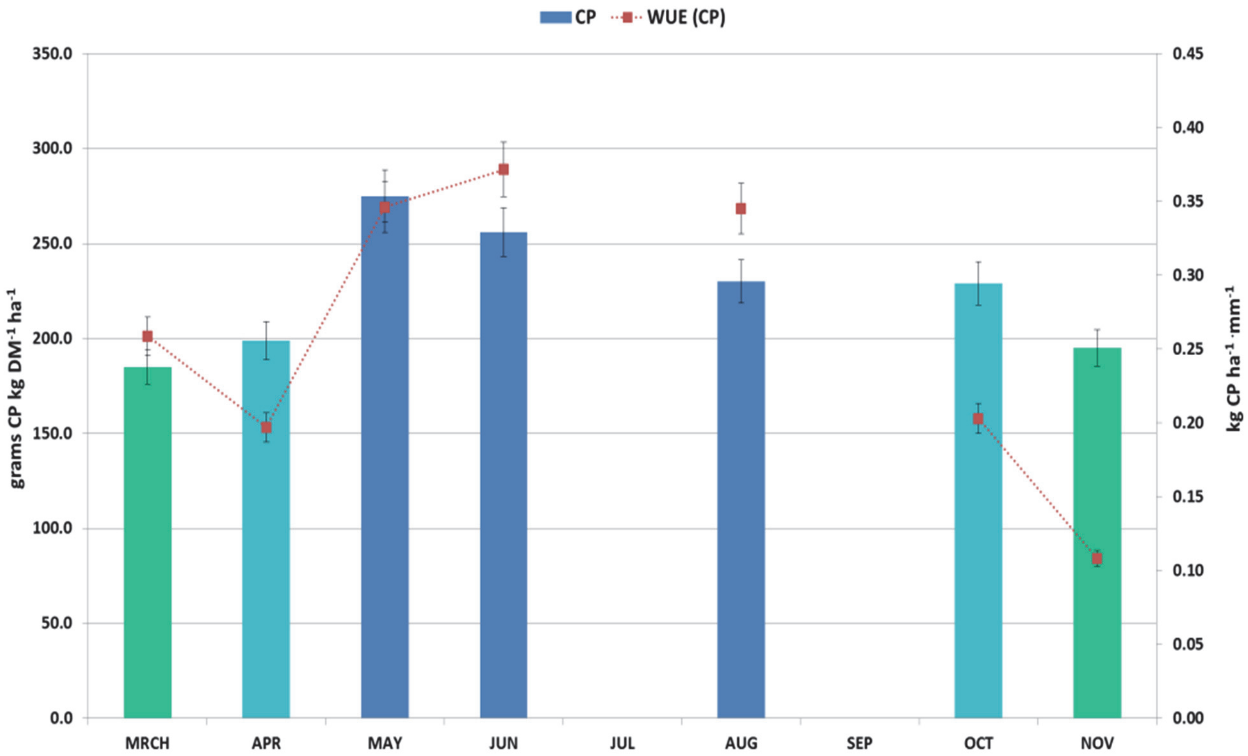


Figure 4.24 Water use efficiency (WUE – kg CP $ha^{-1}mm^{-1}$) of mixed kikuyu / lucerne pasture in terms of crude protein yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.4.2 Tall fescue / White clover mixed pasture

Crop coefficients (K_c) (Table 4.6) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.25) using equation (2.2) in section 2.1.4.4.

Table 4.6: Monthly Crop coefficients (K_c) and crop water requirements for tall fescue/white clover mixed pasture crops

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o (mm.day^{-1})	3.4	3.2	2.8	2.3	2.5	2.7	3.7	4.3	5.8
Calculated Water Use (ET_c) (mm.day^{-1})	2.0	3.4	3.3	2.2	1.6	2.0	2.6	3.2	5.3
Calculated Water Use (ET_c) (mm.week^{-1})	14.1	23.5	23.3	15.2	11.3	14.1	17.9	22.7	37.2
Crop coefficient (K_c)	**0.6**	**1.1**	**1.2**	**1.0**	**0.7**	**0.8**	**0.7**	**0.8**	**0.9**

The tall fescue / white clover mixture presented a different scenario, illustrating improved water use and water use efficiency than the individual components. The data does however indicate that in some months there is either a lower yield or slightly higher/lower protein value than the monospecific pastures. It was also important to observe that the white clover species became dominant in the mixture and is a function of the species growth habit (strongly rhizomatous and stoloniferous) and becomes extremely vigorous due to intensive defoliation practices, i.e. mechanical harvesting.

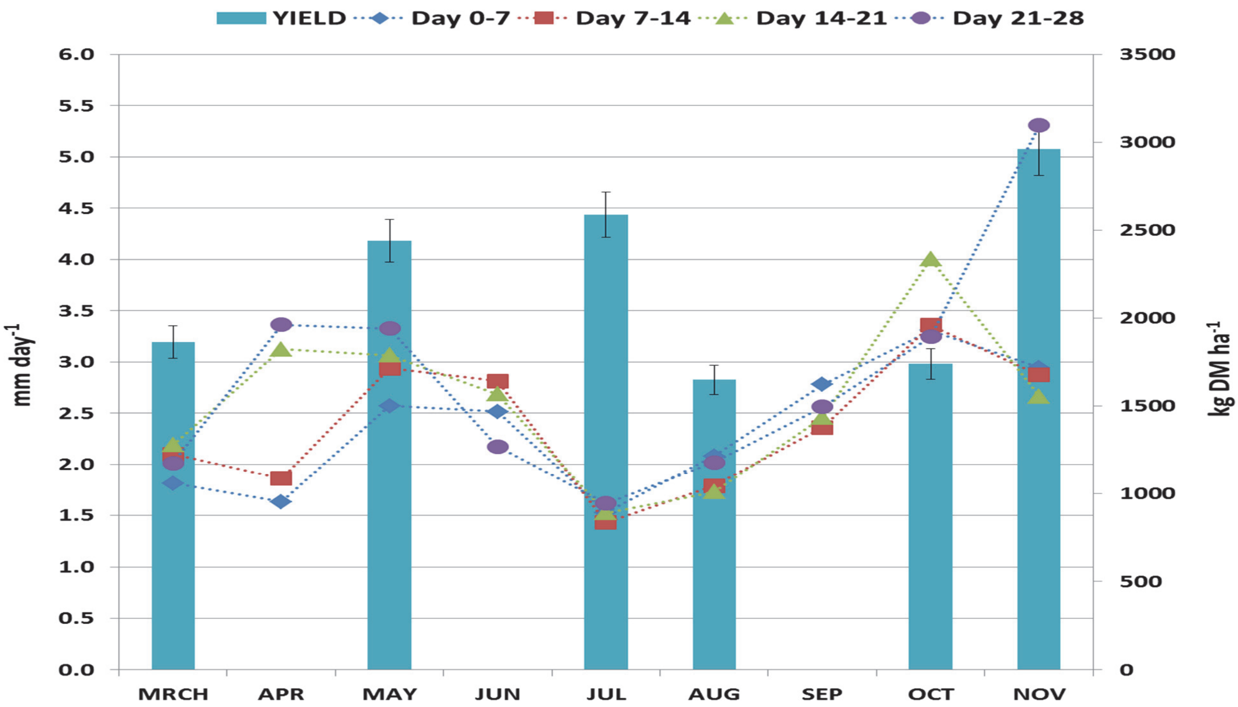


Figure 4.25 Relationship between mixed tall fescue / white clover pasture yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

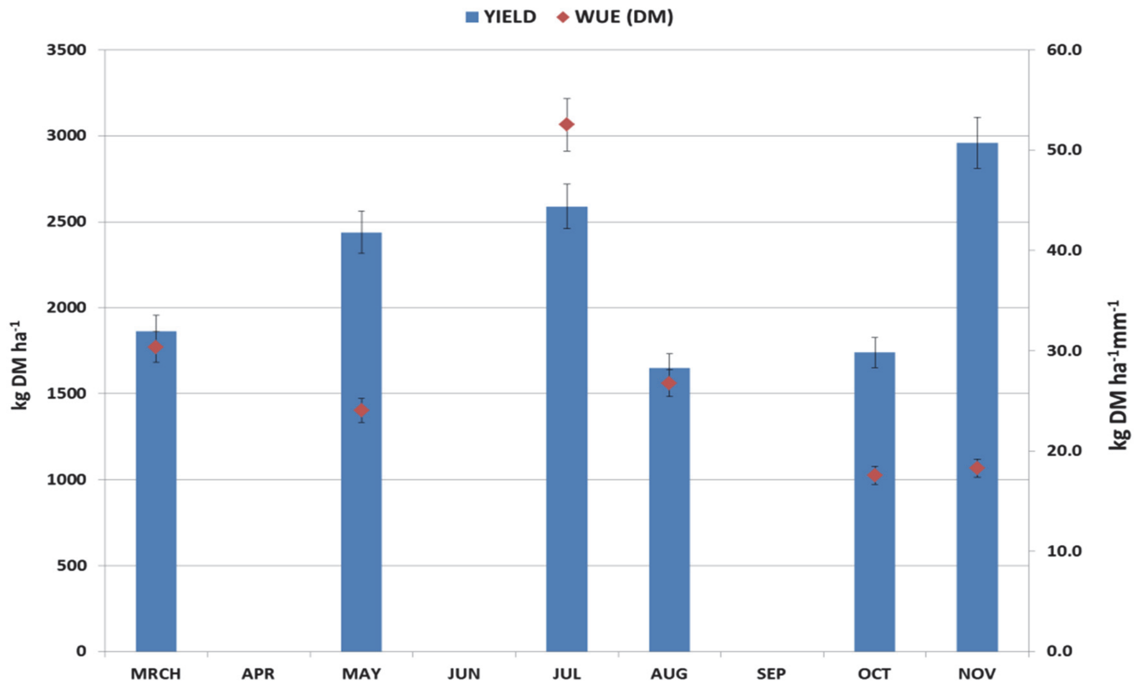


Figure 4.26 Water use efficiency (WUE – kg DM ha^{-1}mm^{-1}) of mixed tall fescue / white clover pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

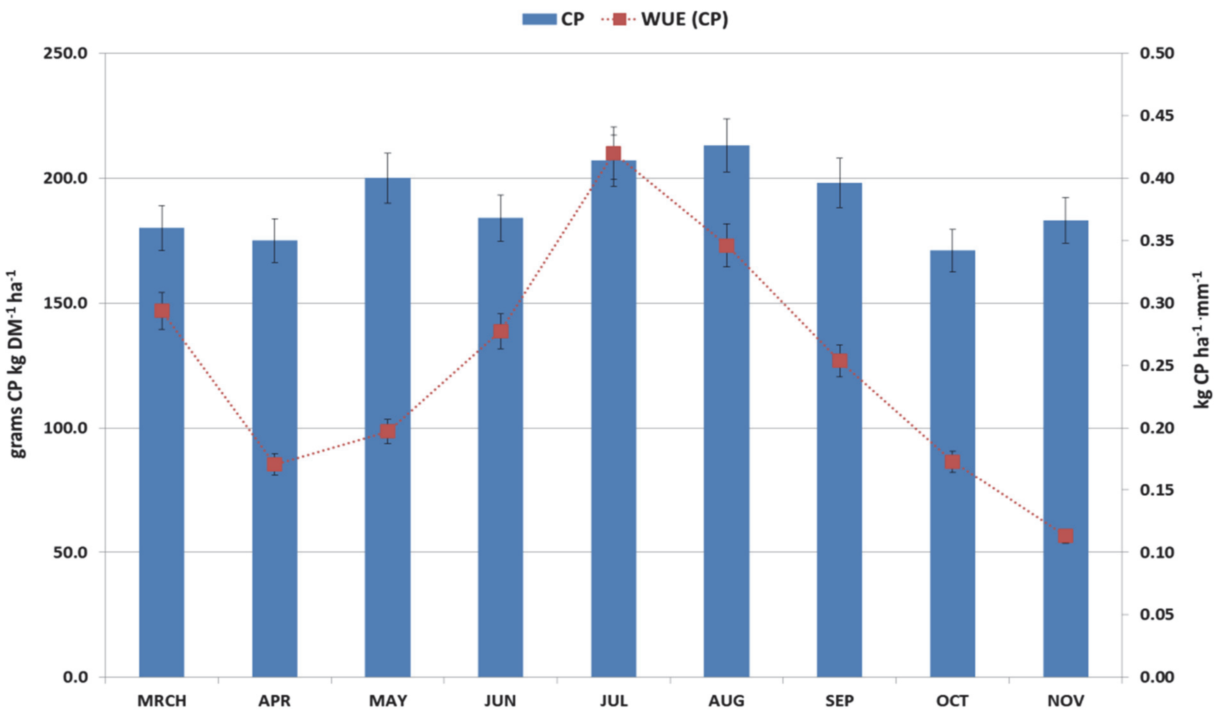


Figure 4.27 Water use efficiency (WUE – kg.DM $ha^{-1}mm^{-1}$) of mixed tall fescue / white clover pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.4.3 Tall fescue / Lucerne mixed pasture

Crop coefficients (K_c) (Table 4.7) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.28) using equation (2.2) in section 2.1.4.4.

Table 4.7: Monthly Crop coefficients (K_c) and crop water requirements for tall fescue / lucerne mixed pasture crops

	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
ET_o ($mm.day^{-1}$)	3.8	3.2	2.8	2.3	2.5	2.7	3.7	4.3	5.8
Calculated Water Use (ET_c) ($mm.day^{-1}$)	2.4	2.9	2.6	2.0	2.0	2.0	2.4	2.9	5.1
Calculated Water Use (ET_c) ($mm.week^{-1}$)	17.1	20.2	18.4	14.2	13.9	14.1	16.6	20.6	35.8
Crop coefficient (K_c)	**0.7**	**0.9**	**1.0**	**0.9**	**0.8**	**0.8**	**0.7**	**0.7**	**0.9**

This mixture presented a more balanced response to climatic conditions and management, but did however become less efficient in the warmer summer months. The water use requirements of this mixture were reflective of the growing seasons. Interestingly, the data for this mixture illustrated that the temperate species will enter into the reproductive phase quicker in the harvest cycle than in their actual growing season, and this results in the mixed pasture using more water to sustain the canopy cover in these months.

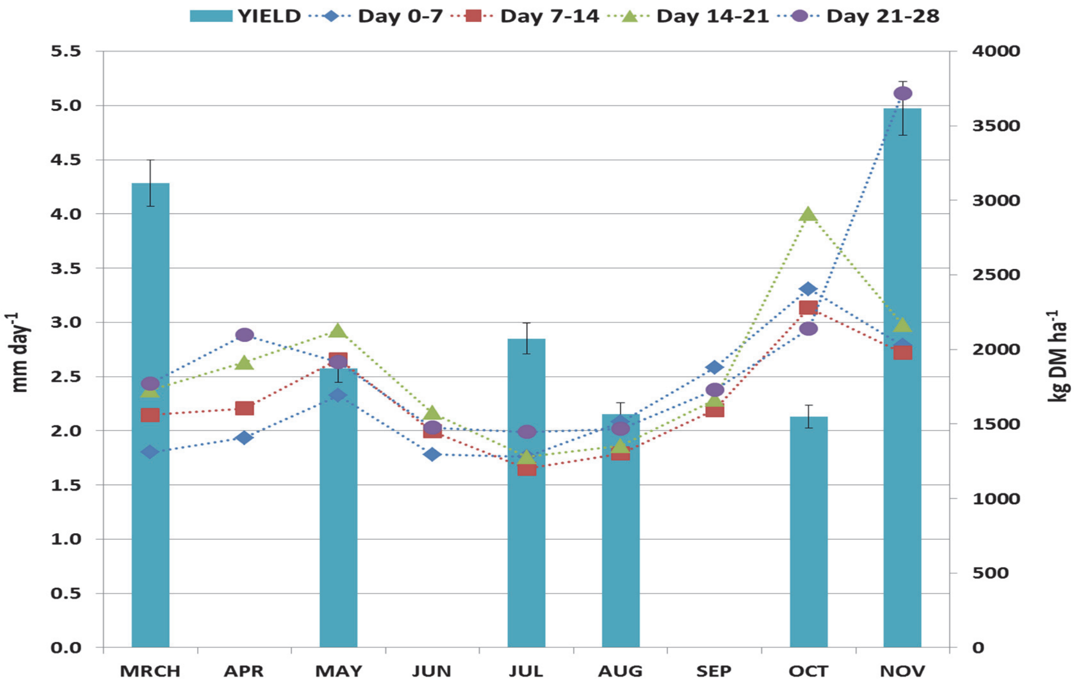


Figure 4.28 Relationship between mixed tall fescue / lucerne pasture yield (kg DM.ha^{-1}) and weekly mean crop water requirements (mm.day^{-1}) for fixed monthly harvest cycles for the growing season March to November on the Hatfield Experimental farm

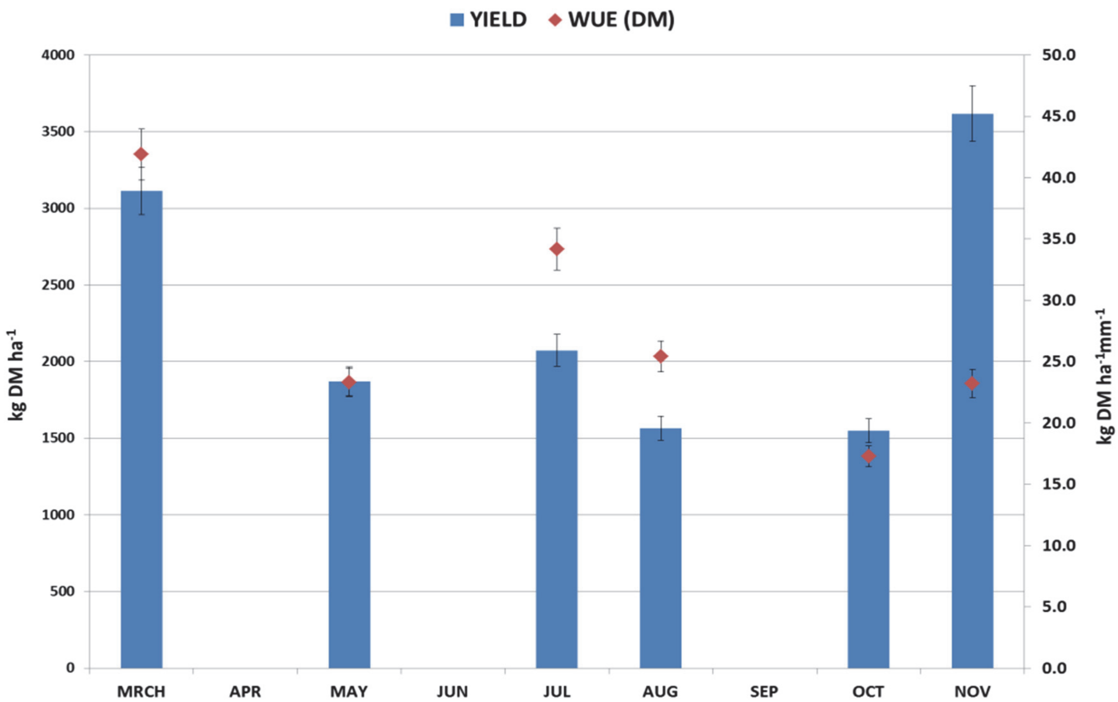


Figure 4.29 Water use efficiency (WUE – kg DM ha^{-1}mm^{-1}) of mixed Tall fescue / Lucerne pasture in terms of DM yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

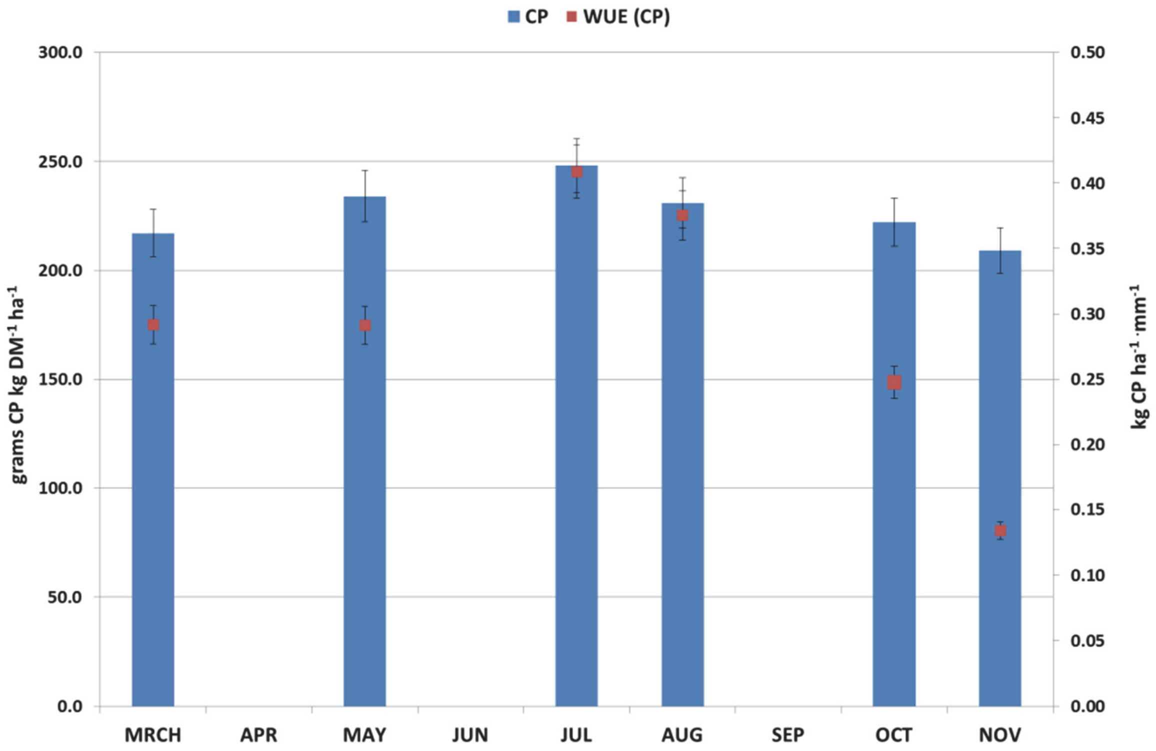


Figure 4.30 Water use efficiency (WUE – kg DM ha^{-1}mm^{-1}) of mixed Tall fescue / lucerne pasture in terms of crude protein (CP) yield for the growing season March to November 2013-2015 on the Hatfield Experimental farm

Figure 4.29 and 4.30 illustrate the overall observation that temperate species are less water use efficient in the months out of their actual growing season. It is also notable that the mixture of species with similar growth forms did have better water use efficiencies than the individual components as a monospecific pasture.

This was however only significant for the warmer months. The improved water use efficiencies did result in a lower yield and in some instances less protein than what would be expected for such a species in a monospecific pasture.

4.1.5 Potential relationship between DM yield estimation technique (Rising Plate Meter) an crop water use

Monitoring the production potential of a pasture can be an extensive task, and since pastures cover large surface areas, it is of utmost importance to find easy, quick and accurate methods of establishing the amount of available pasture for use. To achieve this objective many tools have been developed and the rising plate meter (RPM) is one such method. The RPM method is this most adopted tool currently to assess pastures. This part of the study achieved to establish whether there was any potential in using the RPM reading to deduct the water requirement of the pasture.

It was interestingly to observe that there was a strong correlation between pasture specific calibrated RPM readings and the water use.

4.1.5.1 Mono-specific pastures

4.1.5.1.1 Kikuyu

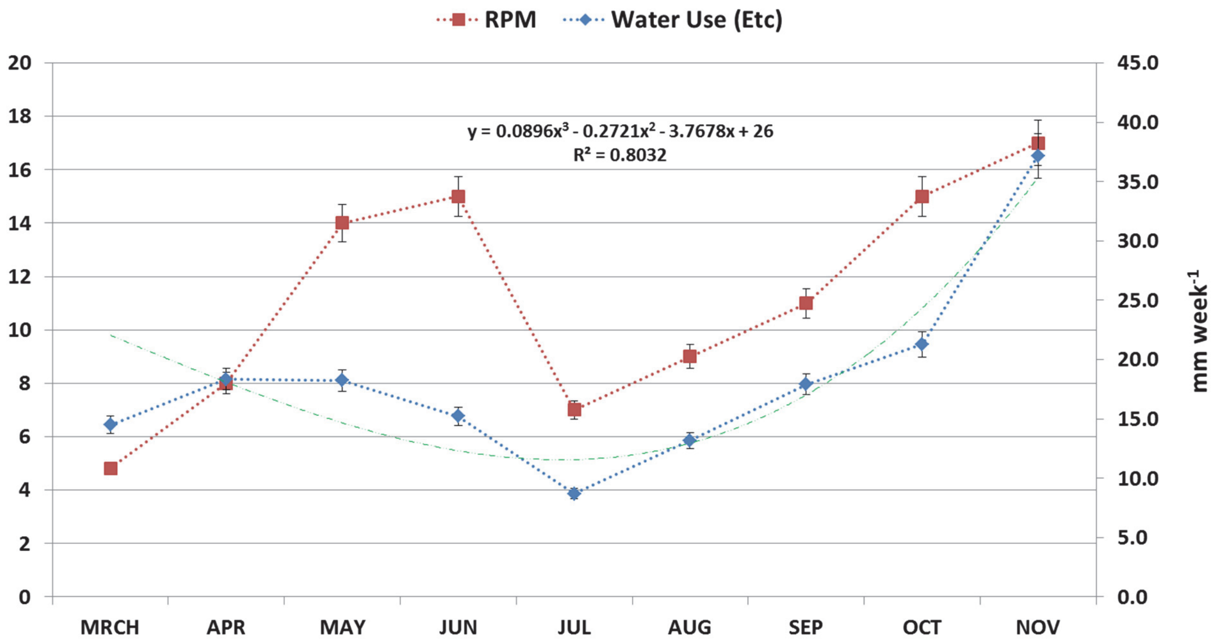


Figure 4.31 Potential relationships of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of kikuyu pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

The data did however confirm the notion that better RPM calibrations are achieved for species that have an erect growth habit. Nevertheless, the more readings taken will provide better calibrations and will better align to water use of non-tufted species.

4.1.5.1.2 Tall fescue

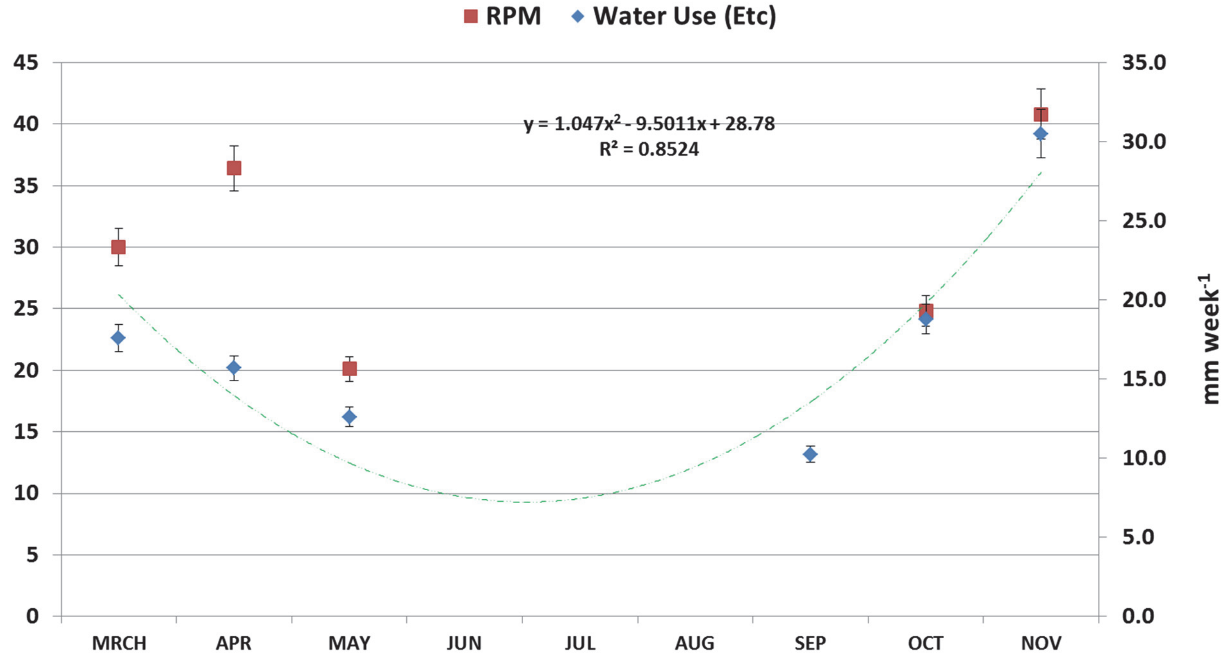


Figure 4.32 Potential relationship of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of Tall fescue pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.5.1.3 Lucerne

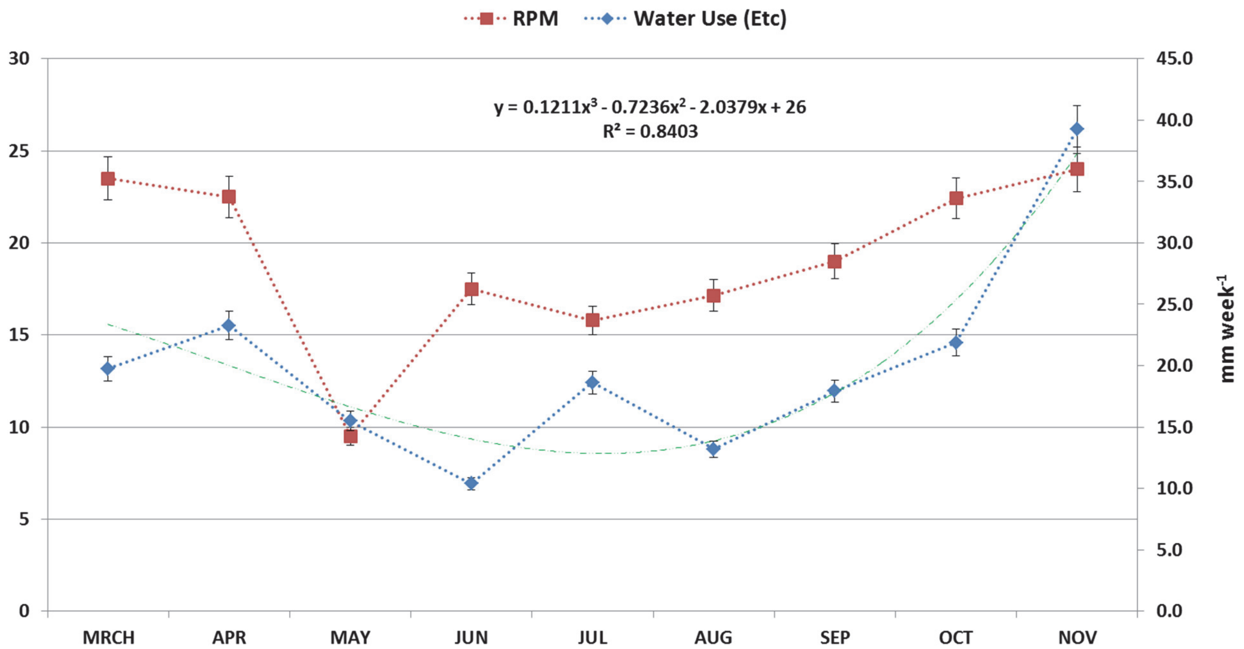


Figure 4.33 Potential relationship of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of lucerne pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.5.1.3 White clover

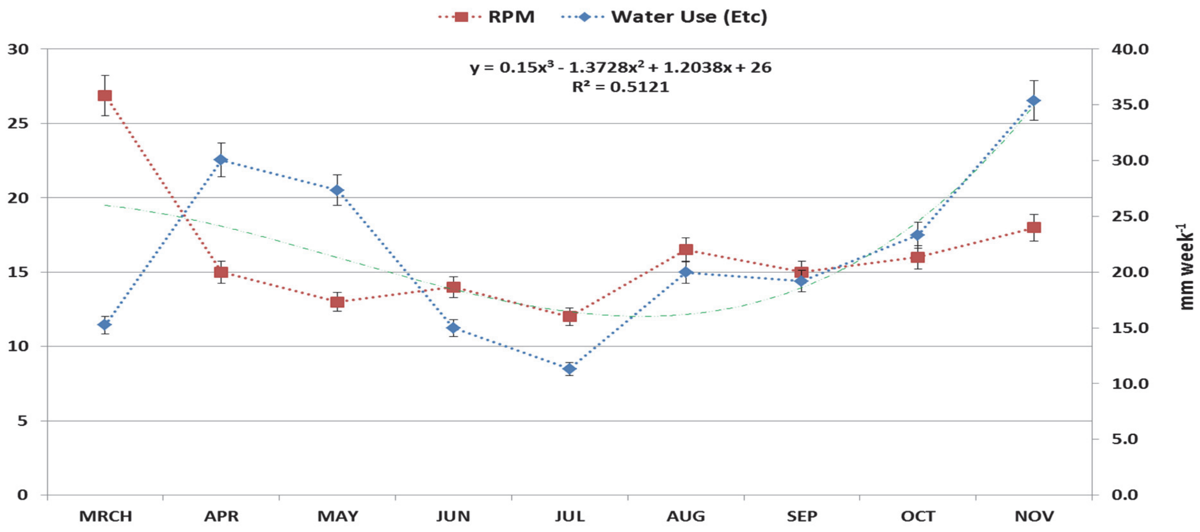


Figure 4.34 Potential relationship of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of white clover pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.5.2 Mixed pastures

Very similar correlations were obtained for the mixed pastures dominated by erect tufted species. Mixed pastures such as tall fescue / lucerne (Figure 4.37) highlighted this observation.

4.1.5.2.1 Kikuyu / lucerne mixed pasture

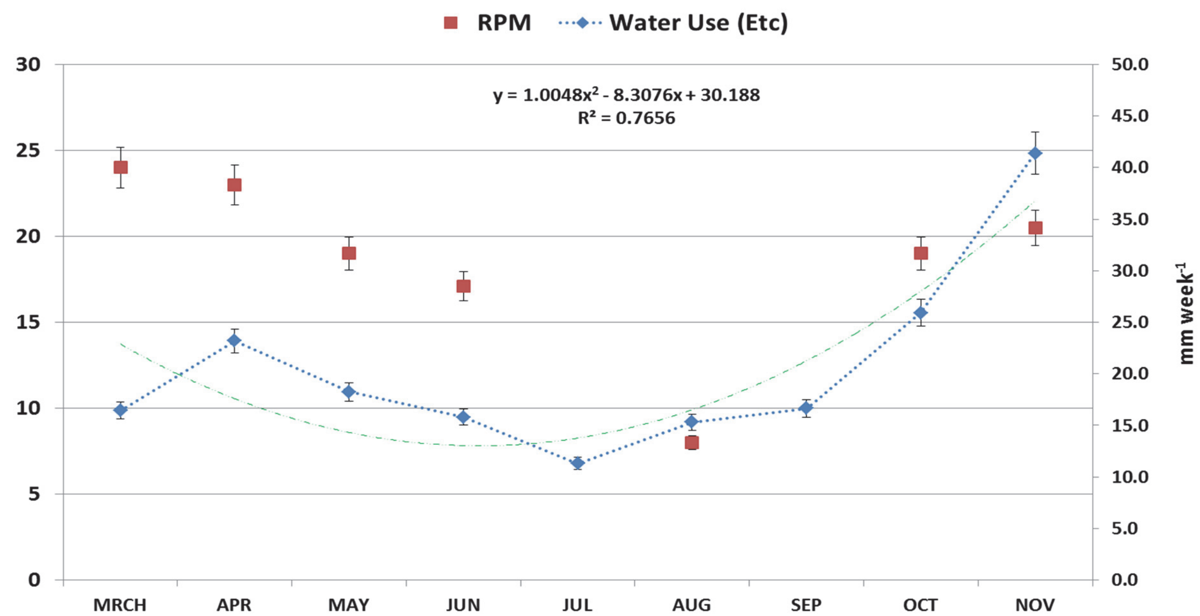


Figure 4.35 Potential relationship of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of mixed kikuyu / lucerne pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.5.2.2 Tall fescue / white clover mixed pasture

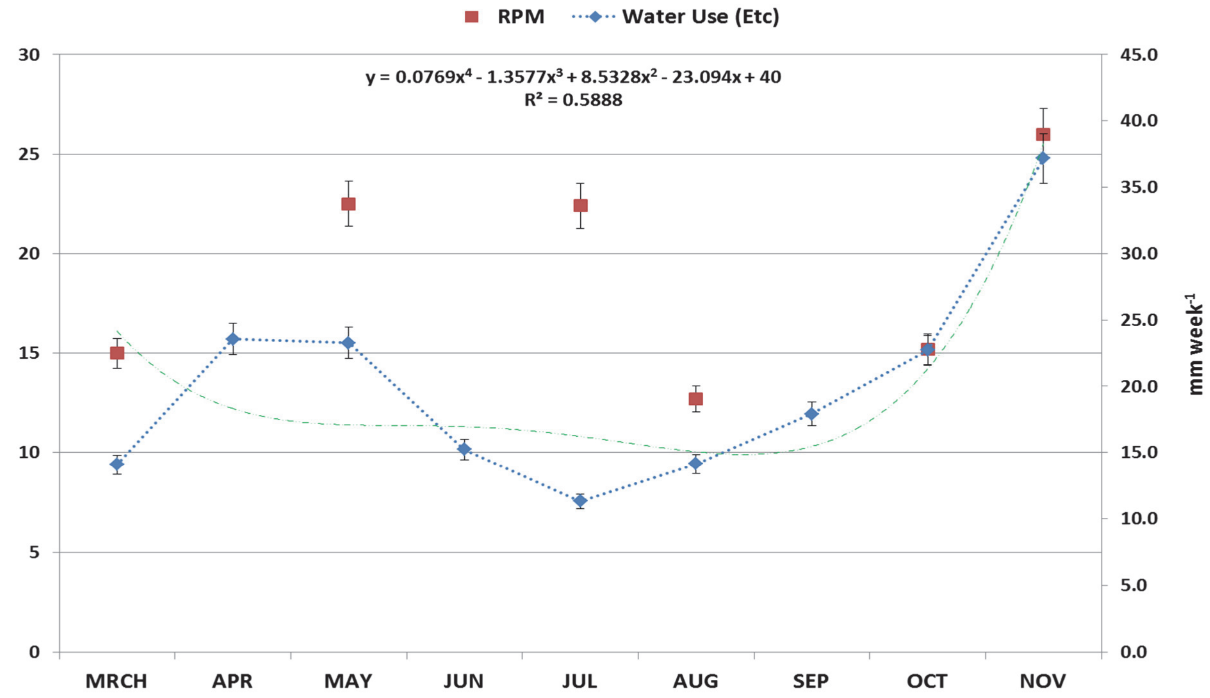


Figure 4.36 Potential relationship of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of mixed tall fescue / white clover pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.1.5.2.3 Tall fescue / lucerne mixed pasture

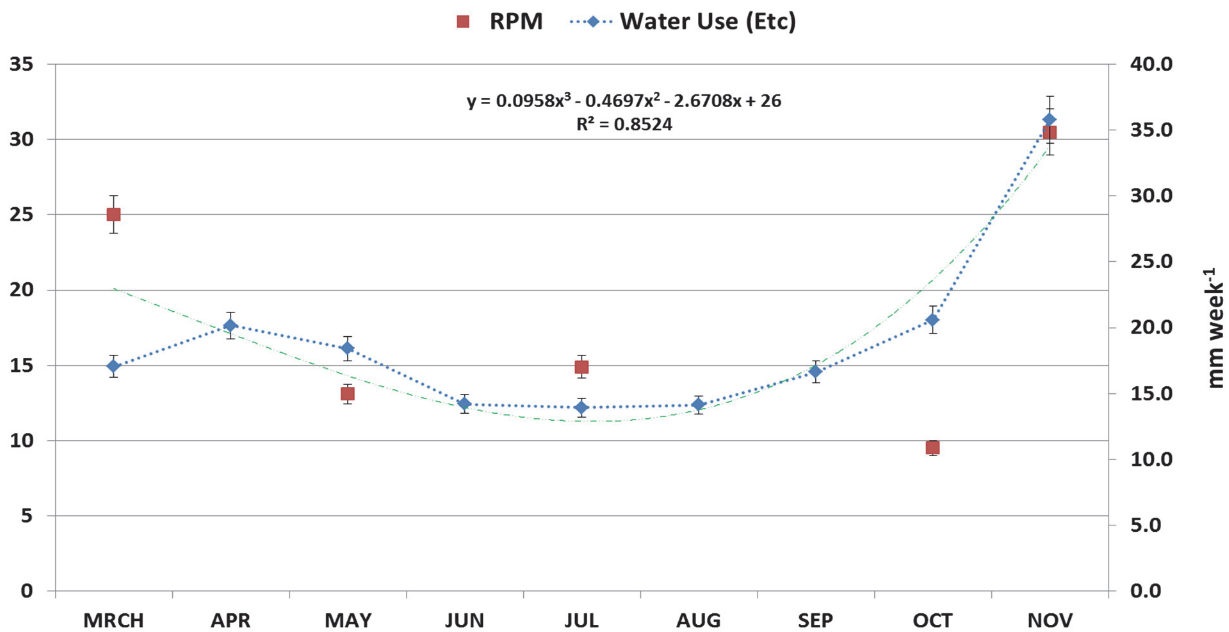


Figure 4.37 Potential relationship of a yield estimation technique (RPM dimensionless reading) and crop water use (ET_c – mm.week^{-1}) of mixed tall fescue / lucerne pasture for the growing season March to November 2013-2015 on the Hatfield Experimental farm

4.2.1 Water use, DM yield and water use efficiency

4.2.1.1 Kikuyu over-sown with lucerne (Site A)

By the end of the experimental period, there were no significant differences (P>0.05) in the total amount of water used, total amount of DM yield produced, and the overall water use efficiency (WUE) between kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711) (Table 4.8). These treatments received similar (P>0.05) total amounts of rainfall and irrigation (Table 4.8) and experienced the same weather conditions.

Table 4.8 Total amount of water use (WU), dry matter (DM) yield, water use efficiency (WUE), rainfall and irrigation of kikuyu/lucerne (cv WL 357) (K/L WL357) and kikuyu/lucerne (cv WL711) (K/L WL711). Values in each column followed by the same letter are not significantly different (P<0.05).

Treatments	WU (mm)	DM Yield (kg DM ha^{-1})	WUE (kg DM mm^{-1})	Rainfall (mm)	Irrigation (mm)	P-value
K/L WL357	791.1 ± 67.3 a	14787 ± 340 a	18.7 ± 1.4 a	548.8 ± 1.4 a	225.9 ± 17.5 a	>0.05
K/L WL711	787.3 ± 67.3 a	14850 ± 340 a	19.1 ± 1.4 a	548.6 ± 1.4 a	217.4 ± 17.5 a	>0.05

Table 4.8 shows however, that seasons had a significant effect (P<0.001) on WU, whilst treatments and the interaction effect between seasons and treatments had no significant effect (P>0.05). Therefore, a mean seasonal WU is illustrated in Figure 4.38. It shows that summer had the highest mean WU with 258.0 mm, although it was not significantly different from autumn with a mean water usage of 235.4 mm. Winter had the lowest mean WU with 111.2 mm.

Table 4.9 Significance of main effects on water use of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	P-value
Season	132.87	3	37.57	6.7	<0.001
Treatment	0.27	1	0.27	12.8	0.612
Season.Treatment	2.97	3	0.84	6.7	0.515

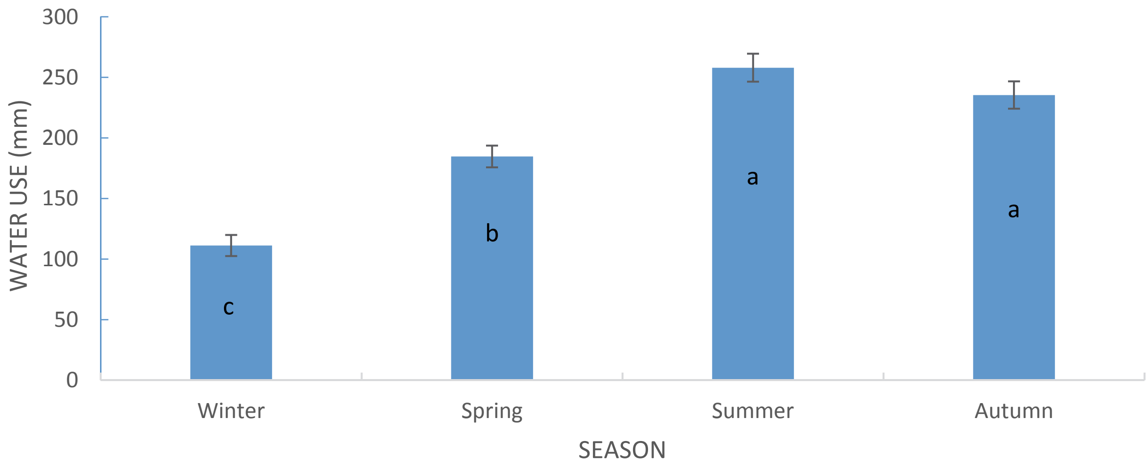


Figure 4.38 Mean water use of two kikuyu/lucerne pastures over seasons. Error bars represent the SEM.

