Water relations of lucerne (*Mecicago sativa* L.) under organic farming conditions

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by

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DEDICATION

"I dedicate this manuscript to my father, Mr. Zulfiqar Ali, who inspired me to receive higher education."

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Abstract (In German)

Aufgrund ihrer Trockentoleranz ist Luzerne für den Anbau in semi-ariden Regionen prädestiniert. Sie erzielt hohe Stickstofffixierleistungen und ihr tiefreichendes Wurzelsystem ermöglicht es, Wasser aus tieferen Bodenschichten aufzunehmen. Aufgrund dieser Eigenschaften ist Luzerne für den Ökologischen Landbau geeignet.

Zur Wassernutzungseffizienz von Luzernesorten im biologischen Landbau gibt es bislang keine Informationen. Schätzungen zur Wurzelbiomasse aus Feldversuchen sind durch die Wahl geeigneter Methoden eingeschränkt. Um die Wirkung von Luzerne – Nutzungssystemen auf den Ertrag und die biologische Stickstofffixierung unter semi-ariden Bedingungen zu untersuchen, ist weitere Forschungsarbeit erforderlich. Mittels eines „Soil Plant Atmosphere" – Simulationsmodells sollten die Auswirkung von Pflanzeneigenschaften und Management-Praktiken wie Nutzungsform und Bewässerung auf den Ertrag sowie den Wasserhaushalt von Luzerne in Österreich untersucht werden.

Dazu wurden folgende Projektziele formuliert:

- Entwicklung eines geeigneten Verfahrens zur Abschätzung der Wurzelbiomasse.
- Vergleich des Ertrags und der Wassernutzungseffizienz der Versuchspflanzen unter bewässerten und normalen Bedingungen.
- Testen der Auswirkung des Nutzungssystems mit / ohne Mulchen auf Ertrag und biologische Stickstofffixierung.
- Analyse des Simulationsmodells CropSyst hinsichtlich Vorhersage des Ertrages von Luzerne sowie Anwendung des Modells, um die Wirkung von Pflanzeneigenschaften und Management-Praktiken auf Ertrag und Wassernutzung zu untersuchen.

Das Projekt beinhaltet zwei Sets an Experimenten: das erste vergleicht die Trockenmasseerträge von oberirdischer- und unterirdischer Biomasse sowie die Wassernutzungseffizienz der drei Luzernesorten Niva, Mohajaren und Sitel unter Bewässerung und normalen Bedingungen an den beiden österreichischen Versuchsstandorten Groß-Enzersdorf und Raasdorf. Im Jahr 2006 wurden Vorversuche angelegt, Daten aus 2007 – 2008 wurden zur Verrechnung und Analyse herangezogen. Das zweite Set vergleicht die Auswirkung des Luzerne-Nutzungssystems auf den Ertrag

der ober- und unterirdischen Biomasse, die Wassernutzungseffizienz und die biologische Stickstofffixierung. Zur Ermittlung der Wassernutzungseffizienz der Produktivität wurde das Wasserbilanz-Konzept und zur Ermittlung der Wassernutzungseffizienz der Photosynthese die Isotopen-Diskriminierungsmethode in beiden experimentellen Sets herangezogen. Zwei Verfahren zur Entnahme von Wurzelproben, Monolith (12,5 cm breit) und Wurzelsonde (9 cm Durchmesser), wurden im zweiten Experiment verglichen. Versuche dazu wurden 2007 und 2008 separat angelegt.

Empirische Daten aus Feldmessungen zum Ertrag und zum Bodenwassergehalt wurden mit Modellierungsergebnissen verglichen, um die Aussagekraft des Simulationsmodells CropSyst zu testen. In den Ergebnissen zeigten sich signifikante Unterschiede ($P < 0.05$) zwischen den beiden Methoden zur Entnahme von Wurzelproben: in beiden Versuchsjahren wurden mit dem Monolith höhere Biomasseerträge ermittelt als mit der Wurzelsonde. Die Ergebnisse zu ober – und unterirdischen Trockemasseerträgen sowie zur Wassernutzungseffizienz waren zwischen den Luzernevarietäten nicht signifikant unterschiedlich. Kumulierte Trockenmasseerträge der oberirdischen Biomasse aus beiden Versuchsjahren erreichten 32.3 - 36.8 t ha^{-1} unter Bewässerung und 8.3 - 25.2 t ha^{-1} unter normalen Bedingungen. Trockenmasseerträge der unterirdischen Biomasse, gemessen in den obersten 60 cm zur letzten Ernte 2008, erreichten Werte von 8.2 - 16.1 t ha^{-1} unter Bewässerung und 8.6 - 11.1 t ha^{-1} unter normalen Bedingungen. Die Wassernutzungseffizienz der Produktivität zu den Hauptternten lag bei 1.4 - 4.6 kg m^{-3} (Bewässerung) und 0.8 - 2.3 kg m^{-3} (normale Bedingungen). Die Unterschiede zwischen den Luzernenutzungssystemen waren nicht statistisch signifikant. Für die Parameter ober- und unterirdische Biomasse, Stickstofffixierleistung und Wassernutzungseffizienz zeigte sich ein Jahreseffekt ($P < 0.01$). Trockenmasseerträge der oberirdischen Biomasse zum zweiten Erntetermin erreichten 2007 0.85 - 0.98 t ha^{-1} und 3.1 - 3.6 t ha^{-1} in 2008. Jene der unterirdischen Biomasse zum zweiten Erntetermin erreichten 2007 5.5 - 6.3 t ha^{-1} und 10.8 - 11.8 t ha^{-1} in 2008. Die gesamte Stickstofffixierleistung lag 2007 bei 177 - 191 kg ha^{-1} und 2008 bei 450 - 517 kg ha^{-1}. Die Wassernutzungseffizienz des zweiten Aufwuchses lag 2007 bei 3.4 - 3.6 kg m^{-3} und 2008 bei 7.8 - 8.7 kg m^{-3}.

Das Simulationsmodell CropSyst ermöglichte Vorhersagen über die oberirdische Biomasse und den Bodenwassergehalt unter Bewässerung und normalen Bedingungen. Die Güte der Modellierung wird angezeigt durch Werte der statistischen Indizes im erwünschten Bereich (Modellierungseffizienzindex und Bestimmtheitsmaß zumeist nahe 1, Koeffizient der Residuen nahe 0). Szenarioanalysen durch Variation von Pflanzeneigenschaften wie maximale Durchwurzelungstiefe, spezifische Blattfläche oder Stängel/Blatt-Verhältnis mittels Szenarioanalyse, ermöglichten die Identifikation eines Luzerne-Ideotyps, der ideal an die Trockenbedingungen am Versuchsstandort Raasdorf angepasst ist. Der Wasserbedarf der bewässerten Luzerne wurde durch unterschiedliche Bewässerungsmengen und –intervalle für Szenarien mit hohen und geringen Niederschlägen ermittelt. Die Ergebnisse zeigten, dass sich der Effekt der zusätzlichen Bewässerung in niederschlagsarmen Jahren stärker auswirkt. Eine Bewässerung mit 40 ml in 20-Tages-Intervallen von Juni bis September bewirkte eine Ertragssteigerung der oberirdischen Biomasse von etwa 6 t ha^{-1}.

Die Modellierung der Auswirkung des Mulchens mittels CropSyst zeigte eine Tendenz zu höheren Bodenwassergehalten in den obersten 10 cm sowie im Bereich 0 - 120 cm. Dieser Effekt spiegelte sich allerdings nicht in einer Akkumulation der Biomasse wider. Geringe Wasserspeicherung und zu kurze Dauer der Feldversuche dürften hierfür ausschlaggebend gewesen sein.

Insgesamt betrachtet stellte sich Sitel als die Sorte mit besseren Erträgen, sowohl unter Bewässerung als auch unter normalen Bedingungen heraus. CropSyst erwies sich als geeignetes Modell zur Simulation von Biomasseerträgen und Bodenwassergehalt bei unterschiedlicher Wasserverfügbarkeit. Weitere langjährige Freilandversuche mit verschiedenen Luzernevarietäten, Bewässerungssystemen und variierten Mulchbiomassen in Verbindung mit Modellierung können unser Verständnis der positiven Wirkung des Mulchens verbessern.