Seasons and treatments had both a significant effect (P<0.001 and P<0.05 respectively) on DM yield, but the interaction between season and treatment had no significant effect (Table 4.9). During summer, kikuyu/lucerne (cv WL357) had a higher (>LSD at 5% level) DM yield than kikuyu/lucerne (WL711) (Table 4.10). Kikuyu/lucerne (cv WL711) was however, significantly higher (>LSD at 5% level) in winter and autumn than kikuyu/lucerne (cv WL357) (Table 4.11). Winter had the lowest DM yield for both kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711) with 1896.5 kg DM ha^{-1} and 2783.6 kg DM ha^{-1} respectively. DM yield was the highest in summer for kikuyu/lucerne (cv WL357) with 5589.5 kg DM ha^{-1} but it was the highest for kikuyu/lucerne (cv WL711) in spring with 4222.7 kg DM ha^{-1} (Figure 4.39).

Table 4.10 Significance of main effects on dry matter yield of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	124.89	3	34.35	6.1	<0.001
Treatment	17	1	17	7.9	0.003
Season.Treatment	14.83	3	4.08	6.1	0.067

Table 4.11 Seasonal dry matter yield of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711). LSD = Least significant differences at 5% level

	Treatments	DM Yield (kg DM ha^{-1})
Winter	kikuyu/lucerne WL357	1897
	kikuyu/lucerne WL711	2784
	LSD	714.8
Spring	kikuyu/lucerne WL357	3966
	kikuyu/lucerne WL711	4223
	LSD	369.4
Summer	kikuyu/lucerne WL357	5589
	kikuyu/lucerne WL711	3934
	LSD	1587.7
Autumn	kikuyu/lucerne WL357	3335
	kikuyu/lucerne WL711	3909
	LSD	384

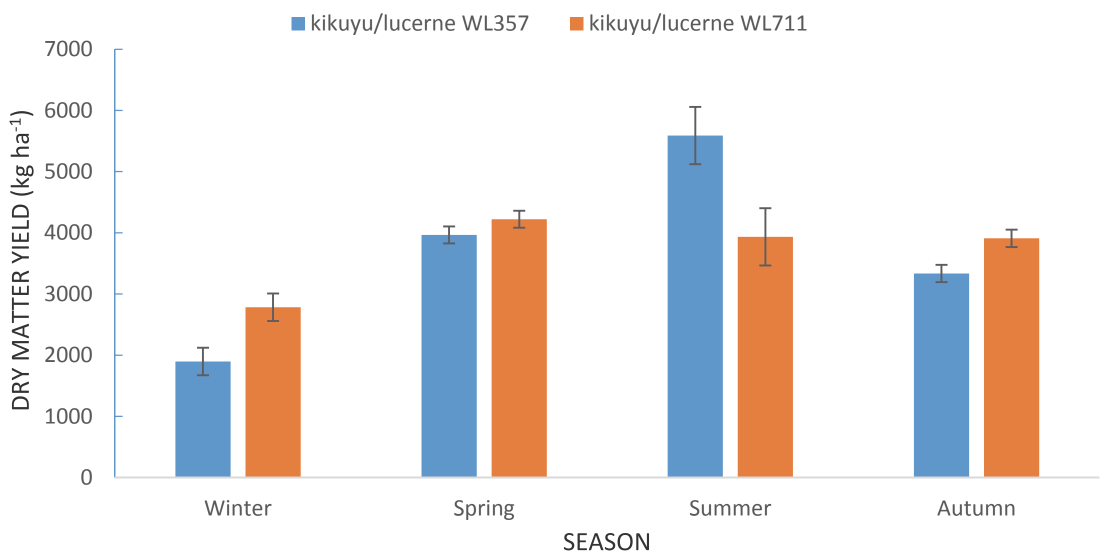


Figure 4.39: Dry matter yield (DM yield) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711) over seasons. Error bars represent the SEM.

Table 4.11 shows that seasons, treatments, as well as the interaction between seasons and treatments had a significant effect on WUE ($P<0.05$). Figure 4.40 illustrates that kikuyu/lucerne (cv WL711) in winter was the most water use efficient (28.57 kg DM mm^{-1}), although it was similar to the WUE of kikuyu/lucerne (cv WL711) in spring (23.95 kg DM mm^{-1}), kikuyu/lucerne (cv WL357) in summer (22.31 kg DM mm^{-1}) and kikuyu/lucerne (cv WL357) in spring (20.78 kg DM mm^{-1}). Kikuyu/lucerne (cv WL357) in autumn was the least water use efficient (14.84 kg DM mm^{-1}), although it was similar to all the other seasons and treatments except kikuyu/lucerne (WL711) in winter and spring (Figure 4.39). When each treatment's WUE for the same seasons are compared with each other, kikuyu/lucerne (cv WL711) was more water use efficient than kikuyu/lucerne (cv WL357) in winter (Table 4.8).

The opposite occurs during summer, when kikuyu/lucerne (cv WL357) is more water use efficient than kikuyu/lucerne (cv WL711) (Table 4.12). Water use efficiency of kikuyu/lucerne (cv WL357) tended to increase from winter to summer and then started to decrease again in autumn (Figure 4.3). The WUE of kikuyu/lucerne (cv WL711) on the other hand, tended to decrease from winter to summer and started to increase again in autumn (Figure 4.40).

Table 4.12: Significance of main effects on dry matter yield of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	43.57	3	12.12	6.2	0.005
Treatment	10.28	1	10.28	10.9	0.008
Season.Treatment	31.97	3	8.89	6.2	0.011

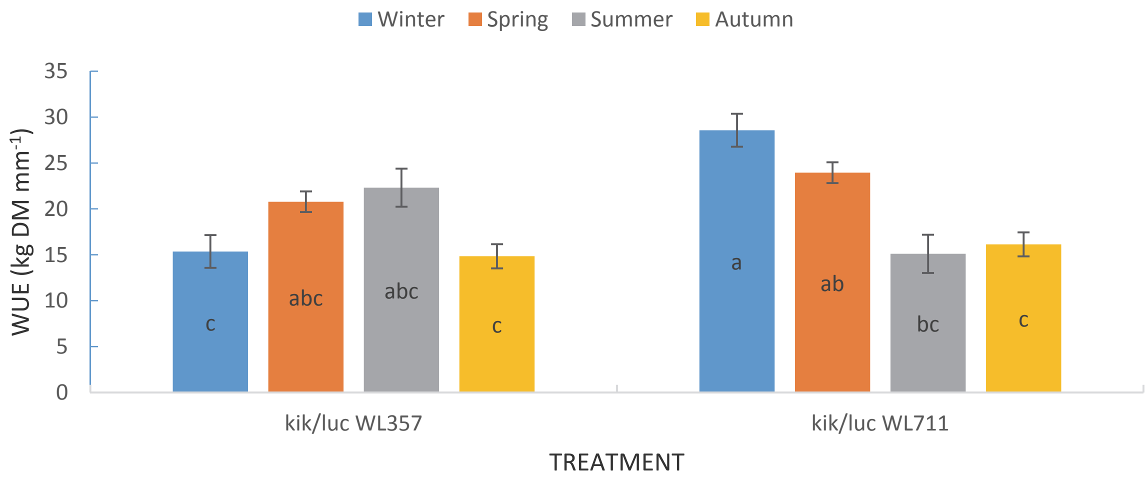


Figure 4.40 Water use efficiency (WUE) of kikuyu/lucerne treatments for every season. Kikuyu/lucerne WL357 = kikuyu/lucerne (cv WL357); kikuyu/lucerne WL711 = kikuyu/lucerne (cv WL711). Error bars represent SEM. Values with the same letter are not significantly different (P>0.05).

Table 4.13: Seasonal water use efficiency (WUE) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711). LSD = Least significant differences at 5% level

	Treatments	WUE (kg DM mm^{-1})
Winter	kikuyu/lucerne WL357	15.4
	kikuyu/lucerne WL711	28.6
	LSD	5.8
Spring	kikuyu/lucerne WL357	20.8
	kikuyu/lucerne WL711	24.0
	LSD	3.4
Summer	kikuyu/lucerne WL357	22.3
	kikuyu/lucerne WL711	15.1
	LSD	6.9
Autumn	kikuyu/lucerne WL357	14.8
	kikuyu/lucerne WL711	16.1
	LSD	4.1

Only seasons had a significant effect on the total amount of water applied to the treatments, either by means of rainfall or irrigation (Table 4.14). Therefore, Figure 4.41 illustrates the mean total amount of water over seasons. Summer received the most water (250.4 mm), although it did not significantly differ from autumn (218.9 mm), and spring (205.4 mm). Winter received the least amount of water with only 104.3 mm (Figure 4.12). Figure 4.41 illustrates the proportions of rainfall and irrigation over seasons for each of the treatments and shows that summer months required the most irrigation.

Table 4.14 Significance of main effects on total amount of water (rainfall and irrigation) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	116.34	3	32.56	6.5	<0.001
Treatment	0.01	1	0.01	9.8	0.915
Season.Treatment	1.65	3	0.46	6.5	0.718

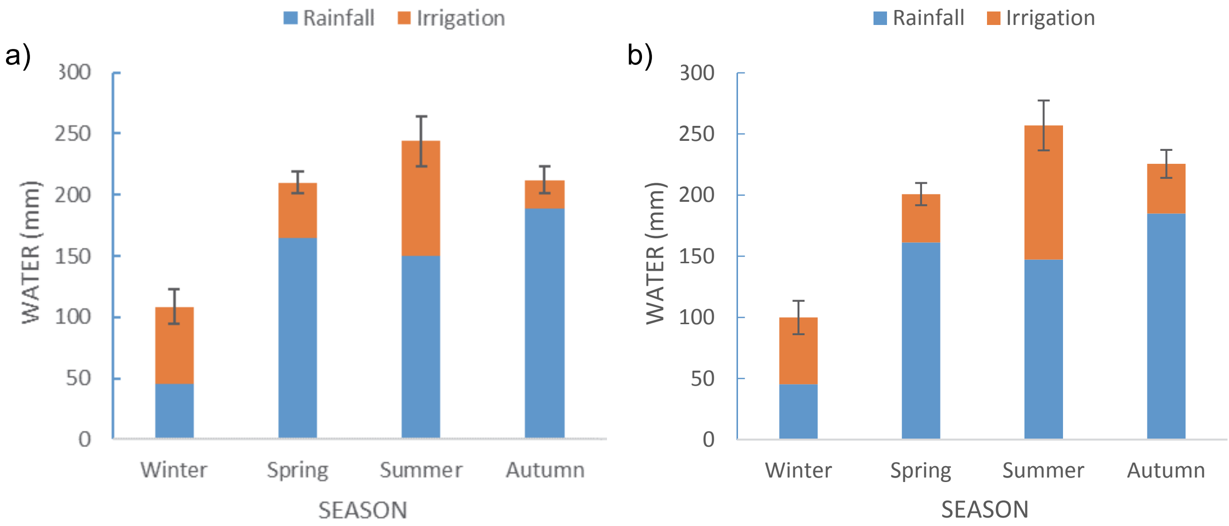


Figure 4.41 Seasonal rainfall and irrigation measured for a) kikuyu/lucerne (cv WL357) and b) kikuyu/lucerne (WL711). Error bars represent the SEM of the total amount of water applied to the treatments.

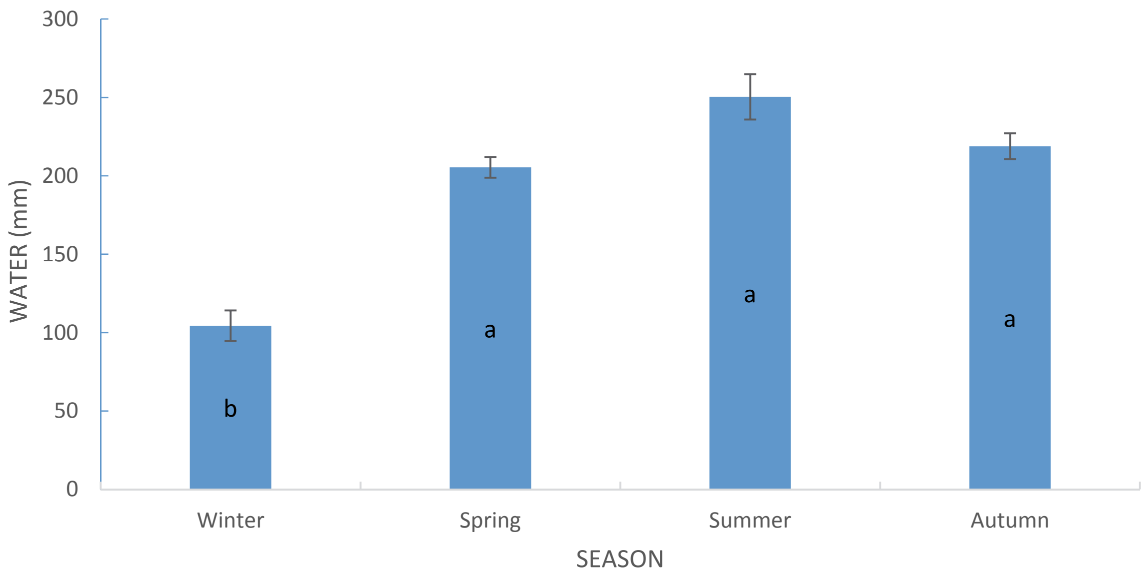


Figure 4.42 Mean total amount of water (rainfall and irrigation) measured at kikuyu/lucerne pastures over seasons. Error bars represent SEM.

4.2.1.1.1 Botanical composition

The percentage of weeds were significantly affected by treatments (P<0.05) and neither by seasons nor the interaction between seasons and treatments (Table 4.15). There were a higher percentage of weeds in the botanical composition of kikuyu/lucerne (cv WL357) during winter and summer than in kikuyu/lucerne (cv WL711) (Table 4.9). Kikuyu/lucerne (cv WL357) had 10.3% weed in winter and 4.8% in summer, while kikuyu/lucerne (cv WL711) had 2.7% weed in winter and 2.6% in summer (Table 4.16).

Table 4.15 Significance of main effects on weed (%) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	7.6	3	2.05	5.7	0.212
Treatment	18.3	1	18.3	6	0.005
Season.Treatment	5.02	3	1.36	5.7	0.345

Table 4.16 Seasonal botanical composition of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711). LSD= Least significant differences (5% level).

	Treatments	Weed (%)	Grass (%)	Lucerne (%)	Clover (%)	Kikuyu (%)
Winter	kikuyu/lucerne WL357	10.3	50.4	23.4	15.1	0.7
	kikuyu/lucerne WL711	2.7	54.8	32.7	9,0	1.3
	LSD	7.5	2.9	18.8	8.7	1.2
Spring	kikuyu/lucerne WL357	3.4	43.9	31.3	17.4	4,0
	kikuyu/lucerne WL711	2.6	51.3	20.4	21.1	4.6
	LSD	2.5	37.4	12.9	24.4	15.9
Summer	kikuyu/lucerne WL357	4.8	25.3	44.9	7.3	17.8
	kikuyu/lucerne WL711	2.6	34.3	27.3	10.7	25.2
	LSD	1.4	40,0	15.3	5.9	42.9
Autumn	kikuyu/lucerne WL357	3.4	14.4	35.3	12.6	34.3
	kikuyu/lucerne WL711	1.7	21.3	18.2	10.6	48.4
	LSD	3.1	34.6	34.6	15,0	101.3

Seasons and treatments had a significant effect on grass (%), but the interaction between seasons and treatments had no significant effect (Table 4.17). On average, kikuyu/lucerne (cv WL711) had a larger grass component than kikuyu/lucerne (cv WL357) with 40.4% and 33.5% respectively. Table 4.17 shows that the highest mean percentage of grass was in winter (52.61%), although it did not significantly differ from spring (47.6%). Autumn, on the hand, had the lowest mean percentage of grass (17.8%), although if did not significantly differ from summer (29.8%) (Table 4.17). The grass component in both treatments tended to decrease from winter to autumn (Figure 4.42). During winter and spring, it was the biggest contributors to botanical composition in both treatments (Figure 4.42).

Table 4.17 Significance of main effects on grass (%) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	97.76	3	26.34	5.3	0.001
Treatment	43.33	1	43.33	2	0.022
Season.Treatment	0.45	3	0.12	5.3	0.944

Table 4.18 Mean botanical composition of kikuyu/lucerne treatments for every season. Values in each column followed by the same letter are not significantly different (P<0.05)

Season	Grass (%)	Kikuyu (%)
Winter	52.6 a	1.0 b
Spring	47.6 ab	4.3 ab
Summer	29.8 bc	21.5 a
Autumn	17.8 c	41.3 a

Treatments were the main significant effect on the percentage of lucerne in the botanical composition (P<0.05) (Table 4.19). The mean seasonal percentage of lucerne was higher for kikuyu/lucerne (cv WL357) (33.7%) than for kikuyu/lucerne (cv WL711) (24.6%). In summer kikuyu/lucerne (cv WL357) had a significantly higher percentage of lucerne than kikuyu/lucerne (cv WL711) (Table 4.16) with 44.9% and 27.2% respectively. Figure 4.40 shows that the lucerne component in kikuyu/lucerne (cv WL357) tended to increase from winter to summer and started to decrease in autumn, but there was an irregular pattern in kikuyu/lucerne (cv WL711). The lucerne component in kikuyu/lucerne (cv WL357) was the biggest component in summer (Figure 4.43).

Table 4.19 Significance of main effects on lucerne (%) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	6.59	3	1.8	5.9	0.249
Treatment	7.11	1	7.11	9.7	0.024
Season.Treatment	8.09	3	2.21	5.9	0.189

There was no significant effect on clover from either seasons, treatments, or the interaction between seasons and treatments (P>0.05) (Table 4.20). The percentage of clover ranged between 10.6% and 21.1% throughout seasons and treatments (Figure 4.43).

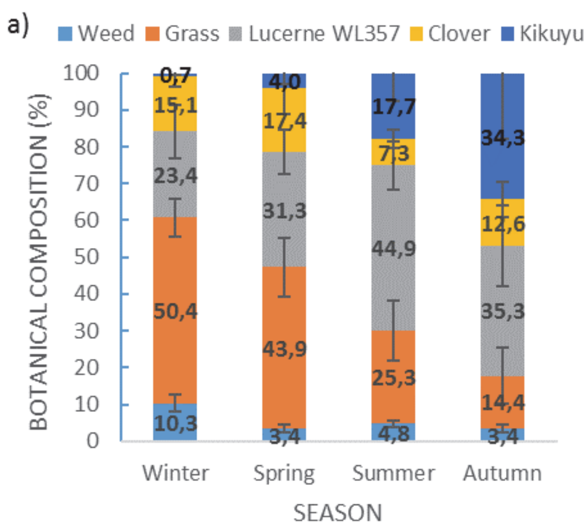
Table 4.20 Significance of main effects on clover (%) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	5.5	3	1.52	6	0.303
Treatment	0.003	1	0.03	7	0.868
Season.Treatment	5.12	3	1.41	6	0.328

Only seasons had a significant effect (P<0.05) on kikuyu (%) as seen in Table 4.21. The mean percentage of kikuyu for both treatments were the highest in autumn (41.3%), although it did not significantly differ from summer (21.46%) (Table 4.16). The kikuyu component in both treatments tended to increase from winter to autumn (Figure 4.43).

Table 4.21 Significance of main effects on kikuyu (%) of kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711)

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	27.96	3	7.52	5.3	0.024
Treatment	4.13	1	4.13	2.1	0.171
Season.Treatment	0.7	3	0.19	5.3	0.9



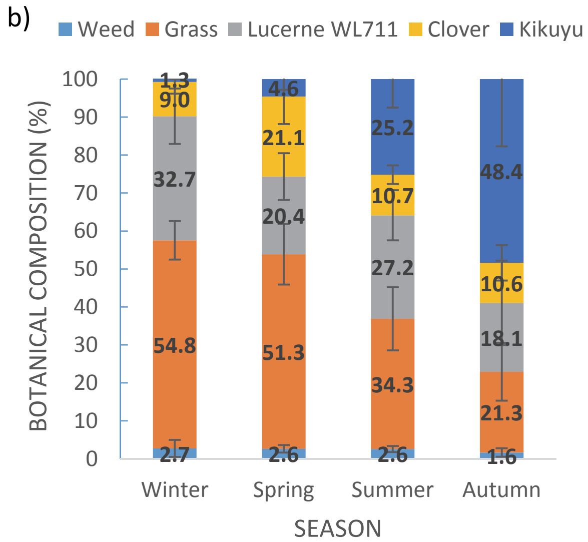


Figure 4.43 Seasonal botanical composition of a) kikuyu/lucerne WL357 and b) kikuyu/lucerne WL711. Error bars represent SEM.

Water use had a strong, positive relationship with the amount of water applied to the treatments (rainfall and irrigation) (r^2 = 0.957; P<0.001), as well as with minimum temperatures (r^2 = 0.923; P<0.001) and maximum temperatures (r^2 = 0.853; P<0.001) (Table 4.21 and 4.22). It had a relatively strong, positive relationship with DM yield (r^2 = 0.652; P<0.001) (Table 4.21 and 4.22). The percentage of grass and kikuyu in the mixed sward did however, have a relatively strong, negative relationship (r^2 = -0.569 and r^2 = -0.511; P<0.05) with WU (Table 4.21 and 4.22). Dry matter yield had relatively strong positive relationships with the amount of water applied to the treatments (r^2 = 0.717; P<0.001), minimum (r^2 = 0.702; P<0.001) and maximum temperatures (r^2 = 0.655; P<0.001) (Table 4.14 and 4.15). The grass component had a relatively strong, negative relationship with minimum and maximum temperatures (r^2 = -0.697 and -0.615 respectively; P<0.001) (Table 4.21 and 4.22). Grass and kikuyu had a relatively strong, negative relationship with each other (r^2 = -0.648; P<0.001) (Table 4.14 and 4.15). Kikuyu had a relatively strong, positive relationship with minimum temperatures (r^2 = 0.537; P<0.05) (Table 4.21 and 4.22).

Table 4.21 Correlation coefficients (r^2) of water use (WU), total amount of water applied to treatments (Water), minimum temperature (Min T), maximum temperature (Max T), dry matter yield (DM yield), and botanical contributions (%) of weed, grass, lucerne, clover and kikuyu

	WU	Water	Min T	Max T	DM yield	Weed %	Grass %	Lucerne %	Clover %	Kikuyu %
WU	1.000									
Water	0.957	1.000								
Min T	0.923	0.885	1.000							
Max T	0.853	0.791	0.960	1.000						
DM yield	0.652	0.717	0.702	0.655	1.000					
Weed %	-0.292	-0.336	-0.337	-0.234	-0.385	1.000				
Grass %	-0.569	-0.473	-0.697	-0.615	-0.347	0.142	1.000			
Lucerne %	-0.008	-0.020	0.171	0.225	0.256	-0.039	-0.251	1.000		
Clover %	-0.103	0.002	-0.209	-0.292	-0.073	0.237	0.106	-0.048	1.000	
Kikuyu %	-0.511	0.415	0.537	0.455	0.174	-0.320	-0.648	-0.448	-0.453	1.000

Table 4.22 Significance of correlations between water use (WU), total amount of water applied to treatments (Water), minimum temperature (Min T), maximum temperature (Max T), dry matter yield (DM yield), and botanical contributions (%) of weed, grass, lucerne, clover and kikuyu

	WU	Water	Min T	Max T	DM yield	Weed %	Grass %	Lucerne %	Clover %	Kikuyu %
WU										
Water	<0.001									
Min T	<0.001	<0.001								
Max T	<0.001	<0.001	<0.001							
DM yield	<0.001	<0.001	<0.001	<0.001						
Weed %	0.166	0.109	0.107	0.271	0.063					
Grass %	0.004	0.020	<0.001	0.001	0.097	0.510				
Lucerne %	0.972	0.926	0.424	0.290	0.227	0.855	0.237			
Clover %	0.631	0.993	0.327	0.166	0.734	0.265	0.621	0.825		
Kikuyu %	0.011	0.044	0.007	0.026	0.415	0.127	<0.001	0.028	0.026	

In a stepwise regression, the following model was able to explain 93.8% (s.e of 15.4 mm) of the variance in WU per season:

$$\boldsymbol{Water\ Use} = -\mathbf{45.2} + \mathbf{0.669}\ \boldsymbol{Total\ Water} + \mathbf{9.41}\ \boldsymbol{Min\ Temp} \quad \textbf{(4.1)}$$

Dry matter yield was able to increase the variance in WU to 94.3% (±14.7 mm), but it was not significant (>P0.05).

The following model was able to explain 54.7% (s.e 748 kg DM ha^{-1}) of the variance in DM yield per season:

$$\boldsymbol{DM\ yield} = \mathbf{494} + \mathbf{13.42}\ \boldsymbol{Total\ Water} + \mathbf{20.4}\ \boldsymbol{Lucerne}\ (\%) \quad \textbf{(4.2)}$$

Only 50% (s.e 3.84 kg DM mm^{-1}) of the variance in WUE per season could be explained by the following model:

$$\boldsymbol{WUE} = -\mathbf{1.1} - \mathbf{0.1915}\ \boldsymbol{WU} - \mathbf{0.575}\ \boldsymbol{Weed}\ (\%) + \mathbf{0.1012}\ \boldsymbol{Total\ Water} + \mathbf{1.854}\ \boldsymbol{Max\ Temp}$$

4.2.1.2 Kikuyu over-sown with grass (perennial ryegrass and cocksfoot) (site B)

Although kikuyu/perennial ryegrass had a higher total amount of WU (761.0 mm), total DM yield (10155 kg DM ha^{-1}) and overall WUE (13.4 kg DM mm^{-1}) at the end of the experimental period, it was not significantly different (P>0.05) from kikuyu/cocksfoot with a total WU of 756.6 mm, DM yield of 8379 kg DM ha^{-1}, and overall WUE of 10.7 kg DM mm^{-1} (Table 4.25). Both these treatments received similar amounts of total rainfall (525.5 mm for kikuyu/perennial ryegrass and 523.5 mm for kikuyu/cocksfoot) and total irrigation (213.4 mm for kikuyu/perennial ryegrass and 207.7 mm for kikuyu/cocksfoot) (Table 4.25).

Table 4.23 Correlations (r^2) between soil water content (SWC) and climate variables for kikuyu/grass treatments. Water = total amount of water applied (rainfall and irrigation), Min Temp = Minimum Temperatures, Max Temp = Maximum Temperatures, Ave Temp = Average Temperatures

	SWC	Water	Min Temp	Max Temp	Ave Temp
SWC	-				
Water	0,2408	-			
Min Temp	-0,2980	0,3809	-		
Max Temp	-0,3039	0,2520	0,8663	-	
Ave Temp	-0,3112	0,3345	0,972	0,9592	-

Table 4.24 Significance of correlation between soil water content (SWC) and climate variables for kikuyu/grass treatments. Water = total amount of water applied (rainfall and irrigation), Min Temp = Minimum Temperatures, Max Temp = Maximum Temperatures, Ave Temp = Average Temperatures

	SWC	Water	Min Temp	Max Temp	Ave Temp
SWC	-				
Water	0,0274	-			
Min Temp	0,0059	<0,001	-		
Max Temp	0,0049	0,0208	<0,001	-	
Ave Temp	0,0050	0,0019	<0,001	<0,001	-

Table 4.25 Total amount of water use (WU), dry matter (DM) yield, water use efficiency (WUE), rainfall and irrigation of kikuyu/per ryegrass (k/per rye) and kikuyu/cocksfoot (k/cocks). Values in each column followed by the same letter are not significantly different (P<0.05)

Treatments	WU (mm)	DM Yield (kg DM ha^{-1})	WUE (kg DM mm^{-1})	Rainfall (mm)	Irrigation (mm)	P-value
k/per rye	761.0 ± 18.2 a	10155 ± 956 a	13.4 ± 1.5 a	525.5 ± 2.8 a	213.4 ± 10.8 a	>0,05
k/cocks	756.6 ± 18.2 a	8379 ± 1351 a	10.7 ± 2.1 a	523.5 ± 2.8 a	207.7 ± 10.8 a	>0,05

There was, however, some seasonal and treatment differences between WU, DM yield and WUE. Table 4.26 shows that seasons had a significant effect (P<0.001) on WU. There was no difference in WU between kikuyu/perennial ryegrass and kikuyu/cocksfoot (<LSD at 5% level) per season (Table 4.27). Therefore, Figure 4.44 illustrates the mean WU of treatments over seasons. It shows that summers had the highest WU with 286.4 mm and spring the lowest with 146.9 mm, although it did not significantly differ from autumn (156.8 mm) and winter (168.7 mm) (Figure 4.44).

Table 4.26 Significance of main effects on water use of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	117.37	3	33.38	7.4	<0.001
Treatment	0.03	1	0.03	14.9	0.854
Season.Treatment	4.90	3	1.39	7.4	0.319

Table 4.27 Seasonal water use (WU), dry matter yield (DM yield) and water use efficiency (WUE) of kikuyu/perennial ryegrass (k/per rye) and kikuyu/cocksfoot (k/cocks). LSD = Least significant differences (5% level)

	Treatments	WU (mm)	DM Yield (kg DM ha^{-1})	WUE (kg DM mm^{-1})	Total Water
Winter	k/per rye	181.1	1973	10.9	159.1
	k/cocks	156.3	1567	8.9	151.4
	LSD	45.4	779	4.8	48.7
Spring	k/per rye	158.3	2588	17.2	171.8
	k/cocks	135.6	2834	21.0	171.3
	LSD	61.9	1379	11.9	10.9
Summer	k/per rye	273.4	3660	13.5	232.3
	k/cocks	299.3	3402	11.5	227.1
	LSD	48.2	1183	6.0	50.0
Autumn	k/per rye	148.2	1935	13.1	175.8
	k/cocks	165.4	1749	10.7	178.5
	LSD	41.1	1356	8.6	9.6

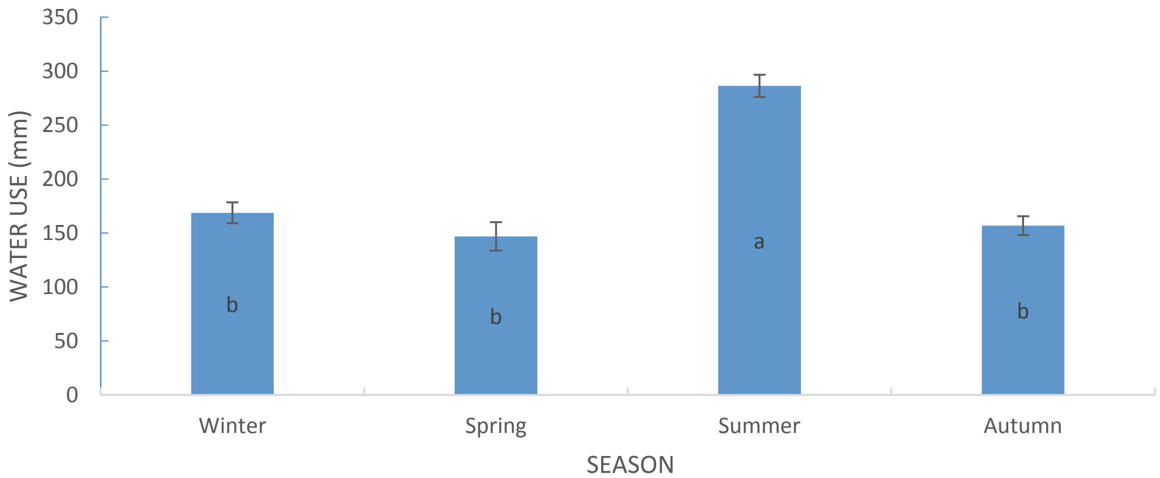


Figure 4.44 Mean seasonal water use of kikuyu/grass pastures. Error bars represent the SEM

The DM yield of kikuyu/perennial ryegrass and kikuyu/cocksfoot were significantly affected by seasons and treatments (Table 4.28). There were, however, no significant difference between these two treatments per season (<LSD at 5% level) (Table 4.27) and therefore,

Figure 4.45 illustrates the mean DM yield per season. Summer had the highest DM yield with 3531 kg DM ha^{-1}, whilst winter and autumn had the lowest DM yield with 1632 kg DM ha^{-1} and 1842 kg DM ha^{-1}, respectively (Figure 4.45).

Table 4.28 Significance of main effects on dry matter yield of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	25.29	3	8.03	8.0	0.009
Treatment	1617.77	1	1617.77	1.0	0.014
Season.Treatment	20.58	3	4.43	3.1	0.122

Only seasons had a significant effect on WUE (Table 4.29). Therefore, kikuyu/perennial ryegrass and kikuyu/cocksfoot had a similar WUE per season (<LSD at 5% level) (Table 4.28) and is illustrated in Figure 4.10. It shows that spring was the most WU efficient at 19.09 kg DM mm^{-1} and winter the least WU efficient at 9.89 kg DM mm^{-1} (Figure 4.9).

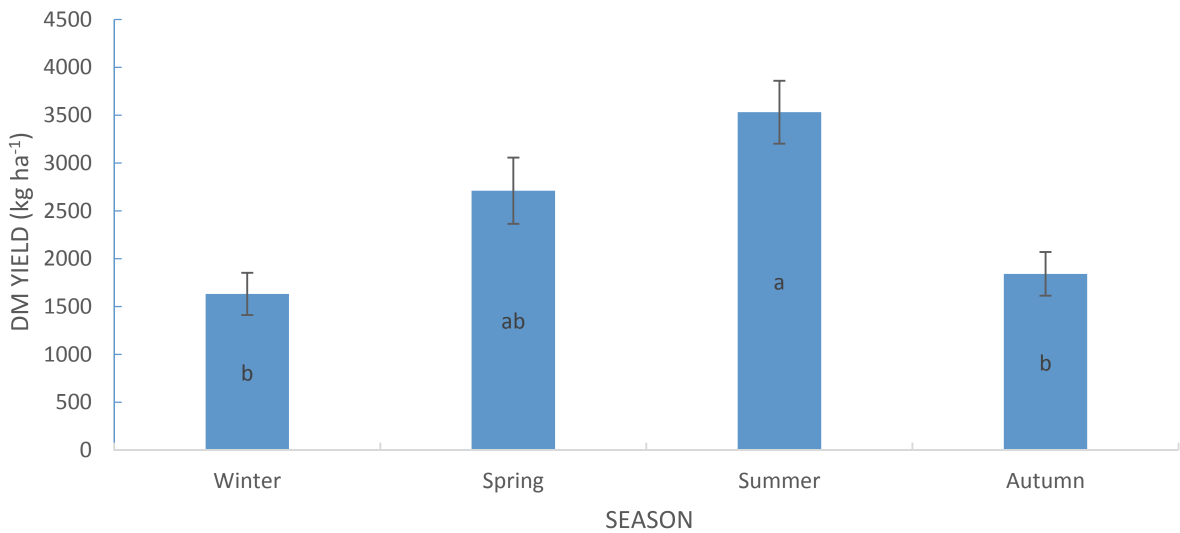


Figure 4.45 Mean seasonal dry matter yield (DM Yield) of kikuyu/grass pastures. Error bars represent the SEM.

Table 4.29 Significance of main effects on dry matter yield of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	16.98	3	4.76	6.7	0.043
Treatment	2.66	1	2.66	8.2	0.141
Season.Treatment	1.77	3	0.5	6.7	0.697

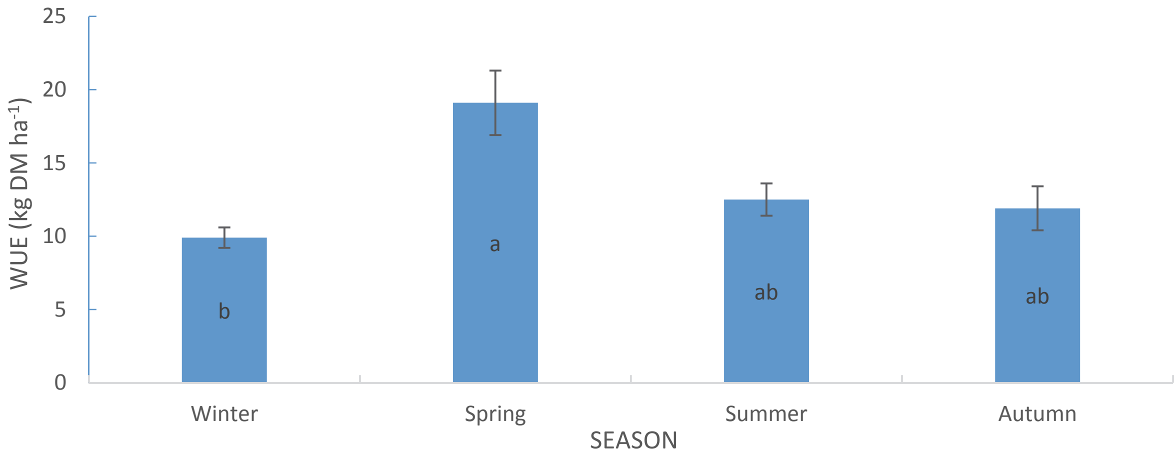


Figure 4.46 Mean water use efficiency (WUE) of kikuyu/grass pastures per season. Error bars represent the SEM

Kikuyu/perennial ryegrass and kikuyu/cocksfoot received similar total amounts of water in the form of rainfall and irrigation per season (<LSD at 5% level) (Table 4.27). The proportion of rainfall and irrigation per treatment are illustrated in Figure 4.10. The total amount of water was significantly affected by season as seen in Table 4.30, but since it did not differ between treatments, Figure 4.48 illustrates the seasonal mean total amount of water applied to treatments. Summer received the most water (229.7 mm) and winter received the least (155.3 mm), although it was similar to the amounts received in spring (171.5 mm) and autumn (177.1 mm) (Figure 4.48).

Table 4.30 Significance of main effects on total amount of water (rainfall and irrigation) applied to kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	36.12	3	9.82	6.0	0.010
Treatment	0.12	1	0.12	6.2	0.743
Season.Treatment	0.59	3	0.16	6.0	0.918

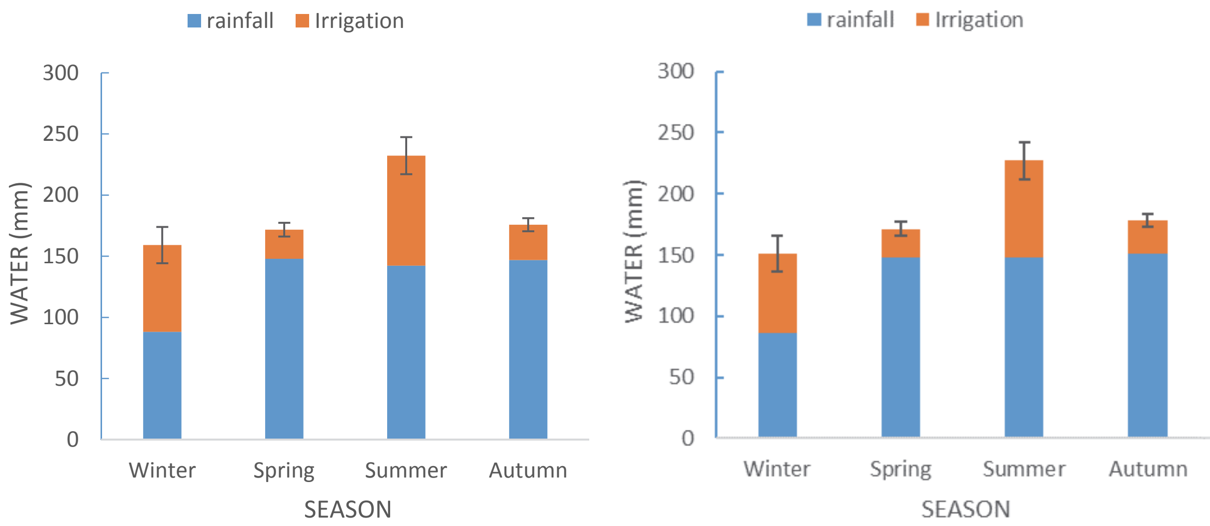


Figure 4.47 Seasonal rainfall and irrigation measured for a) kikuyu/perennial ryegrass and b) kikuyu/cocksfoot. Error bars represent the SEM of the total amount of water

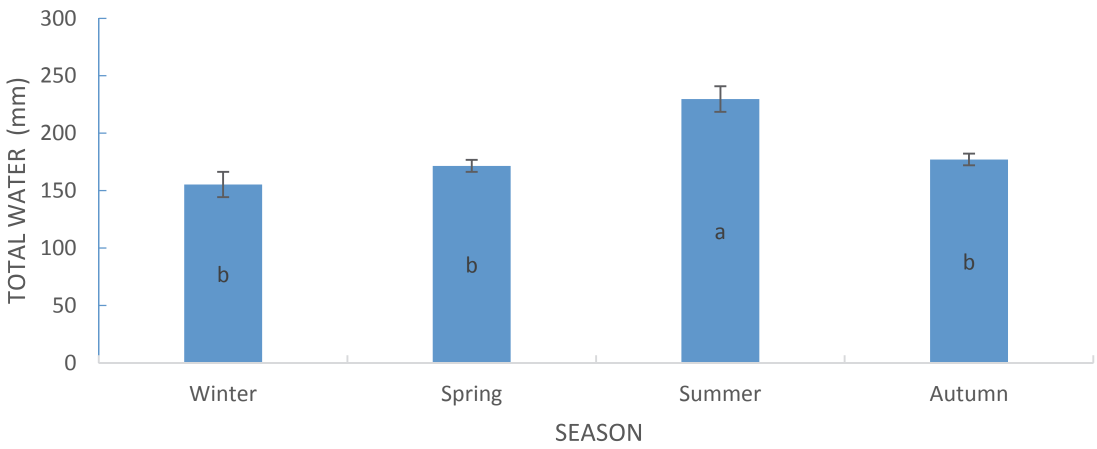


Figure 4.48 Mean total amount of water applied to kikuyu/grass pastures per season. Error bars represent the SEM

4.2.1.2.1 Botanical composition

Table 4.31 shows that only treatments had a significant effect (P<0.05) on the percentage weed in the mixed sward. There was no significant difference in the mean percentage weed of both treatments between seasons, but the overall mean percentage weed was higher (P<0.05) in kikuyu/cocksfoot (37.75%) than in kikuyu/perennial ryegrass (14.50%).

Table 4.31 Significance of main effects on percentage weed in the botanical composition of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	0.61	3	0.17	6.6	0.913
Treatment	11.36	1	11.36	13.9	0.005
Season.Treatment	1.81	3	0.51	6.6	0.690

Both seasons and treatments had a significant effect (P<0.05) on the percentage grass in the botanical composition (Table 4.25). The grass component in kikuyu/perennial ryegrass was larger than the grass component in kikuyu/cocksfoot during winter and spring (Figure 4.12). Winter also had the highest mean percentage of grass (65.33%) and autumn the lowest (22.33%), although is not similar to the percentage in summer (22.67%) (Table 4.28). The grass component of both treatments tended to decrease from winter to autumn as seen in Figure 3.22. During winter, perennial ryegrass was the biggest botanical component in kikuyu/perennial ryegrass (Figure 4.12a) and cocksfoot the biggest botanical component in kikuyu/cocksfoot (Figure 4.12b).

Table 4.32 Significance of main effects on percentage grass (perennial ryegrass or cocksfoot) in the botanical composition of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	25.3	3	7.15	4.9	0.031
Treatment	5.98	1	5.98	6.3	0.048
Season.Treatment	4.59	3	1.24	4.1	0.402

The clover component in the botanical composition of kikuyu/perennial ryegrass and kikuyu/cocksfoot were significantly affected by seasons and treatments (P<0.05) (Table 4.33). During all four seasons kikuyu/perennial ryegrass had a higher percentage of clover in its botanical composition than kikuyu/cocksfoot (Figure 4.49). Summer and spring had the highest mean seasonal percentage of clover with 31.83% and 31.17% respectively (Table 4.36). Winter had the lowest percentage of clover with 4.52% (Table 4.36). The clover component in both treatments tended to be higher is spring and summer than in winter and autumn.