Abstract

Lucerne is a suitable crop for semi-arid regions as it is fairly drought tolerant. It is efficient in biological nitrogen fixation and its deep roots enable it to extract water from deeper soil layers. These features make it a suitable choice for organic farming conditions. Water use efficiency of lucerne varieties used under organic farming conditions is not known. Estimation of its root biomass from field experiments is constrained by the choice of appropriate methods. Experimentation is required to investigate the effect of lucerne utilization system on yield and biological nitrogen fixation under semi-arid conditions. Soil plant atmosphere continuum simulation model shall be used to study the effect of management practices such as utilization system and irrigation and plant traits on yield and water relations of lucerne in Austria. To address these issues, a project was designed with the objectives to find a suitable method for the estimation of root biomass, to compare the yield and water use efficiency of lucerne varieties under irrigated and rain fed conditions, to study the effect of lucerne utilization system on yield and biological nitrogen fixation, to study the efficacy of simulation model CropSyst to predict yield of lucerne varieties and to apply the model to investigate the effect of plant traits and management practices on yield and water use.

The project comprised of two sets of experiments. First set compares the shoot and root dry matter yield and water use efficiency of three lucerne varieties viz. Niva, Mohajaren and Sitel under irrigated and rain fed conditions, at Gross-Enzersdorf and Raasdorf, Vienna, Austria, respectively. This set of experiments was established in 2006 and 2007-2008 were regarded as experimental years. Second set compares the effect of lucerne utilization system on its shoot and root dry matter yield, water use efficiency and biological nitrogen fixation. Water use efficiency of productivity was determined using water balance approach and water use efficiency of photosynthesis was determined using carbon isotope discrimination techniques in both sets of experiments. Root sampling methods viz. monolith (12.5 cm wide) and soil corer (9 cm diameter) were compared in second set and these experiments were laid out separately in 2007 and 2008. Empirical data on yield and soil water content from field experiments were compared with modeling results to study the efficacy of simulation model CropSyst.

Results revealed that significant ($P < 0.05$) differences were observed among root sampling methods as soil monolith estimated relatively higher biomass than soil corer method in both years. Non-significant differences were observed among varieties for shoot and root dry matter yield and water use efficiency. Cumulative shoot dry matter yield during two years of experimental period was in the range of 32.3-36.8 tones ha^{-1} and 18.3-25.2 tones ha^{-1}under irrigated and rain-fed site, respectively. Root dry matter yield in top 60 cm determined at the time of final harvest in 2008 varied from 8.2-16.1 tones ha^{-1} and 8.6-11.1 tones ha^{-1} under irrigated and rain-fed site, respectively. Water use efficiency of productivity at major harvests varied from 1.4-4.6 kg m^{-3} under irrigated site and 0.8-2.3 kg m^{-3} under rain-fed site. Differences among lucerne utilization system treatments were found non-significant as determined at the time of second harvest in each year while differences among years were found significant ($P < 0.01$) for shoot and root dry matter yield, biological nitrogen fixation and water use efficiency. Shoot dry matter yield at second harvest varied from 0.85-0.98 tones ha^{-1} and 3.1-3.6 tones ha^{-1} in 2007 and 2008, respectively. Root dry matter yield at second harvest ranged from 5.5-6.3 tones ha^{-1} and 10.8-11.8 tones ha^{-1} in 2007 and 2008, respectively. Total biological nitrogen fixation varied from 177-191 kg ha^{-1} in 2007 and 450-517 kg ha^{-1} in 2008. Water use efficiency determined for the period between first and second harvest was 3.4-3.6 kg m^{-3} in 2007 and 7.8-8.7 kg m^{-3} in 2008.

Simulation model CropSyst performed satisfactorily to predict above ground biomass and profile soil water content under both irrigated and rain-fed conditions. Goodness of model performance is indicated by values of statistical indices in desirable ranges as modeling efficiency index and coefficient of determination were usually found close to 1 and coefficient of residual mass was found close to 0. Scenario analysis by varying plant traits such as maximum rooting depth, specific leaf area and stem/leaf partitioning coefficient helped to hypothesize a lucerne ideotype for water limited conditions at Raasdorf. Irrigation requirements of rain-fed lucerne were assessed by varying amounts and interval of irrigation under high and low rainfall scenarios. Results revealed that the effect of supplemental irrigation is more pronounced in low rainfall years and irrigation with 40 mm of water at 20 days interval during the period from June-September can help to achieve about 6 tones ha^{-1} of additional above ground biomass.

Modeling the effect of mulch using CropSyst indicated that mulching tends to increase soil water content in upper 10 cm soil layer as well as in the profile (0-120 cm) under the present site conditions but this effect is not translated into biomass accumulation probably due to the smaller amounts of water conserved as well as due to the smaller duration of field experiments.

On the overall basis, Sitel was found superior variety in terms of its better yield under both irrigated and rain-fed conditions. Potential of CropSyst to simulate crop biomass and soil water content under varying levels of water availability is demonstrated. Intensive large duration field experiments using different lucerne varieties, irrigation and mulch masses in conjunction with modeling will further improve our understanding on the positive role of mulches under the present site conditions.

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Chapter 1

Introduction

1.1 Problem description

Use of modern agricultural practices for meeting food requirements of rapidly growing population has led to exhaustion of natural resources (Kesavan and Swaminathan, 2008). Soil and water are two precious resources that need to be utilized efficiently to ensure sustained food supplies (Lal, 2009). The rapid degradation of natural resources intensifies the need to switch over to system that can make efficient use of soil and water (Lal, 2008). Organic farming systems, being a component of sustainable agriculture, offer a great prospect. Land use under certified organic farming systems in the world has reached over 32 million hectares (IFOAM, 2009). Organic farming is getting popularity in Europe and its share towards global organic surface area is over 24 %. In terms of certified land under organic management as a proportion of national agricultural area, the Alpine countries, such as Austria (13.4 %) and Switzerland (11 %), top the statistics (IFOAM, 2009).

Organic farming improves soil fertility and nutrient management at farm level and has positive effects on biodiversity conservation (Biao et al., 2003). Nutrient supply to crop plants is supported through recycling, the management of biologically-related processes such as nitrogen fixation legumes, and the limited use of unrefined, slowly-soluble off-farm materials that decompose in the same way as soil minerals or organic matter Organic farming systems may be sustainable and have the potential to deliver significant environmental benefits, but these depend on specific cropping and management practices on each farm (Goulding et al., 2008). The main nitrogen source in organic farming systems is nitrogen fixed by legumes (Loges et al., 2000). Lucerne (*Medicago sativa* L) is the main forage legume in many European countries due to its contribution to sustainable agriculture (Huyghe, 2003, Shen et al., 2009). Lucerne crop has shown potential to thrive well under conditions of low water availability and can survive long periods of drought (White, 1967).

Most of the lucerne varieties used in organic farming are originally developed for conventional farming systems. There is no information about water use efficiency (WUE) in the description of the varieties by the breeding companies. Their performance needs to be evaluated experimentally in terms of yield and water use under organic farming to find suitable varieties. Yield and water use are affected by soil and crop management (Peterson and Westfall, 2004). It is imperative to study water use by crops by taking into account soil, weather and management factors. Research efforts in recent past have been made to identify water use efficient lucerne crop varieties using different methods that do not take into account information on all related parameters that can affect water relations in soil-plant –atmosphere continuum. Most of the studies carried out on this aspect take into account only parameters recorded above ground without considering water balance, rooting depth and root densities within the soil, (Cole et al., 1970; Johnson and Tieszen, 1994; Ray et al., 1998; Basbag et al., 2004; Ray et al., 2004) thereby, do not generate a true picture what is going within soil, water and root continuum for water uptake.

Roots are important for anchoring plants, uptake of water and nutrients, storage of carbohydrates, and synthesis of growth regulators. Quantification of root growth and distribution is necessary to understand plant-soil interactions (Heeraman and Juma, 1993). The root systems are often referred as hidden half of plants (Waisel et al., 2002) and are less studied than shoots (Gleba et al., 1999). Many yield and water use experiments do not take into account contribution from roots as roots are difficult to study being labor and time intensive. Plant roots especially from legumes play important role in fixing atmospheric nitrogen. This biological nitrogen fixation (BNF) is the main source of nitrogen in organic farming systems (Pietsch et al., 2007). Finding an appropriate method for estimation of root biomass in row crops such as lucerne is crucial due to relative importance of roots in organic farming systems. Soil corer and soil monolith are mostly used for root studies in field experiments and they need to be compared experimentally.

Mulching is known to affect water storage through moisture conservation under field conditions (Baumhardt and Jones, 2002). Mulching tends to reduce runoff and increase infiltration (Papendick et al., 1990). These findings need further confirmation while using lucerne mulch in organic farming under semi-arid site conditions. Field experiments with replicated water measurements will improve our understanding on the effect of mulching with lucerne.

Water relations of lucerne crop need to be evaluated experimentally by taking replicated water measurement using sophisticated water measurement devices under controlled irrigation and natural rain-fed field conditions along with data on related meteorological, plant and soil parameters. These detailed data sets can improve our understanding on water relations of lucerne. We can use this detailed information for modeling yield and water balance.

Simulation models offer a great prospect to evaluate the effectiveness of a proposed intervention over a given area with minimum time and research cost (Farahani et al., 2009). CropSyst is a soil plant atmosphere continuum (SPAC) model which takes into account morphological and physiological processes at the level of plant components. CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. CropSyst simulates the soil water and nitrogen budgets, crop growth and development, crop yield, residue production and decomposition, soil erosion by water, and salinity (Stöckle et al., 2003). These features make it a suitable choice for studying the effect of different plant traits and management practices on water use by lucerne.

1.2 Objectives

Present project has been designed with the following objectives:

1- To analyze aboveground and belowground components of water use efficiency for different lucerne varieties under rain-fed and irrigated conditions (empirical field study). Particularly the relevance of root traits will be studied (methodological aspect of root sampling).

2- To determine the impact of different plant traits underlying distinct WUE of lucerne varieties on their growth performance under different environmental conditions using a SPAC model (CropSyst). This should allow to better interpret empirical data in a physical way and answer the question of which components making up a better WUE (root versus shoot components) will be effective for better growth/yield under which environmental conditions (Modeling study on variety x environment interaction).
3- To quantify effect of mulching with lucerne on yield, biological nitrogen fixation and water storage (Field and modeling study on management x environment interaction).

The project will yield valuable information regarding yield and water use efficiency of lucerne genotypes under organic farming conditions with and without water stress. Besides this it will improve our understanding on the effect of mulching on yield, water relations and nitrogen fixation of lucerne.

The use of simulation model CropSyst with different lucerne varieties will improve our understanding regarding its use with other crops suitable for the present experimental site. Results of simulation study can be extended to other sites in Austria to evaluate the performance of same varieties in a different environment. The information generated will be helpful for related research organizations and breeding companies for further utilization in varietal development program of water use efficient genotypes for organic farming conditions.

1.3 Improving water use efficiency for sustainable agriculture

Abstract

Fresh water resources are becoming scarce and polluted while their demands for agriculture, domestic, industrial, environmental and recreational uses are on a continuous rise around the globe. Traditional ways to increase yield by extending the area under cultivation, using high intensity of external inputs and breeding for yield potential in high input agro-ecosystems offer limited possibilities under limiting resource availability Improved agricultural systems are required that ensure high yields via an efficient and sustainable use of natural resources especially water.. This prospect has evoked calls for a “blue revolution” based on the core idea of obtaining more crop per drop of water. Objective of this review was to discuss approaches to improve water use efficiency by better crop, soil and irrigation management and analyse underlying physiological and hydrological mechanisms.

We found that most management measures contribute to better water use efficiency by improving water availability to the crop while reducing unproductive water losses. The main effect of crop, soil and irrigation management is an increase of the transpiration component in relation to runoff, soil evaporation and drainage. Also the effect of deficit irrigation methods is achieved partially by reducing stomata conductance that results in higher transpiration efficiency. Redistribution of water from soil evaporation to plant transpiration is the key for better water use efficiency of residue management and most measures in crop rotation design. Improved water use efficiency by better agronomy is achieved most effectively by an integral set of measures that are evaluated over the whole crop rotation. Processes underlying most improvements of water use efficiency in agronomy suggest that research should target plant water uptake capacity. We concluded that an integral system approach and an interdisciplinary focus on possibilities for root system management are most promising for a better water use and sustainable productivity in agriculture.

1.3.1 Introduction

World population is projected to reach 9.4 billion by 2050 and 10 billion by 2100 (Fischer and Heilig, 1997). Highest increase (3.5 billion) is expected to occur in developing countries of South Asia and sub-Saharan Africa. Agriculture is confronted with the challenge of feeding the rapidly growing population under a scenario of decreasing land and water resources worldwide (Bossio and Geheb, 2008). Global estimates of food-insecure populations comprise 825 million (Lobell et al., 2008) to 850 million (Borlaug, 2007), mainly in South and Southeast Asia and sub-Saharan Africa. Contrary to United Nations' Millennium Development Goals of cutting hunger by half by 2015, the number of food-insecure populations in the world is likely to grow (WWAP, 2009).

Since the 1990s yields have not increased at the pace registered since the 1950s, while world population continues to rise (Araus et al., 2008). The "yield-gap" (Rockström, 2001) is expected to further aggravate due to climatic change impacts such as extending soil degradation and higher frequency of droughts (IPCC, 2007; Bates et al., 2008; Trondalen, 2008).

Globally, agriculture accounts for 80–90 % of all freshwater used by humans, and most of that is in crop production (Wallace, 2000; Shiklomanov, 2003; Morison et al., 2008). Still, water is the main abiotic stress limiting crop production in several regions of the world (Araus et al., 2002; Ali and Talukder, 2008). In 2030, 47 % of the world population will be living in areas of high water stress (WWAP, 2009). Even where water for irrigation is currently plentiful, there are increasing concerns about future availability (Falkenmark, 1997). The competition from industrial and urban uses is increasing with demographic pressure and rapid industrialization (Gleick, 2003; Kondratyev, 2003; Johnson et al., 2001). The scarcity of fresh water is also exacerbated by non-point and point source pollutions (Tilman et al., 2006), particularly salinization of groundwater aquifers (UNEP, 1996). Global water pollution is on rise as every day 2 million tons of sewage and industrial and agricultural waste are discharged into the world's water (WWAP, 2003). 70 % of untreated industrial wastes in developing countries are disposed into water where they contaminate the existing water supplies (UN-Water, 2009). Mean nitrate levels have risen globally by an estimated 36% in global water ways since 1990, with the most dramatic increase seen in Eastern Mediterranean and Africa, where nitrate concentration has more than doubled (GEMS, 2004).

Traditional approaches of yield maximization were based on (i) increase in area under cultivation, (ii) high intensity of external inputs (fertilizer, irrigation) and (iii) breeding for high yield potential in high input agroecosystems ("green revolution varieties") (Richards, 2004; Waines and Ehdaie, 2007).With decreasing land and water resources, for the future these ways offer limited possibilities to satisfy the increasing food demand. Improved agricultural production systems are required that ensure high yield via an efficient and sustainable use of available natural resources. This prospect has been evoked calls for a "blue revolution" (e.g. Lynch, 2007; Finkel, 2009) based on the core idea of obtaining "more crop per drop" (UNIS, 2000).

Improvements in agricultural water use can be achieved at several points along the production chain, such as (1) the irrigation system (2) the proportion of water attributed to plants use, and (3) the conversion of crop water consumption into yield (Hsiao et al., 2007). Gravity driven irrigation systems can have efficiencies as low as 40%, being a main limiting factor for a productive water management (Howell, 2001). Better water use efficiency in field crop production can be achieved by adequate soil and crop management measures. Wallace and Batchelor (1997) resumed four options for enhancing water use efficiency in irrigated agriculture (Table 1.1) and pointed out that focusing on only one category will likely be unsuccessful.

Based on this concept we will use the term transpiration efficiency for the strict dry matter-to-transpiration ration, while water use efficiency integrates other fluxes such as soil evaporation. Based on a recommendation of practical measure for improved water use efficiency by Food and Agriculture Organization (FAO, 1997), the review will discuss related scientific findings reported in literature. Our analysis will cover agronomic options of crop, soil and irrigation management, while engineering and breeding aspects are beyond the scope of this article. The particular scope of this review is to provide a mechanistic understanding and interpretation of agronomic approaches for better water use efficiency by relating practical measures to the underlying processes of stress physiology and soil hydrology. This should support a more targeted search for promising roads and instrument for a better agricultural water use.