Table 4.33 Significance of main effects on percentage clover (perennial ryegrass or cocksfoot) in the botanical composition of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	40.66	3	10.34	4.7	0.016
Treatment	8.44	1	8.44	9.3	0.017
Season.Treatment	3.32	3	0.85	4.7	0.528

Table 4.34 Significance of main effects on percentage kikuyu in the botanical composition of kikuyu/perennial ryegrass and kikuyu/cocksfoot

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Season	22.77	3	5.98	4.7	0.046
Treatment	4.49	1	4.49	2.0	0.166
Season.Treatment	4.99	3	1.31	4.7	0.374

Table 4.35 Seasonal botanical composition composed of weed, grass, clover, and kikuyu of kikuyu/perennial ryegrass (k/per rye) and kikuyu/cocksfoot (k/cocks). LSD = Least significant differences (5% level).

	Treatments	Weed (%)	Grass (%)	Clover (%)	Kikuyu (%)
Winter	k/per rye	13.3	78.3	4.0	4.4
	k/cocks	35.0	53.1	5.0	11.8
	LSD	73.8	41.8	20.3	17.7
Spring	k/per rye	10.0	50.0	36.0	3.5
	k/cocks	46.7	25.3	26.3	2.2
	LSD	43.4	29.9	18.9	2.4
Summer	k/per rye	17.0	22.7	39.7	20.6
	k/cocks	40.3	22.7	24.0	13.0
	LSD	42.9	40.5	13.3	46.6
Autumn	k/per rye	17.7	18.3	23.3	40.9
	k/cocks	29.0	26.3	16.0	29.1
	LSD	45.0	48.8	27.6	80.2

Kikuyu was only significantly affected (P<0.05) by seasons (Table 4.34). There was no significant difference in the percentage of kikuyu between treatments in the same season (<LSD at 5% level) (Table 4.35). The mean percentage of kikuyu for both seasons were however, highest in autumn (35.03%) and the lowest in spring (2.82%) (Table 4.36). The kikuyu component tended to increase from winter to summer in both treatments and was the biggest component during summer (Figure 4.12).

Table 4.36 Mean botanical composition of kikuyu/grass treatments for every season. Values in each column followed by the same letter are not significantly different (P<0.05)

Season	Grass (%)	Clover (%)	Kikuyu (%)
Winter	65.3 a	4.5 b	8.1 ab
Spring	37.7 ab	31.2 a	2.8 b
Summer	22.7 b	31.8 a	16.8 ab
Autumn	22.3 b	19.7 ab	35.0 a

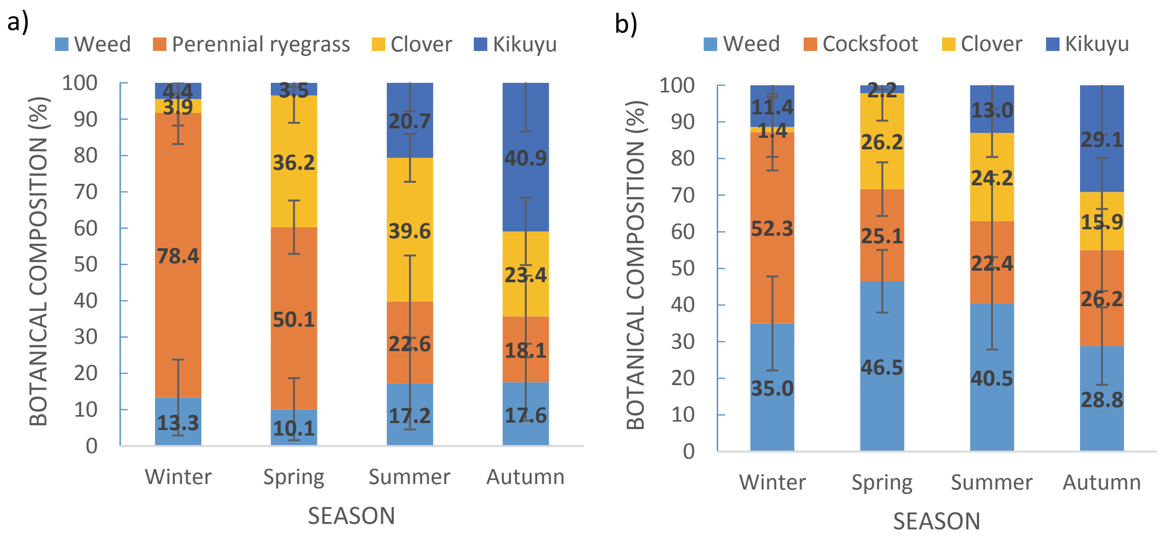


Figure 4.49 Seasonal botanical compositions of a) kikuyu/perennial ryegrass and b) kikuyu/cocksfoot

Water use had a relatively strong, positive relationship with the total amount of water applied to the treatments ($r^2 = 0.733$; $P<0.001$), maximum temperature ($r^2 = 0.557$; $P<0.05$), and DM yield ($r^2 = 0.604$; $P<0.05$). Dry matter yield also had a relatively strong, positive relationship with the total amount of water applied to pastures ($r^2 = 0.571$; $P<0.05$) (Table 4.37 and 4.38). The grass component had a relatively strong, negative relationship with minimum and maximum temperatures ($r^2 = -0.694$ and -0.667 respectively; $P<0.001$). Grass and clover had a relatively strong, negative relationship with each other ($r^2 = -0.519$; $P<0.05$) (Table 4.37 and 4.38). The percentage of kikuyu in the mixed sward had a relatively strong, positive relationship with minimum temperatures ($r^2 = 0.531$; $P<0.05$) as well as with maximum temperatures ($r^2 = 0.498$; $P<0.05$) (Table 4.37 and 4.38).

Total amount of water applied to the treatments were able to explain 51.5% (s.e 43.7 mm) ($P<0.05$) of the variation in WU with a stepwise regression. The model is as follows:

$$WU = -70.9 + 1.424\,Total\,Water \qquad (4.4)$$

Dry matter yield increased the variation in WU to 54.7% (s.e 42.2 mm) but was not significant ($P>0.05$).

An insignificant 38.2% of variance in DM yield could be explained by WU and percentage of clover, whilst the same model could explain only 14.7% of the variance in WUE.

Table 4.37 Correlation coefficients (r^2) of water use (WU), total amount of water applied to treatment (Water), minimum temperature (Min T), maximum temperature (Max T), dry matter yield (DM yield), and percentage botanical contributions of weed, grass, clover and kikuyu

	WU	Water	Min T	Max T	DM yield	Weed %	Grass %	Clover %	Kikuyu %
WU	1.000								
Water	0.733	1.000							
Min T	0.445	0.662	1.000						
Max T	0.557	0.729	0.990	1.000					
DM yield	0.604	0.571	0.377	0.437	1.000				
Weed %	0.060	0.235	0.054	0.058	-0.067	1.000			
Grass %	0.217	-0.473	-0.694	-0.667	-0.194	-0.433	1.000		
Clover %	0.265	0.328	0.422	0.411	0.422	-0.197	-0.519	1.000	
Kikuyu %	0.016	0.089	0.531	0.498	-0.054	-0.331	-0.446	0.017	1.000

Table 4.38 Significance of correlations between water use (WU), total amount of water applied to treatments (Water), minimum temperature (Min T), maximum temperature (Max T), dry matter yield (DM yield), and percentage botanical contributions of weed, grass, lucerne, clover and kikuyu

	WU	Water	Min T	Max T	DM yield	Weed %	Grass %	Clover %	Kikuyu %
WU	1.000								
Water	<0.001	1.000							
Min T	0.033	<0.001	1.000						
Max T	0.006	<0.001	<0.001	1.000					
DM yield	0.002	0.004	0.077	0.037	1.000				
Weed %	0.786	0.281	0.806	0.794	0.762	1.000			
Grass %	0.320	0.023	<0.001	<0.001	0.376	0.039	1.000		
Clover %	0.222	0.127	0.045	0.052	0.045	0.368	0.011	1.000	
Kikuyu %	0.944	0.687	0.009	0.016	0.807	0.123	0.033	0.940	1.000

The results showed that the total water usage, total DM yield and overall WUE were the same for kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711), but that there were some differences between these treatments over seasons. The main reason for these seasonal differences was because lucerne (cv WL711) is a highly winter-active cultivar and lucerne (cv WL357) is a semi-winter dormant cultivar. Thus, kikuyu/lucerne (cv WL711) had a higher DM yield than kikuyu/lucerne (cv WL357) in the cooler seasons and vice versa for the warmer seasons. Even though the mean WU of both treatments was the highest in summer, kikuyu/lucerne (cv WL711) was not as WU efficient as kikuyu/lucerne (cv WL357). This means that regardless of the amount of water applied to a treatment, if it is semi-dormant, it will not grow to its full potential, produce a high DM yield, and be WU efficient. Therefore, it is not recommended to apply the same amount of water to kikuyu/lucerne (cv

WL357) and kikuyu/lucerne (cv WL711) during all seasons. Therefore, an amount of 25 mm per week as described by Jones (2006) and MacDonald (2006) cannot be applied to both these pasture treatments regardless of the season.

The botanical composition of kikuyu/lucerne (cv WL357) comprised mostly of grass during winter, lucerne during summer, and similar compositions of kikuyu and lucerne in autumn. Lucerne (cv WL357) is semi-winter dormant, therefore it's contribution to the mixed sward was small during winter and large during summer. Even though lucerne (cv WL711) is winter-active, it was not the biggest component in the mixed sward during winter. Grass was the biggest component. Lucerne (cv WL711) did however, have the highest contribution in winter compared to the other seasons.

The correlations between the variables showed that WU increased with an increase in the total amount of water applied to the treatments, an increase in both minimum and maximum temperatures, and an increase in DM yield. On the other hand, WU tended to increase with a decrease in the percentages of grass and kikuyu in the mixed sward. Since there was no correlation between WU and lucerne (%), weed (%) or clover (%), the increase in WU with a decrease in grass and kikuyu (%) cannot be ascribed to an increase in either lucerne (%), weed (%) nor clover (%). Nevertheless, in a stepwise regression model, only the total amount of water applied to the treatments and minimum temperatures explained 93.8% of the variance in WU, while the remaining 6.2% remained unexplained. This means that WU was highly dependent on rainfall and irrigation (total water) as well as the minimum temperatures. Thus, climate variables played a bigger role in the amount of water usage than the botanical composition of the mixed sward.

The DM yield of kikuyu/lucerne pastures also had a relatively strong positive correlation with the total amount of water applied to it, and minimum and maximum temperatures. This means that with an increase in the total amount of water applied to the pastures and an increase in temperatures, DM yield were higher. A stepwise regression could however, only explain 54.7% of the variance in DM yield as a result of the total amount of water applied to the pasture and the percentage of lucerne in the botanical sward.

Water use efficiency represents the relationship between DM yield and WU, which were higher in die warmer seasons for kikuyu/lucerne (cv WL357) and higher in the cooler seasons for kikuyu/lucerne (cv WL711). This corresponded to the dormancy periods of the two lucerne cultivars. However, only 50% of the variance in WUE could be explained by WU, percentage of weed in the mixed sward, the total amount of water applied to it, and the maximum temperatures. The other half of the variance in WUE remains unexplained.
There was no difference in the total amount of WU, DM yield and overall WUE between kikuyu/perennial ryegrass and kikuyu/cocksfoot. Although there were also no differences over seasons between these two treatments, there were differences in the mean values of WU, DM yield and WUE between seasons. Mean WU and mean DM yield was the highest in summer, which can be ascribed to higher temperatures and thus higher evaporation, but WUE was the highest in spring. Most of the irrigation was applied to the pastures during summer to satisfy the high evaporative demand.

The grass component (perennial ryegrass and cocksfoot) was the biggest contributor to the botanical composition during winter. Since these two grass species are cool season perennials, this was expected. DM yield and WUE were however, low during winter. Although the grass component was smaller in spring than in winter, DM yield and WUE were significantly higher. This might be as result of temperatures being too low during winter for these two grass species to grow to its full potential. Kikuyu, on the other hand, was the largest component in both treatments during autumn. The percentage of clover was much higher in the warmer seasons, which might have an influence on the higher WU, DM yield and WUE for the same period. Kikuyu/cocksfoot had a substantial percentage of weed throughout all the seasons, which is also significantly higher than the percentage of weed in kikuyu/perennial ryegrass. The reason for this occurrence of weed in kikuyu/cocksfoot is unknown.

The relatively strong, positive relationship that WU has with the total amount of water applied to the pastures, maximum temperatures and DM yield, means that WU increased with an increase in water applied, an increase in maximum temperatures as well as an increase in DM yield. However, in a stepwise regression only 51.5% of the variation in WU could be explained by the total amount of water applied to the pastures. DM yield was also higher as the amount of water applied to the treatments increased. The stepwise regression could however, not explain the percentage of variance significantly. The contribution of grass to the mixed sward became larger with a decrease in minimum and maximum temperatures, which corresponded with the fact that ryegrass and cocksfoot are winter-active species. Kikuyu, which is a summer-active species, had a relatively strong and positive relationship with temperatures. Therefore, kikuyu's contribution to the mixed sward was larger in the warmer months.

The high WUE in spring can be attributed to high DM yield and low WU for this period. Unfortunately, there was no significant model in a stepwise regression that was able to explain the variation in WUE.

4.2.2 Relationship of canopy cover to water use of grazed kikuyu pasture over-sown with temperate grasses or legumes

4.2.2.1 Kikuyu over-sown with lucerne (site A)

The WU of kikuyu/lucerne (cv WL357) had a relatively strong, positive relationship with PAR and LAI (r^2 = 0.685 and 0.689 respectively; P<0.001) (Table 4.39 and 4.40) throughout ten grazing cycles as illustrated in Figure 4.50 and 4.51.

Table 4.39 Correlation between water use (WU), photosynthetically active radiation (PAR), Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357)

	WU	PAR	LAI
WU	1.000		
PAR	0.685	1.000	
LAI	0.689	0.920	1.000

Table 4.10 Significance of correlation between water use (WU), photosynthetically active radiation (PAR), Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357)

	WU	PAR	LAI
WU	-		
PAR	<0.001	-	
LAI	<0.001	<0.001	-

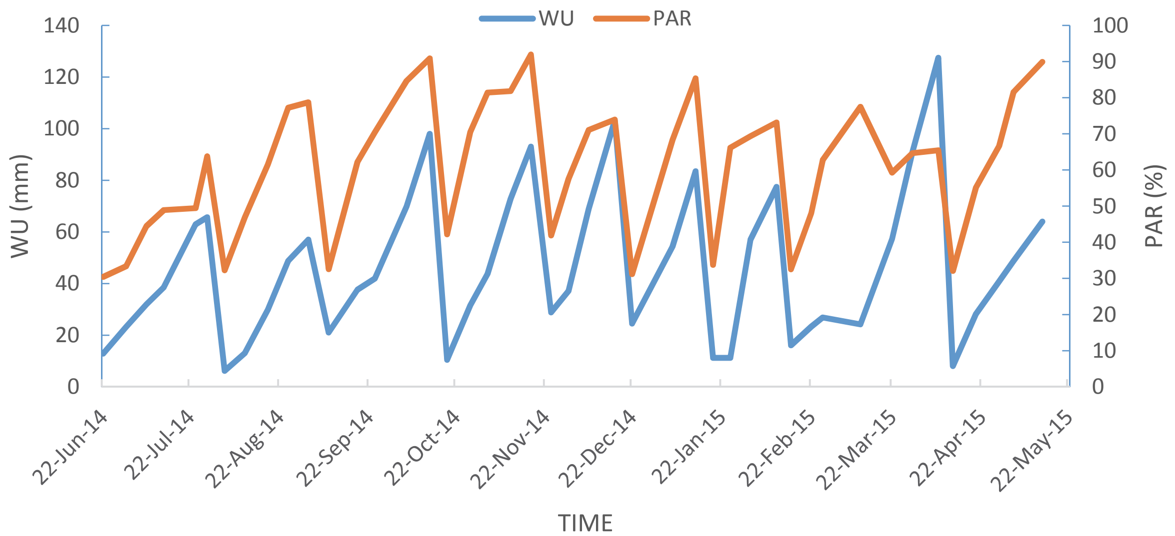


Figure 4.40 Relationship between water use (WU) and Photosynthetically Active Radiation (PAR) of kikuyu/lucerne (cv WL357) over grazing cycles

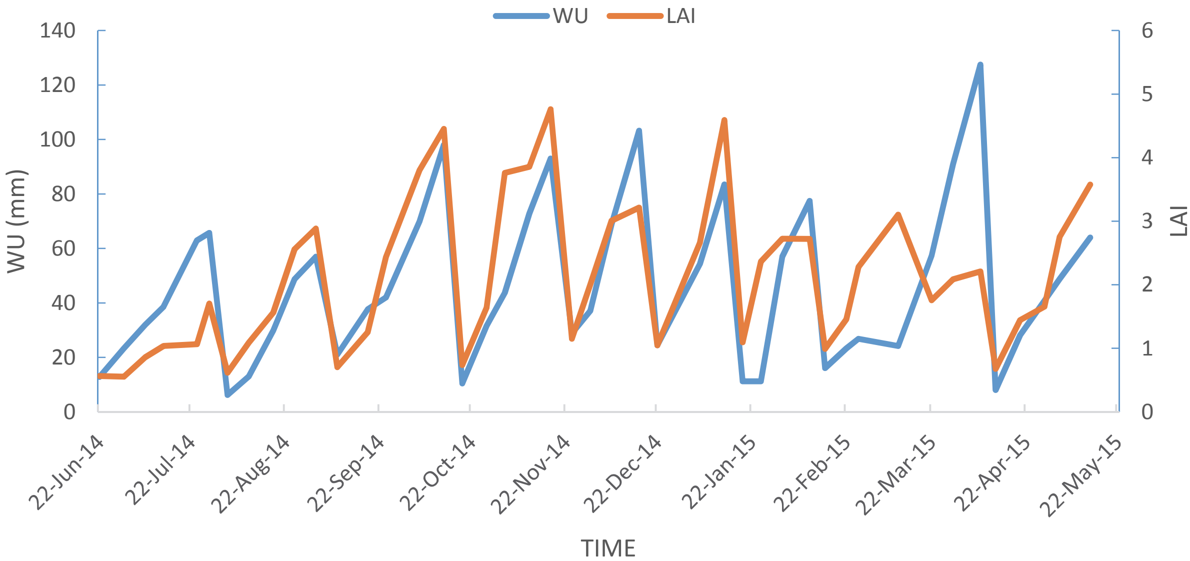


Figure 4.51 Relationship between water use (WU) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357) over grazing cycles

Table 4.41 and Table 4.42 show that there was only a significant relatively strong, positive correlation between DM yield and LAI with $r^2 = 0.661$ ($P<0.05$) of kikuyu/lucerne (cv WL357) and is illustrated in Figure 4.52.

Table 4.41 Correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357)

	WU	PAR	LAI
DM	0.422	0.456	0.661

Table 4.42 Significance of correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357)

	WU	PAR	LAI
DM	0.225	0.186	0.037

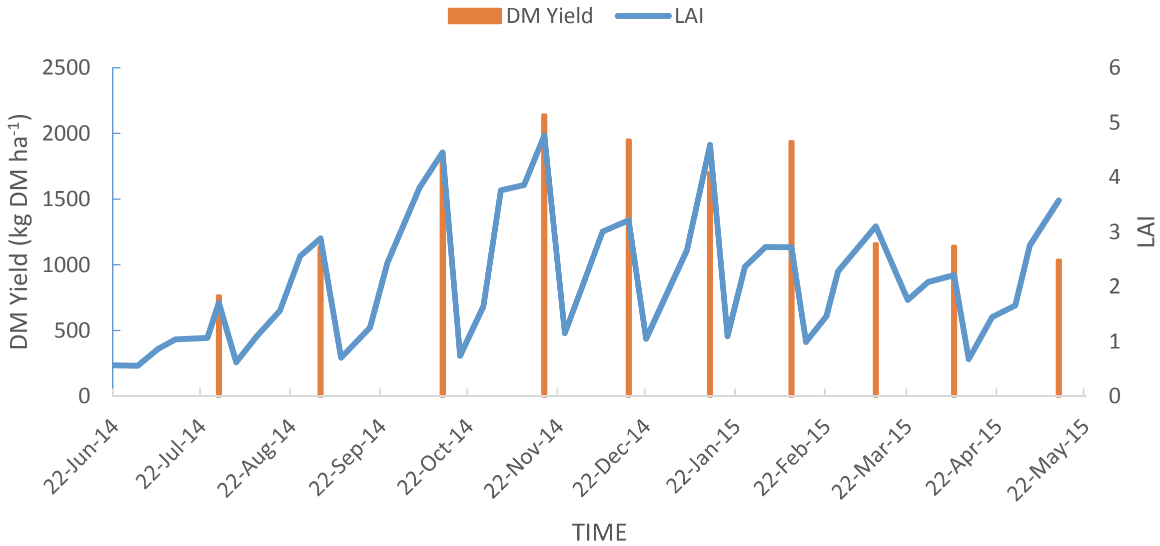


Figure 4.52 Relationship between dry matter yield (DM Yield) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357) over grazing cycles

The WU of kikuyu/lucerne (WL711) also had a relatively strong, positive relationship with PAR and LAI and is illustrated in Figure 4.53 and 4.54. The respective correlations between WU and PAR, and WU and LAI were $r^2 = 0.595$ ($P<0.01$) and $r^2 = 0.635$ ($P<0.01$) (Table 4.43 and 4.44).

Table 4.43 Correlation between water use (WU), photosynthetically active radiation (PAR), Leaf Area Index (LAI) of kikuyu/lucerne (cv WL711)

	WU	PAR	LAI
WU	1.000		
PAR	0.595	1.000	
LAI	0.635	0.909	1.000

Table 4.44 Significance of correlation between water use (WU), photosynthetically active radiation (PAR), Leaf Area Index (LAI) of kikuyu/lucerne (cv WL711)

	WU	PAR	LAI
WU	-		
PAR	<0.001	-	
LAI	<0.001	<0.001	-

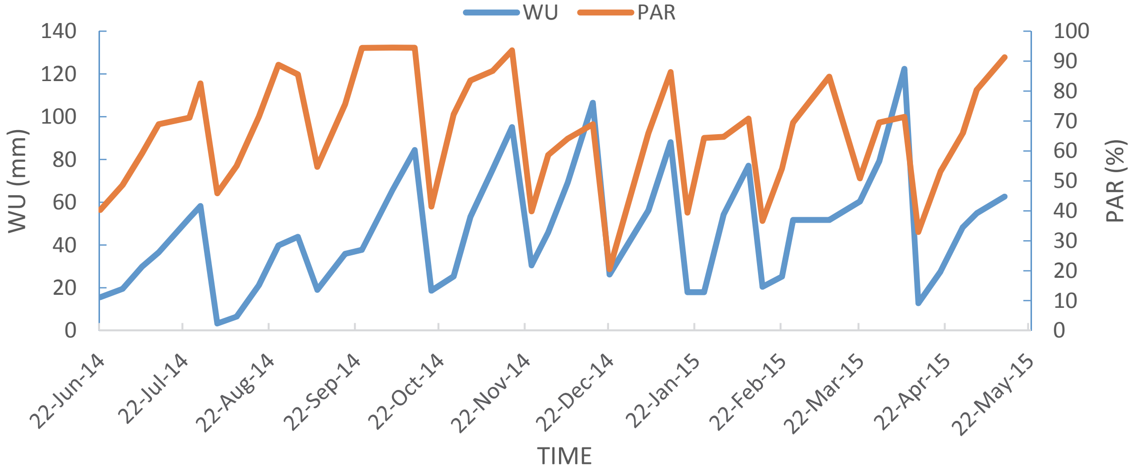


Figure 4.53 Relationship between water use (WU) and Photosynthetically Active Radiation (PAR) of kikuyu/lucerne (cv WL711) over grazing cycles

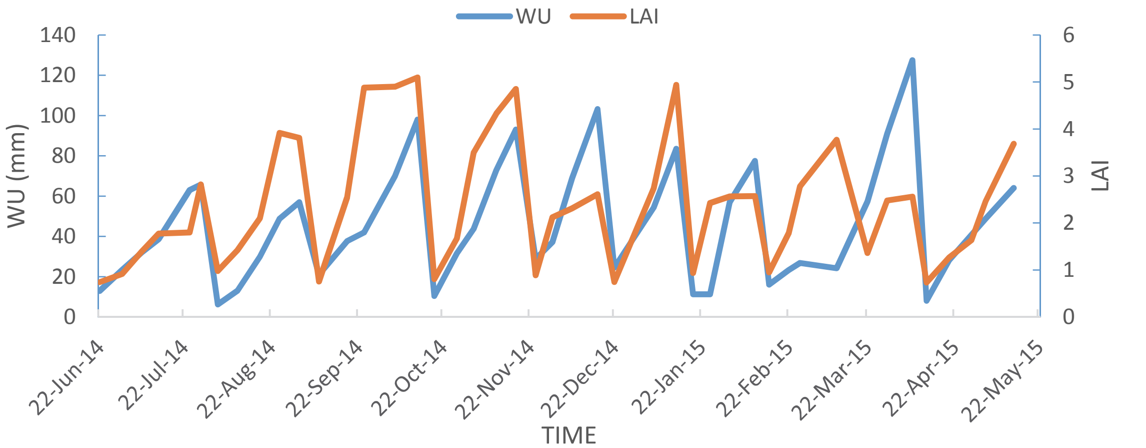


Figure 4.54 Relationship between water use (WU) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL711) over grazing cycles

No significant correlation (P>0.05) was however found between DM yield and LAI of kikuyu/lucerne (cv WL711) (Table 4.49 and 4.50).

Table 4.45 Correlation between dry matter yield (DM), photosynthetically active radiation (PAR), Leaf Area Index (LAI) of kikuyu/lucerne (cv WL711)

	WU	PAR	LAI
DM	0.360	0.111	0.517

Table 4.46 Significance of correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL711)

	WU	PAR	LAI
DM	0,307	0,761	0,126

4.2.2.1 Kikuyu over-sown with grass (perennial ryegrass and cocksfoot) (site B)

Statistical analysis showed that there were correlations between WU, PAR and LAI. Table 4.47 and 4.48 shows that the WU of kikuyu/perennial ryegrass had a strong, positive relationship with PAR (r^2 = 0.801; P<0.001) as well as with LAI (r^2 = 0.763; P<0.001). These relationships are illustrated in Figure 4.55 and 4.56.

Table 4.47 Correlation between water use (WU), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/perennial ryegrass

	WU	PAR	LAI
WU	1.000		
PAR	0.801	1.000	
LAI	0.763	0.906	1.000

Table 4.48 Significance of correlation between water use (WU), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/perennial ryegrass

	WU	PAR	LAI
WU	-		
PAR	<0.001	-	
LAI	<0.001	<0.001	-

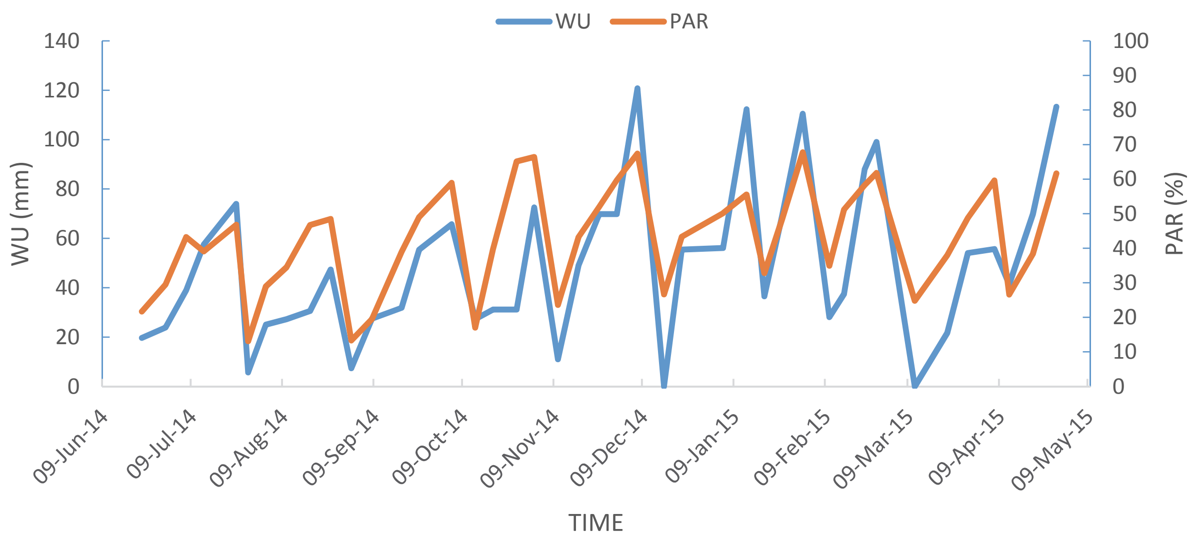


Figure 4.55 Relationship between water use (WU) and Photosynthetically Active Radiation (PAR) of kikuyu/perennial ryegrass over grazing cycles

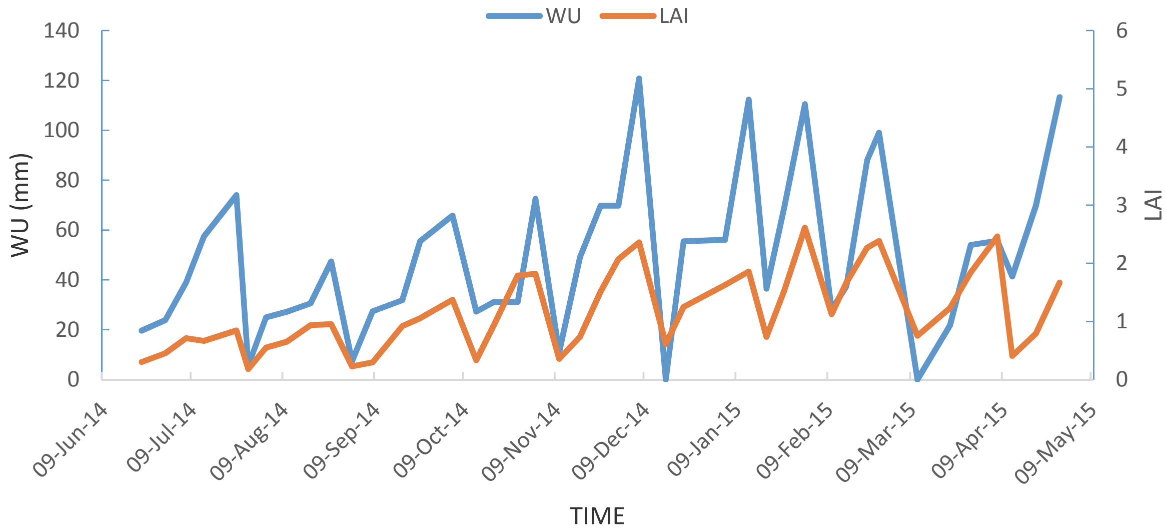


Figure 4.56 Relationship between water use (WU) and Leaf Area Index (LAI) of kikuyu/perennial ryegrass over grazing cycles

Dry matter yield of kikuyu/perennial ryegrass had a significant strong, positive relationship with PAR and with LAI (r^2 = 0.757 and 0.844; $P<0.05$ respectively) (Table 4.49 and 4.50). Figure 4.55 illustrates the former and Figure 4.57 illustrates the latter.

Table 4.49 Correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/perennial ryegrass

	WU	PAR	LAI
DM	0,455	0,757	0,844

Table 4.50 Significance of correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357)

	WU	PAR	LAI
DM	0,187	0,011	0,002

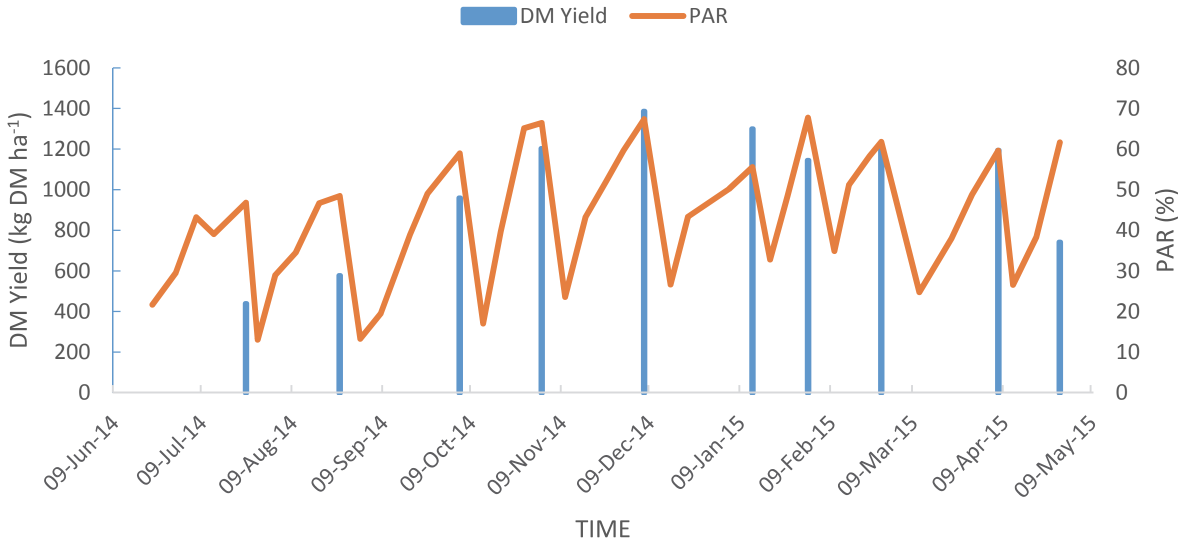


Figure 4.57 Relationship between dry matter yield (DM yield) and photosynthetically active radiation (PAR) of kikuyu/perennial ryegrass over grazing cycles

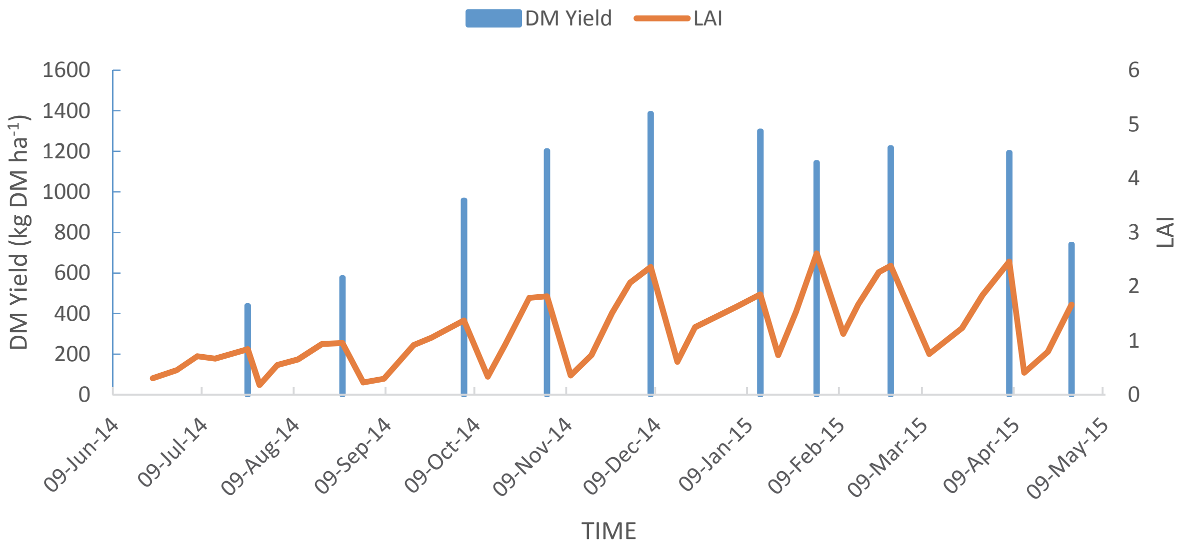


Figure 4.58 Relationship between dry matter yield (DM Yield) and Leaf Area Index (LAI) of kikuyu/perennial ryegrass over grazing cycles

Kikuyu/cocksfoot showed relatively strong, positive relationships between its WU and PAR (r^2 = 0.718; P<0.001) and between WU and LAI (r^2 = 0.698; P<0.001) as seen in Table 4.51 and 4.52. Figure 4.59 and 4.60 illustrates these relationships.

Table 4.51 Correlation between water use (WU), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) kikuyu/cocksfoot

	WU	PAR	LAI
WU	1.000		
PAR	0.718	1.000	
LAI	0.698	0.952	1.000

Table 4.52 Significance of correlation between water use (WU), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/cocksfoot

	WU	PAR	LAI
WU	-		
PAR	<0.001	-	
LAI	<0.001	<0.001	-

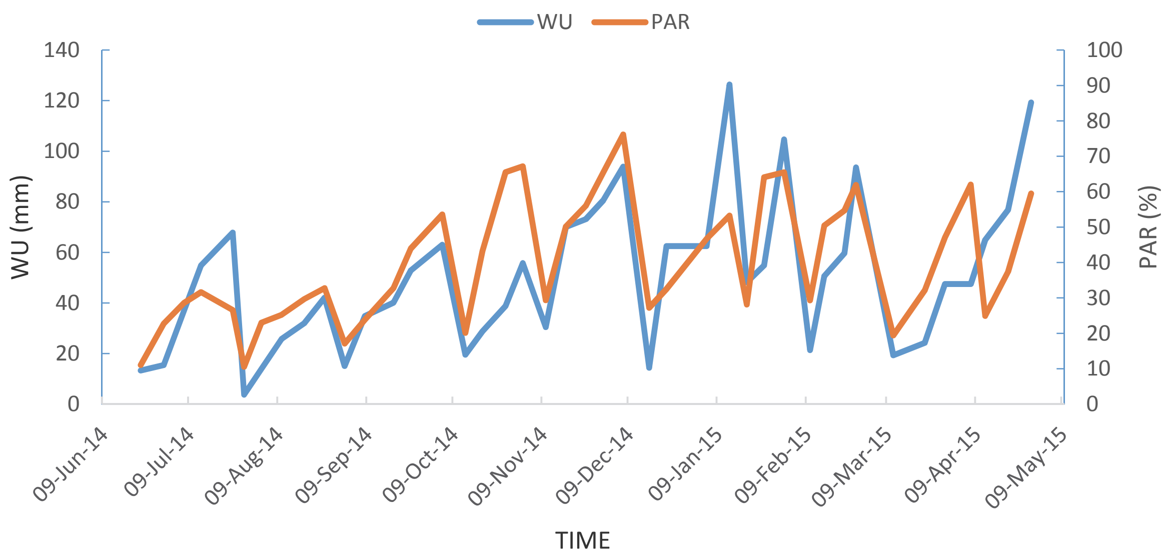


Figure 4.59 Relationship between water use (WU) and Photosynthetically Active Radiation (PAR) of kikuyu/cocksfoot over grazing cycles

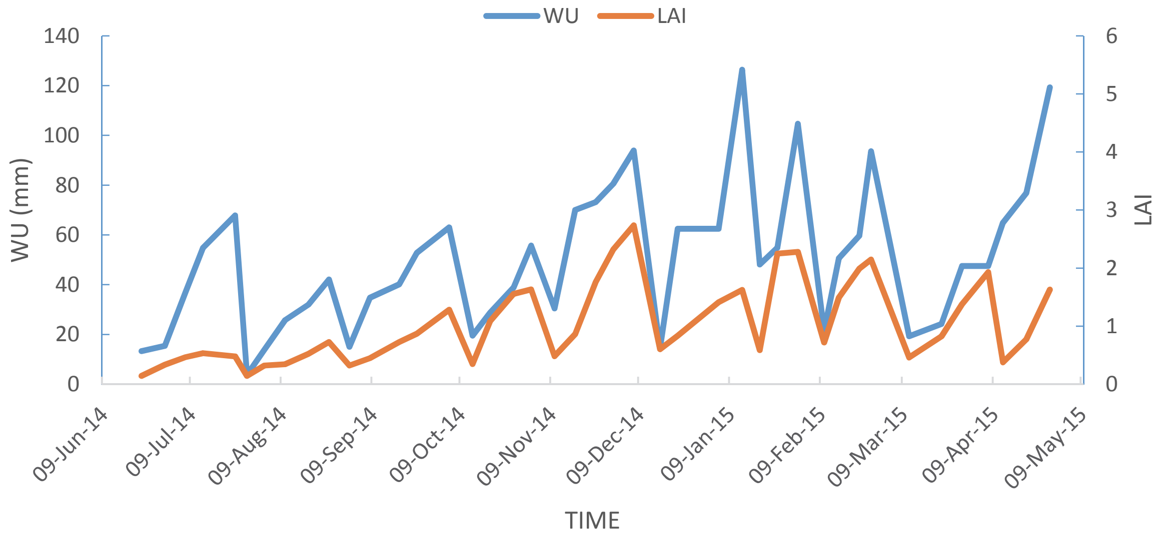


Figure 4.60 Relationship between water use (WU) and Leaf Area Index (LAI) of kikuyu/cocksfoot over grazing cycles

In Table 4.17 and 4.18 it is clear that a strong, positively relationship also exists between DM yield and PAR as well as between DM yield and LAI of kikuyu/cocksfoot (r^2 = 0.929 and 0.855; P<0.00 and P<0.05 respectively). These relationships are shown in Figure 4.61 and 4.62.

Table 4.53 Correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/perennial ryegrass

	WU	PAR	LAI
DM	0,366	0,929	0,855

Table 4.54 Significance of correlation between dry matter yield (DM), photosynthetically active radiation (PAR) and Leaf Area Index (LAI) of kikuyu/lucerne (cv WL357)

	WU	PAR	LAI
DM	0,299	<0,001	0,002

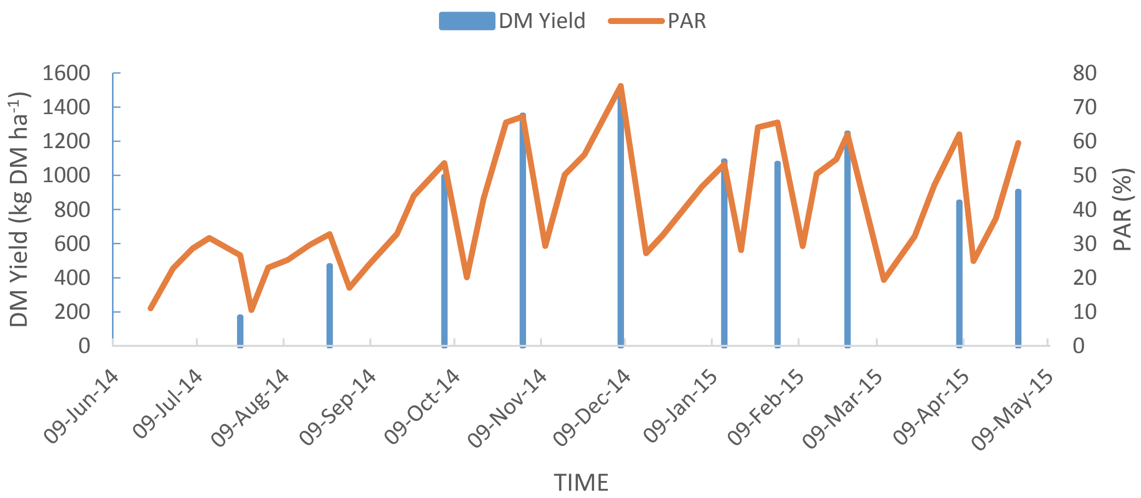


Figure 4.61 Relationship between dry matter yield (DM yield) and photosynthetically active radiation (PAR) of kikuyu/cocksfoot over grazing cycles

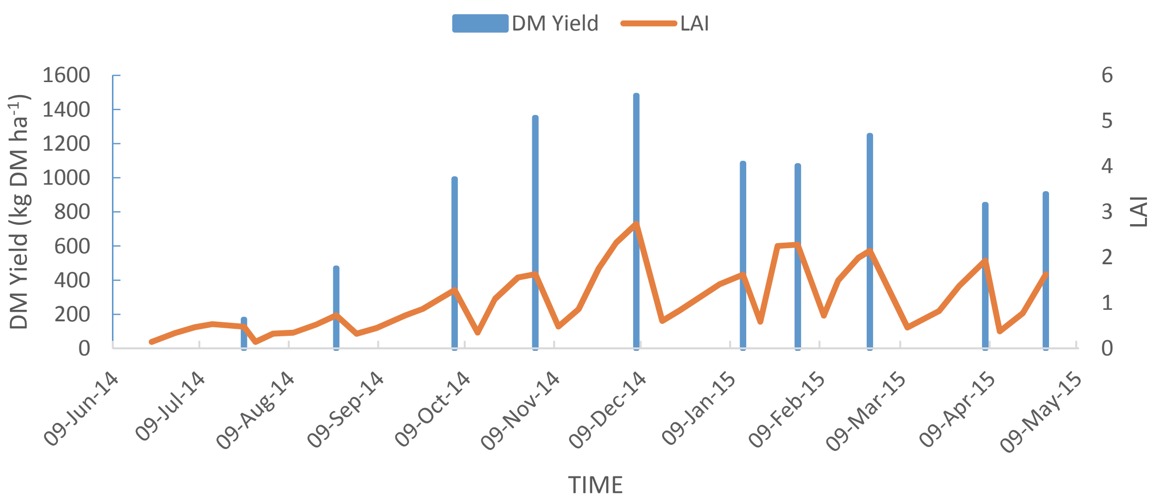


Figure 4.62 Relationship between dry matter yield (DM Yield) and Leaf Area Index (LAI) of kikuyu/cocksfoot over grazing cycles

The WU of both kikuyu/lucerne (cv WL357) and kikuyu/lucerne (cv WL711) could be related to canopy cover (PAR and LAI). There was a clear pattern that showed with an in increase in canopy cover, WU also increased. After the pasture was grazed and the canopy cover was small, WU was also at its lowest point and started to increase as the canopy grew larger.