Table 1.1 Options for improving irrigation efficiency at a field level (Adapted from Wallace and Batchelor, 1997).

Improvement category	Options
Agronomic	1. Crop management to enhance precipitation capture or reduce water evaporation e.g., crop residues, conservation till, and plant spacing 2. Improved varieties 3. Advanced cropping strategies that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater likelihood of occurrence.
Engineering	1. Irrigation systems that reduce application losses, improve distribution uniformity, or both 2. Cropping systems that can enhance rainfall capture e.g., crop residues, deep chiseling or paratilling, furrow diking, and dammer-diker pitting.
Management	1. Demand-based irrigation scheduling 2. Slight to moderate deficit irrigation to promote deeper soil water extraction 3. Avoiding root zone salinity yield thresholds 4. Preventive equipment maintenance to reduce unexpected equipment failures
Institutional	1. User participation in an irrigation district or scheme operation and maintenance 2. Water pricing and legal incentives to reduce water use and penalties for inefficient use 3. Training and educational opportunities for learning newer, advanced techniques.

1.3.2 Definitions, concept and critical remarks on water use efficiency

Water use efficiency can be defined for different spatial and temporal scales and according to the respective research focus (Passioura, 2002; 2006). Table 1.2 gives an overview of common definitions and scales where water use efficiency (WUE) is studied.

Table 1. 2 Definitions of water use efficiency

Term	Definition	Scale	Reference
Gas exchange WUE measures			
Intrinsic WUE	$WUE_{\text{int}} = \frac{A}{g_s}$	Stomata	Jones (2004a)
Instantaneous WUE	$WUE_{inst} = \frac{A}{T}$	Leaf	Polley (2002)
Integrative WUE measures			
Transpiration efficiency	$TE = \frac{M}{T}$	Biomass	Gregory (2004)
Water productivity	$WP = \frac{Yield}{T}$	Yield	Pereira et al. (2002)
Irrigation WUE	$WUE_I = \frac{Yield}{Irrigation}$	Yield	Howell (2001)

WUE is water use efficiency, TE is transpiration efficiency, WP is water productivity, A is assimilation, g_s is stomatal conductance, T is transpiration, M is biomass.

Different integrative water use efficiency terms are often used interchangeably in literature, e.g. transpiration efficiency, biomass water-use efficiency (WUE_b; e.g. Tambussi et al. 2007) and biomass water productivity (WUE_b; e.g. Steduto et al., 2007). Subscripts can be used to clearly indicate the relation of the numerator to either biomass or yield.

Up scaling of water use efficiency from instantaneous leaf gas exchange to a time integrated biomass or yield related parameter is complex and requires consideration of relevant processes and environmental influences at the distinct scales (Steduto et al., 2007). While intrinsic water use efficiency is largely controlled by stomatal resistance, boundary layer effects can substantially affect the ratio of carbon to water vapour fluxes at the leaf and canopy level when plant-atmosphere coupling is imperfect (Jones, 2004a; Passioura, 2006).

At the whole plant level, transpiration efficiency of vegetative biomass under given environmental conditions is a rather conservative measure (Steduto et al., 2007) and mainly a function of the photosynthetic pathway. When targeting yield, the distinct energy cost of yield components must be taken into consideration (cereals < legumes < oil crops), suggesting the use of glucose equivalents for better comparison (Jones, 2004a).

The dominant role of environment for the biomass-water relation is expressed in the classical equation of De Wit (1958),

$$\frac{M}{T} = \frac{k}{ET_0} \qquad (1)$$

where transpiration efficiency (M/T) is a linear function of a plant-specific coefficient *k* normalized for the environment using e.g. reference evapotranspiration (ET_0).
From an agronomic point of view, Gregory (2004) proposed the following relation:

$$WUE = \frac{M}{T}\frac{1}{1+\frac{E_s + R + D}{T}} \qquad (2)$$

where total water use efficiency is separated into transpiration efficiency (M/T) and a water balance based term for the magnitude of plant water use (T) compared to unproductive losses (E_s being soil evaporation, R being runoff and D being deep drainage.

Passioura (1977) proposed a framework of factors determining yield formation in water limiting environments which since then has been applied extensively in plant breeding.

$$Yield = WU * WUE * HI \qquad (3)$$

where WU is plant water uptake, WUE is water use efficiency and HI is harvest index.
An extended model of overall water use efficiency across several scales was proposed by Hsiao et al. (2007) to allow a stepwise analysis of all relevant efficiencies along the whole production chain. This conceptual model covers the efficiency of the irrigation system, the efficiency of crop water use at the field scale and the efficiency of assimilation and yield formation with a given amount of water. In rain-fed agriculture Hsiao et al. (2007) introduced two soil management related terms, being infiltration and

rhizostorage efficiency. These terms again point to the water balance concept as given in equation 2.

Equations 1 to 3 reveal the two relevant sides for a mechanistic analysis of agronomic options to improve water use efficiency, being (i) physiological processes of biomass production and drought tolerance of plants, and (ii) hydrological and soil physical mechanisms of water dynamics.

Knowledge on relevant drought tolerance mechanisms is of high importance to improve crop production in water limiting environments (see Farooq et al., 2009). Figure 1.1 gives an overview of plant responses to drought in natural ecosystems following Levitt (1972).

Most adaptations that have evolved in plant communities of dry ecosystems are at the cost of reduced plant growth while ensuring reproductive survival. Comparing two wheat varieties differing in carbon isotope discrimination, Condon et al (2004) demonstrated that superior water use efficiency translated to better crop performance only under high drought stress of soil water storage-driven environments. As shown by Blum (2005), the potential agronomic use from a given mechanism of drought tolerance depends on the characteristics of the drought environment (severity, duration and timing of stress). He critically analyzed the breeding focus on water use efficiency because drought tolerance traits improving plant water extraction and leading to sustained stomata opening and assimilation might even result in lower water use efficiency (Blum, 2009). Therefore he suggests a shift to the concept of effective water use which agrees to the conclusion of Jones (2004a) on the key importance of and efficient use of available soil water in field crop production.

Affectivity of water use is considered in equation 3 in terms of the proportion of transpiration in relation to the loss components in a water balance frame. In the conceptual model of Hsiao et al. (2007) for dry land cropping, this uptake efficiency would correspond to the combined effect of infiltration, rhizostorage, consumptive and transpiration efficiencies.

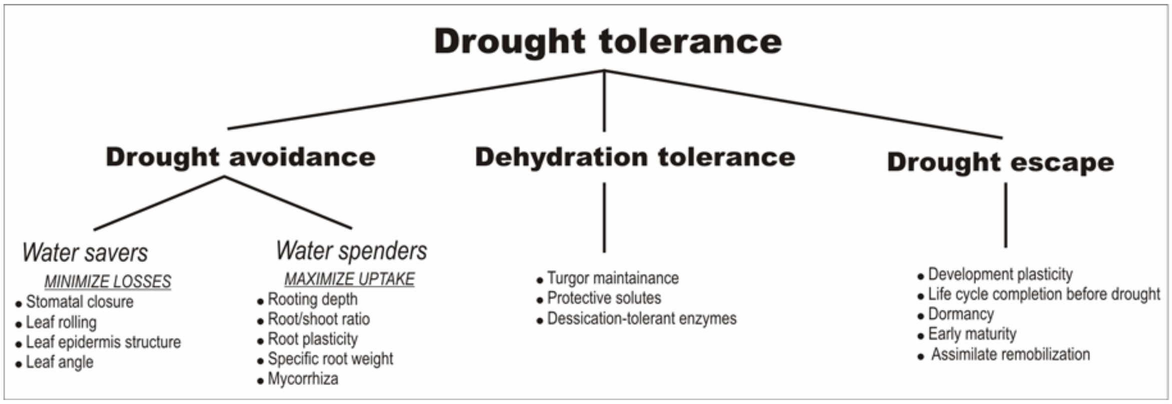


Figure 1.1 Mechanism of drought tolerance. Plants tolerate drought by using different mechanisms including drought avoidance, dehydration tolerance and drought escape. These mechanisms are governed by physiological processes and help plants to sustain growth and reproduction under drought conditions (after Levitt, 1972 and Jones, 2004a)

An effective water use requires consideration of soil hydrological aspects and their interaction with plant traits. In simplified way water use effects of soil and plant parameters can be characterized by a relationship commonly used in hydrological modelling (e.g. Šimůnek et al., 2008).

$$T_a = ET_p(1 - e^{-kLAI}) \int_{LR} \alpha(h) b(x) dx \qquad (4)$$

where actual transpiration (or water use) is a function of potential evapotranspiration (ET_p), a light extinction coefficient (*k*), leaf area index (LAI), a stress reduction function (α) and root distribution (*b*) over the root depth (LR). Canopy traits (*k*, LAI) influence the surface energy balance and determine the amount of energy available for potential soil evaporation and plant transpiration. In the rhizosphere, soil hydraulic properties and root system characteristics determine actual root water extraction (T_a). Potential water uptake is attributed to distinct soil layers according to the root distribution and adjusted to its actual amount by the soil water status (e.g. soil matrix potential *h*) in the distinct layers using an appropriate functions for α (e.g. Feddes et al. ,1974; Van Genuchten, 1987).

While plant physiologists, breeders and agronomists have directed most attention on the aboveground plant parts (stomata, leaf, and canopy) and their role for water use efficiency, soil hydrologists focused more on plant water uptake. They tended to reduce water uptake to a macroscopic sink term in their models. If effective water use is an essential target (Blum, 2009) together with high water use efficiency, future efforts should be directed to better understand root system processes and root-soil interactions to achieve an overall improvement of agricultural water use.

1.3.3 Methodological challenges

The definitions of water use efficiency as given in Table 1 imply that appropriate methods have to be used for quantification at different scales. At the leaf scale, water use efficiency is characterized by measurements of gas exchange and stomatal conductance. The underlying methods of measuring CO_2 and H_2O fluxes are straightforward and several types of measurement devices are available.

A method relying on gas exchange physiology, but providing a time integrated view of water use efficiency is carbon isotope discrimination (Farquhar and Richards, 1984). Carbon isotope technique has been used to select genotypes possessing better water use efficiency (Johnson et al., 1990; Martin et al., 1999; Condon et al., 2004). Still the use of carbon isotope discrimination for crop improvement strongly depends on the hydrological regime (Monneveux et al., 2005). It has been applied most successfully to select adapted genotypes in storage driven and terminal drought environments. This was explained by the conservative water use of varieties with high water use efficiency (low carbon isotope discrimination) ensuring sufficient water availability at grain filling. Also their phenology was adapted to terminal drought environments showing earlier flowering which is a characteristic drought escape strategy (Condon et al., 2004). Under intermittent drought and potential yield conditions, carbon isotope discrimination can also be negatively related to crop performance.

A proper quantification of water use efficiency on the whole plant scale requires an accurate measurement of the transpiration component. Frequently water relations are studied in pot experiments which allow a simple and precise measurement of transpiration when withholding soil evaporation. Still care must be taken when extrapolating results from pot experiments to the field due to (i) alterations of root growth in the confined system and (ii) influences of pot size on water availability and transpiration (Ray and Sinclair, 1998).

In field studies, transpiration is mostly calculated via the water balance equation. This however implies at least two uncertainties. First the other components of the water balance (i.e. precipitation/irrigation, runoff, drainage, and change in profile water content) have to be quantified accurately. While runoff can easily be avoided by a proper site selection, the drainage component is very difficult to measure. The most adequate instrument to determine all water balance components are lysimeters. As they are not available in most cases, water use efficiency values are frequently derived from measurements of change in profile water content only using different water monitoring techniques and assuming zero drainage. We therefore assume that differences in water use efficiency estimates found in literature often derive from methodological difficulties of quantification of the water balance components and errors originating in simplified assumptions.

Even with properly measured evapotranspiraion, a further uncertainty arises from the separation between soil evaporation and plant transpiration. Although there are efforts to develop methods based on isotope composition (Hsieh et al., 1998), still most studies rely on calculations based on Beer's law and measurements of leaf area index and radiation extinction coefficients (Brisson et al., 2006).

Due to difficulties in measurement, water use efficiency effects are frequently evaluated using simulation models. Policy makers and water resource managers have to deal with multitudinous scenarios of cropping systems, amounts, timing and method of irrigation and fertilizer application for bringing improvement in water use efficiency. Experimentation cannot address all scenarios, but accurate simulation models may fill in the gap when appropriately parameterized and validated. Different simulation models (e.g. AquaCrop, CropSyst, DSSAT, GOSSYM, WOFOST) have been used to simulate yield and water use under a variety of environmental, management and cropping regimes.

Simulation of crop performance in the FAO model, AquaCrop (Steduto et al., 2007) is based on a normalized biomass-to-transpiration ratio, taken the conservative nature of this ratio (Steduto et al., 2007). The model has been used to predict yield and water use under full and deficit irrigation management with sufficient accuracy (Farahani et al., 2009; Fang et al*.,* 2009).

Beside management assessment and decision support, models were also successfully applied to better interpret the potential impact of carbon isotope discrimination on the performance of wheat varieties under different environmental conditions (Condon et al., 2004).

Although simulation models are based on straightforward physical theory such as the Richards' equation for water flow, an accurate parameterization of plant water uptake is essential. Beside the problem of spatial and temporal variability in soil hydraulic properties, most simulation studies do not have measurements of root distribution that underlie the sink term calculation in water uptake modelling (Feddes and Raats, 2004), let alone parameters for more complex root architecture models (Leitner et al., 2010). Furthermore plant-soil interactions involved in water uptake compensation (Šimůnek and Hopmans, 2009), root tropism (Eapen et al., 2005) and biochemical signalling (Comstock, 2002), that essentially effect plant stress response and water use efficiency, are rarely considered in crop models.

Evett and Tolk (2009) concluded that models adequately simulate water use efficiency under well watered conditions, but tend to misestimate water use efficiency under conditions of water stress. This reveals the need for a better representation of plant-soil interactions in current models, overcoming empirical stress reduction functions and simplified root system descriptions. However, even with more physically based models, a major challenge for their reliable application in agricultural water management will remain the quality of parameterization of sensitive components determining water uptake and plant growth.

1.3.4 Better agronomy

Food and Agriculture Organization (FAO, 1997) provided a summary of practical measures recommended in order to improve water use efficiency (Table 1.3). Measures oriented to enhance crop growth can be classified into those dedicated to crop rotation design and crop husbandry (1 to 3), fertilizer management (4), soil management (5 and 6) and appropriate irrigation management (7 and 13).

Table 1.3 Food and Agriculture Organization recommendations for practical measures to improve agricultural water use efficiency in irrigated agriculture (FAO, 1997)

Objective	Measure
Enhancement of crop growth	1.) Select most suitable and marketable crops for the region.
	2.) Use optimal timing for planting and harvesting.
	3.) Use appropriate insect, parasite and disease control.
	4.) Apply manures and green manures where possible and fertilize effectively preferably by injecting the necessary nutrients into the irrigation water.
	5.) Use optimal tillage to avoid excessive cultivation
	6.) Practice soil conservation for long-term sustainability.
	7.) Irrigate at high frequency and in the exact amounts needed to prevent water deficits, taking account of weather conditions and crop growth stage.
Conservation of water	8.) Avoid progressive salinization by monitoring water-table elevation and early signs of salt accumulation, and by appropriate drainage.
	9.) Reduce direct evaporation during irrigation by avoiding midday sprinkling. Minimize foliar interception by under-canopy, rather than by overhead sprinkling.
	10.) Reduce runoff and percolation losses due to over irrigation.
	11.) Reduce evaporation from bare soil by mulching and by keeping the inter-row strips dry.
	12.) Reduce transpiration by weeds, keeping the inter-row strips dry and applying weed control measures where needed.
	13.) Reduce conveyance losses by lining channels or, preferably, by using closed conduits.