A similar relationship between WU and canopy cover exists for kikuyu/grass pastures. This relationship between WU and canopy cover were however, stronger for kikuyu/perennial ryegrass and kikuyu/cocksfoot pastures than for the kikuyu/lucerne pastures. With an increase in canopy cover, there was an increase in WU. The opposite occurred when canopy cover is small.

4.3.1 Pasture growth

4.3.1.1 Dry matter Yield (Measured and Estimated)

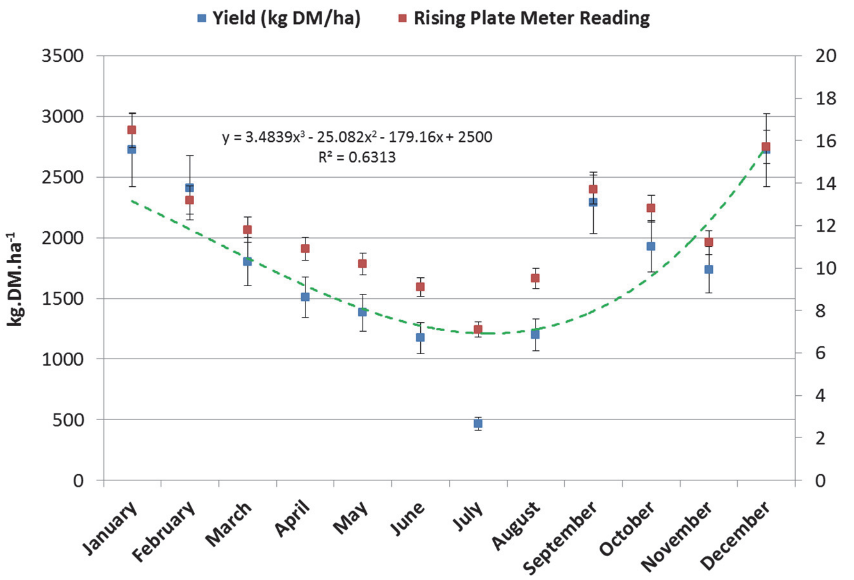


Figure 4.63 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for lucerne pasture

4.3.1.2 Forage quality

4.3.1.2.1 Crude protein

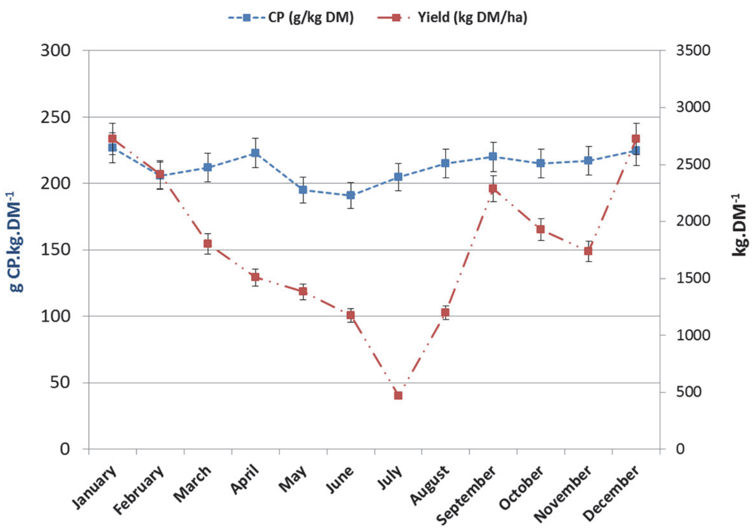


Figure 4.64 Relationship between measured dry matter yield (kg DM.ha^{-1}) and crude protein (CP) yield in relation to growing season

4.3.2 Water use

With the limited amount of data collected from the on farm observation sites, the data was used in conjunction with the crop coefficients calculated using the on station experimental data and historical data and literature. All this data did give a good understanding of the water use of pastures on farm. Precipitation (Irrigation + rainfall) amount received was accurately measured, and it was clear where the farmer over or under irrigated.

4.3.2.1 Crop coefficient

Crop coefficients (Table 4.55) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.65).

Table 4.55 Crop growth parameters for lucerne production areas with frost

	JAN	FEB	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET_o ($mm.day^{-1}$)	6.4	5.9	4.7	4.1	3	3.1	3.2	4	5.3	6.4	6.7	6.5
Crop coefficient (K_c)	0.85	0.85	0.9	0.8	0.6	0.5	0.5	0.6	0.7	0.85	0.9	0.95
Calculated Water Use (ET_c) ($mm.day^{-1}$)	5.4	5.0	4.2	3.3	1.8	1.6	1.6	2.4	3.7	5.4	6.0	6.2

It is clearly shown in Figure 4.65 that the farmer over irrigated in the winter months (April-August) and too much precipitation was received in September, November and December.

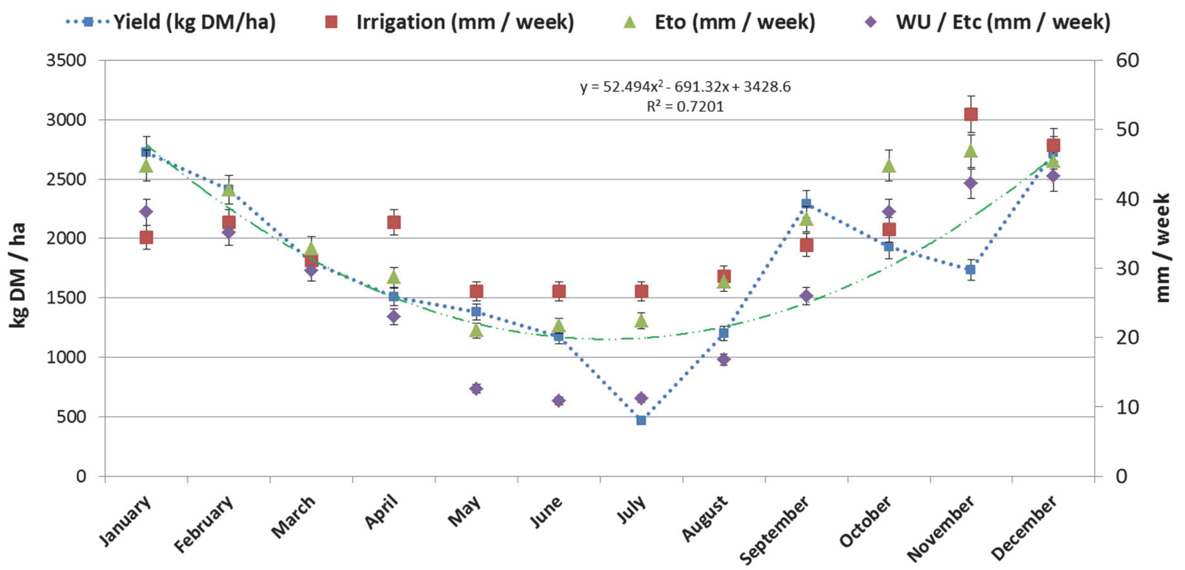


Figure 4.65 Relationship between measured dry matter yield (kg $DM.ha^{-1}$) and pasture crop water requirements ($mm.week^{-1}$) and precipitation ($mm.month^{-1}$) received over 2013-2015 growing season

Too little water was given in October and January but was not that significant. It is clear from all the on farm data that the months where the Et_o is low, too much water was applied through irrigation.

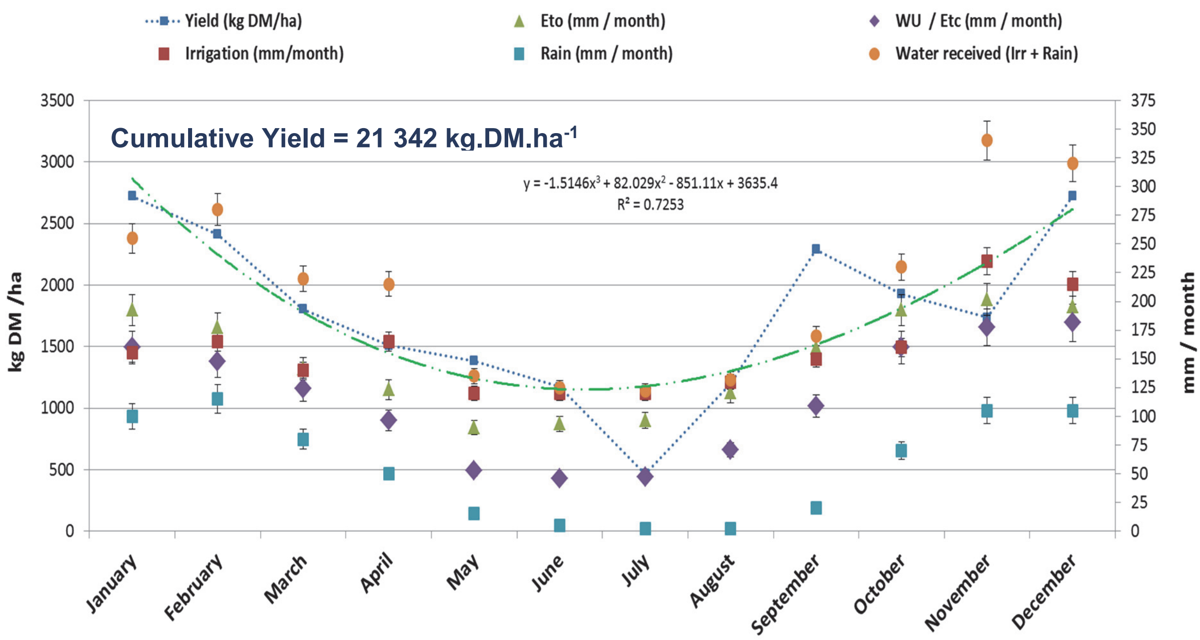


Figure 4.66 Relationship between measured dry matter yield (kg DM.ha^{-1}) and pasture crop water requirements (mm.month^{-1}) and precipitation (mm.month^{-1}) received over 2013-2015 growing season

4.3.3 Water use efficiency

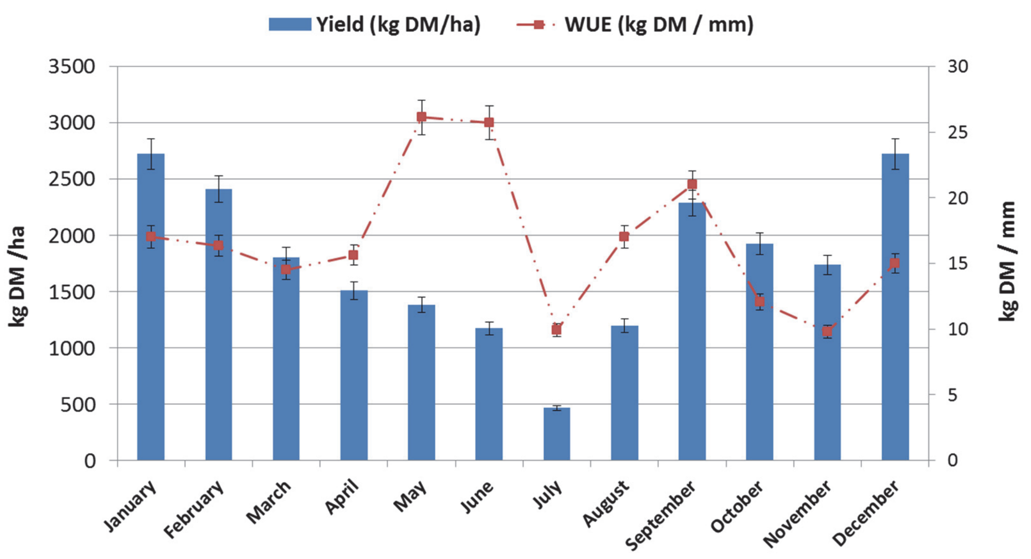


Figure 4.67 Mean water use efficiency (WUE – kg.DM ha^{-1}mm^{-1}) of lucerne pasture in terms of dry matter (DM) yield for the growing season 2013-2015

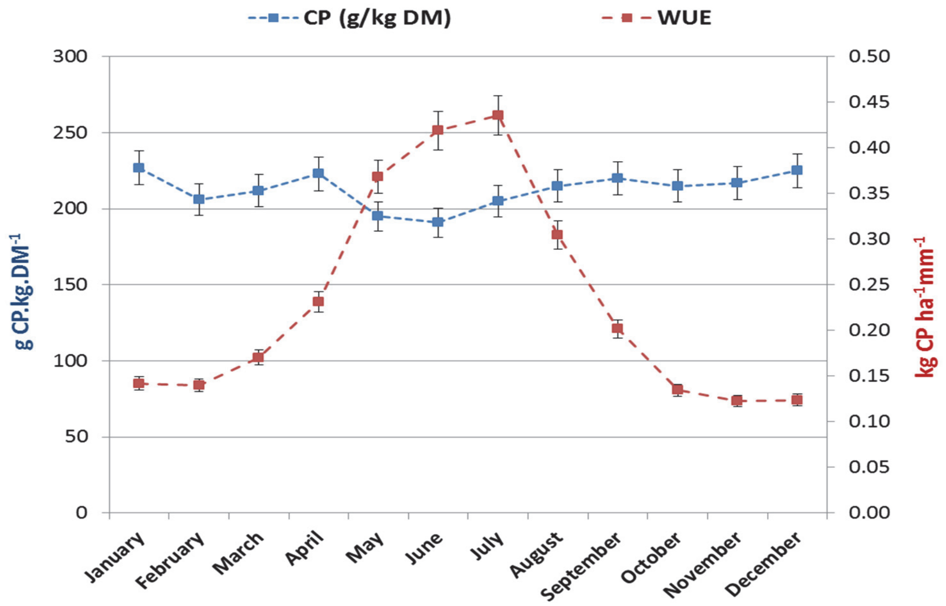


Figure 4.68 Mean water use efficiency (WUE – kg.DM ha^{-1}mm^{-1}) of lucerne pasture in terms of crude protein (CP) yield for the growing season 2013-2015

The hypothesis that there is a strong relationship between RPM reading and water use was tested and good data was obtained to show that there is merit in this hypothesis. The value of this will become more pronounced the better the RPM calibration is for the pasture.

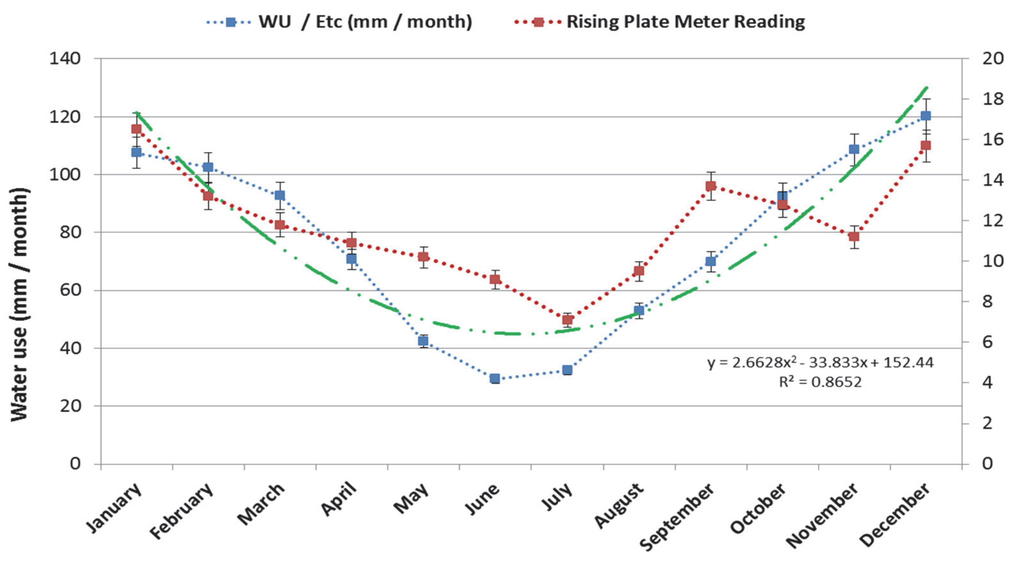


Figure 4.69 Potential relationship between pasture crop water use (ET_c) (mm.month^{-1}) and estimated yield using a rising plate meter for Lucerne pasture

4.4.1 Pasture growth

4.4.1.1 Dry matter Yield (Measured and Estimated)

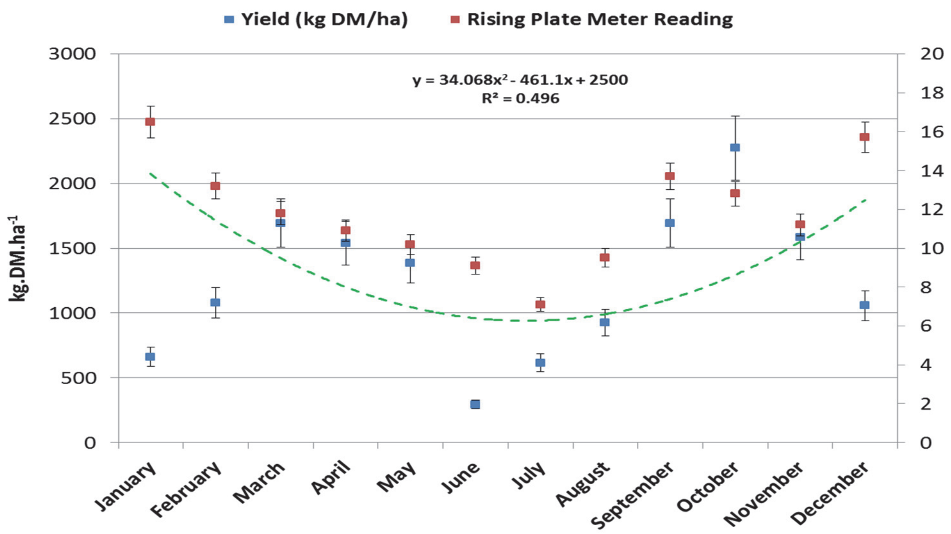


Figure 4.70 Relationship between measured dry matter yield (kg DM.ha^{-1}) and estimated yield using a rising plate meter for mixed kikuyu / ryegrass pasture

4.4.1.2 Forage quality

<u>*4.4.1.2.1 Crude protein*</u>

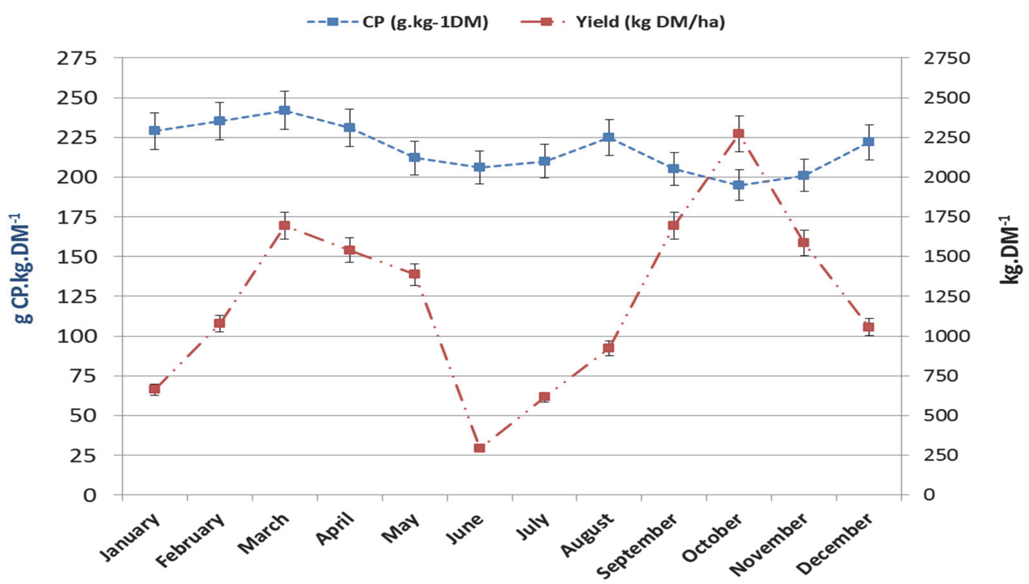


Figure 4.71 Relationship between measured dry matter yield (kg DM.ha^{-1}) and crude protein (CP) yield in relation to growing season

4.4.2 Water use

Crop coefficients (Table 4.56) were determined from the research trials at the Hatfield Experimental Station and were used together with ET_o to calculate the amount of water required by the pasture crop (Figure 4.72).

Table 4.56 Crop growth parameters for mixed kikuyu / ryegrass pastures

	JAN	FEB	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ET_o (mm.day^{-1})	4.3	4.1	3.5	3	2.4	2	2.2	3	3.4	3.7	4.1	4.3
Crop coefficient (K_c)	0.7	0.7	0.6	0.6	0.65	0.55	0.5	1	0.75	0.75	0.7	0.7
Calculated Water Use (ET_c) (mm.day^{-1})	**3**	**2.9**	**2.1**	**1.8**	**1.6**	**1.1**	**1.1**	**3.0**	**2.6**	**2.8**	**2.9**	**3.0**

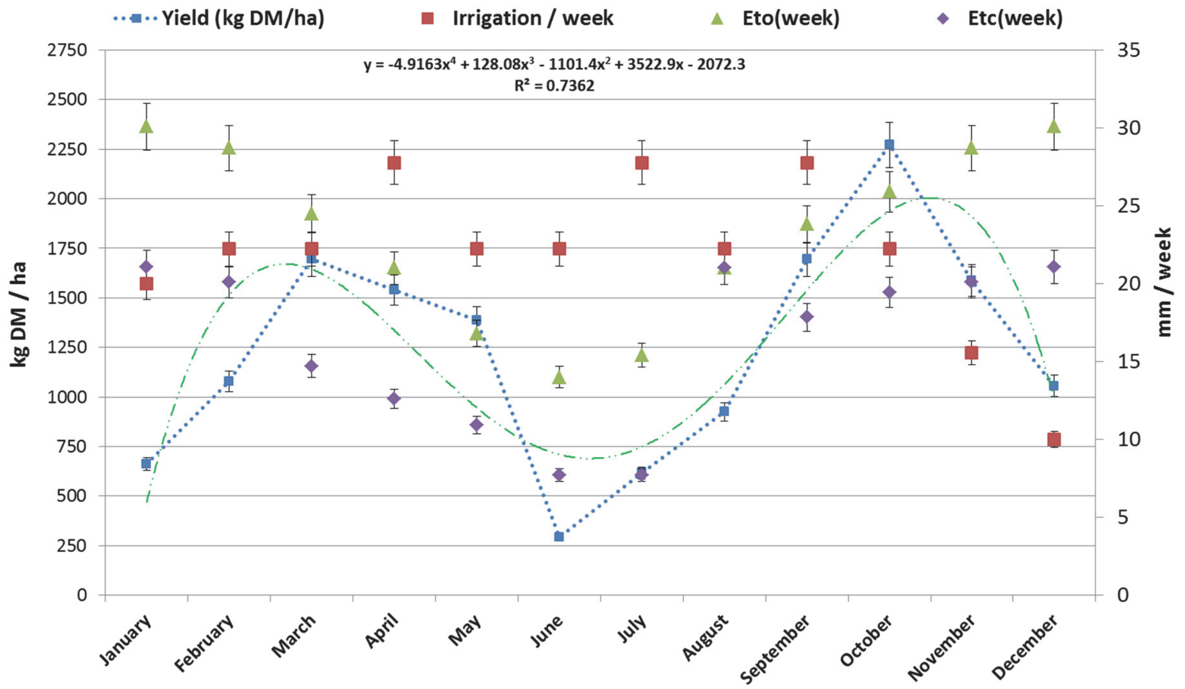


Figure 4.72 Relationship between measured dry matter yield (kg DM.ha^{-1}) and pasture crop water requirements (mm.week^{-1}) and precipitation (mm.month^{-1}) received over 2013-2015 growing season

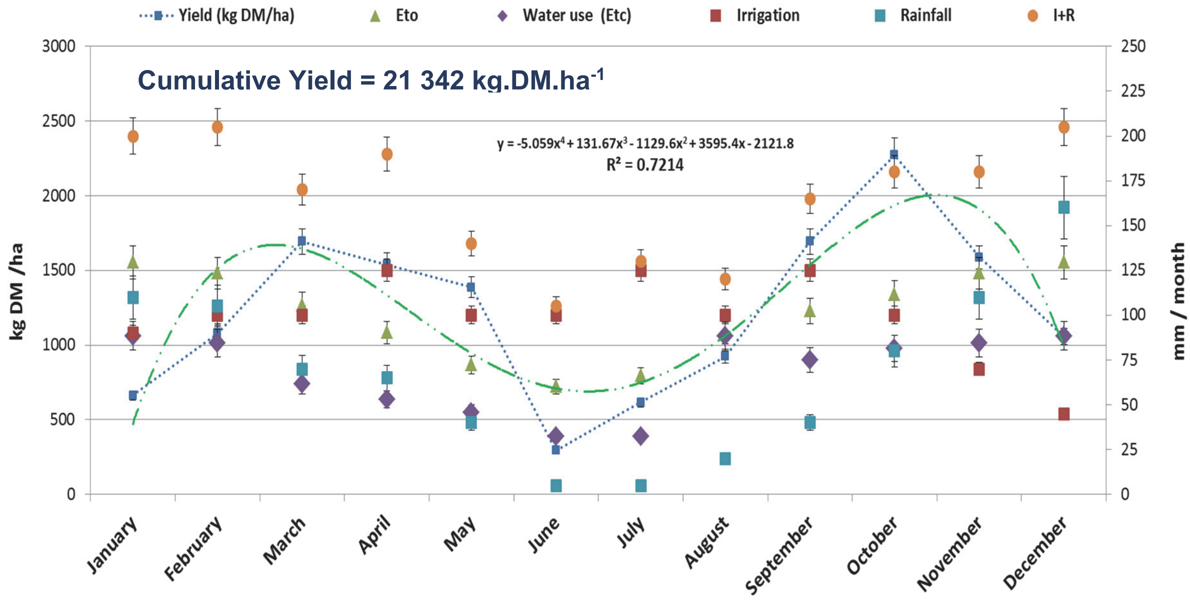


Figure 4.73 Relationship between measured dry matter yield (kg DM.ha^{-1}) and pasture crop water requirements (mm.month^{-1}) and precipitation (mm.month^{-1}) received over 2013-2015 growing season

4.4.3 Water use efficiency

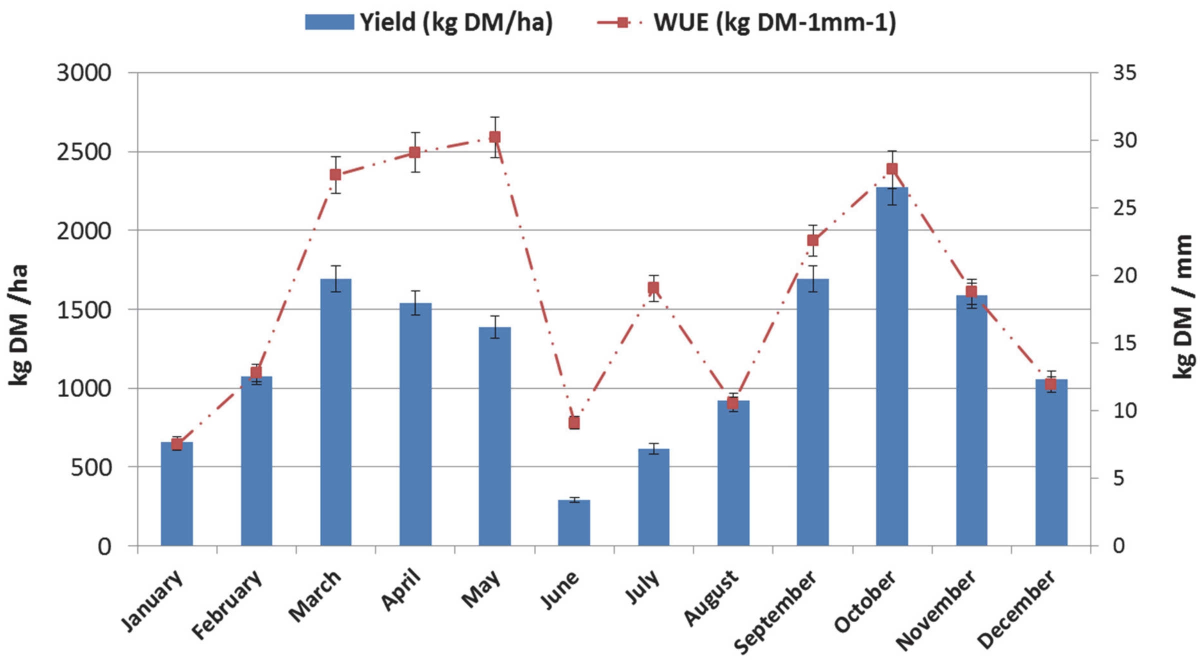


Figure 4.74 Mean water use efficiency (WUE – kg.DM ha^{-1}mm^{-1}) of mixed kikuyu / ryegrass pasture in terms of dry matter (DM) yield for the growing season 2013-2015.

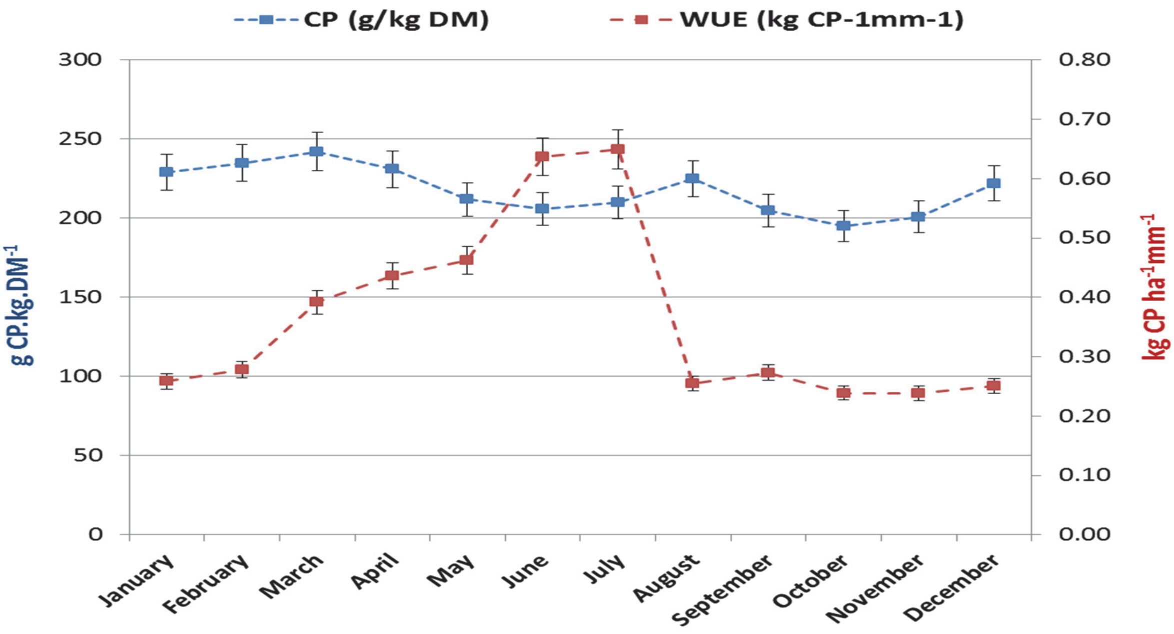


Figure 4.75 Mean water use efficiency (WUE – kg.DM ha^{-1}mm^{-1}) of mixed kikuyu / perennial ryegrass pasture in terms of crude protein (CP) yield for the growing season 2013-2015

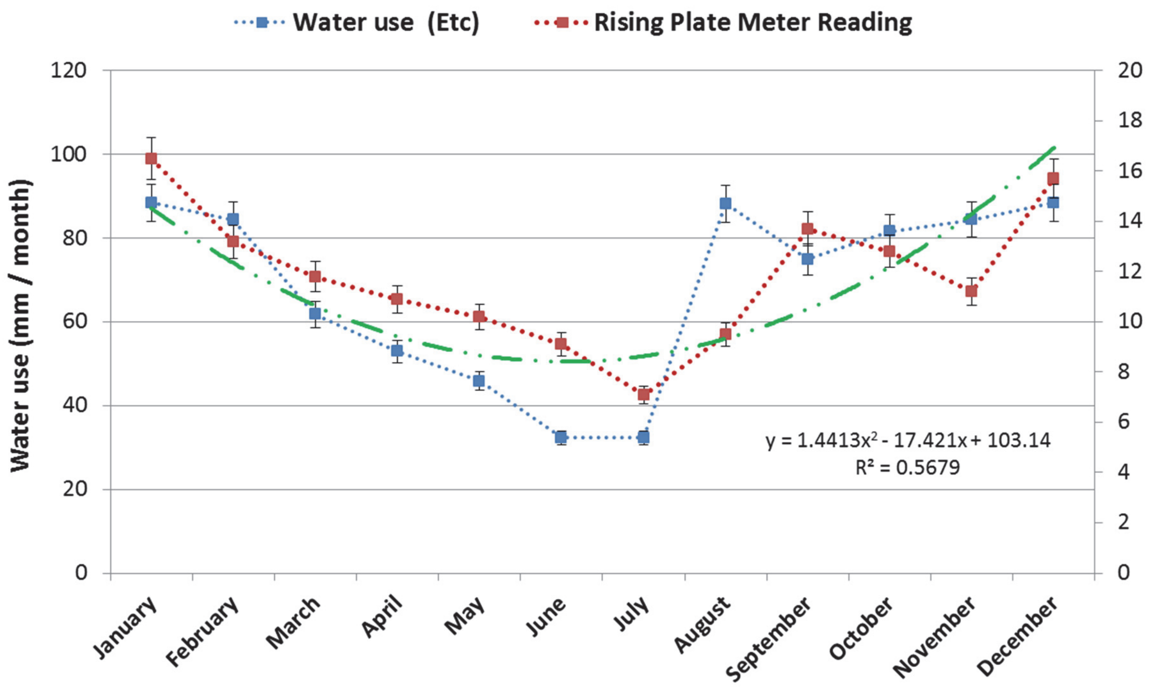


Figure 4.76 Potential relationship between pasture crop water use (ET_c) (mm.month^{-1}) and estimated yield using a rising plate meter for Lucerne pasture

CHAPTER 5 – MODELLING THE WATER USE OF PASTURES

By Wayne Truter, Melake Fessehazion, Omphile Sehoole and John Annandale

The selected models being evaluated for this study include **Dairy Mod** and **SWB** (Soil Water Balance). The Dairy Mod model was selected to account for the grazing effects on the production potential of various mixed grass pastures including legumes such as *Medicago sativa* and *Trifolium repens* and their water use requirements.

The following chapter will include the evaluation, parameterisation, test and validation of the selected models. This chapter will highlight some of the requirements for using the different models in addition to some of the changes that need to be made to achieve good model simulations.

5.1 DAIRY MOD

Dairy Mod is a model that has been developed by and for **IMJ Consultants**, **The University of Melbourne, Dairy Australia and Meat and Livestock Australia under the leadership of Prof. Ian Johnson.** The model has a strong focus on the integration of the soil, plant and animal factors (data) to have a better understanding of how the entire grazing system functions (Figure 5.1) (Johnson et al. 2008).

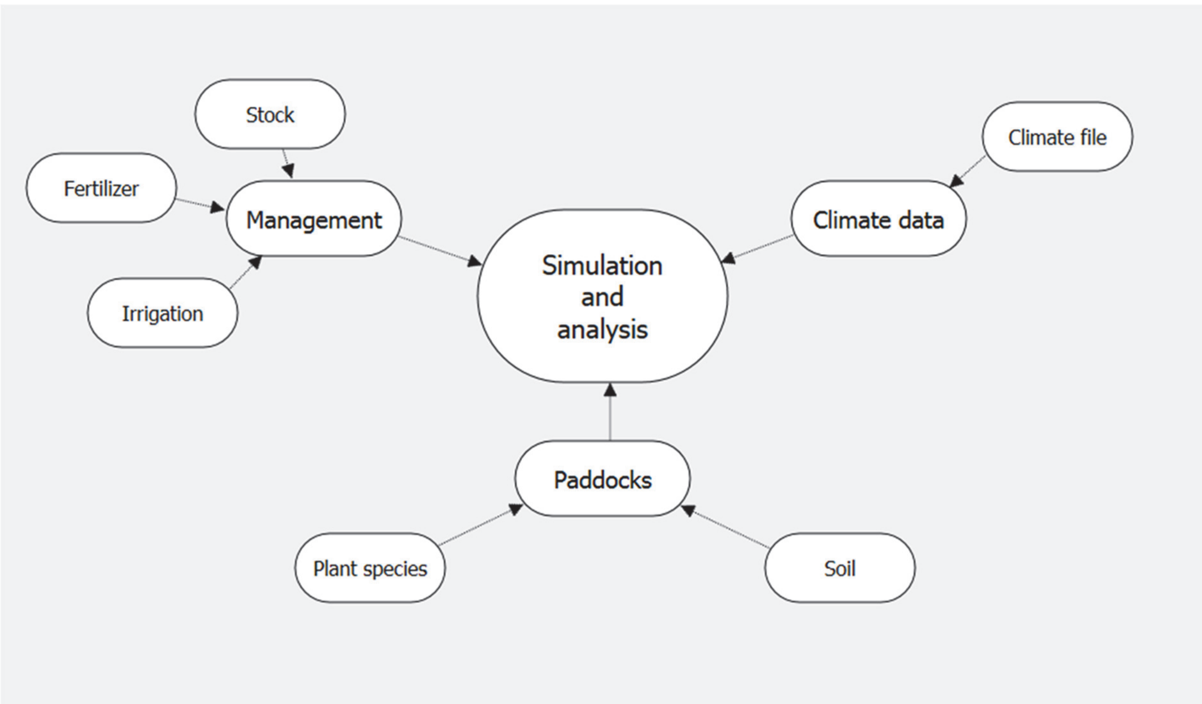


Figure 5.1 Overview of the parameters used for the model simulations (DairyMod http://imj.com.au/dairymod/)

The model has the ability to incorporate local weather data and to adjust specific parameters related to the soil, pasture growth and animal management factors. It also has the option to have nine different output screens (Figure 5.2) that provide simulations of the expected soil, water or vegetation responses to climate and management factors.

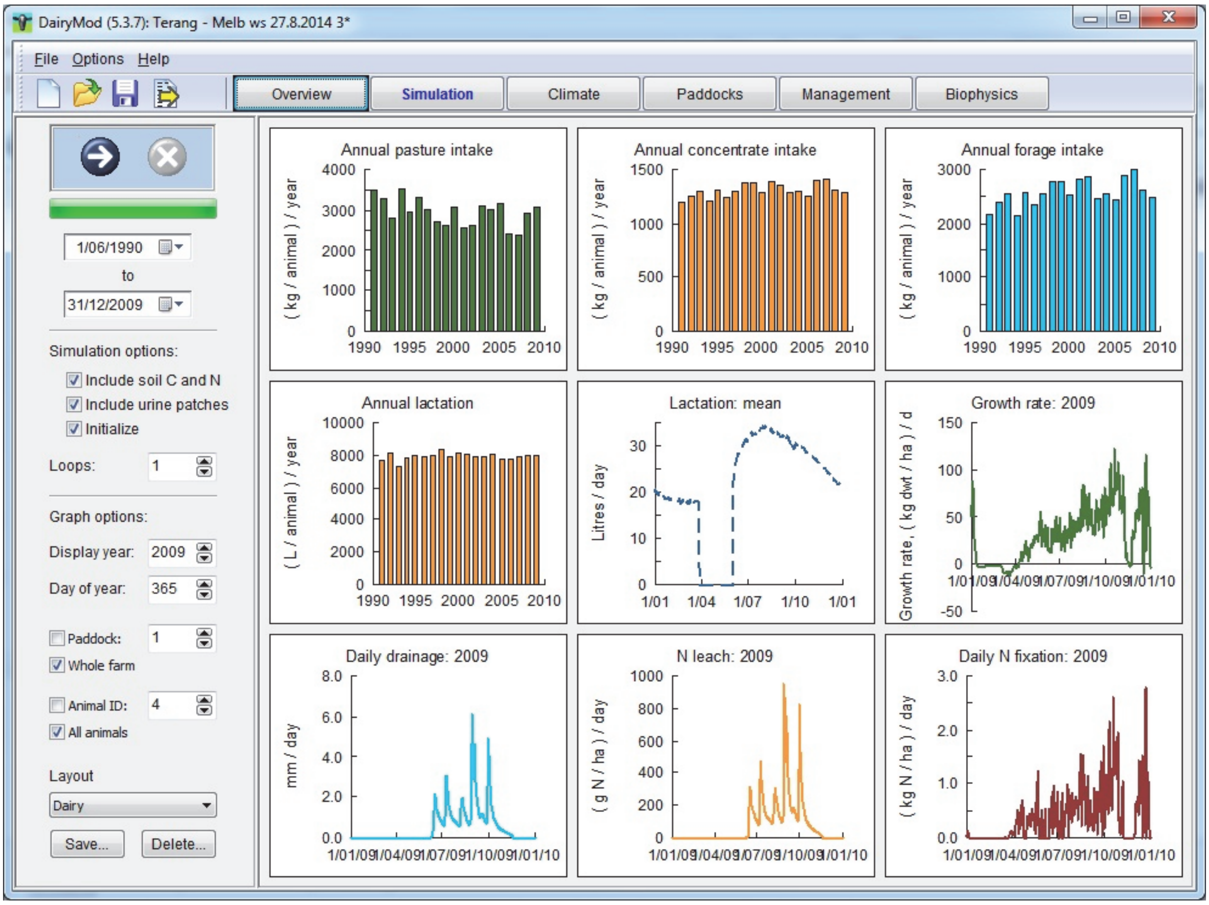


Figure 5.2 Output from Dairy Mod simulation (DairyMod http://imj.com.au/dairymod/)

The model provides the option of changing the Biophysical parameters where possible, but also provides the opportunity to rely on well tested basic growth parameters of a range of species. Figure 5.3 illustrates which parameters can be changed according to data sets available locally.