The basic assumption underlying these set of instruments is that any management measure that helps to improve yield will ultimately lead to a better water use efficiency (Gregory, 2004; Machado et al., 2008; Ritchie and Basso, 2008). This includes changes in transpiration efficiency (e.g crop type) as well as change in the proportion of transpiration to the loss components in the water balance components by soil and crop management measures (Figure 1.2). The affectivity of a given management decision to obtain an improvement in overall water use efficiency will be determined also by its interaction with environmental site characteristics (Abbate et al., 2004).

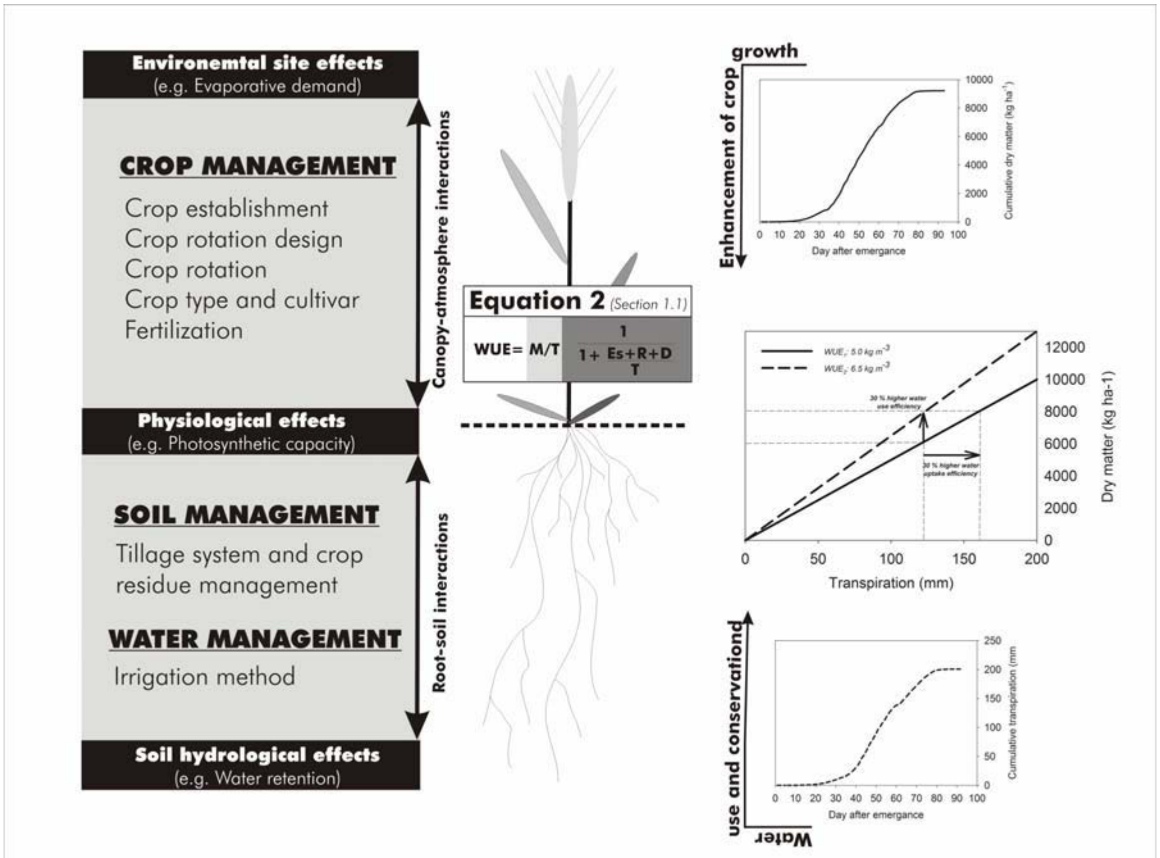


Figure 1.2. Effect of management practices on water use efficiency. Management practices can improve water use efficiency by affecting yield and transpiration efficiency. The affectivity of any management practice will depend on its interaction with environment.

The following section will review the potential impact of crop soil and irrigation management practices as well as the mechanisms underlying their expected effects on water use efficiency.

1.3.4.1 Crop management

Crop management practices include decisions on sowing date, planting density, crop rotation, phytosanitary measures and variety selection. These practices influence agronomic water use efficiency by adapting the cropping system to the environmental site conditions and providing optimum growth conditions for the single crop in order to obtain maximum yield with available resources.

Crop management practices influence water use efficiency at the level of field crop stands, single plants and physiological processes (Figure 1.3). Beside crop husbandry, also management of soil fertility by fertilization is considered here, although it strongly interacts with soil management measures that are considered in 2.2.

Sowing and stand establishment practices

Sowing date of crops can significantly affect water use efficiency (Morrison and Stewart, 2002; Turner, 2004; Gunasekera et al., 2006). Early sowing has frequently been found to improve yield and water use efficiency (Gregory, 2004) while yields were reduced by delayed sowing (Oweis et al., 2000; Faraji et al., 2009).

In environments where water is the limiting factor, sowing date should adapt crop growth and development to water availability (water storage, rainfall distribution) within the restrictions imposed by other constraints (early droughts, frost, timing of weed management). An appropriate sowing date can enhance early vigour of the crop with better canopy cover of the soil surface. This reduces evaporation losses in favour of transpiration (Tambussi et al., 2007). Increased water use efficiency of early sown crops and winter-grown varieties is also related to the lower evaporative demand of the atmosphere during part of the growing period (Purcell et al., 2003).

Humphreys et al. (2001) showed that early sowing of winter crops immediately after rice harvest increased the water use efficiency of rice-based cropping systems by better use of stored soil water and capture of winter rainfall instead of loosing it as runoff or deep percolation. An appropriate sowing time of cereals also contributes to avoid summer drought in Mediterranean climates, i.e. it benefits from a drought escape strategy which ensures sufficient water supply for yield formation (Tambussi et al., 2007).

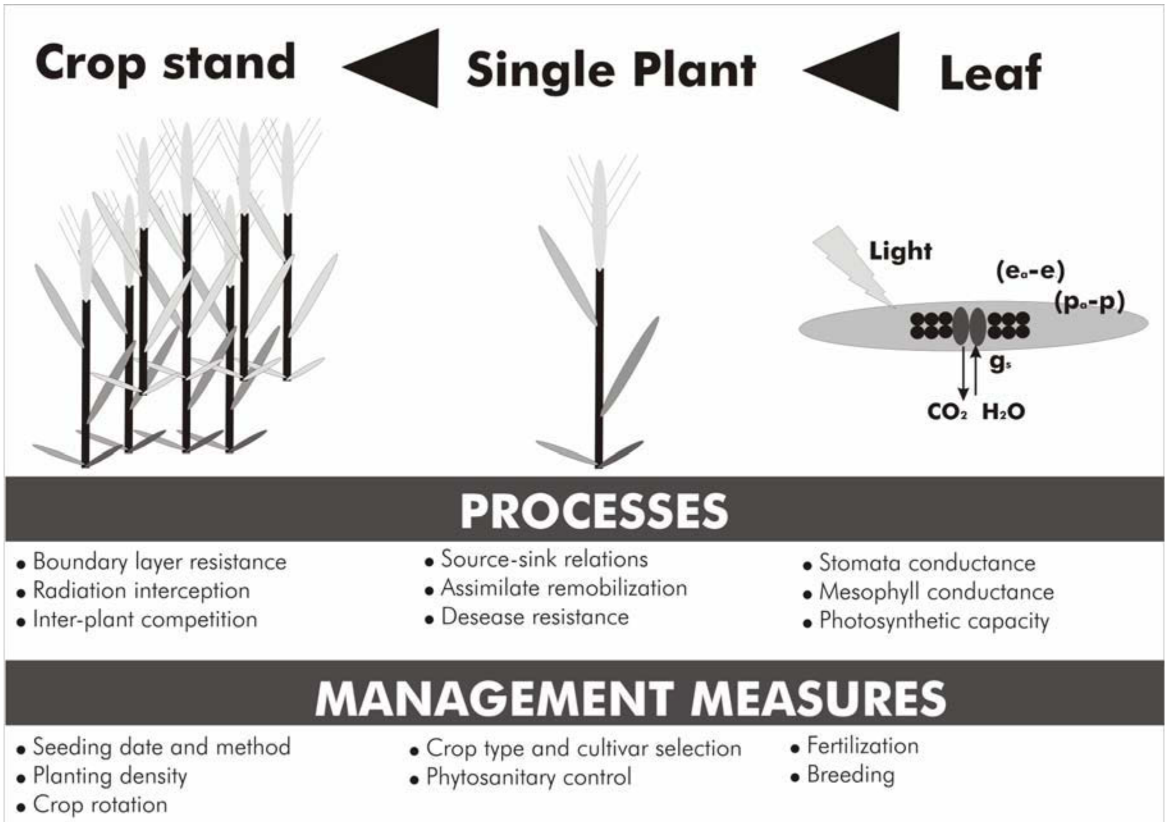


Figure 1.3. Measures and processes involved in regulation of water use efficiency. Management measures positively affect physiological processes at single leaf scale. These effects are transformed into better growth of individual plants with consequences of increase in overall water use efficiency of crop stands