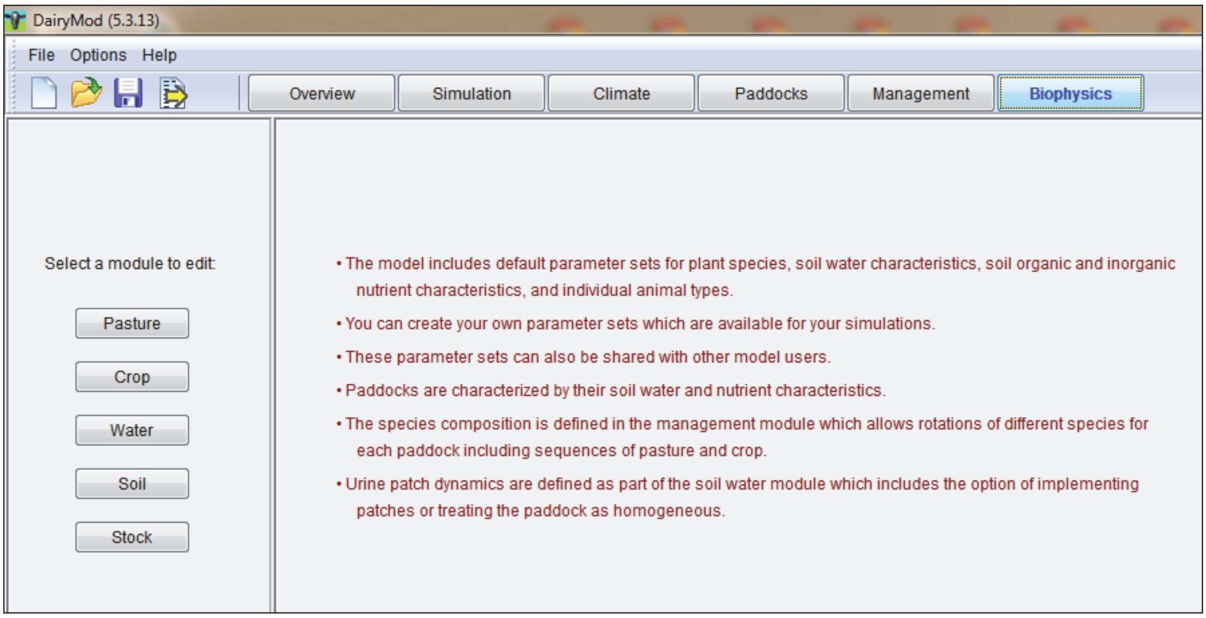


Figure 5.3 Biophysical input parameters (DairyMod http://imj.com.au/dairymod/)

5.1.1 Biophysical parameters

The biophysical parameters that can be changed include:

- Pasture
- Crop
- Water
- Soil
- Stock

5.1.1.1 Pasture

With regards to the pasture parameters, the options exist to use templates for the different species and adjust their values according to the data you have available (Figure 5.4). Plant parameter sets can be defined for different plant characteristics. The new plant parameter sets are created by changing all the individual parameters of each plant characteristic. These include:

- Canopy Structure
- Roots
- Photosynthesis
- Nitrogen
- Temperature Stress
- Transpiration
- Grazing
- Regrowth

If local data is unavailable for a parameter set, the template used provides well tested values that one can rely on.

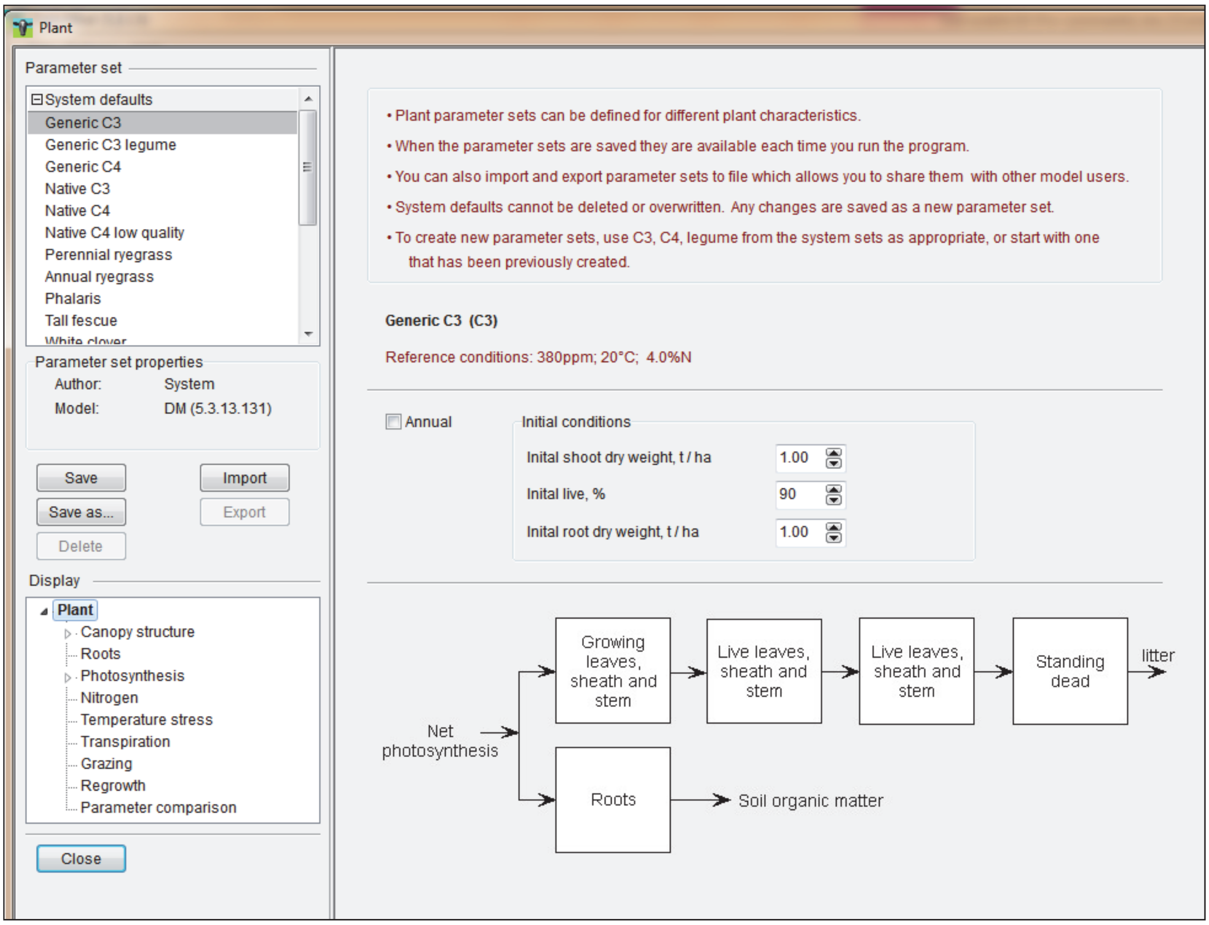


Figure 5.4 Plant parameter set options (DairyMod http://imj.com.au/dairymod/)

The following section discusses the different plant characteristics that can be adjusted for better simulation of the pasture responses.

a. *Canopy Structure* (Figure 5.5)

This parameter set includes:

- Canopy structure
  - Plant structure during new growth
  - Plant senescence
  - Plant Height
- Plant nitrogen composition

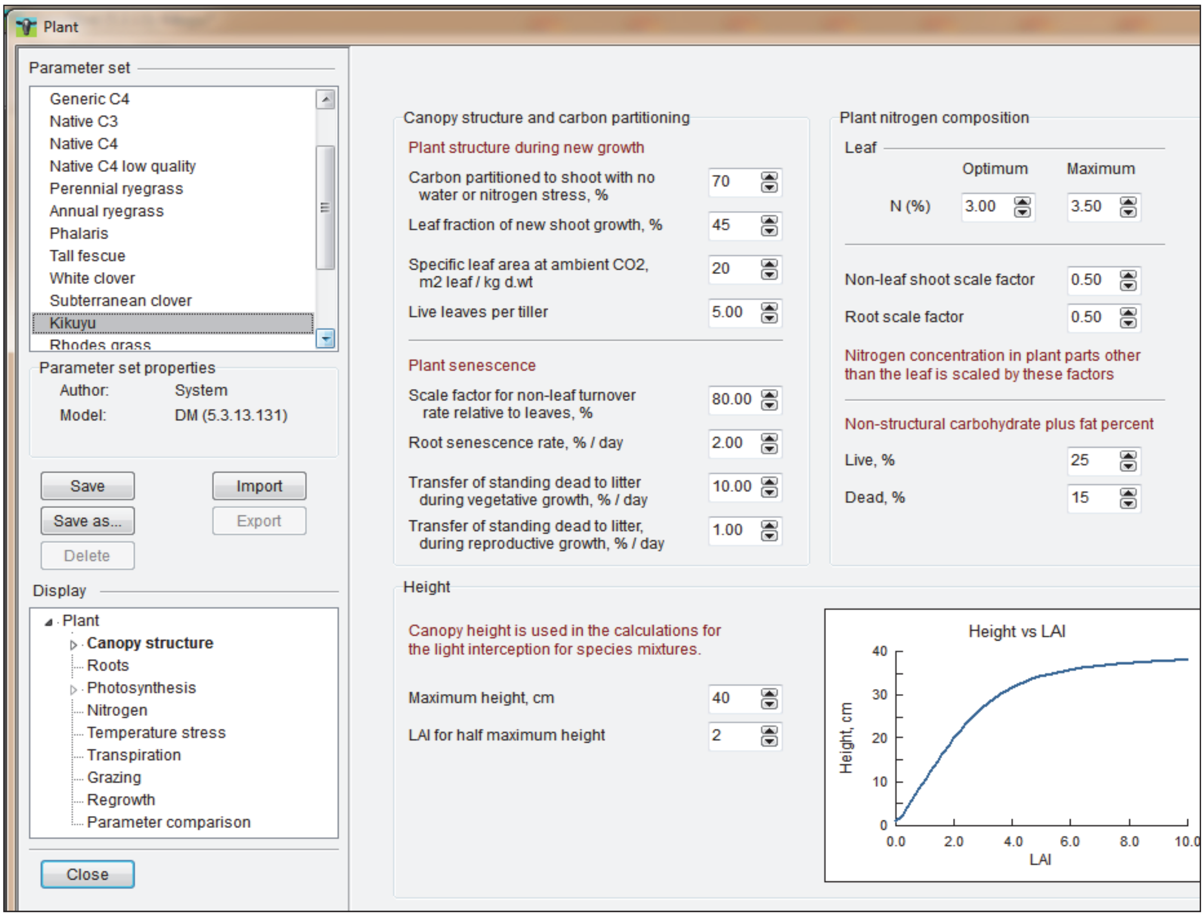


Figure 5.5 Canopy structure input parameter set (DairyMod http://imj.com.au/dairymod/)

b. *Roots* (Figure 5.6)

This parameter set includes:

- Root distribution
  - Root depth
  - Root depth for 50% distribution
  -

c. *Photosynthesis* (Figure 5.7)

This parameter set includes:

  - Plant response to defoliation

The only parameter to change here is the **Effective Minimum LAI**:

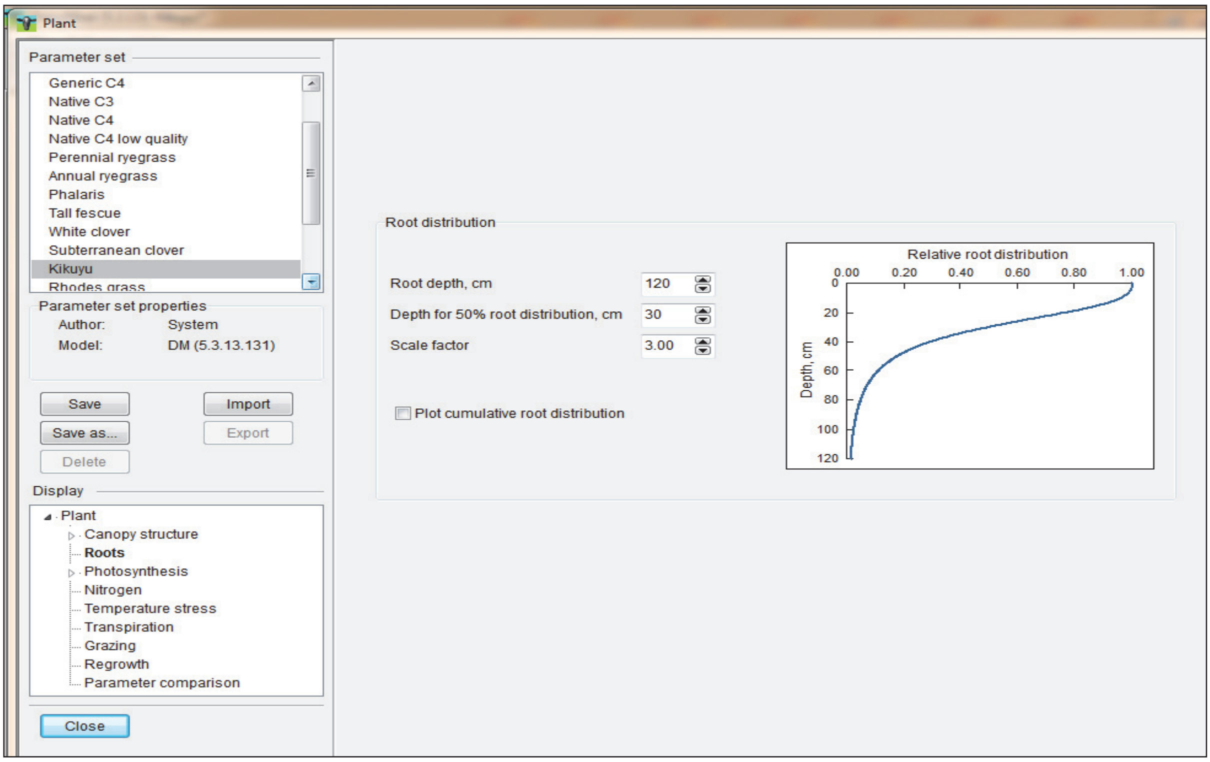


Figure 5.6 Root input parameter set (DairyMod http://imj.com.au/dairymod/)

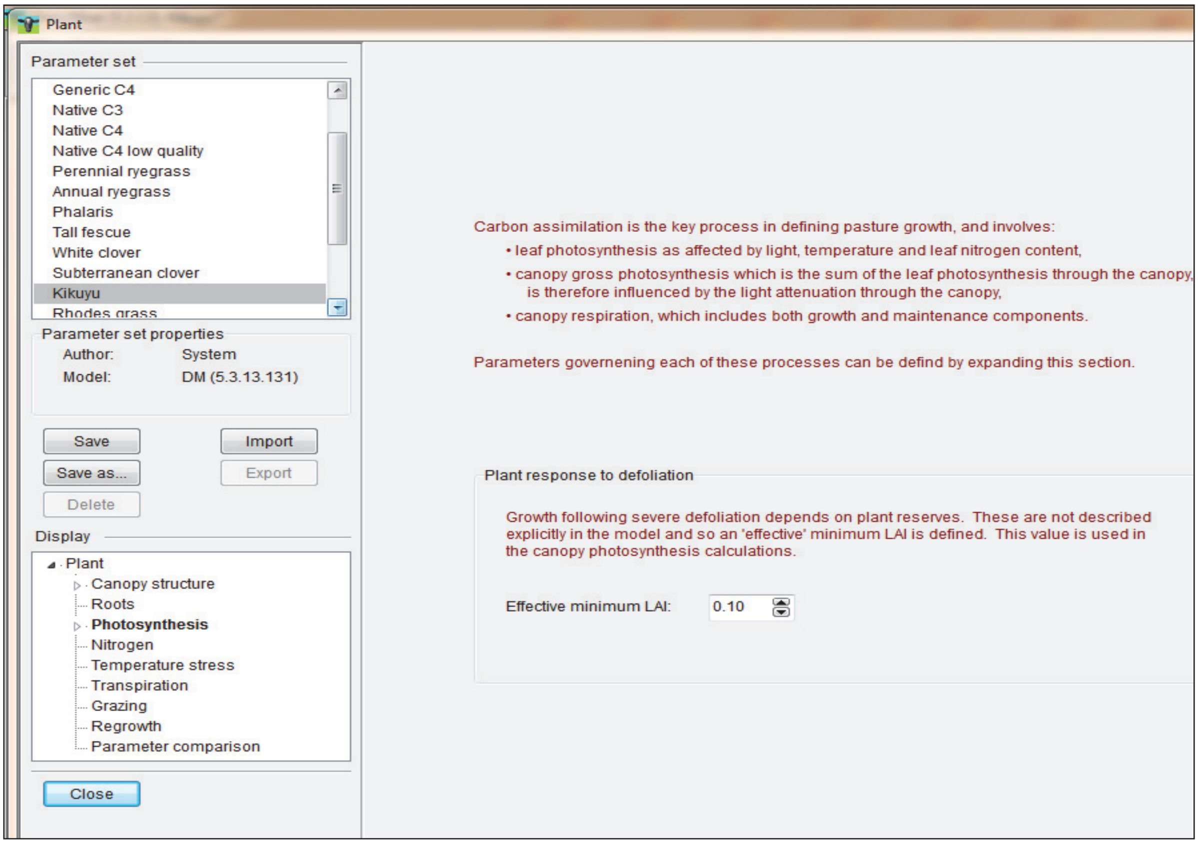


Figure 5.7 Photosynthesis input parameter set (DairyMod http://imj.com.au/dairymod/)

d. *Nitrogen* (Figure 5.8)

This parameter set includes:

- Nitrogen uptake
- Potential nitrogen remobilization

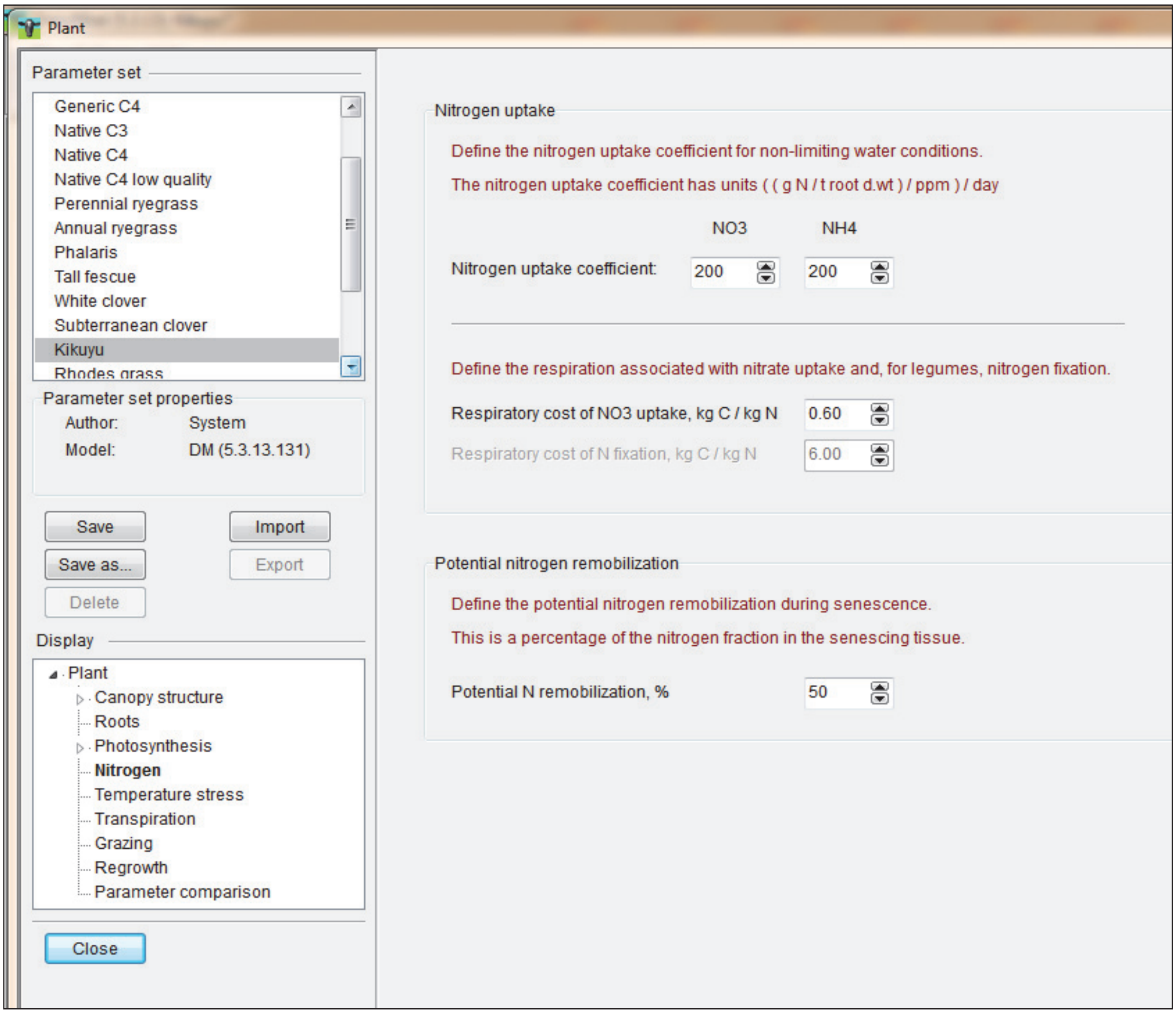


Figure 5.8 Nitrogen input parameter set (DairyMod http://imj.com.au/dairymod/)

e. *Temperature Stress* (Figure 5.9)

This parameter set includes:

- Low temperature stress
- High temperature stress

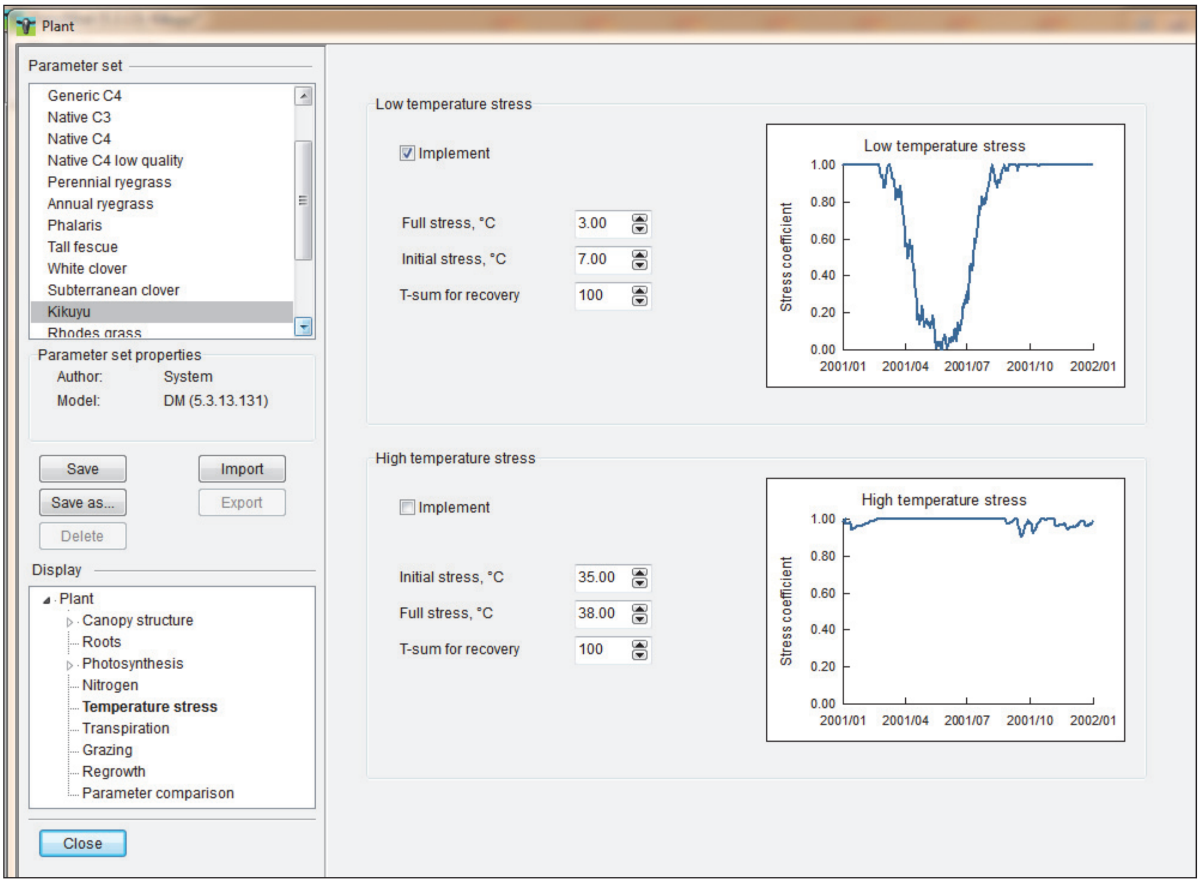


Figure 5.9 Temperature stress input parameter set (DairyMod http://imj.com.au/dairymod/)

f. *Transpiration* (Figure 5.10)

The parameter set addresses the generic function for the reduction in transpiration in response to soil water content. The function is applied to each soil layer for the particular soil water content.

g. *Grazing* (Figure 5.11)

This parameter set includes:

- Digestibility
- Grazing

This parameter set provides the opportunity to change the digestibility parameters of the pasture as it has been analysed of both the living material as well as the dead material. The other important factor to change includes the leaf to stem ration which affects the grazing value of the pasture.

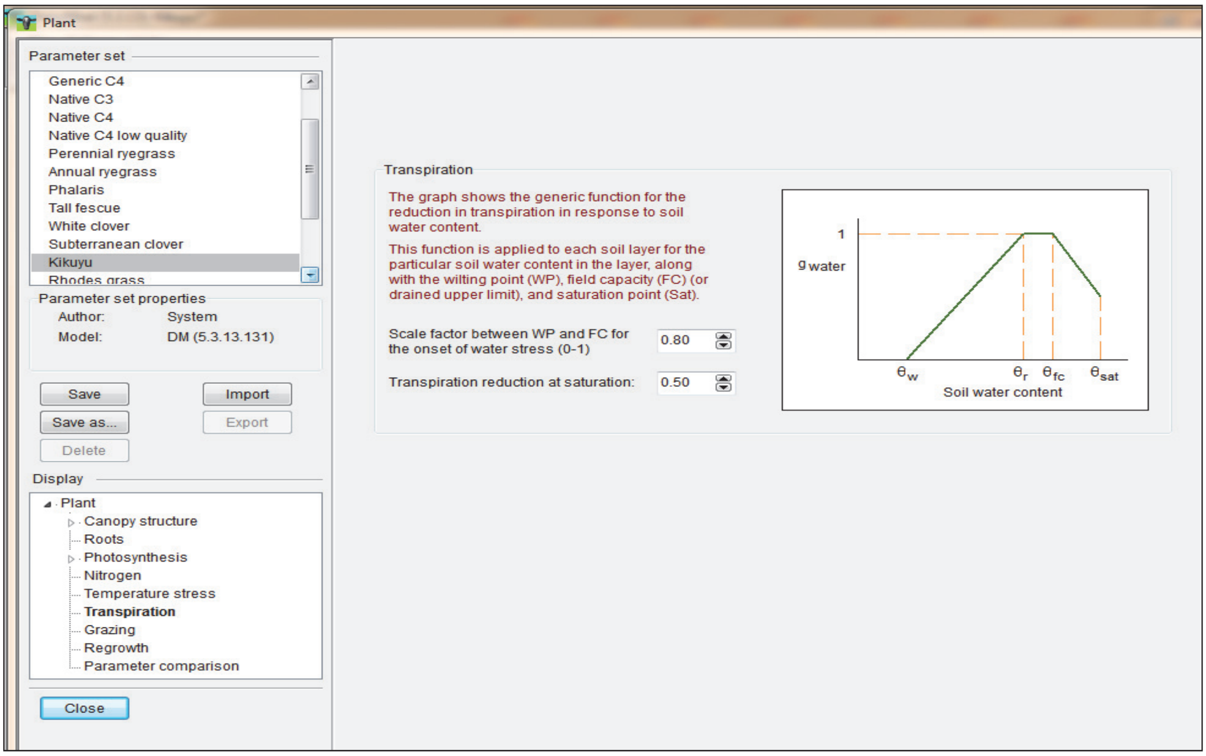


Figure 5.10 Transpiration input parameter set (DairyMod http://imj.com.au/dairymod/)

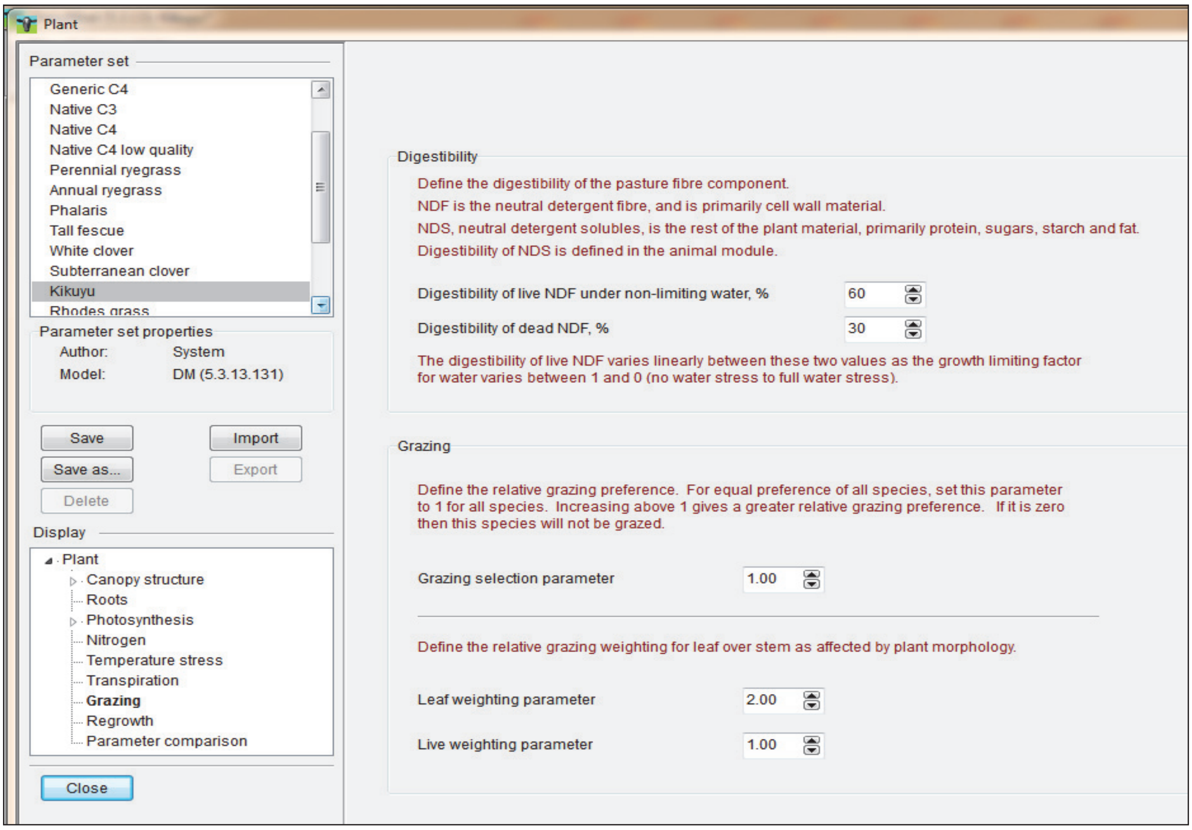


Figure 5.11 Grazing input parameter set (DairyMod http://imj.com.au/dairymod/)

h. *Regrowth* (Figure 5.12)

This parameter set includes:

- Regrowth characteristics
- Regrowth starting residual
- Climate

This parameter set provides the opportunity to change the initial dry weights of pasture in conjunction with the regrowth duration. All this date is integrated with the baseline climatic data of the growing pasture.

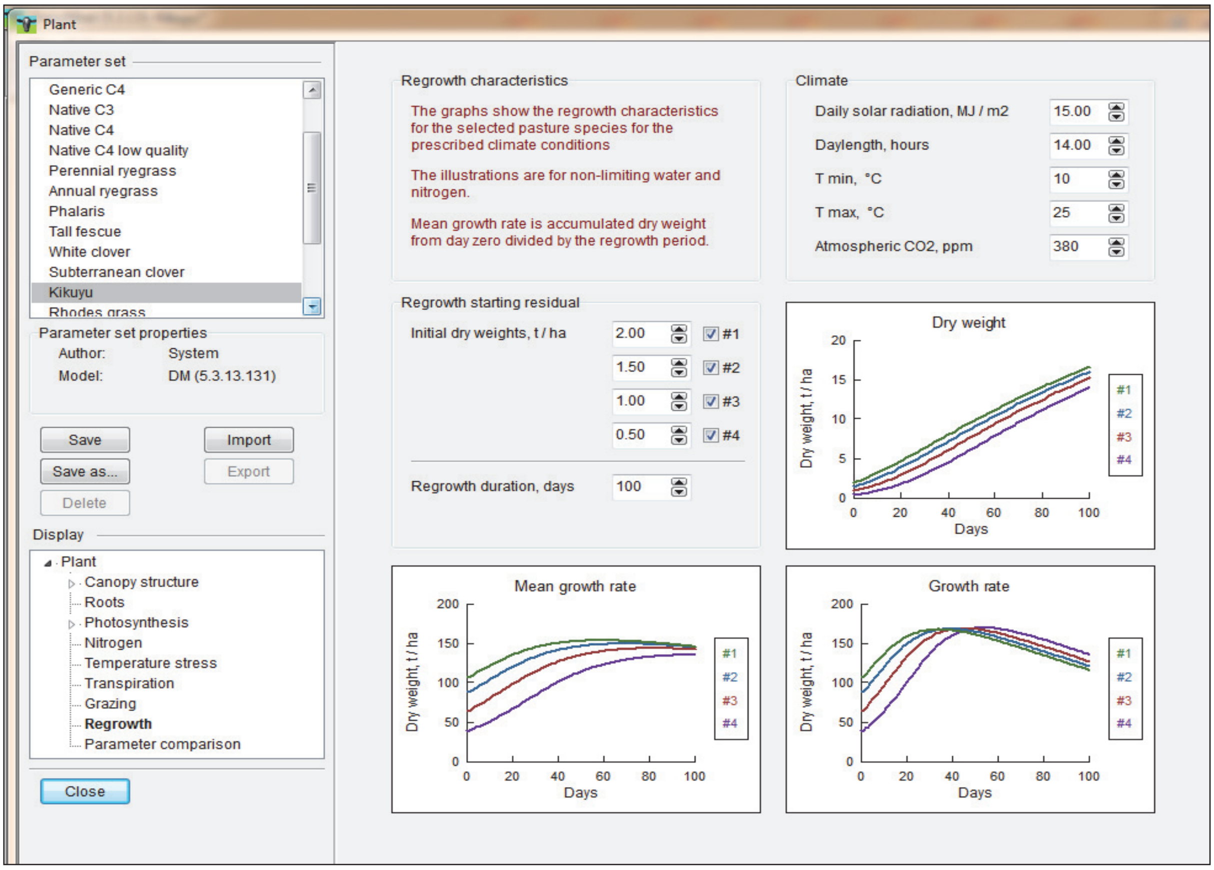


Figure 5.12 Regrowth input parameter set (DairyMod http://imj.com.au/dairymod/)

5.1.1.2 Crop

This part of the model makes provision for a winter or spring rotational crop. For the purpose of this study it has no relevance at this stage. It could however be an option when pastures are entirely removed and reseeded with a winter annual, as is the practice for the western Cape region with their overseeding practices.

5.1.1.3 Soil Water

Soil water is a major factor that drives these systems. The new soil water parameter sets are created by changing all the individual parameters of each factor that influences the soil water properties (Figure 5.13). These include:

- Soil physical parameters
- Runoff
- Evaporation
- Leaching

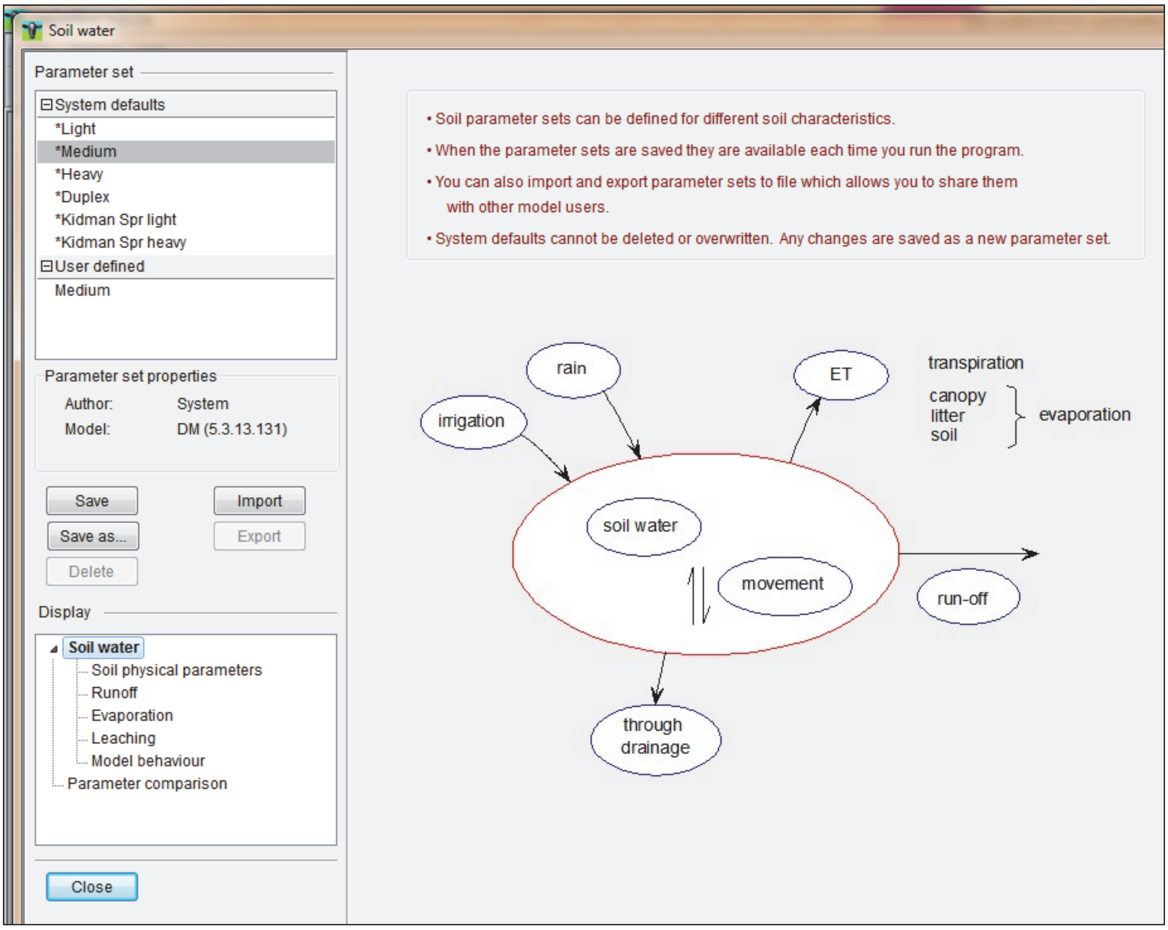


Figure 5.13 Soil water parameter sets for different soil characteristics (DairyMod http://imj.com.au/dairymod/)

a. *<u>Soil Physical properties</u>* <u>(Figure 5.14)</u>

This parameter set includes:

- Profile depths and characteristics
- Initial soil water content

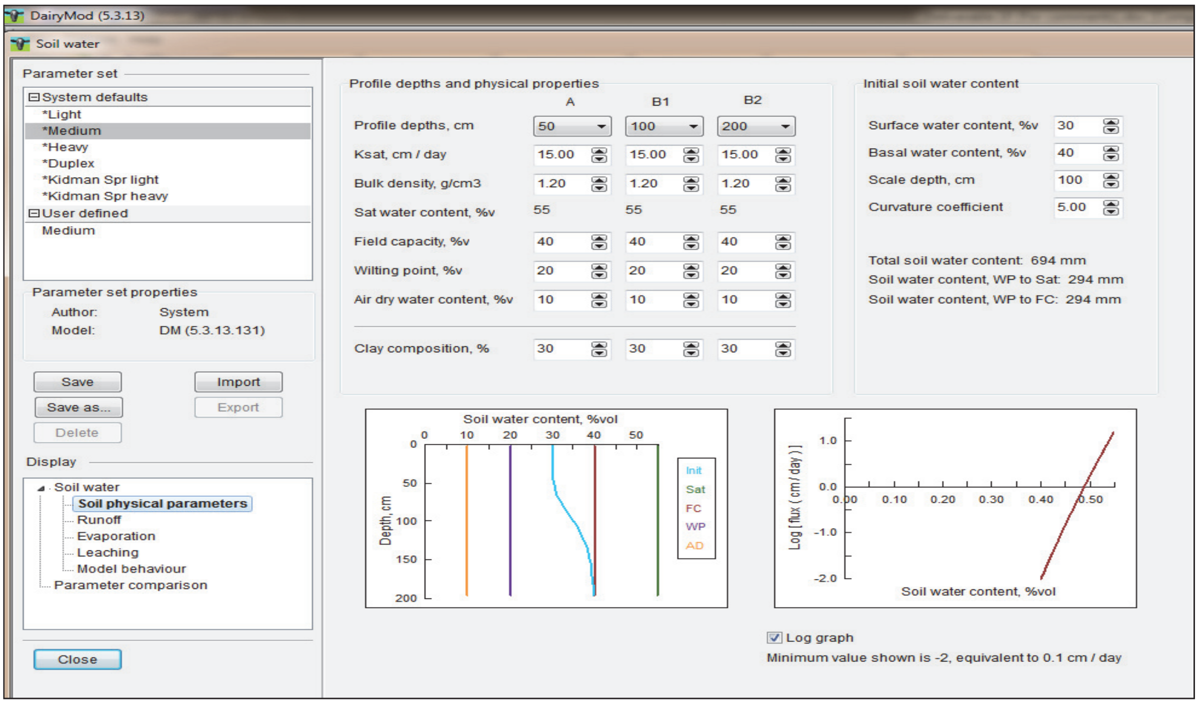


Figure 5.14 Soil physical properties input parameter set
(DairyMod http://imj.com.au/dairymod/)

b. *Runoff*

This parameter set includes:

- Runoff characteristics (Figure 5.15)

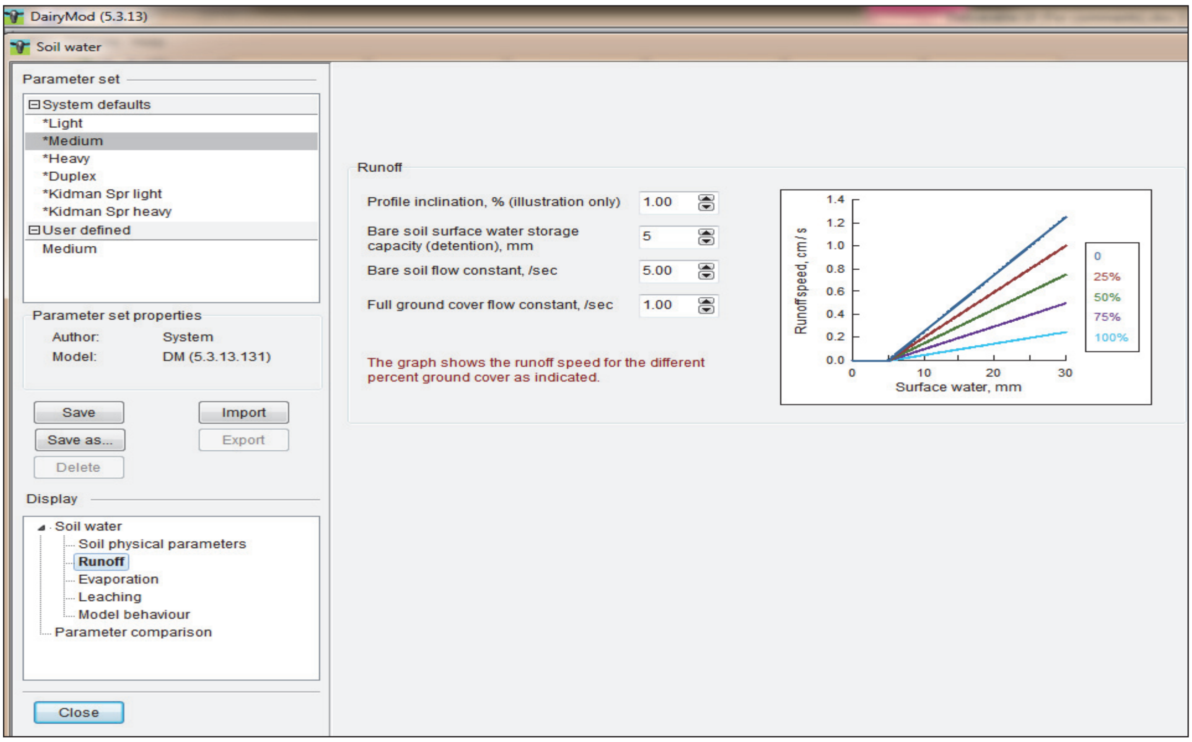


Figure 5.15 Runoff input parameter set (DairyMod http://imj.com.au/dairymod/)

c. *Evaporation parameters* (Figure 5.16)

This parameter set includes:

- Soil evaporation
- Litter
- Canopy and litter water interception

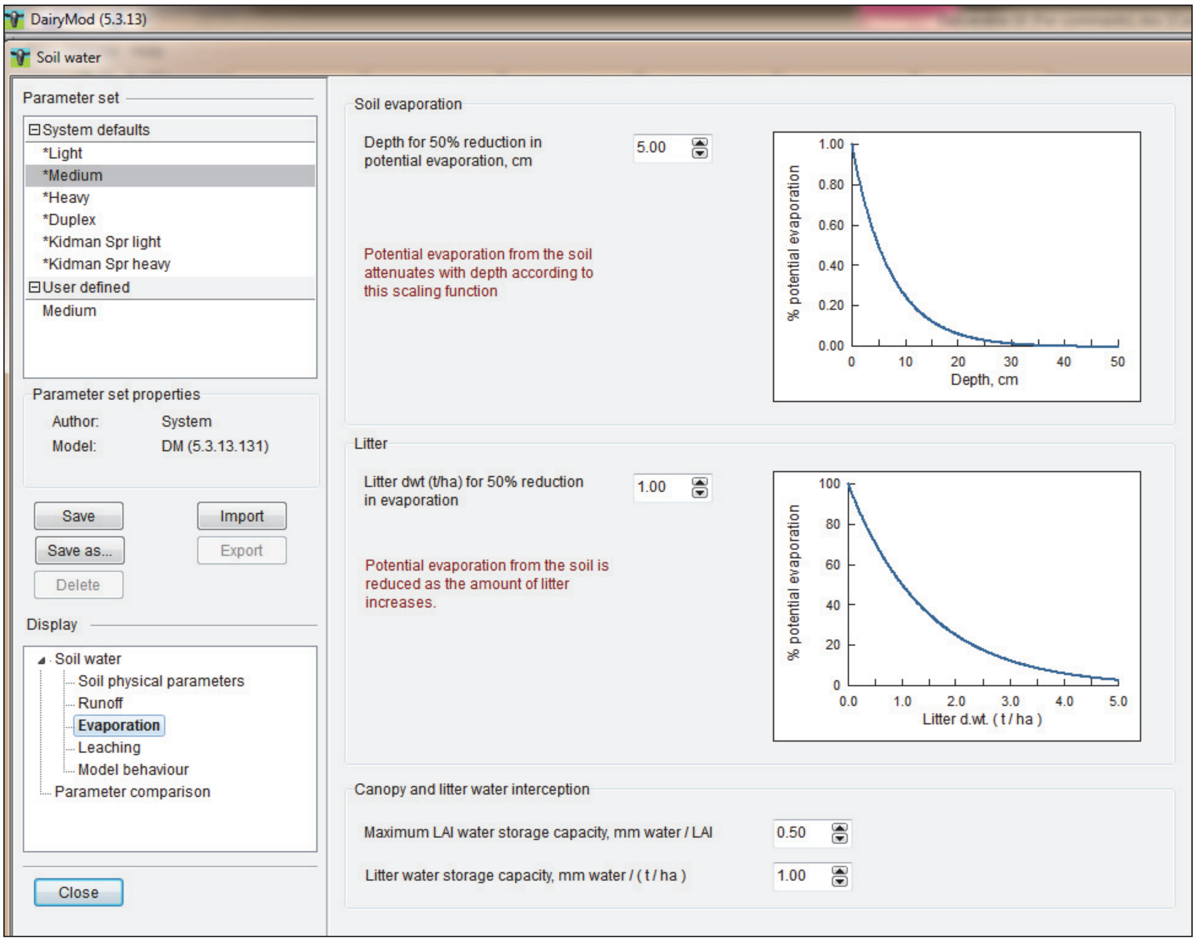


Figure 5.16 Evaporation input parameter set (DairyMod http://imj.com.au/dairymod/)

d. *Leaching* (Figure 5.17)

This parameter set only concentrates on the dispersion coefficient. The rationale is that the higher the dispersion coefficient the higher the leaching fraction.