Using appropriate method of sowing can also help to improve water use efficiency. Particularly sowing depth can influence early vigour and hence soil evaporation (Ali and Talukder, 2008). Deeper sowing combined with varieties with longer coleoptiles was found to increase growth vigour, yield and water use efficiency of wheat in environments with early droughts as seedlings could make better use of soil moisture (Rebetzke et al., 2007). Research in southern Queensland found that water use of rice grown on beds was 32 % less than when grown using conventional permanent flood, while yields were maintained, resulting in a large increase in water use efficiency (Borrell et al., 1997). Sowing of crops on precisely levelled fields can also affect water use efficiency positively by ensuring uniform distribution of irrigation water over the entire field and thereby ensure homogeneous and quick stand establishment. Laser levelled fields exhibited 98.7 % and 29.4 % higher water use efficiency as compared to unlevelled and traditionally levelled fields in case of wheat. Use of laser land levelling surely increases grain yield and save irrigation water as compared to traditional method of sowing (Asif et al., 2003).

Sowing of crops with proper row spacing can also affect water use efficiency. Karrou (1998) found that water use efficiency decreased with increasing row spacing from 12 to 24 cm in wheat. Azam-Ali et al. (1984) on the contrary found that increasing row spacing in pearl millet from 37.5 to 150 cm increased water use efficiency for dry matter production from 2.1 to 4.7 kg m^{-3}. It was due to the reason that widely spaced plants used water more efficiently as compared to narrow and medium spaced plants in this study. A major influence of row spacing is related to soil evaporation that can be reduced by narrowing row distance (Chen et al., 2010). High stand densities increase intra-plant competition. Therefore the effect of row spacing on yield strongly depends on crop species, formation of yield components and seasonal water availability. Ritchie and Basso (2008) for example showed that modern varieties of maize can be planted at higher densities as traditionally used, thereby increasing yield and decreasing evaporation losses. Crops such a cereals have high plasticity in plant architecture and yield components (Simane et al., 1993) so that yield formation remains unaffected over a wide range of row spacing (Gregory, 2004).

The technique of seed priming has been shown to improve plant stands and provide benefits in terms of earlier canopy closure and increased seed yield for a range of crops such as wheat, maize, lentil, chickpea in rain fed as well as for irrigated crops (Ali, 2004; Rashid et al., 2002). Seed priming involves soaking seeds in water for a specific period usually overnight, then surface dried and then sown. This technique reduces the pre- or post-sowing irrigation needs, saves water and increases the water use efficiency. Germination and water use efficiency of barley was improved by 95 % and 44%, respectively due to seed priming as compared to unprimed seed (Ajouri et al., 2004).

Crop rotation

Larcher (1994) compared net prime production of agricultural to natural ecosystems. Agricultural systems averaged 0.65 kg m^{-2} of annual dry-matter production, which is in the range of natural grassland and steppe (0.6 kg m^{-2}). Most natural terrestrial ecosystems have a higher productivity than agricultural systems, particularly those with high average leaf area index. This indicates an optimized use of growth factors over the year by natural plant communities. Site specific crop rotation design is intended to achieve a high utilization efficiency of light, water and nutrients to maximize growth and yield. Crop rotation can optimize water use efficiency by (i) increasing the number of crops grown per year, (ii) more effective use of available resources, and (iii) better phytosanitary conditions.

Passioura (2006) indicates that water use efficiency depends not only on how a crop is managed during its life, but also how it is fitted into the whole management system. Continuous cropping that avoids fallow can increase single crop as well as system water use efficiency and avoids damages caused by bare fallows (Schillinger et al., 1999; Li et al., 2000). Pala et al. (2007) evaluated several wheat based crop rotations under Mediterranean conditions in Syria. Water use efficiency of wheat decreased in the following crop rotation sequence: fallow, medic, lentil, chickpea, and continuous wheat. However, on a system basis, wheat-lentil and wheat-vetch systems were more efficient than the wheat-fallow system. Sadras et al. (2003) proposed a strategy to adapt crop rotation decision flexibly to conditions at the start of the growing season for south-eastern Australian dry-land farming. Introduction of canola (*Brassica napus*) into a wheat based rotation in wetter years improved whole farm profitability and water use efficiency.

Cover cropping is a common crop rotation practice to avoid negative environmental effects of autumn fallows after cash crop harvest by prolonging soil coverage and plant growth over the season (Bodner et al., 2010). It is intended to control erosion, prevent nutrient leaching, fix nitrogen and improve soil conditions. Additional water use of cover crops however could negatively affect soil water availability for the next crop. Bodner et al. (2007) showed that water use efficiency of cover crops species is high compared to cash crops of similar habitat and same families. This is due to the substantially lower evaporative demand of the atmosphere during the vegetation period of the cover crops. Negative effects due to soil water depletion was highest after dry autumn conditions when cover crops continued water extraction from deeper layers, while fallow evaporation was reduced (Islam et al., 2006). Potential yield effects are dependent on the height of winter precipitation, water storage capacity of the soil, phenology and water uptake characteristics of the subsequent cash crop as well as rainfall distribution over the cash crop growing period.

Crop rotation is an important management tool to improve resource use of the cropping system. Interrupting a series of cereal crops by oilseeds or grain legumes can increase the yields of the subsequent cereal crops. The inclusion of oilseed and pulses in traditional, cereal-based cropping systems has been shown to improve nutrient use efficiency (Walley et al., 2007), increase the overall productivity and water use efficiency (Miller et al., 2003), and improve economic sustainability (Zentner et al., 2002). The role of canola (*Brassica napus)* as a "break" crop in southern Australia has been especially notable (Passioura, 2002). The development of winter-growing chickpeas in the Mediterranean region may serve a similar role (Singh et al., 1997).

Inclusion of deep rooted legumes like lucerne in farming systems of semi arid regions for 2-3 years has also been suggested as a measure towards efficient utilization of soil water and nutrients by many researchers (Rasse and Smucker, 1998; Latta et al, 2001; Ridley et al*.,* 2001). Introducing a legume crop in a cereal rotation can improve soil fertility by nitrogen fixation and addition of organic matter in the soil, increase the yields of the subsequent cereal crops and help to control disease, pests, and weeds that build up in continuous cereal production systems (Papastylianou, 1993; Diaz-Ambrona and Miniguez, 2001; Ali and Talukder, 2008). Wheat–legume rotation systems with additional nitrogen input in the wheat season not only ensure sustainable production, but also are more efficient in utilizing limited rainfall by better root water uptake and increased transpiration efficiency (Pala et al., 2007). Pulse crops with oilseeds or wheat in a well planned crop sequence may improve water use efficiency for the entire cropping systems in semiarid environments. Pulses extract water slowly only from shallower soil depths thereby leaving sufficient water in the soil for subsequent crops in rotation (Gan et al., 2009). Effect of crop management practices on water use efficiency is shown in Table1.4. These values are indicated here only to demonstrate the potential of a crop management practice on water use efficiency and may vary greatly among regions as well as with application of supporting soil and irrigation management practices.