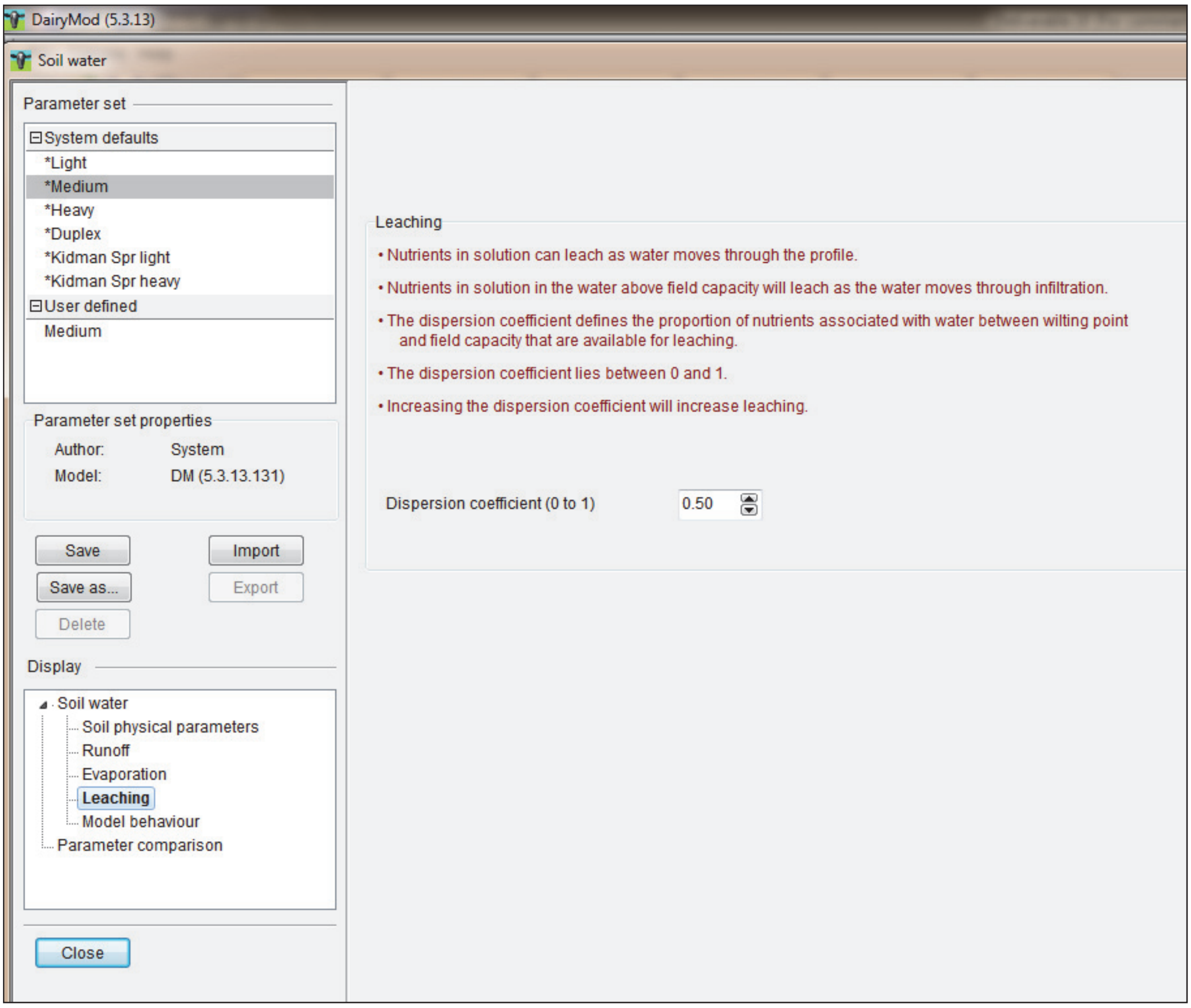


Figure 5.17 Evaporation input parameter set (DairyMod http://imj.com.au/dairymod/)

5.1.1.4 Soil

The new soil parameter sets are created by changing all the individual parameters of each factor that influences the soil water properties (Figure 5.18). These include:

- Initialization
- Organic matter dynamics
- Inorganic nutrient dynamics
- Inputs
- Water and Temperature

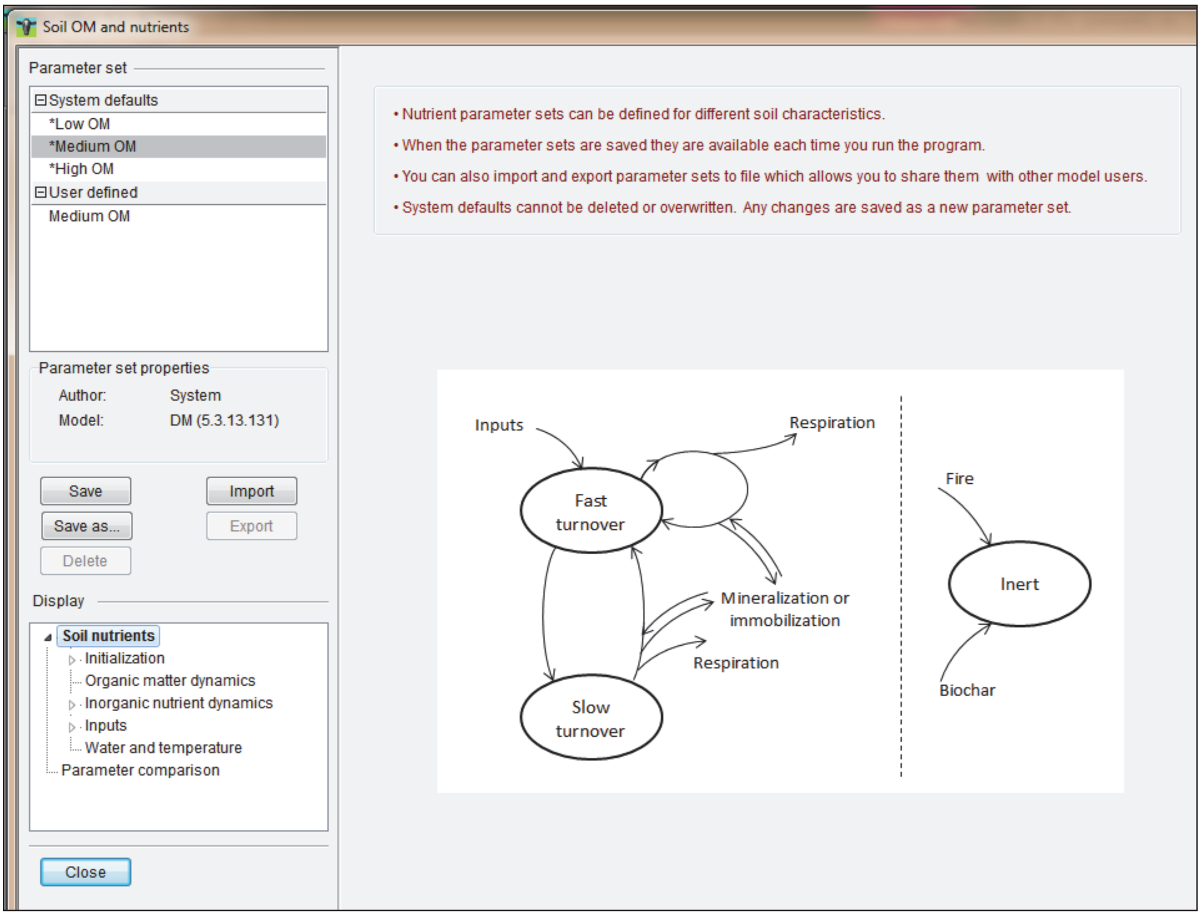


Figure 5.18 Soil parameter sets as affected by different soil characteristics (DairyMod http://imj.com.au/dairymod/)

a. <u>*Initialization* (Figure 5.19)</u>

This parameter set includes:

- Bulk density for illustration
- Clay fraction for illustration

b. <u>*Organic matter dynamics* (Figure 5.20)</u>

This parameter set includes:

- Organic matter dynamics parameters
- Display options of daily input and decay rate factors

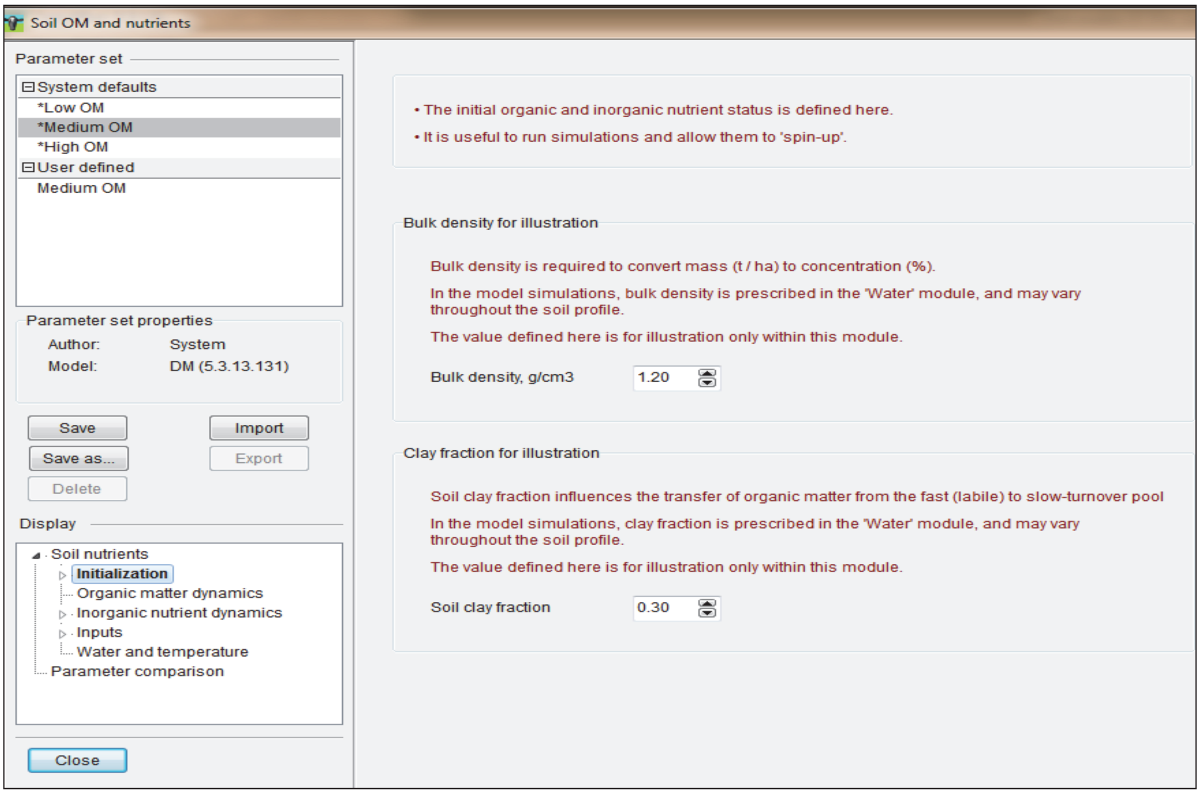


Figure 5.19 Initialization input parameter set (DairyMod http://imj.com.au/dairymod/)

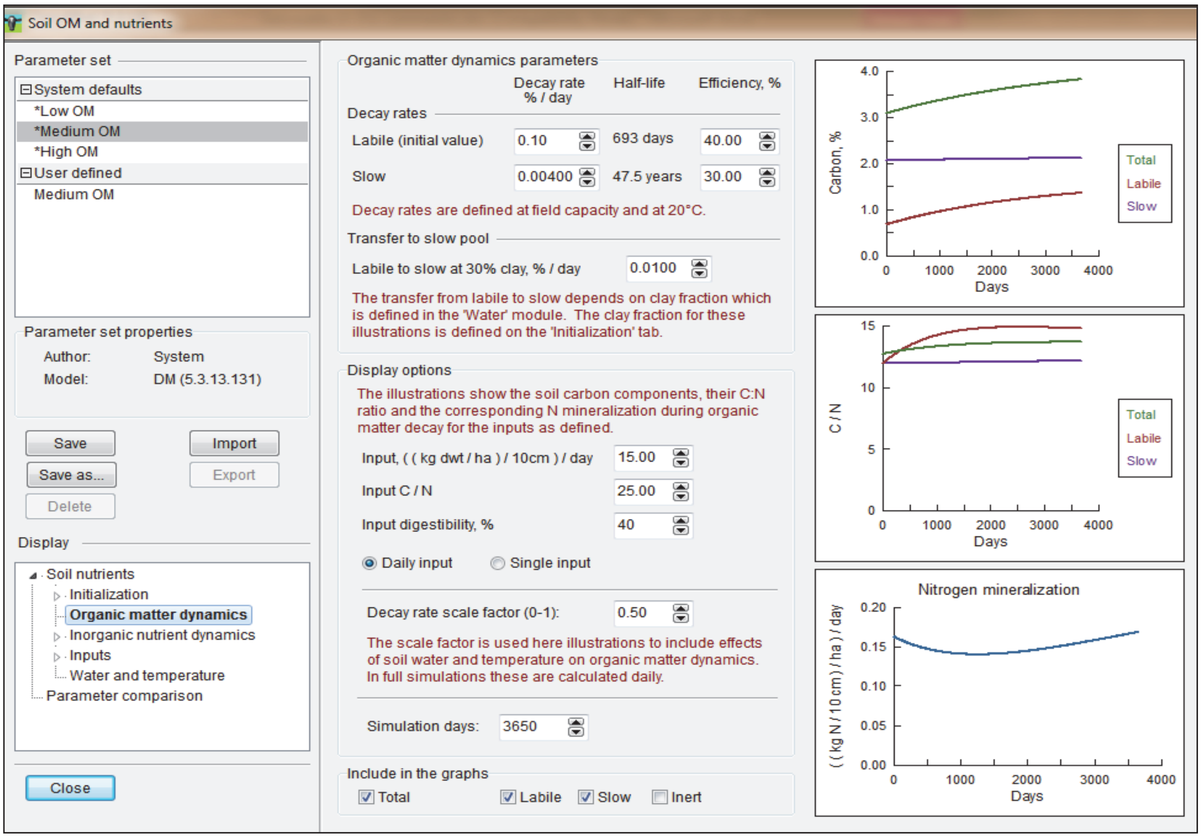


Figure 5.20 Organic matter input parameter set (DairyMod http://imj.com.au/dairymod/)

c. *Inorganic nutrient dynamics*

This parameter set does not provide an option at the moment to key in inputs. Since inorganic nutrient dynamics involves many processes of mineralization, or immobilization of organic matter, nitrification of ammonium as well as denitrification.

d. *Nutrient inputs*

This is normally maintained by fertilizer inputs, animal dung and urine as well as small amounts of atmospheric inputs and senescence of plant roots. The fertilizer component is addressesed in the management module.

e. *Water and temperature* (Figure 5.20)

This parameter set includes:

- Soil water effect
- Temperature effect

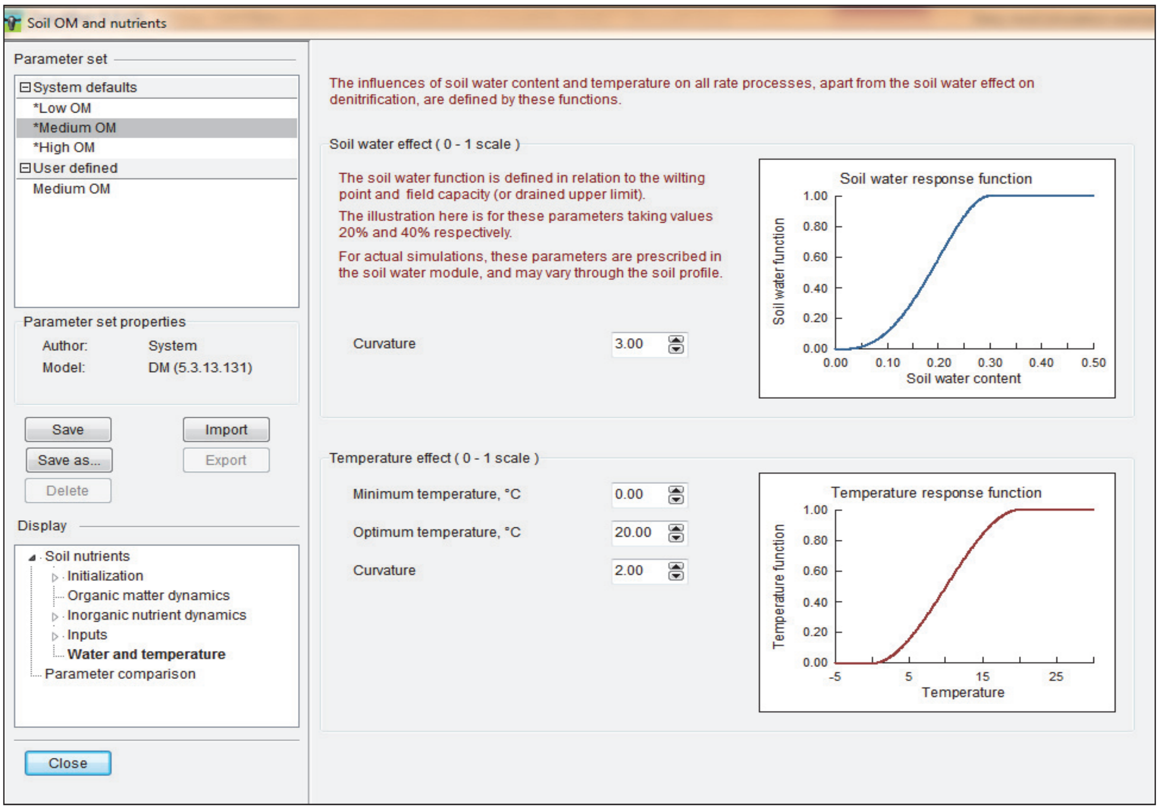


Figure 5.21 Water and temperature input parameter set (DairyMod http://imj.com.au/dairymod/)

5.1.2 Climate data

Dairy Mod has the function to import local weather data representing a particular region for which the simulation is to be run for (Figure 5.22). The model makes it easy to upload data from an excel spread sheet. It also provides the function to identify the different climatic input parameters in the spread sheet by selecting the parameter aligned in the programme dropdown menu.

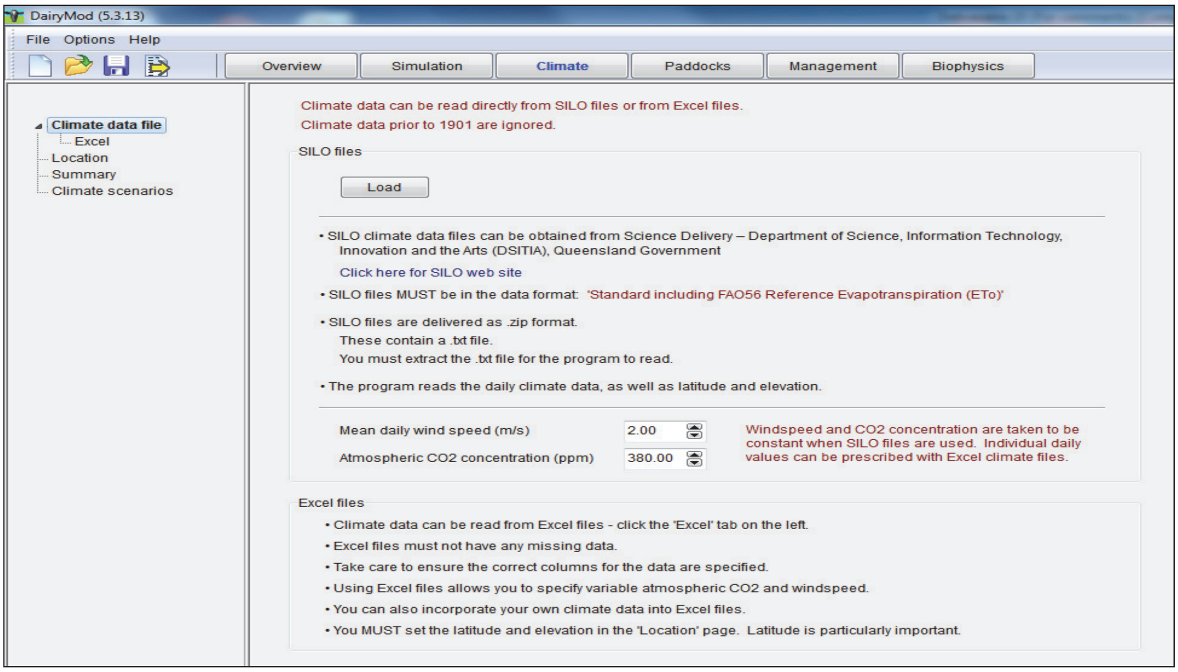


Figure 5.22 Climate file upload function (DairyMod http://imj.com.au/dairymod/)

This section also takes into account the global location (Figure 5.23) where the weather data is captured, and allows the user to change latitude and elevation, etc.

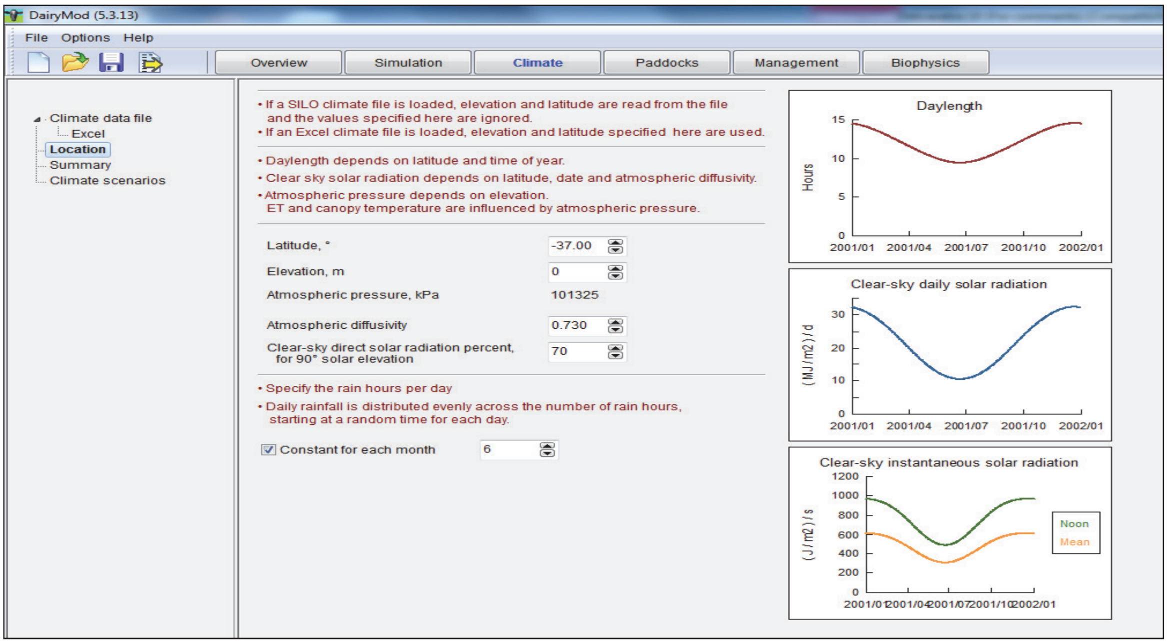


Figure 5.23 Global location parameters (DairyMod http://imj.com.au/dairymod/)

5.1.3 Management

Dairy Mod provides the option of changing various management factors such as:

- Livestock
- nutrient removal
- nitrogen fertilizer (Figure 5.24)
- Irrigation
- nitrification inhibition
- Fire

a. Nitrogen fertilizer

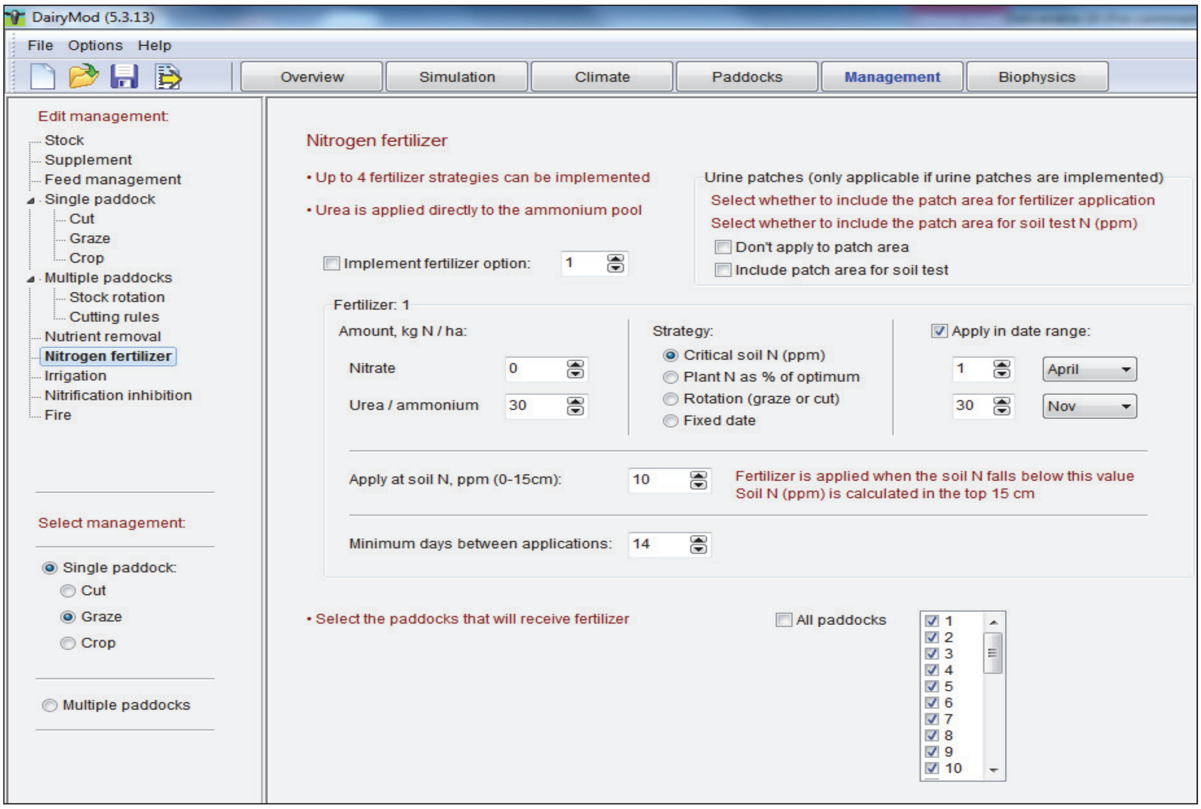


Figure 5.24 Nitrogen fertilizer input parameter set (DairyMod http://imj.com.au/dairymod/)

b. Paddock management

The option to simulate single paddock (Figure 5.25) or multiple paddocks (Figure 5.26) in the model exists too. This can further be linked to the defoliation function of cutting or grazing. With regards to grazing the stocking rate can be adjusted to simulate various particular scenarios.

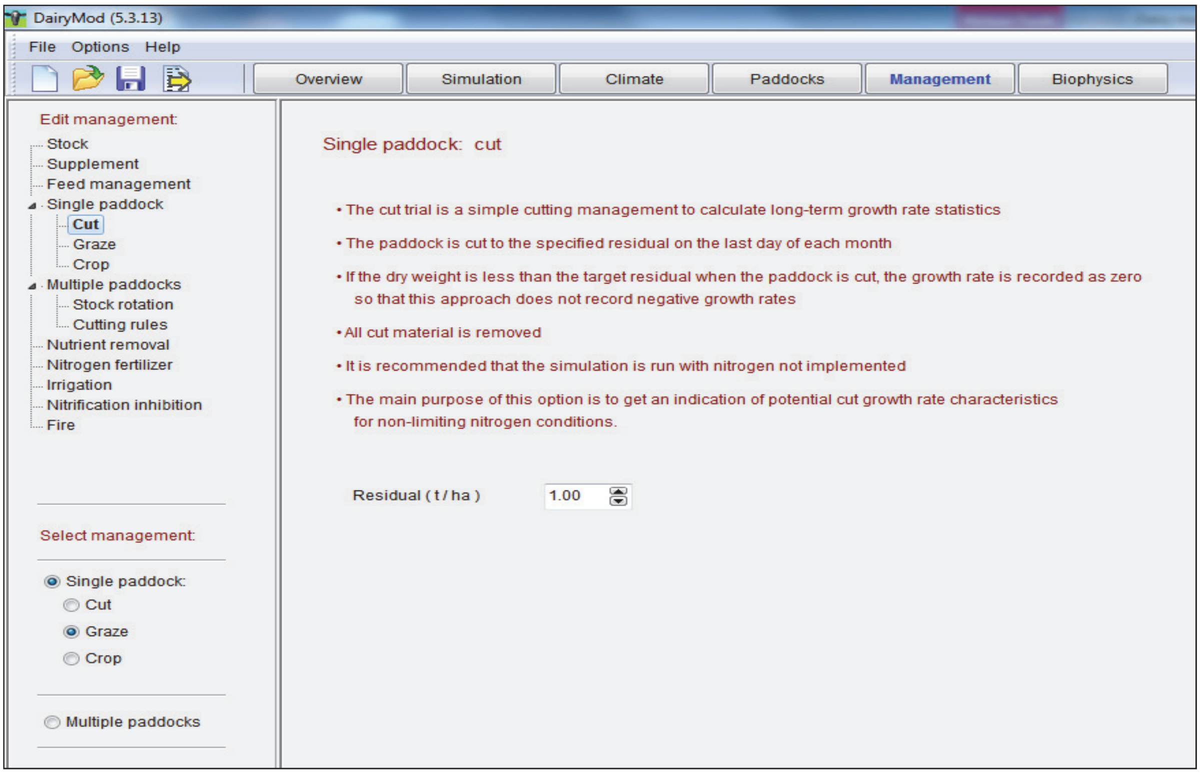


Figure 5.25 Single paddock input parameter set (DairyMod http://imj.com.au/dairymod/)

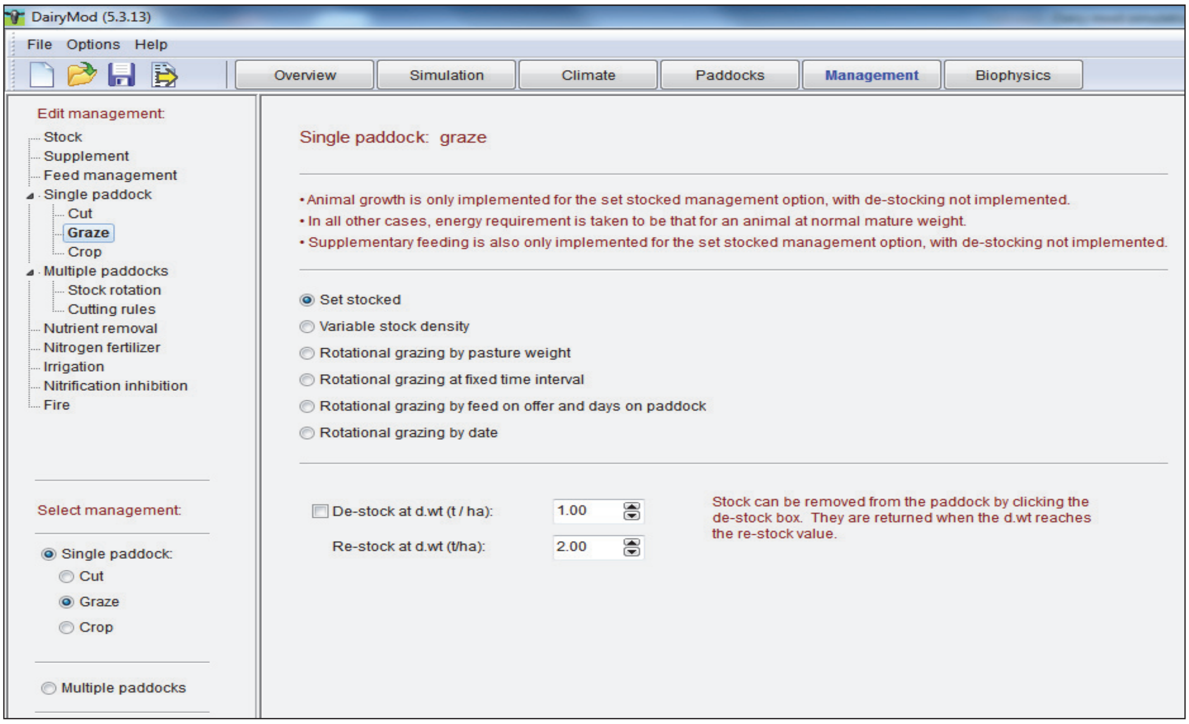


Figure 5.26 Multiple paddock input parameter set (DairyMod http://imj.com.au/dairymod/)

c. <u>Irrigation</u>

The irrigation input parameters (Figure 5.27) allows the simulations to include the farmers own irrigation system.

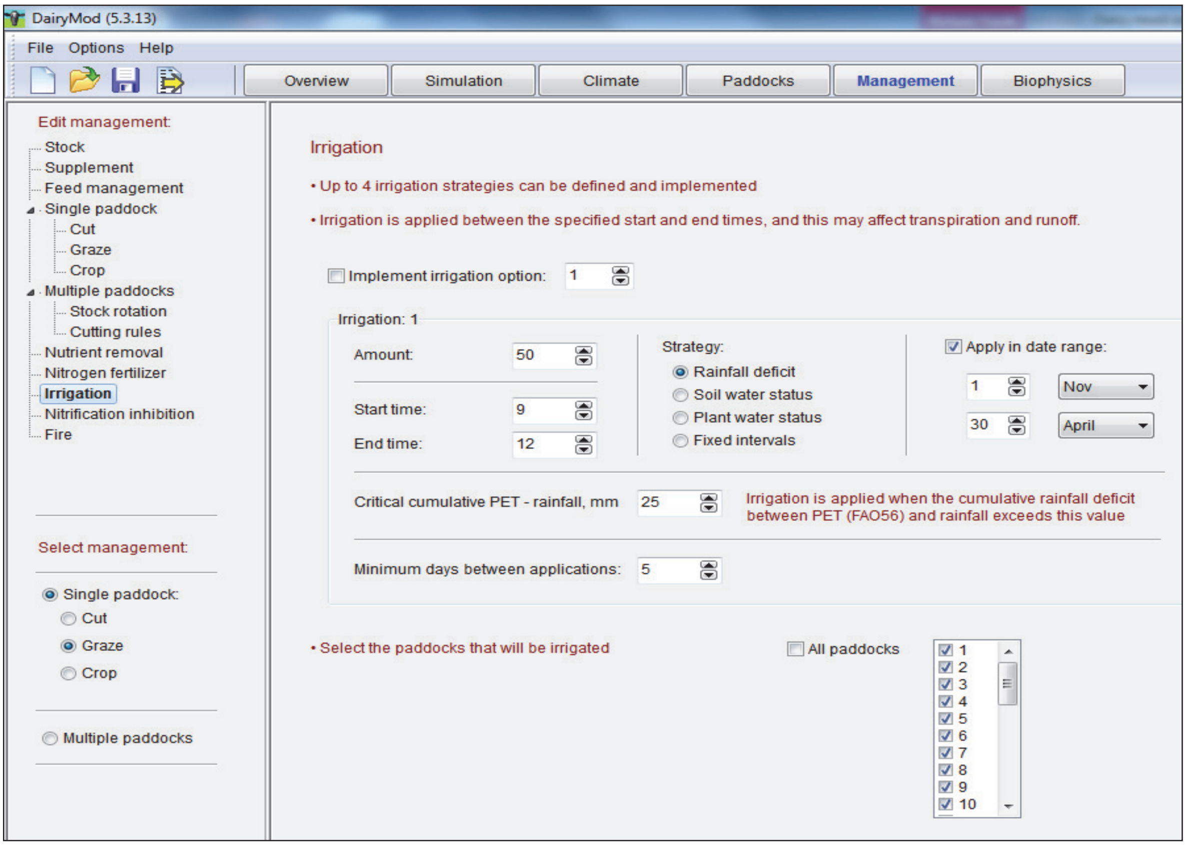


Figure 5.27 Irrigation input parameter set (DairyMod http://imj.com.au/dairymod/)

5.1.4 Paddocks

This component of the model provides the function of selecting the following input parameters (Figure 5.28):

- Different pasture species used in either the single paddock or multiple paddock grazing or cutting system. Various species defaults occur, and the option exists to alter the data according to local data collected for better representation of a particular farming system.
- Soil hydraulic properties
- Soil organic matter and nutrients

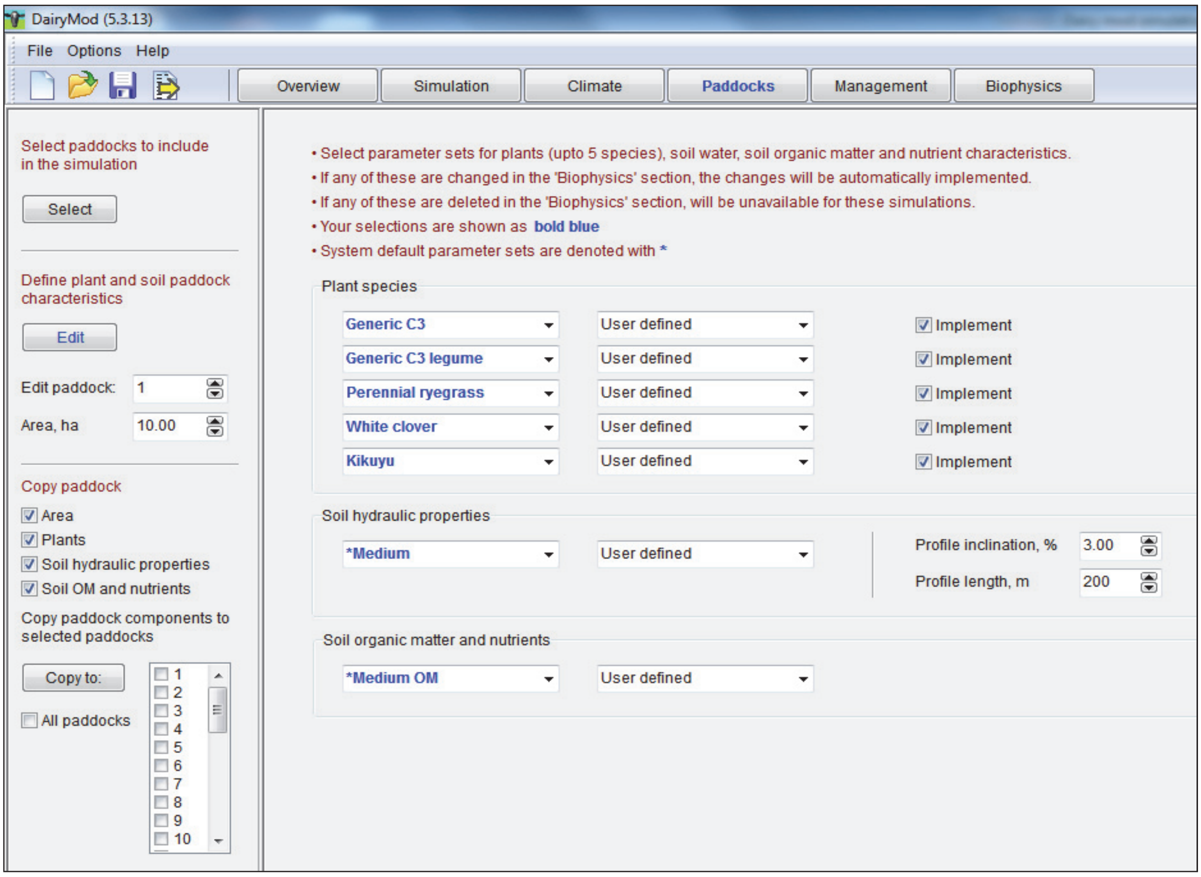


Figure 5.28 Plant species parameter set (DairyMod http://imj.com.au/dairymod/)

5.2 DAIRY MOD SIMULATIONS

The following data figures represent model simulations using input parameters collected at Hatfield Experimental farm. For illustration purposes, only one mono-specific pasture crop (lucerne) and one mixed pasture crop (tall fescue / white clover) is used.

Based on the research data and collected on-farm data the following simulations (Figure 5.29 – 5.36) were run for lucerne and tall fescue/white clover mixed pastures to predict the following production information: All data presented has been generated using DairyMod.

5.2.1 Lucerne

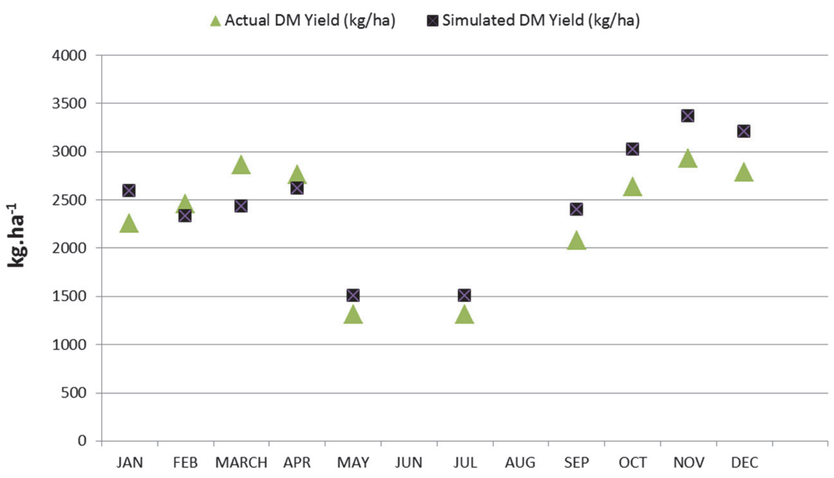


Figure 5.29 Simulated lucerne dry matter (DM) production using DairyMod

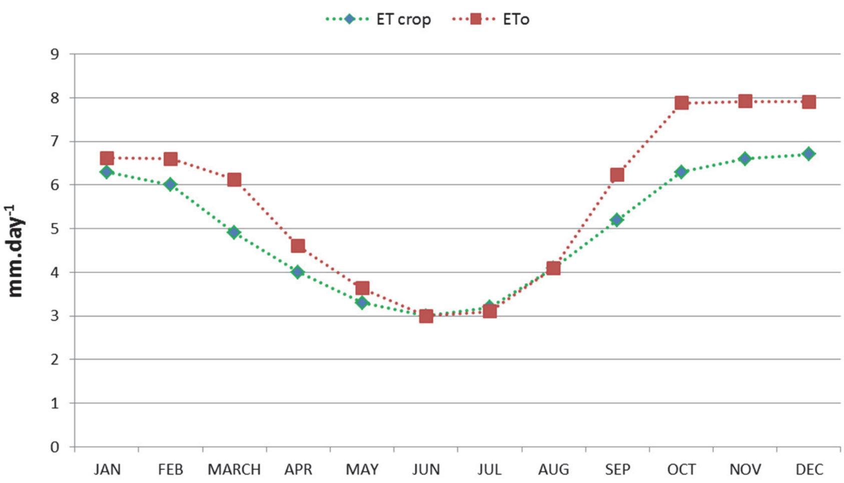


Figure 5.30 Simulated lucerne crop water requirements using DairyMod

5.2.1.1 Irrigation requirements

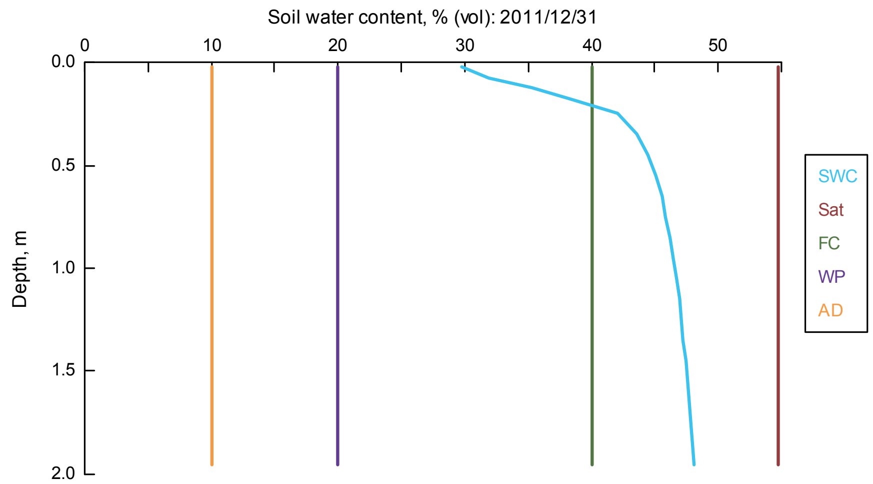


Figure 5.31 Soil water content requirements for lucerne pasture production in this region

Highest day peak growth rate was in May producing 80 kg / DM / ha / day (Figure 5.29) requiring 2.6 mm / day, however to account for evaporation and transpiration losses 3.5 mm / day (24.5 mm /week) of irrigation required.

Lowest day peak growth rate was in May producing 45 kg / DM / ha / day (Figure 5.29) requiring 3.6 mm / day, however to account for evaporation and transpiration losses 3.5 mm / day (24.5 mm /week) of irrigation required.

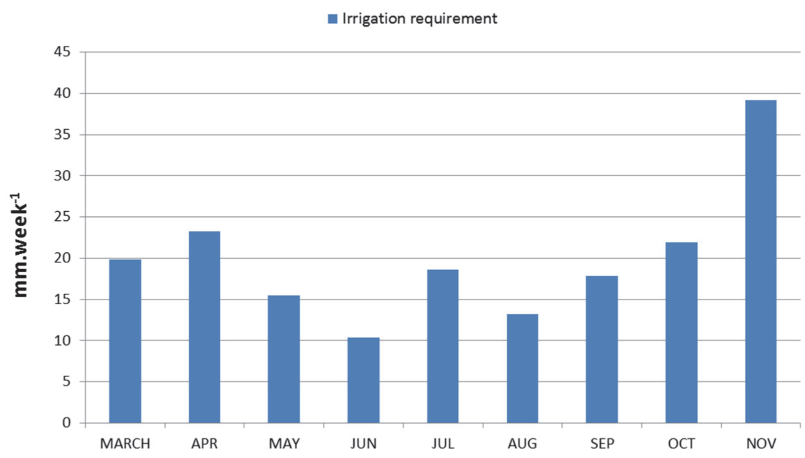


Figure 5.32 Simulated irrigation requirements for lucerne pasture using DairyMod

5.2.1 Tall fescue / White clover pasture

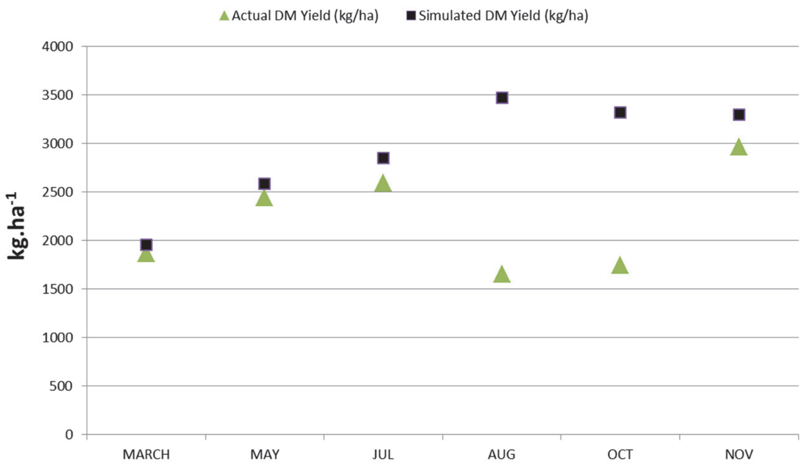


Figure 5.33 Simulated Tall fescue / white clover pasture dry matter (DM) production using DairyMod

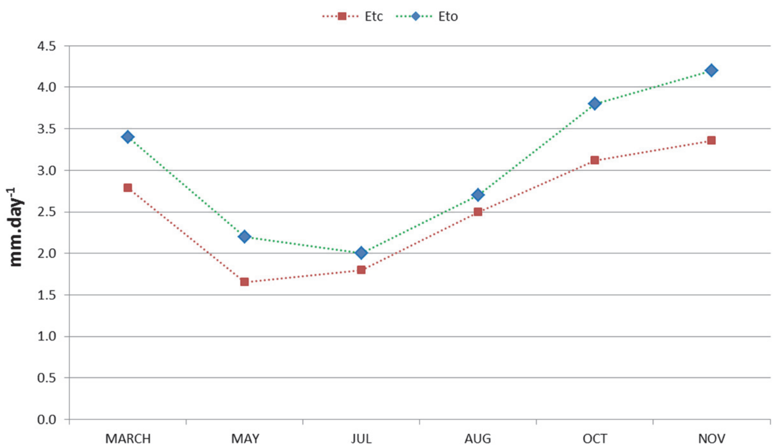


Figure 5.34 Simulated Tall fescue / white clover crop water requirements using DairyMod

5.2.1.1 Irrigation requirements

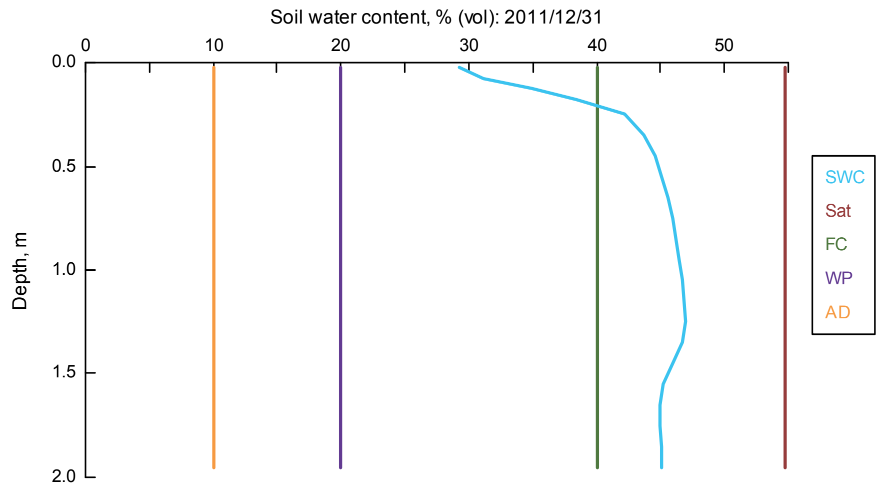


Figure 5.35 Soil water content requirements for Tall fescue / White clover pasture in this region

Highest day peak growth rate is in March producing 42 kg / DM / ha / day (Figure 5.33) requiring 3.5 mm / day, however to account for evaporation and transpiration losses in addition to potential rainfall, **3.5 mm / day (24.5 mm /week) of irrigation** required.

Lowest day peak growth rate is in February / September producing 5 kg / DM / ha / day (Figure 5.33) requiring 3.6 mm / day, however to account for evaporation and transpiration losses in addition to potential rainfall, **3.3 mm / day (23 mm /week)** of irrigation required.

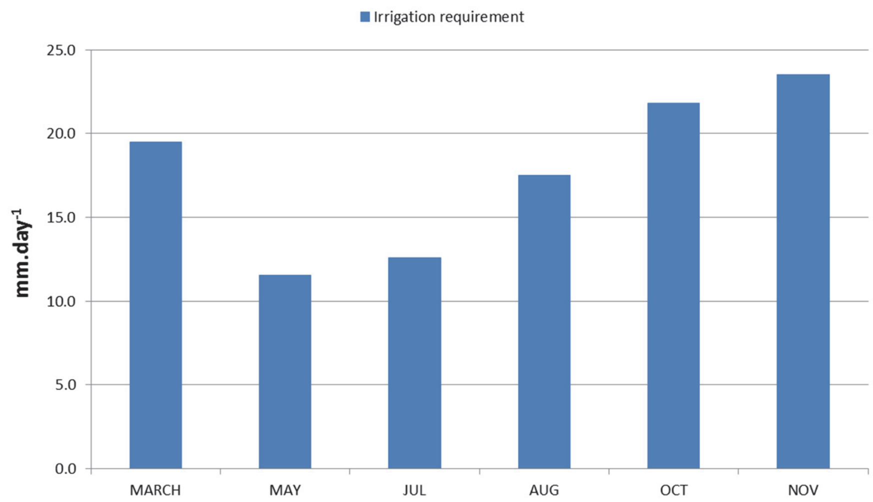


Figure 5.36 Simulated irrigation requirements for mixed Tall fescue / white clover pasture using DairyMod

5.3 SWB MODEL

By Melake Fessehazion, Omphile Sehoole, John Annandale and Wayne Truter

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

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

The model was parameterised and extensively tested for many crops (Annandale et al. 2000; Jovanovic et al. 1999; Geremew et al. 2008; Singles et al. 2010, Fessehazion 2012). To improve applicability for monospecific pastures various defoliation practices including fixed date, thermal time and accumulated forage biomass were included in the SWB model (Fessehazion 2012, Fessehazion et al. 2012; 2014 a,b).

In the Soil Unit of SWB, potential evapotranspiration is divided into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area. This represents the upper limits of evaporation and transpiration and these processes will only proceed at these rates if atmospheric demand is limiting. Supply of water to the soil surface or plant root system may, however, be limiting. This is simulated in the case of soil water evaporation, by relating evaporation rate to the water content of the surface soil layer. In the case of transpiration, a dimensionless solution to the water potential based water uptake equation is used. This procedure gives rise to a root density weighed average soil water potential, which characterizes the water supply capabilities of the soil-root system. This solution has been shown to work extremely well (Annandale et al. 2000). If actual transpiration is less than potential transpiration, the crop has undergone stress and leaf area expansion is reduced if the crop is still in the vegetative phase of growth. In other words, there is feedback between the crop and the soil in SWB.

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 the more mechanistic growth model negates the need to specify length of developmental stages as crop factors modelling approach to express crop development, which varies for different planting dates and regions (Olivier and Annandale 1998). Hence in the growth model, water-limited growth is calculated using parameters that directly limit biomass accumulation including a crop stress index and leaf water potential (Annandale et al. 2000). In addition, the growth model enables an accurate description of deficit irrigation strategies, where water use is supply limited (Annandale et al. 1999).

Soil water balance model can estimate real-time crop water requirements and recommend the irrigation amount and date, based on the current crop water usage and set user preferences. If farmers do not have access to irrigation monitoring tools, SWB can be used to develop site-specific irrigation calendars. The calendar, which recommends irrigation dates and amounts, can be printed out and used as a guide to manage irrigations. Calendar recommendations must be corrected by subtracting rainfall from recommended irrigation amounts if applicable (Fessehazion et al. 2012; 2014 a,b)

The model has three versions: 1) Irrigator or farmer version used by farmers to develop irrigation calendars, 2) Consultant version is applicable for those who want to use their own user defined inputs (e.g. different soils in different layers) and/or simulate and display crop growth and soil water balance components, and 3) Researcher version used by researchers for complex simulations pertaining to specific research questions. In this report the simple irrigator vision is used to develop irrigation calendars (Fessehazion et al. 2012; 2014 a,b).

The irrigation calendar screen of the irrigator version of the SWB model includes, insert new calendar, edit calendar, generate calendar, view calendar and delete calendar (Figure 5.38).

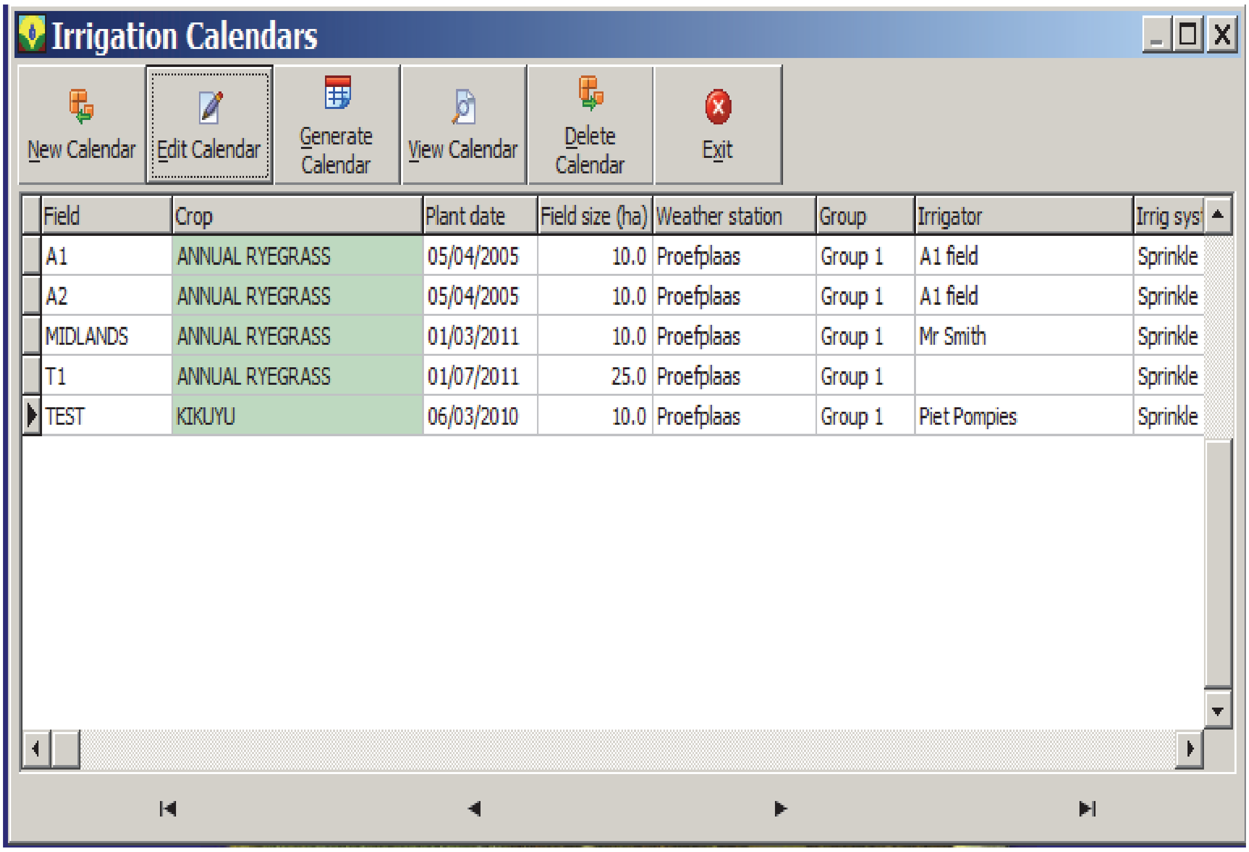


Figure 5.37 SWB model opening screen showing user-friendly interface

5.3.1 Input

The model can be used by farmers or consultants to develop their own calendars with relatively few and simple inputs. The model requires input for crop, weather, soil and irrigation management. The minimum required inputs presented in Figure 5.39 are discussed briefly.

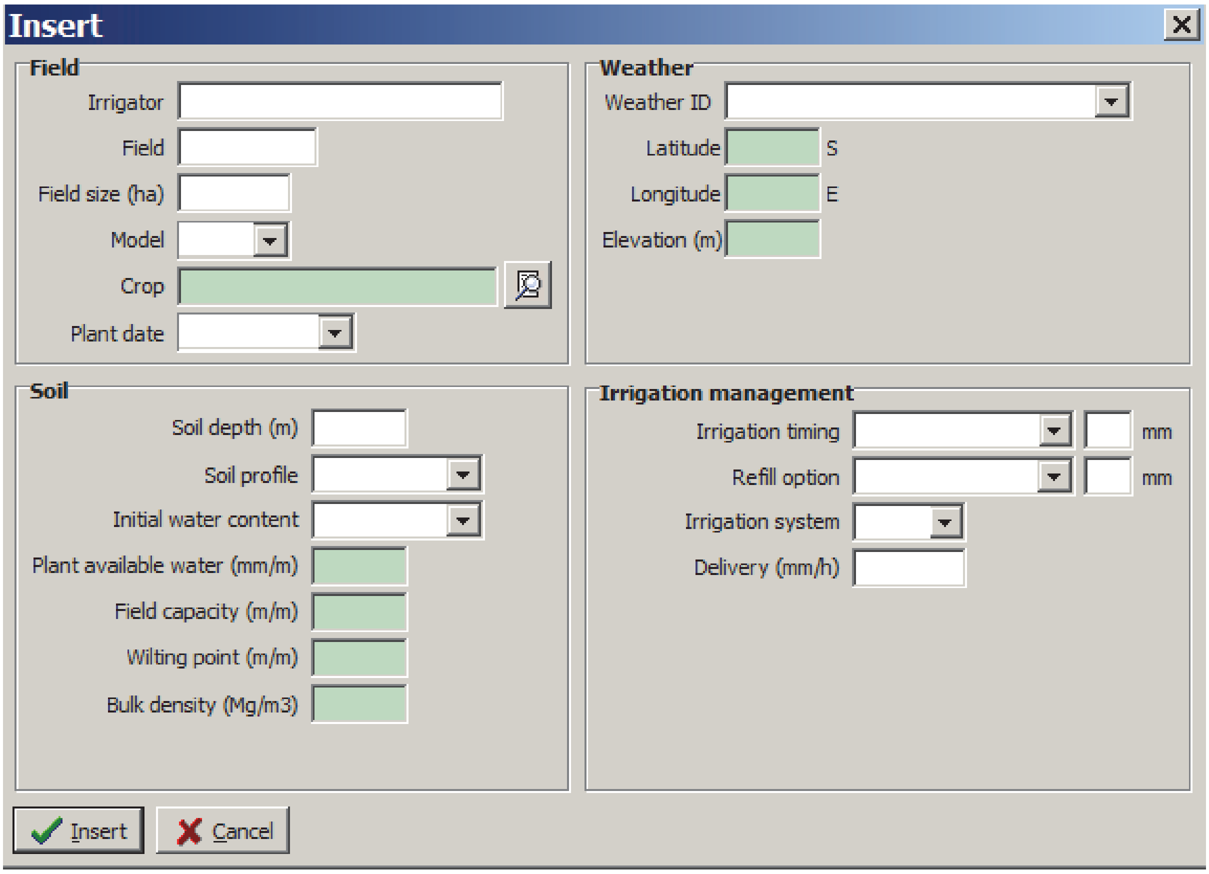


Figure 5.38 Input screen of the SWB irrigator version model

5.3.2 Field/Crop input

Two types of crop models can be selected in the Field form. The Crop growth model is based on the calculation of dry matter partitioning to plant organs and leaf area. Crop specific input parameter data sets for the mechanistic growth model or FAO crop coefficient model are available in the model. Depending on circumstances, calendars for a single pasture can be easily developed with either model. If crop growth model parameters are not available for a specific crop, the FAO model, based on FAO Kcb basal crop coefficients, may be selected. The model does not simulate growth and water use for mixed pastures. However, for ryegrass dominated pastures, similar water use can be expected to ryegrass, because the canopy cover is similar.

5.3.3 Weather input

The location and long-term weather data including minimum and maximum or mean temperatures from a nearby weather station are the minimum inputs required. The model will then use daily average weather data for recommending irrigations. If available, using other weather input parameters like solar radiation, relative humidity or vapour pressure deficit and wind speed will improve accuracy.

5.3.4 Soil input

The model requires soil input parameters including soil depth, soil type and initial soil water content. Soil water content at field capacity and wilting point and bulk density can be estimated from soil texture.

5.3.4.1 Soil depth

Depth of soil can be determined by digging profile holes at representative sites in the field.

5.3.4.2 Soil type

Soil textural class or type can be determined by taking soil samples and conducting textural analyses in any soil laboratory. In the irrigator version of SWB, soils can be grouped as very light (coarse sand), light (sandy), medium (sandy clay loam) or heavy (clay) soils.

5.3.4.3 Initial water content

Initial soil water content can either be set to dry (wilting point – WP), medium (moist) or wet (field capacity – FC).

5.3.5 Irrigation management

Irrigation management includes irrigation system, delivery rate, and irrigation timing and refill options.

5.3.5.1 Irrigation timing

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), often follow fixed time schedules (e.g. irrigate every 7 days). b) Farmers use 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).

5.3.5.2 Refill option

Several site-specific considerations need to be taken into account when selecting a sensible refill strategy. Such as: How fast is my crop using water? What are the chances of getting rain? What is a reasonable amount to expect? Are there salts in the profile that need to be leached? For refill options, farmers can irrigate to the full point (field capacity), follow a form of deficit irrigation (leave room for rain) or apply water exceeding the storage capacity for leaching salts.

5.3.5.3 Irrigation system

A range of irrigation systems can be selected including furrow, sprinkler, pivot, micro and drip.

5.3.5.4 Delivery rate

This depends on the irrigation system:

Sprinkler: mm per hour

Pivot: application rate (at 100%) in mm and hours required for one revolution (at 100%)

5.3.6 Run options (Generate calendars)

In order to run the model, the start and end date of the simulation or the intended duration of the irrigation calendars to be developed needs to be specified (Figure 5.40).

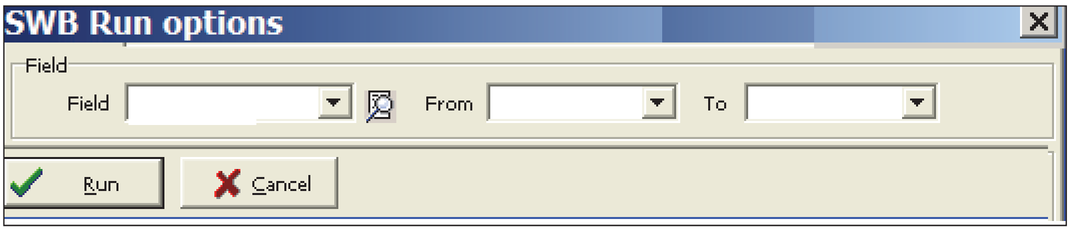


Figure 5.39 SWB run options screen of the irrigator version

5.3.7 Output

In Figures 5.2 a-d , model simulation output is displayed as lines, whilst measured data are presented in symbols given with error bars if available. Simulation generally agreed well with the measured data for all parameters during model calibration (Figure 5.41).

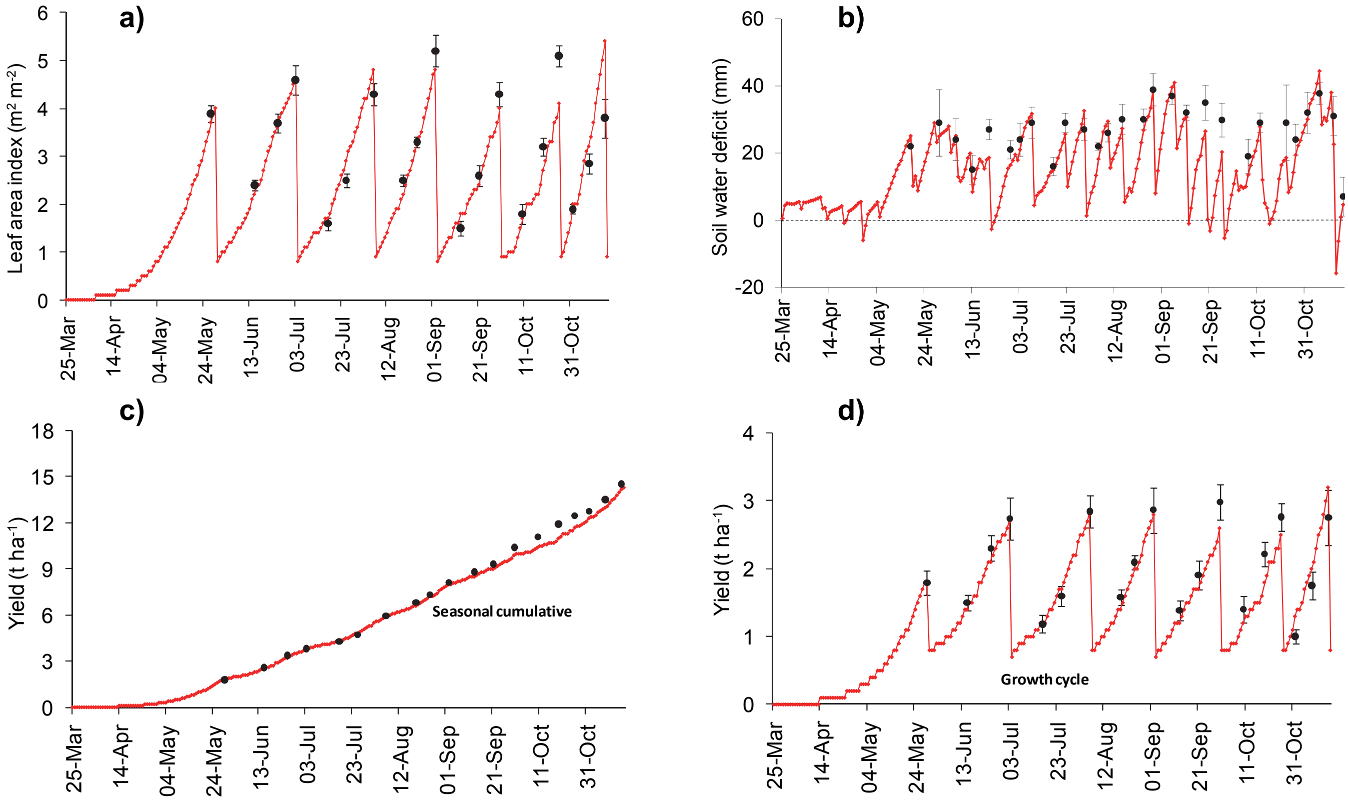


Figure 5.40 Simulated (lines) and measured data (symbols) of above ground dry matter for a) growth cycles and b) from whole season, c) leaf area index and d) soil water deficit to field capacity for model calibration of lucerne at Hatfield during the 2014-2015 growing season (Vertical bars are the standard deviation of measured data)

5.3.8 Irrigation recommendations

The recommendation table includes details of the irrigator, crop type, farm location, planting date, weather station, irrigation system and irrigation management (timing and refill options) used (Figure 5.41). The table has the following four columns:

- A column when the pasture should be irrigated 'date and day'
- A column of recommended water requirement in mm.
- A column to enter rain since previous irrigation in mm
- A column to calculate recommended irrigation amount by subtracting rain (if more than 3 mm) from water requirement
- A column to write comments

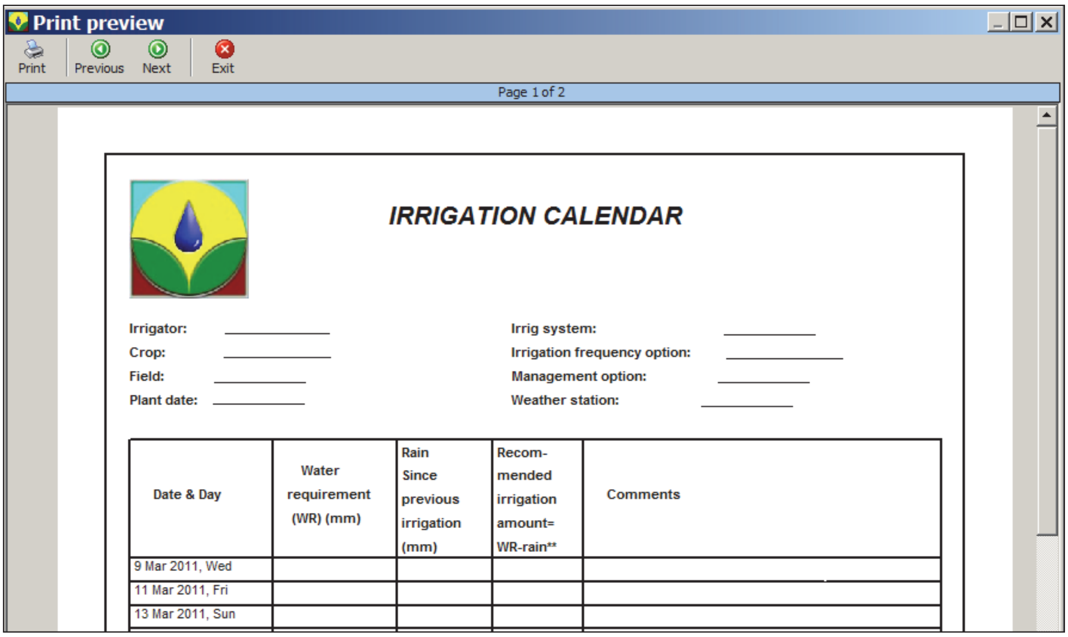


Figure 5.41 Irrigation calendar recommendation output

CHAPTER 6 – POTENTIAL OF DETERMINING WATER USE OF PASTURES USING REMOTE SENSING

By Melake Fessehazion, Wayne Truter, Caren Jarmein, Mpendulo Dlamini, David Taverna-Turisan, Ernesto Bastidas-Obando, Michael van der Laan, John Annandale and Colin Everson

6.1 RESEARCH OBJECTIVES

- To test remote sensing technology for a possible future use for irrigation management of pastures.
- To measure water use of selected irrigated pastures (subtropical grass/temperate grass mixture, temperate grass/temperate legume mixtures and pure lucerne stands) at representative sites of the major irrigated pasture growing areas.
- To generate information on growth analysis, crop model parameters and water balance studies for selected irrigated pastures in the major growing regions (winter and summer rainfall areas).

6.2 APPROACHES

Irrigation recommendations are typically developed from field experiments conducted for a 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. 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. 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 farmers to select best management options. 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 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 use efficiency and determine site specific irrigation requirements and calendars.

Currently, satellite-based remote sensing (SEBAL) is showing promising results in estimating irrigation requirements of fruit trees in the Western Cape and sugarcane in Mpumalanga. In the near future, this technology could become a more affordable tool for managing the irrigation of pastures. This study will take the opportunity of acquiring data collected by an on-going remote sensing satellite-based crop water use measurement project funded by the WRC (K5/2079/4). The accuracy of the technology for pasture management will hereby be assessed. This can therefore inform any potential future use of this technology for real time irrigation scheduling for pasture management.

6.3 OVERVIEW OF MODELS

In the last five decades, several irrigation and N 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. Various computer models, which integrate the soil, plant and atmospheric approaches by estimating soil water and nutrient balance components, have been developed for improving irrigation scheduling (Hillel 1990; Allen et al. 2011). The most common and potential models to be used in the project including SWB and SEBAL are reviewed.

6.3.1 SEBAL model

The Surface Energy balance algorithm for Land (SEBAL model) was used to model evapotranspiration and biomass production and estimate evapotranspiration deficit and biomass water use efficiency.

6.3.1.1 SEBAL description

SEBAL is a model which uses the energy balance equation. The simplified energy balance model uses a combination of earth observations to estimate ET. It is based on the actual intake of carbon dioxide and the evaporation of water from plants. Use of complex algorithms using radiation and temperature data improves accuracy of the energy balance (Ramesh 2008). According to Bastiaanssen et al. (2000) SEBAL gives an indirect measurement of ET. Equations are used in a strict hierarchical sequence to convert the spectral radiance measured by satellites into actual ET estimates (Bastiaanssen and Bos 1999). This is a cheaper way of measuring ET as compared to point measurements because the tools used in those methods are expensive and SEBAL is now an operational tool for evaluating and monitoring of irrigation and drainage systems (Bastiaanssen and Bos 1999).

Evapotranspiration is related to the surface energy balance equation which is:

$$\boldsymbol{Rn} = \boldsymbol{G} + \boldsymbol{H} + \boldsymbol{LE} \quad \textbf{(6.1)}$$

where **Rn** = the net radiation;
G = the soil heat flux;
H = the sensible heat flux; and
LE = the latent heat flux associated with evapotranspiration.

Equation (3.1) can be rewritten by taking into consideration the evaporative fraction (EF) and net available energy (Rn – G).

$$\boldsymbol{LE} = \boldsymbol{EF}(\boldsymbol{Rn} - \boldsymbol{G}) \quad \textbf{(6.2)}$$

Where

$$EF = LE/(Rn - G) = LE/(LE + H) \quad \textbf{(6.3)}$$

The net available energy (Rn−G) in Eq. (3.2) may have different timescales, from instantaneous (e.g. during a satellite overpass) to daily integrated values, or to periods elapsing between consecutive satellite measurements. Depending on the timescale chosen, different time integrations of (Rn−G) need to be obtained. In SEBAL, the assumption is that the evaporative fraction (EF) remains unchanged during daytime hours. In actual fact EF, Rn and G should be known. The incoming solar radiation (ISR) is measured directly using pyranometers (Shuttleworth et al. 1989; Brutsaert and Sugita 1992; Nicols and Cuenca 1993; Kustas et al. 1994; Crago 1996; Franks and Beven 1997; Farah 2001).

6.3.1.2 Satellite images acquired and used

SEBAL requires information captured in the visible, near-infrared and thermal infrared range of the electromagnetic spectrum. A combination of Disaster Monitoring Constellation (DMC) sensor data and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data was used to ensure spatial data provision in an operational mode (Jarmain 2014).

The DMC sensor was programmed to acquire two scenes (images) over the study area per month for the period 28 September 2012 to 30May 2013 November 2013 and an example of the coverage of one such image is shown in Figure 1. The DMC sensor acquires high resolution data (30 m x 30 m) in three bands – in the visual (green, red) and near-infrared ranges. It does not acquire thermal information required for the SEBAL modelling. This information (land surface temperature maps) is obtained from the MODIS satellite at a coarse (1 km) resolution, which is re-sampled to 30 m resolution (Jarmain 2013).

For the land surface thermal data from the VIIRS sensor is used. The VIIRS sensor provides thermal information with a spatial resolution of 375 m and 750 m, where MODIS provides data at a spatial resolution of 1 000 m. Both sensors have a daily revisit time. The overpass time of VIIRS is very similar to the overpass time of the Aqua sensor on the MODIS satellite, hence the data from the two sensors can be compared to investigate the impact of the higher resolution thermal information on the SEBAL outputs (Jarmain 2013).

It is expected that the higher resolution VIIRS data used in this part of the project will reduce the impact of neighbouring pixels and hence in future the land surface temperature captured by VIIRS (spatial resolution of 375 m) was used in this part of the project. The VIIRS data acquisition has been automatized. The data is first resampled to 300 m and then it is downscaled to 30 m using the sharpening tool developed by WaterWatch (Jarmain 2013).

6.3.2 Output parameters

Model parameters including soil, weather, pasture and management parameters collected from field experiments as inputs to run the selected models. After successful calibration and validation, the following parameters are simulated using the above reviewed models: actual evapotranspiration (mm/week).

For users to evaluate the spatial datasets provided through this part of the project, a website (GrainLook.co.za) was developed. The website was launched in the beginning of October 2012 and an example of the data output is shown in Figure 6.1.

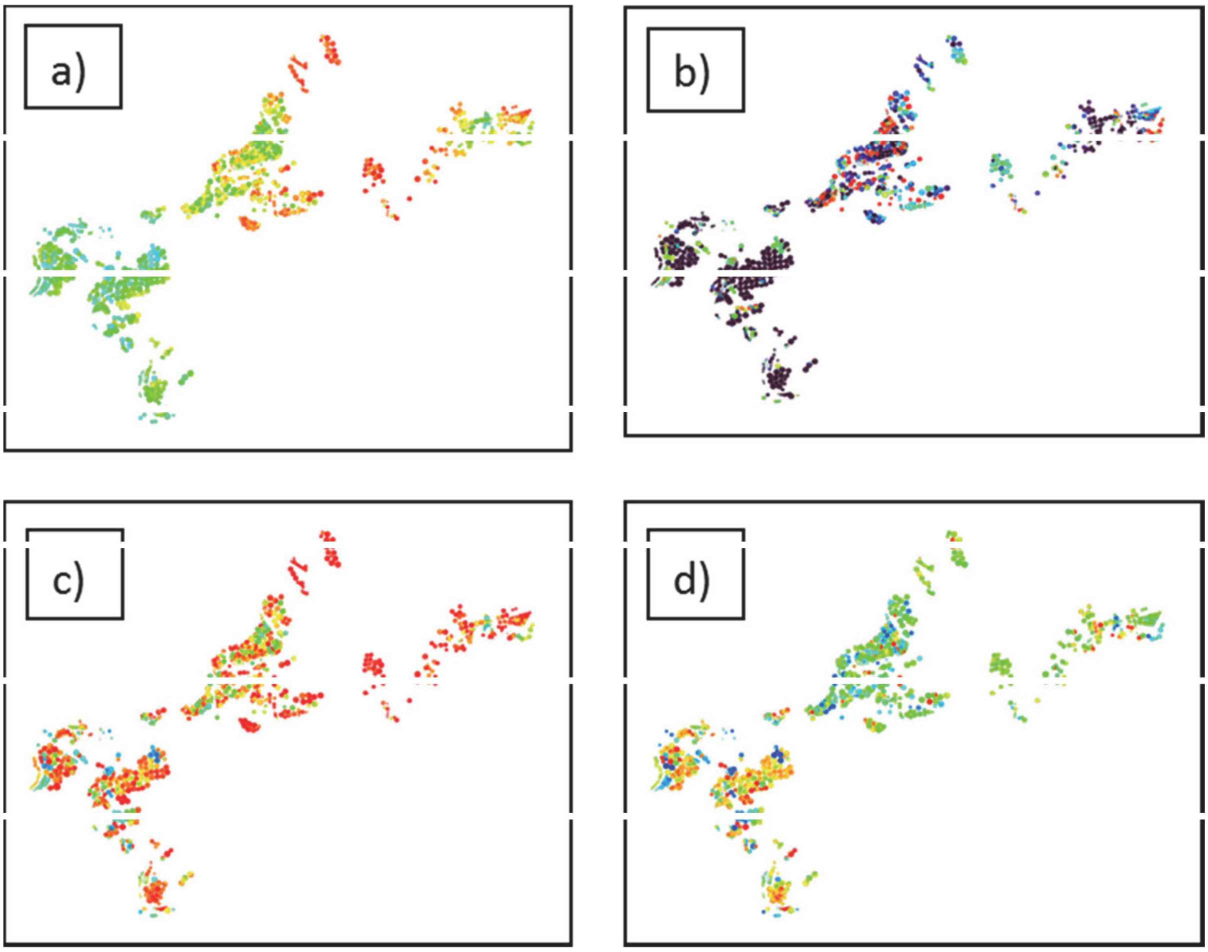


Figure 6.1 Data components for the week 07-13 December 2012, showing a) actual evapotranspiration (mm.week^{-1}), b) evapotranspiration deficit (mm.week^{-1}), c) actual biomass production (kg.ha^{-1}week^{-1}) and d) biomass water use efficiency (kg.m^{-3})

6.4 METHODOLOGY

6.4.1 Site and crop management description

6.4.1.1 Site description

In this study the focus is to investigate technologies for improved water use efficiency of irrigated pastures (mainly lucerne) using remote sensing (SEBAL model) and we partnered in this part of the project with GWK. The focus area selected covers an area around Douglas where lucerne and other pastures are produced under irrigation on commercial farms in Douglas (Figure 6.2) in Northern Cape (28° 25' S and 21° 15' E). Douglas area is 1029 m above sea level and has an annual rainfall of about 211 mm with average temperatures during midday of 18.4°C, reaching a maximum of 32.9°C. Therefore it has a semi-arid climate. It is located near the confluence of the Orange River and its main tributary, is the Vaal River. The land is sparsely cultivated and is covered with closed to open grassland.

The soils are high in arenosols with sandy or loamy sand texture. Generally the soils have high magnesium content and there are yellow sands next to the Orange River.

Figure 6.2 Location of Douglas study site

6.4.1.2 Irrigation system and layout

The irrigation system used for these pastures is centre pivot. The area under irrigation is approximately 21750 ha which falls under the Riet Irrigation Scheme. The main rivers which support irrigation in Douglas are the Vaal and Orange where-by irrigation takes place in a 250 km radius around this area.

6.4.1.3 Pasture species

Mixed pastures of temperate grasses and lucerne are the pasture species being monitored in this study. There is one farm with mixed pastures and three farms of lucerne being monitored which fall in the 60 x 60 km satellite image. Lucerne field monitored is managed for hay production (Figure 6.3) while the mixed pasture is grazed by cattle for beef production.

Figure 6.3 A view of one of the selected farms with irrigated Lucerne.

6.4.1.4 Irrigation scheduling

Irrigation scheduling is how much and when to apply irrigation. Soil water deficit measurements are made using a neutron water meter model 503 DR CPN Hydroprobe. Access tubes were installed to a depth of 1.2 m and the measurements were taken at 0.3 m interval. The cumulative water deficit of the profile is calculated over a soil depth of 1.2 m.

6.4.1.5 Fertilisation

Fertiliser recommendations are done based on the soil analyses. Soils in this area have almost the same ratio of sodium to potassium. Proper soil fertility analyses are imperative because plants cannot differentiate between these elements. Fertilizers are applied by fertigation.

6.5 INSTRUMENTATION FOR WATER USE MEASUREMENTS

6.5.1 Weather

Weather data were collected from an automatic weather station located near the selected sites. The automatic weather stations consisted of an LI 200X pyranometer (LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, an electronic relative humidity and temperature sensor installed in a Gill screen, an electronic cup anemometer (MET ONE, Inc. USA) to measure wind speed, an electronic rain gauge (RIMCO, R/TBR tipping bucket rain gauge, Rauchfuss Instruments Division, Australia) and a CR 10X data-logger (Campbell Scientific Inc. USA) is used.

6.5.2 Water balance

For estimating ET using the soil water balance the components were measured or estimated as follows:

$$ET = P + I - RO - DP + CR \pm dS \quad \textbf{(6.4)}$$

Where: **ET** : Evapotranspiration
P : Precipitation
I : Irrigation
RO : Runoff
DP : Deep Percolation
CR : Capillary rise
***d*S** : Change in soil water content

Precipitation was collected from the weather data from the infield weather station. Irrigation was recorded using manual rainguages which were installed at each monitoring site. Deep percolation, runoff and capillary rise are virtually impossible to measure under field conditions. The challenge of calculating ET using the soil water balance equation is when rain and irrigation water added to the soil exceeds the water holding capacity of the soil. As it is difficult to measure the amount of water lost through runoff and deep percolation then it was assumed that the quantity lost is about equivalent to the total soil water content after the rain or irrigation event minus the soil water storage capacity minus the theoretical crop evapotranspiration for that day. The equation which is used in determining water lost is:

$$(RO + DP) = ds + I + P - ETo \quad \textbf{(6.5)}$$

6.5.3 Energy balance

For comparison with the spatial energy balance and evapotranspiration data sets estimated with the SEBAL model, for one lucerne field (Taaibosch farm 6) was instrumented with energy balance systems (Figure 4). A surface renewal system was installed in a lucerne field in December 2012 and this was replaced with a one-sensor eddy covariance system in January 2013.

Evapotranspiration was estimated using the shortened energy balance method. The simplified energy balance used by SEBAL model is described as:

$$LE = Rn - G - H \quad \textbf{(6.6)}$$

Where Rn is the net radiation, G is the soil heat flux density, H is the sensible heat flux density and LE is the latent energy flux density.

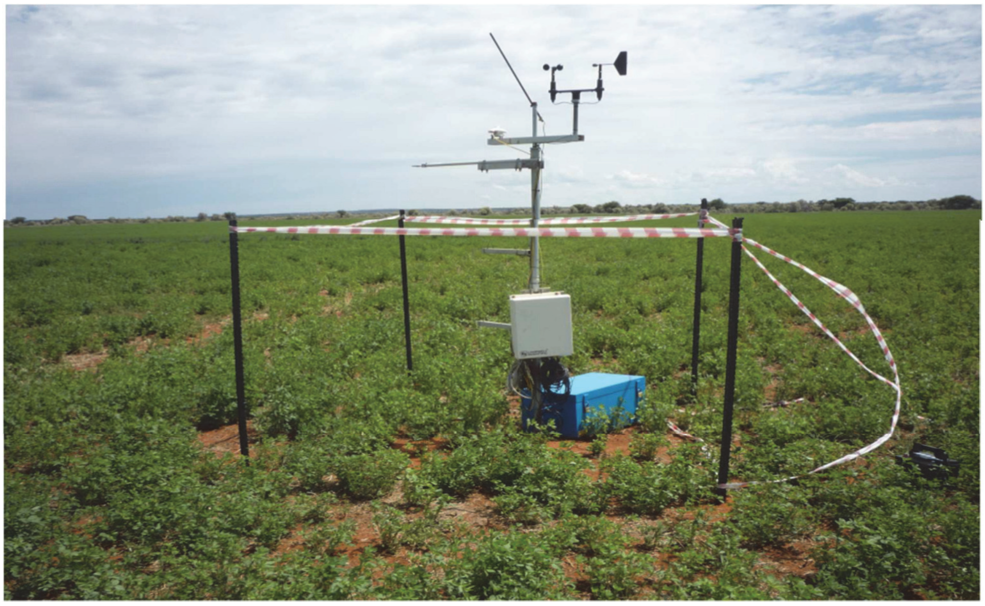


Figure 6.4 Eddy covariance system installed at lucerne field in Douglas

The measurements of eddy covariance or surface renewal systems were used for estimating sensible heat flux (H). The NR-LITE net radiometer (Kipp & Zonen, Delft, The Netherlands) placed 0.5 m above the crop canopy was used to measure net irradiance (Rn). Soil heat flux (G) was measured using two soil heat flux plates (model HFT-S, REBS, Seattle, USA) placed 80 mm below the soil surface. For measuring the soil heat stored above the soil heat flux plates, thermocouples were installed at depths of 20 and 60 mm. A CS616 time domain reflectometer (TDR) was also be used for measuring volumetric water content of the top 80 mm.

6.5.4 Modelled parameters

Model parameters including soil, weather, pasture and management parameters collected from field experiments as inputs were used to run the selected models. The calibrated models were used to estimate water use or ET.

6.6 RESULTS AND DISCUSSION

Evapotranspiration data, which indicates the crop water use, was extracted from the SEBAL model, an Eddy Covariance system (installed at Taaibosch 6), and the SWB model and by undertaking field measurements. This data together with in-field crop measurements and data obtained from weather stations in the area were used to draw up graphs which illustrate seasonal changes in weather, evapotranspiration, accumulated evapotranspiration throughout the growing season for the different pasture fields.

6.6.1 Weather

The nearest weather station was used to for modelling for all lucerne and fixed pasture. Minimum and maximum temperature and reference evaporation (FAO 56-ET_o) are presented in Figure 6.5 while the rainfall is presented in Figure 6.6. Reference ET_o varied from less than 2 mm on rainy days to greater than 8 mm in the hot spring and summer periods (Figure 5). These data was used to predict the atmospheric evaporative demand of the site and was used to develop coefficient of lucerne. Total rainfall at the study site was 286 mm for the period 28 September 2012 to 30 May 2013 (Figure 6.6).This was higher than the long term average (211 mm) for this period of the year.

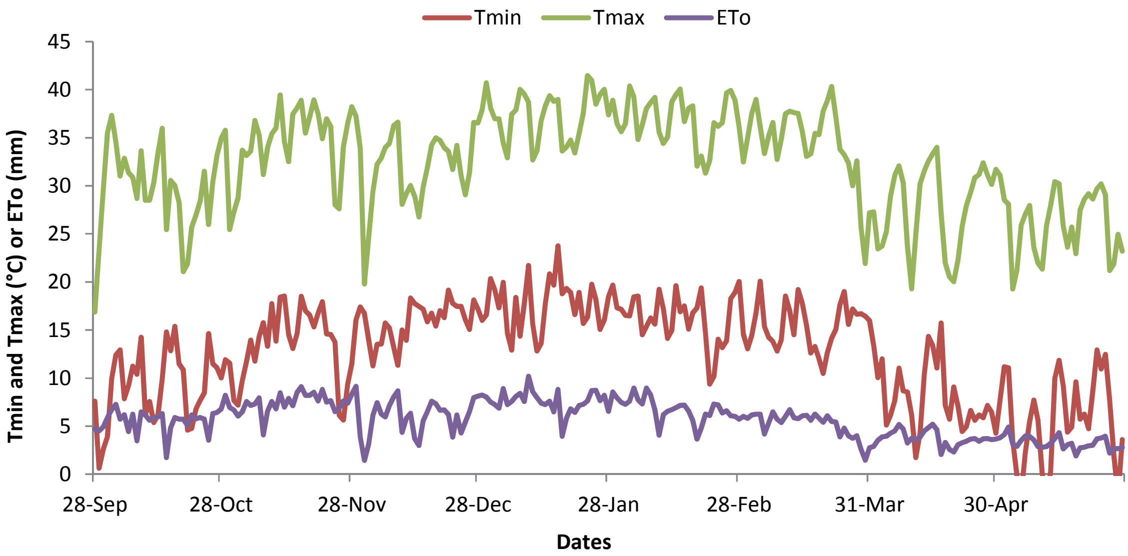


Figure 6.5 Rainfall data for the different pasture fields

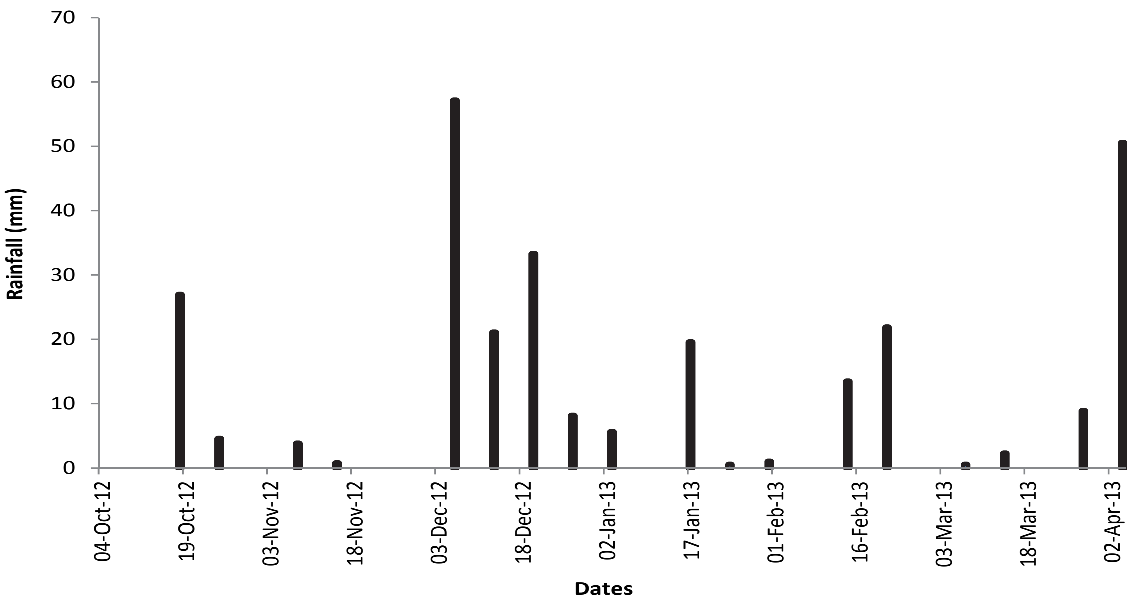


Figure 6.6 Rainfall data for Douglas site

6.6.2 Water use (ET)

Water use (evapotranspiration) estimated using eddy covariance and surface renewal methods in comparison to the reference evapotranspiration calculated using FAO-56 is shown in Figure 6.7. During the growth cycle water use was ranged from 3.5 mm during easily stages immediately after harvest when the canopy cover was very low but the water use increase to 8.5 mm per day as the canopy increases and then started to decline before harvest. Generally the water use estimated using EC was lower than the ET_o.

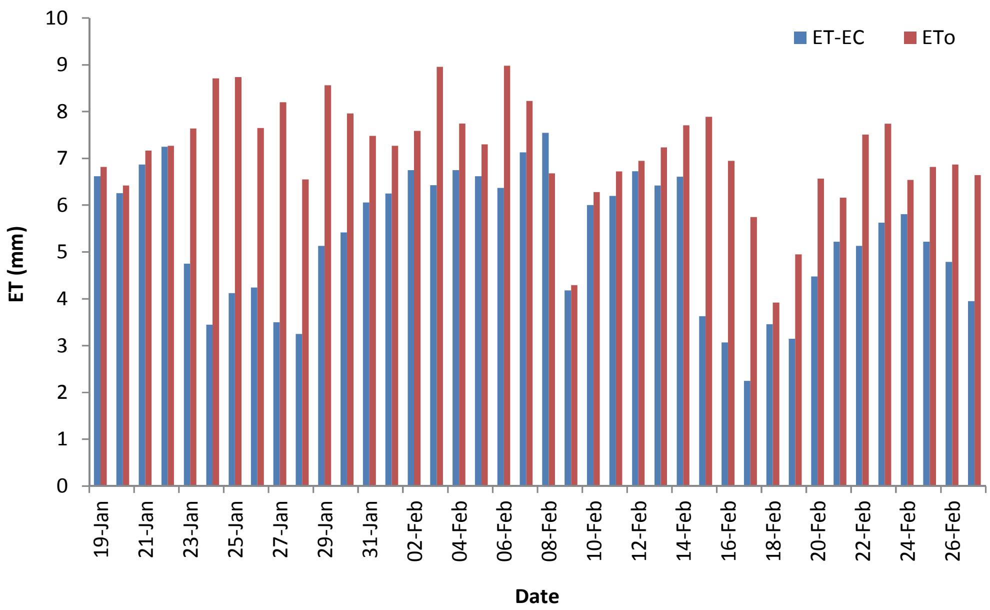


Figure 6.7 Diurnal variation in evapotranspiration estimates (mm) using the EC method and reference evapotranspiration calculated using the FAO 56

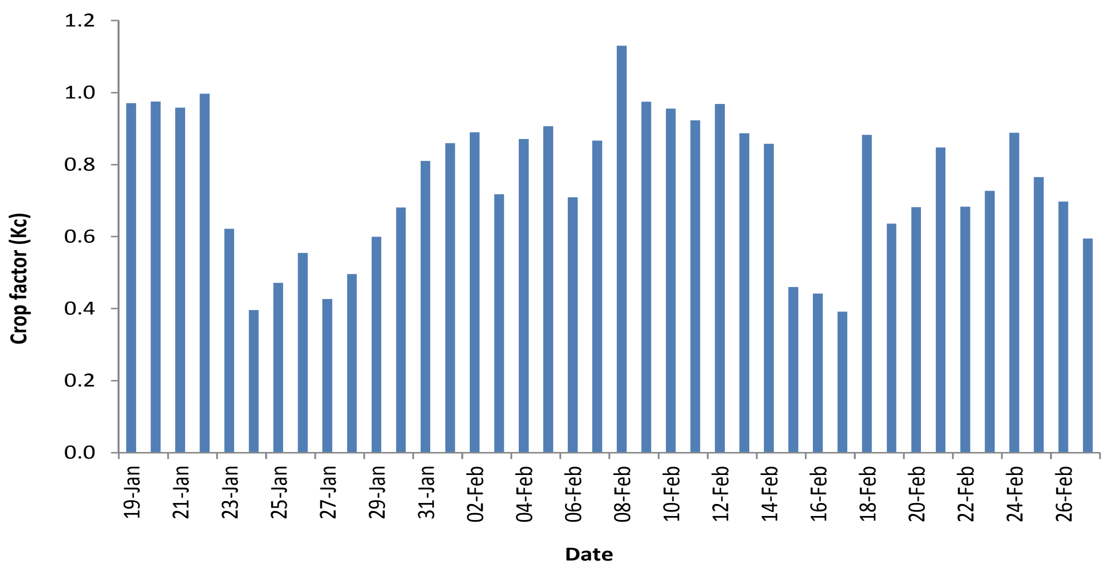


Figure 6.8 Crop coefficient variations of lucerne in Taaibosch 6 calculated as a ratio of ET_c estimated from EC method and ET_o

Crop coefficients (K_c) of optimally fertilized lucerne were developed for one growth cycle (37 days) using daily ET during summer (Figure 8). K_c was calculated as ET/ET_o. ET was determined from ET measurements of EC method. There was high variation of K_c among days ranging from 0.4 to 1.1, for most of the days depending on the evaporative demand of the day. The K_c also matched with the canopy growth of lucerne starting at about 0.4 during initial stage, and increase up to 1.0 until it reach the mid stage after starting to reduce again just before harvest. Water stressing of lucerne before harvest is a common practice for reducing moisture content of the hay and improving quality.

Evapotranspiration was calculated for all the lucerne fields as well as the mixed pastures field throughout the period of study. This was done to observe how ET varied between fields in different locations. Figure 9 illustrates this variation between the fields. The Luneburg field had the highest water use. This may be explained by the drainage problems present in this field which were not taken into account when calculating the ET, since it is difficult to monitor drainage under field conditions.

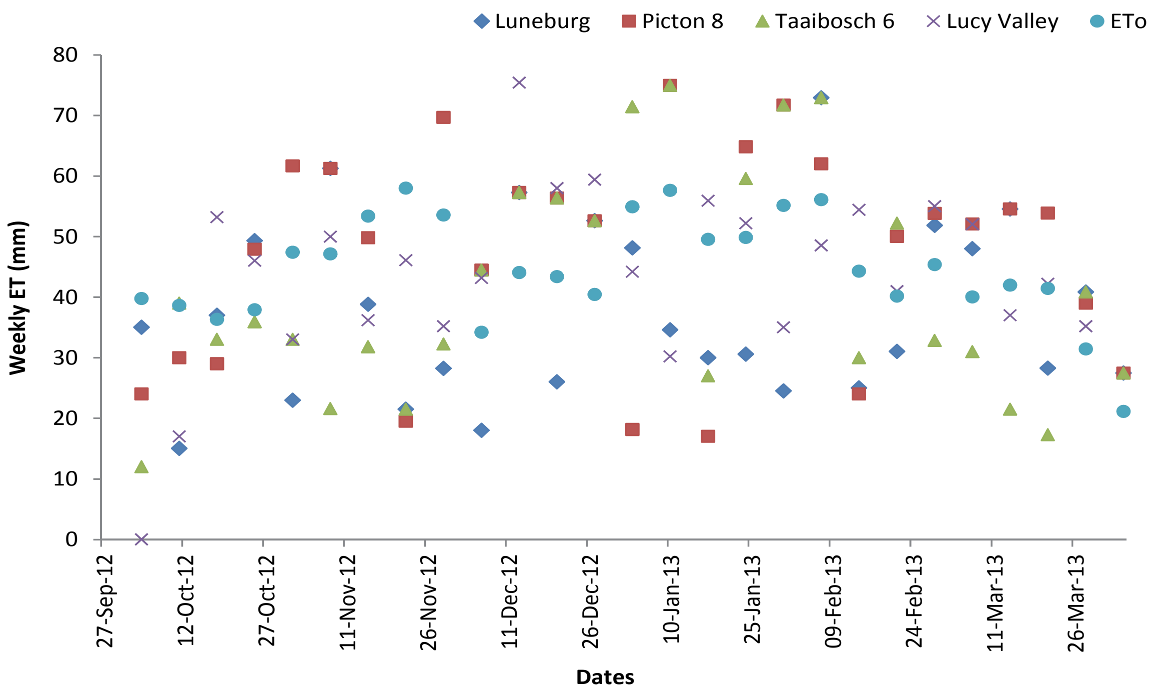


Figure 6.9 Weekly ET estimations from the field soil water balance measurements for Lucerne fields compared to ET_o

6.7 DATA COMPARISON

Weekly ET estimated from field measurements using the soil water balance were compared with ET estimated using the SWB and SEBAL models as well as the infield measured ET and ETo for all lucerne and mixed pasture fields (Figure 6.10). In Taaibosch 6, ET estimation conducted using the eddy covariance system was compared to field measurements and model simulations. Generally, ET simulated using SEBAL and SWB models as well as ET measured using the eddy covariance system (in Taaibosch 6) was lower than the ET_o.

However, ET measured in the field using the soil water balance was higher than the ET_o and model simulated ET. The reasons for this could be: 1) due to exclusion of runoff and drainage while calculating ET using the soil water balance and 2) the mismatch in time intervals between infield soil water content measurement and satellite remote sensing.

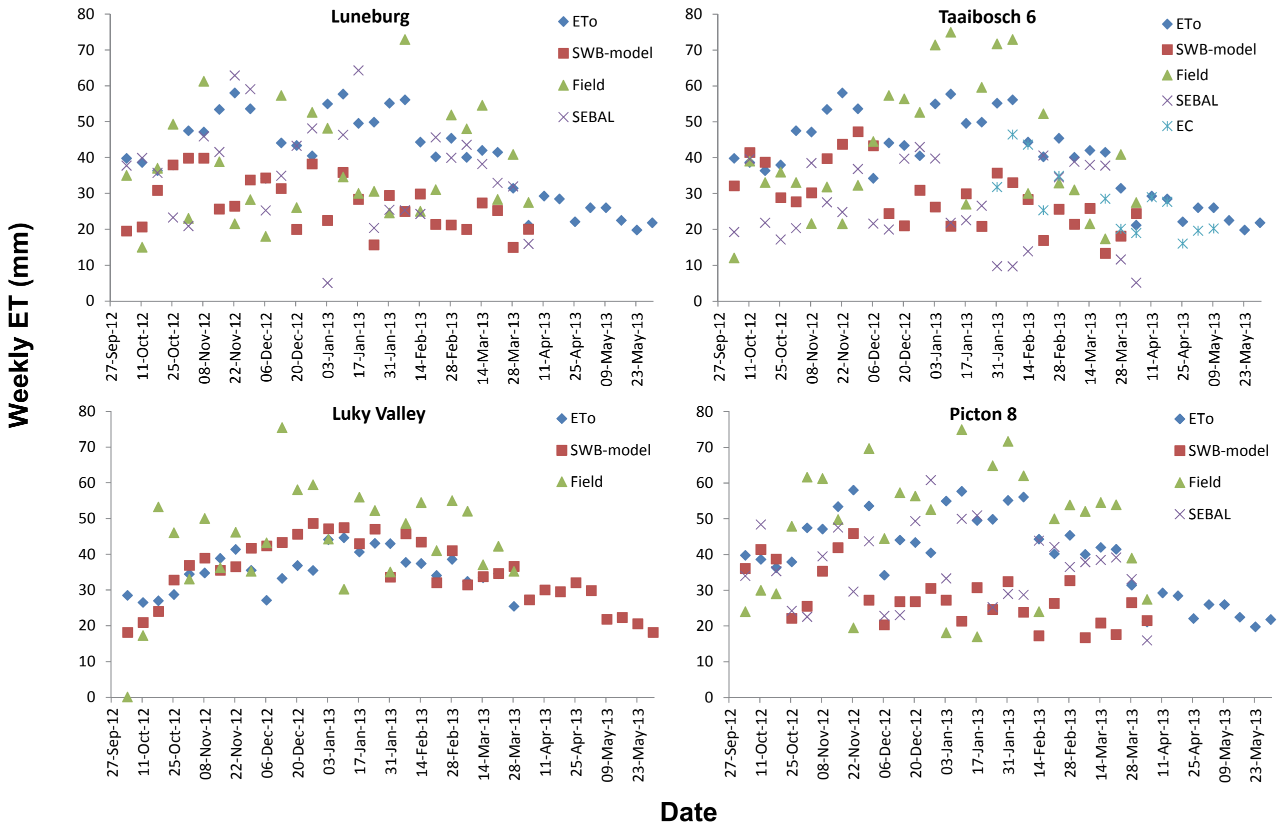


Figure 6.10 Comparisons of weekly ET estimations using different models against field measurements and ET_o for three lucerne fields (Luneburg, Picton 8 and Taaibosch 6) and one fixed pasture (Lucy Valley) field

Accumulative ET was also calculated (Figure 6.11) for the period of study which can be used to determine crop water use and water use efficiency for this period. The difference in seasonal water use among different methods used in this study in Luneburg was the smallest when compared to other field. Generally, in all field the highest water use was observed from field measurements while the lowest was from SWB model. Water use simulations using SEBAL were somehow in between.

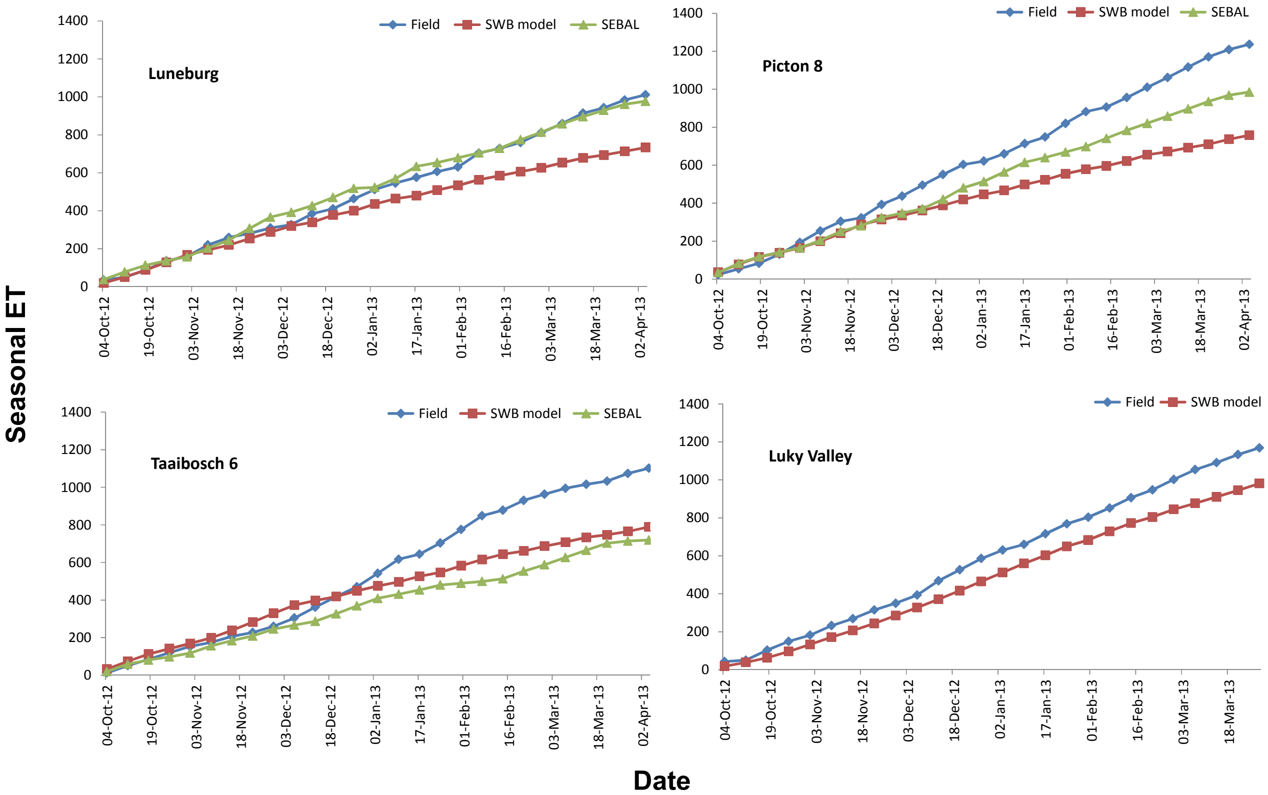


Figure 6.11 Comparisons of cumulative ET estimations using different models against field measurements and ET_o for three lucerne fields (Luneburg, Picton 8 and Taaibosch 6) and one fixed pasture (Lucy Valley) field

CHAPTER 7- CONCLUSION AND RECOMMENDATIONS

Sustainable pasture production requires optimal nutrient, water and defoliation management practices in order to attain good yield and forage quality. The basic understanding of the water requirements and drivers of irrigated pasture production systems, are essential for the development of sound water management strategies. Pasture systems, however are highly complex involving interactions between crop growth, soil and plant nutrient dynamics, and livestock and pasture management systems. This project focussed on mixed pastures which either included the subtropical kikuyu pasture oversown with a temperate grass, or a temperate grass mixed with a temperate legume. The two most important legume species evaluated in this project included lucerne and white clover. Considering temporal and spatial complexity, it is difficult to evaluate an entire system with short-term monitoring experiments. Development of site specific optimal irrigation management practices requires costly long-term trials. Since it is expensive and impractical to test multiple irrigation application strategies, this project has focussed on synthesizing on-station and on-farm data together with fragmented historical data and the use of empirical models to provide a better understanding of the behaviour of different pasture systems and to identify and develop tools and general guidelines in order to increase water use efficiency at farm level.

In evaluating various pasture treatments and production systems, it was imperative to assess a few important plant growth parameters to understand the effects of irrigation and defoliation on pasture production. With respect to defoliation, two approaches were taken during this study.

- One approach was to monitor pasture under well managed conditions which included **mechanical harvesting**, representing at least a 90 % defoliation rate and a hay production system.
- The second approach was to monitor pasture treatments under a **grazing system** to represent on-farm practices.

Most monospecific and mixed pastures are predominantly perennial production systems with a lifespan of more than 5 years, resulting in successional regrowth cycles after defoliation. A regrowth cycle of 6-8 weeks until the pasture reaches a physiologically optimal defoliation stage, has variable moisture requirements and losses.

7.1 Botanical composition

Botanical composition is an important parameter to measure, as it indicates how the mixed pasture is changing due to either management and/or changing growth conditions. It is clear from the study that the mixed pastures botanical composition changed during the growing season due to management, specifically the intensity of defoliation which favoured some species more than others in a mixture. This complicates the consistent measuring of such pastures and it is concluded from this part of the study that the more dominant species are responsible for the majority of the water used in the mixture. These results have pre-concluded that monitoring the canopy cover of a mixed pasture might be more valuable than understanding individual species in the mixture due to the change in botanical composition over time due to management. This hypothesis was further tested throughout the remaining parts of the study.

The more dominant species in a mixed pasture in its specific growing season is responsible for the majority of the water used.

7.2 Pasture canopy cover

It is evident from the data presented in the study that in certain climatic conditions and under certain management practices, that some species are more responsive than others to irrigation, resulting in more superior growth in certain seasons. To establish the rate and availability of pasture in field (on-farm), the RPM method is well adopted. This is a quick tool to assess the dry matter availability, and this study confirmed strong correlations between RPM readings and DM yield measurements obtained for mixed pastures. This was obviously due to the good growth interaction of species with the more dominant species being supported by the less dominant species. Mixtures have a better canopy density and thus better resistance during the RPM measurement process.

Mixed pastures have a better canopy density throughout the year resulting in a good yield estimate with a Rising Plate Meter.

With the multiple readings taken and the yield measurements obtained, promising correlations were obtained for the monospecific and mixed pastures. It can be noted that RPM readings can give a good estimate of the potential yield of the pasture, if the RPM is calibrated for the specific pasture. These calibrations become more accurate the more RPM readings are taken and correlated with yield data measurements. It is noted that there is a better correlation for species that do have a distinctive leaf: stem ratio as lucerne does.

The monitoring of the production potential of a pasture is an extensive task, and the RPM method has been established to be an easy, quick and accurate method of establishing the amount of available pasture, irrespective of the amount of water used. This research also focused on whether there is an acceptable correlation between RPM reading and a pastures water use.

It was interesting to observe that there was a good correlation between pasture specific calibrated RPM readings and the water use.
(This research requires further investigation)

The data collected for monospecific pastures illustrate the different water requirements per week, which relates to the physiological growth stage (maturity) of the pasture at a specific period after defoliation. It is evident that less water needs to be applied to a pasture in the first two weeks after defoliation. In this time the evaporation factor is at its highest since there is a small canopy present to cover the soil surface and only enough water should be applied for pasture growth. Once the pasture canopy develops, less water is evaporated and more water is available for pasture growth. It is also interesting to note that some pasture species require less water once the pasture stand goes into a reproductive phase, highlighting the opportunity to save water when harvesting the pasture at the proper time.

After defoliation occurs, less water than current guidelines is required for initial regrowth since more moisture is lost through evaporation. An increase in canopy results in an increase in water use efficiency if not over irrigated.

7.2 Water use and efficiency

To establish how well a pasture utilises the water being applied to it, it is essential to calculate the water use efficiency (WUE) in relation to the amount of dry matter (kg $DM.ha^{-1}$) and/or crude protein (kg $CP.ha^{-1}$) produced for these pastures. Notably some pastures are more water use efficient in their known growing seasons and as soon as growth conditions become less suitable, too cold or too hot, or shorter or longer day lengths they require more or less water to survive these periods.

Very often their comes a time when there is a major difference between yield and quality in certain months and it will become important to decide what is required from the production system at that stage, and then adapt the management system accordingly. Water requirements change when the temperate species enter into a reproductive phase quicker in the warmer months due to heat stress. Once the canopy has fully developed and is in the reproductive phase at that time, a higher water requirement is evident.

If a grazing or cutting cycle is too long and a pasture reaches a mature and reproductive stage, canopy cover is large and WU high, but DM and quality will start to decrease and so will water use efficiency decrease.

The data obtained for the mixed pastures clearly highlights the value of combined species from a water use perspective. It must be remembered that mixed pastures can represent the following:

a) a perennial subtropical pasture oversown with an annual /perennial temperate species providing growth in both summer and winter months or
b) two temperate species, either grass/grass or grass legume mixtures with slow to no growth in summer months. In addition to understanding these systems properly, it is always important to take note of the vigour of the individual species in the mixture. This is important because certain individual species become more dominant than others, as they are influenced by either preferential climatic conditions or management intensity.

From the grazing study, it was concluded that kikuyu mixed with different cultivars of lucerne use a similar amount of water, yields a similar amount of DM and are equally water use efficient. Due to the fact that the lucerne cultivars are dormant during different seasons, the irrigation management of these two pastures differed between seasons. Kikuyu/lucerne (WL357) needs less water during cooler seasons and more during the warmer seasons, whilst kikuyu/lucerne (WL711) needs more water during the cooler seasons and less during the warmer seasons. Kikuyu/perennial ryegrass and kikuyu/cocksfoot also use a similar amount of water, they yield a similar amount of DM and are equally water use efficient. One irrigation management strategy can be applied to both these pastures, but should be adjusted to seasonal requirements. In summer, pastures require more water than in winter.

Research to date has shown that there is an insignificant difference between different cultivars of a species under grazing conditions.

(This research requires further investigation)

This study concluded that it is possible to predict WU for kikuyu/lucerne (cv WL357 and cv WL711), kikuyu/perennial and kikuyu/cocksfoot pastures from measuring parameters of the canopy cover (PAR and LAI). Water use can consequently give an indication of the amount of water required by these over-sown pastures and can be irrigated accordingly. The WU of grazed kikuyu/lucerne mixed pastures and kikuyu oversown with perennial ryegrass or cocksfoot had a relatively strong, positive relationship with PAR and LAI. The research found that with an in increase in canopy cover, WU also increased. After the pasture was grazed and the canopy cover was small (PAR and LAI low), WU was also at its lowest point and started to increase as the canopy grew larger. It is recommended that this research be further explored.

This research concludes that when a fixed irrigation rate (e.g. 25 mm.week^{-1}) is used for a pasture at an earlier stage of regrowth (small canopy), there is higher percentage moisture lost as a result of evaporation than the later stages of canopy development. With the same fixed rate while the canopy is fully developed and the species enters a mature and reproductive stage, then a higher percentage of water is lost to drainage in dormant seasons resulting in a lower WUE.

When considering mechanically harvested / or intensively grazed mixed pastures, there are a few important factors to keep in mind when assessing the water requirements of such a pasture. Firstly, mixed pastures can have improved water use and water use efficiency than the individual components. The study concludes that in some months there is either a lower yield or slightly higher/lower protein value than monospecific pastures. It is important to observe that some species can become dominant in the mixture and this is a function of the species growth habit (strongly rhizomatous and stoloniferous) which can also become extremely vigorous due to intensive defoliation practices, i.e. mechanical harvesting. It is therefore important that if a mixed pasture is considered, that the species selected to be planted together, have the same growth habit as far as possible, or that the more vigorous species are planted in lower proportions, giving the less competitive species an opportunity to grow.

Using calculated crop coefficients which are defined as the ratio of ET determined from researched pastures and their soil surfaces to reference ET as defined by weather data, can help establish pasture irrigation requirements.

$$ET_c = K_c \, ET_o$$

Where:
ET_c crop evapotranspiration [mm d^{-1}]
K_c crop coefficient [dimensionless]
ET_o reference crop evapotranspiration [mm d^{-1}]

Table 7.1 Calculated crop coefficients of various pasture species and their mixtures (full canopy)

	Monthly crop coefficients (K_c)											
Pasture	JAN	FEB	MRCH	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ON-STATION (2 year research period)												
Lucerne (without frost)	*	*	0.7	1.2	1.0	0.8	1.1	0.7	0.7	0.7	1.0	*
White Clover	*	*	0.7	1.3	1.4	1.0	0.7	1.1	0.8	0.8	0.9	*
Tall fescue	*	*	0.6	0.8	0.9	1.0	0.5	0.7	0.7	0.7	0.9	*
Kikuyu	*	*	0.8	0.7	0.7	0.0	0.0	0.0	0.4	0.6	0.8	*
Kikuyu / Lucerne	*	*	0.7	0.9	0.8	0.9	0.7	0.7	0.7	0.7	0.8	*
Tall fescue / White clover	*	*	0.6	1.1	1.2	1.0	0.7	0.8	0.7	0.8	0.9	*
Tall fescue / Lucerne	*	*	0.7	0.9	1.0	0.9	0.8	0.8	0.7	0.7	0.9	*
ON-FARM (2 year monitoring period + model simulations)												
Lucerne (with frost)	0.85	0.85	0.9	0.8	0.6	0.5	0.5	0.6	0.7	0.85	0.9	0.95
Kikuyu / ryegrass	0.7	0.7	0.6	0.6	0.65	0.55	0.5	1.0	0.75	0.75	0.7	0.7

** Unknown*

Research has provided the following general guidelines to irrigate various pastures.

Table 7.2 Estimated water requirements of various pasture species and mixtures thereof (full canopy)

Pastures	Autumn	Winter	Spring	Summer
		(mm.week^{-1})		
Subtropical (Warm season) pastures – ON STATION				
Kikuyu (*Pennisetum clandestinum*)	17.0	12.0 #	20.0	30.0
Temperate (Cool season) pastures – ON STATION				
Tall fescue *(Festuca arundinacea)*	16.0	14.0	17.5	30.0 *
Lucerne *(Medicago sativa)*	21.0	15.0	15.5	30.5 *
White clover *(Trifolium repens)*	23.0	18.0	19.5	29.0 *
Subtropical (Warm season) grass – Temperate (Cool season) legume mixed pasture - ON STATION				
Kikuyu / Lucerne	20.0	15.0	19.0	34.0
Temperate (Cool season) grass – Temperate (Cool season) legume mixed pasture - ON STATION				
Tall fescue / Lucerne	18.5	15.5	17.0	28.0
Tall fescue / White clover	19.0	16.5	18.0	30.0
Temperate (Cool season) pastures – ON FARM				
Lucerne (Hay crop)	28.0	12.5	32.0	44.0
Subtropical (Warm season) grass – Temperate (Cool season) grass mixed pasture - ON FARM				
Kikuyu / Perennial ryegrass (Grazing)	14.6	9.5	21.0	29.5

** High evaporative loss (Dormant season)*
 # Risk of increased drainage (Dormant season)

7.4 Modelling and remote sensing

As it is noted there are so many different pasture production scenarios that exist, and it becomes impossible to simulate such systems in research projects, and therefore one has to rely on other tools to provide good estimates of a pastures water requirements. Modelling is an extremely important and powerful tool, and was successfully used to focus on the integration of the soil, plant and livestock factors (data) to obtain a better understanding of how the entire pasture production system functions. The international model, DairyMod was successfully evaluated and tested and has shown its ability to incorporate local weather data and to adjust specific parameters related to the soil, pasture growth and livestock management factors. This model has been used to test mixed pastures specifically. It also has the option to have nine different output screens that provide simulations of the expected soil, water or vegetation responses to climate and management factors. This project also helped parameterize SWB to estimate real-time crop water requirements and recommend the irrigation amount and date, based on the current crop water usage and set user preferences for lucerne. If farmers do not have access to irrigation monitoring tools, SWB can be used to develop site-specific irrigation calendars. The calendar, which recommends irrigation dates and amounts, can be printed out and used as a guide to manage irrigations. Calendar recommendations must be corrected by subtracting rainfall from recommended irrigation amounts if applicable.

The final objective of the research was to opportunistically link to an on-going WRC Remote sensing project (no. TT 602/14). It was concluded that the water use of lucerne and mixed pastures estimated using remote sensing is similar to the water use estimated using SWB model, eddy covariance and field water balance measurements. From the results of water use, the remote sensing technology looks promising and could be used as a tool for irrigation scheduling of pastures studied in this project. The results are also expected to be improved when the models are calibrated for specific crops. To avoid repetition an in-depth analyses and comparisons of water use, growth, biomass and nitrogen uptake of lucerne and mixed pastures was conducted in the remote sensing project (no. K5/2079//4). It is recommended that more dedicated remote sensing research be conducted on irrigated pasture production systems in the livestock industry.

Finally, it can be concluded that the water (irrigation) requirements of mixed and monospecific pastures can be determined by the following approach:

Step 1: Determine the pasture components (which species) of the mixture and their expected growth cycles according to production system (grazing intensity or harvesting period)

Step 2: Derive / use available crop coefficients (K_c)

Step 3: Determine and use the areas ET_o together with crop coefficients to calculate ET_c

Step 4: Obtain RPM readings (Calibration important)

Step 5: Measure the canopy cover (PAR and LAI) – if possible

Step 6: Run DairyMod or SWB (generate irrigation calendars) with available resource parameters including ET_o

CHAPTER 8 – CAPACITY BUILDING AND KNOWLEDGE DISSEMINATION

8.1 FORMAL TRAINING OF INDIVIDUAL STUDENTS

The following students from the University of Pretoria were registered on the WRC PROJECT K 5 / 2173 / 4;

STUDENT NAME AND SURNAME	GENDER	RACE	DEGREE	Time spent	COUNTRY OF ORIGIN
Mr. Omphile Sehoole – Completed	Male	Black	MSc(Agric)	100%	South Africa
Ms. Malissa Murphy – Completed	Female	White	MSc(Agric)	100%	South Africa
Ms. Makda Maherai – Completed	Female	Black	BSc(Hons)	100%	Eritrea
Mr. Arno Rautenbach	Male	White	MSc(Agric)	25%	South Africa
Ms. Makda Maherai	Female	Black	MSc(Agric)	25%	Eritrea
Ms. Alice Gwelo	Female	Black	PhD	25%	Zimbabwe
Mr Dlamini Mpendulo	MAle	Black	MSc(Agric)	10%	South Africa

8.1.1 Dissertations

Mahrai MA. 2015. Determining the water use of irrigated pastures in relation to quality (crude protein and digestibility) and production. Submitted in partial fulfilment of the requirements for the degree BSc (Agric) Hons Crop Science in the Department of Plant Production and Soil science, University of Pretoria.

Sehoole O. 2016. Water use of selected irrigated mixed grass and legume pastures. Submitted in partial fulfilment of the requirements for the degree MSc (Agric) Pasture Science in the Department of Plant Production and Soil science, University of Pretoria. **(In Progress)**

Murphy M. 2016. Water use of grazed kikuyu (*Pennisetum clandestinum*) pasture over-sown with temperate grasses or legumes. Submitted in partial fulfilment of the requirements for the degree MSc (Agric) Pasture Science in the Department of Plant Production and Soil science, University of Pretoria. **(In Progress)**

8.1.2 Awards

Ms. Alice Gwelo received the award for the best research protocol presented at the Annual conference of the Grassland Society of Southern Africa (GSSA) in 2014.

8.2 PUBLICATIONS

8.2.1 Conference proceedings

Truter WF., Sehoole O., Murphy M., 2016. Determining the water requirements of common irrigated pastures used in the livestock industry. *SANSOR Annual Conference Proceedings*. Magaliesburg.

Sehoole O., Truter WF. and Annandale JG., 2015. Water Use of Mixed grass (Kikuyu, Tall fescue, Ryegrass, Coscksfoot) and Legume (Clover and Lucerne) pastures. *Proceedings of the 50th Annual Congress of the Grassland Society of Southern Africa*. Pietermaritzburg.

Gwelo FA., Truter, WF, Annandale JG. 2015 The water use efficiency of irrigated SA Standard and Super Cuf lucerne varieties. *Proceedings of the 50th Annual Congress of the Grassland Society of Southern Africa*. Pietermaritzburg.

Murphy M., Truter WF., Swanepoel PA. and Botha PR., 2015. Relating canopy cover to water use of kikuyu pasture over-sown with temperate grasses or legumes. *Proceedings of the 50th Annual Congress of the Grassland Society of Southern Africa*. Pietermaritzburg

Gwelo FA., Truter, WF, Annandale JG. 2014 Understanding the nitrogen use of Lucerne and mixed pastures for yield and quality in relation to water use. *Proceedings of the 49th Annual Congress of the Grassland Society of Southern Africa*. Bloemfontein.

Sehoole O., Truter WF, Gwelo FA., Annandale JG. 2014. Water use of Lucerne and mixed pastures under irrigated and mechanically harvested conditions. *Proceedings of the 49th Annual Congress of the Grassland Society of Southern Africa.* Bloemfontein.

Murphy M., Botha PR., Truter WF., Swanepoel PA., 2014. On-farm management challenges of irrigation scheduling for planted pastures. *Proceedings of the 49th Annual Congress of the Grassland Society of Southern Africa.* Bloemfontein.

Truter WF., Annandale JG., Everson C., and Fessehazion MK. 2014. Status quo of irrigation guidelines for cultivated pastures in South Africa. *Proceedings of the 49th Annual Congress of the Grassland Society of Southern Africa.* Bloemfontein.

8.2.2 Popular articles

Can we determine the water use of mixed pastures? 2015. Grass Roots Magazine.

8.2.3 Scientific articles

M Murphy, PA Swanepoel, WF Truter, JG Annandale. 2016. Water use, dry matter yield, and water use efficiency of grazed kikuyu (*Pennisetum clandestinum*) pasture over-sown with temperate grasses or legumes. **(In process)**

M Murphy, PA Swanepoel, WF Truter, JG Annandale. 2016. Relating canopy cover to water use of grazed kikuyu (*Pennisetum clandestinum*) pasture over-sown with temperate grasses or legumes. **(In process)**

8.3 INFORMATION WORKSHOPS

Knowledge dissemination workshop was held on the 24th of February 2016 at the Swartberg Country Club, Franklin KwaZulu-Natal. Twenty five farmers and consultants attended the workshop.

Field demonstration was held on the 25th May 2015 in Thabazimbi / Brits for lucerne farmers. Thirty farmers attended.

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