Table 1.4: Effect of crop management practices on water use efficiency

Practice	Increase in water use efficiency (%)	Reference
Seed priming	44	Ajouri et al. (2004)
Sowing time	30	Jalota et al. (2008)
Method of sowing	15-20	Zhang et al. (2007a)
Row spacing	> 100	Azam-Ali et al. (1984)
Weed control	>100	Cooper et al.(1987)
Crop rotation	0-57	Pala et al. (2007)

Appropriate choice of crop sequence can improve water use efficiency by helping to control diseases and weeds. Weeds compete for water and nutrient resources of the main crops. Weeds can considerably decrease crop growth and water use efficiency particularly in food legume crops which have slower initial growth than many cereals. Weed control ensures that water stored in soil is used by the crops (Gregory, 2004). Also the efficiency of fallowing to increase water availability for the next season is highly dependent on weed control (Gregory, 2004). In lentil for example weed control almost doubled dry matter production and water use efficiency (Cooper et al., 1987). Control of pests and diseases by an appropriate crop rotation can be an efficient way to increase yield and water use efficiency. Paul and Ayres (1984) for example reported that plants infected with leaf rust showed reduced water use efficiency, particularly under dry conditions.

Crop type and variety selection

Crop type and variety selection contributes to adapt the production system to environmental growth conditions and it is fundamental for site specific optimization of water use efficiency. Distinct response to water limiting conditions occurs due to (i) different photosynthetic pathway and (ii) different energy requirements for yield formation, as well as (iii) progress in breeding of adapted drought tolerant varieties. Plants with the C3 photosynthetic pathway are less efficient in water use than plants with the C4 pathway, especially at higher temperatures and lower CO_2 concentrations (Condon et al., 2004; Long, 2006; Ali and Talukder, 2008). In species with C4 photosynthesis high photosynthetic rates can be associated with low stomatal conductance, leading to high water use efficiency (Cowan and Farquhar, 1977; Schulze and Hall, 1982). In C4 plants carboxylation is carried out by an enzyme (PEP carboxylase) with stronger affinity for CO_2 than in C3 species (Rubisco), leading to a lower intercellular CO_2 concentration and thus a higher driving force gradient for CO_2 uptake (Nobel, 1991; Chavez et al., 2004). With rising atmospheric CO_2 levels, it is likely that transpiration efficiency will increase in C3 crops. Except for maize and sorghum, the world's major food crops are C3 plants.

Field experiments with free-air CO_2 enrichment have shown substantial improvement in biomass, especially where water is limiting. With C4 crops such as maize and sorghum, free-air CO_2 enrichment experiments have shown negligible growth responses to elevated CO_2 (Passioura and Angus, 2010). Some benefit of elevated CO_2 on C4 crops was shown in drought conditions due to reduced water use (Sun et al., 2009). Following attempts to use conventional hybridization to get C3–C4 hybrids, some biotechnological advances to transformed C3 plants to acquire C4 characteristics have been reported (Matsuoka et al., 2001; Parry et al., 2005).

In relation to yield, water use efficiency decreases from cereals over legumes to oil crops due to higher energy requirements in yield formation (Steduto et al., 2007; Jones, 2004a). High water use efficiencies are obtained in forage crops where the entire aboveground portion of the plant is harvested. Higher water use efficienyc for forage crops when compared to seed crops is also related to lower non-productive water losses through evaporation under their closed canopies (Hatfield et al., 2001). Nielsen et al. (2005) found the highest average water use efficiency among forage crops for forage pea (2.28 kg $m^{-3\ 1}$), declining to 1.14 kg m^{-3} for corn silage (Nielsen et al., 2005). Table 1.5 gives an overview of water use efficiencies of different crops grown under Mediterranean conditions.

Table 1.5: Water use efficiency (kg m^{-3}) of crops in the Mediterranean region. Values refer to relationship between yield and evapotranspiration (After Katerji et al., 2008)

Crop	Water use efficiency	Reference
Wheat	0.5–9.4	Oweis (1997); Katerji et al. (2005b); Pala et al. (2007)
Corn	1.36–2.15	Karam et al. (2003); Dagdelen et al. (2006)
Sunflower	0.39–0.72	Marty et al. (1975) ; Katerji et al. (1996)
Soybean	0.39–0.77	Katerji et al. (2003); Karam et al. (2005)
Broad bean	0.45–1.37	Katerji et al. (2003); Katerji et al. (2005a)
Chickpea	0.4–0.98	Oweis et al. (2004); Katerji et al. (2005a)
Lentil	0.36–2.09	Katerji et al. (2003); Oweis (2004)
Cotton	0.61–1.3	Dagdelen et al. (2006); Karam et al. (2006)
Barley	1.46–2.78	Katerji et al. (2006)
Sorghum	0.67–1.59	Mastrorilli et al. (1995)
Potato	16.2–18.5	Katerji et al. (2003)
Sugar beet	6.6–7.0	Katerji et al. (2003)
Tomato	4.4–8.3	Katerji et al. (2003)
Grapes	16–18.1	Rana and Katerji (2007)

Water use efficiency varies between different genotypes of the same crop (Hufstetler et al., 2007; Jaleel et al., 2008; Rajabi et al., 2009). Much effort has been dedicated to breed for higher water use efficiency. Reynolds and Tuberosa (2008) give an overview of breeding advances for improved productivity in drought-prone environments. Following Passioura' framework, most success was achieved via higher harvest index (Condon et al., 2004). Only recently breeding efforts for enhanced water uptake capacity by targeting root parameters are reported (Yusuf Ali et al, 2005; Kato et al., 2006; Gregory et al., 2009). Substantial progress therefore can be expected in future from improved root systems as Waines and Ehdaie (2007) showed that breeding of high yielding "green revolution" varieties has lead to small root systems with low uptake capacity.

Useful traits for improved drought tolerance depend on the characteristics of the drought environment itself (van Ginkel et al., 1998). In relation to water use efficiency, Condon et al. (2004) showed that wheat varieties efficient in water use and selected based on carbon isotope discrimination by reduced stomatal conductance performed better and attained higher yields in stored-moisture environment, than in environments where they have to rely upon in-season rainfall. Genotypes where higher water use efficiency is related to photosynthetic capacity ("capacity types") and not to lower stomatal conductance ("conductance types") would result in sustainable yield improvements. Considering the typically erratic nature of rainfall in dry areas with dry and wet years, Blum (2005, 2009) concluded that sustainable optimization of yield should be obtained by maximising water uptake efficiency rather than water use efficiency. Figure 1.4 gives an overview of expected yield response to drought of varieties from these different selection targets.

Fertilizer management

Relationships between nutrients and water use efficiency were first described by Viets (1962). The roles of different nutrient elements are discussed by Marschner (1995) and their effect on water use efficiency was reviewed by Davis (1994) and Raven et al. (2004).

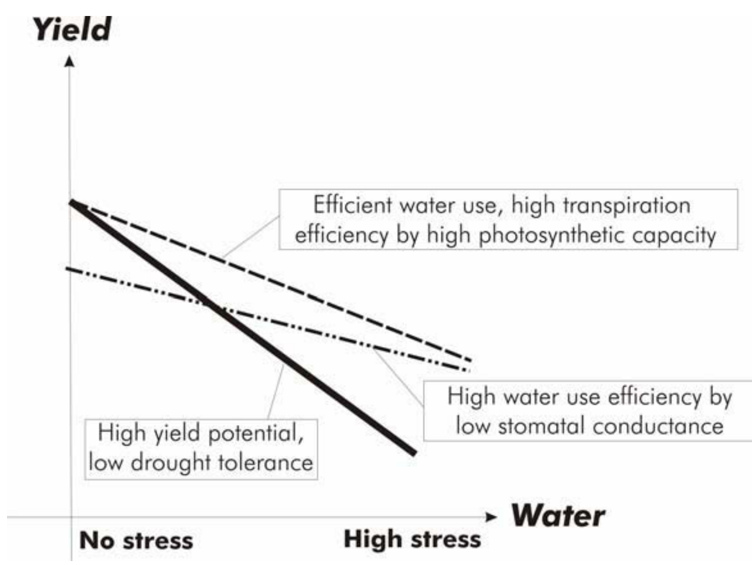


Figure 1.4: Response of varieties under water stress. Varieties may vary in their response to water stress. High water use efficiency under water stress can be due to increase in transpiration efficiency, low stomatal conductance or high yield potential.

Water availability and nutrient supply are interacting factors in determining crop growth and crop water use efficiency. The efficiency of nutrients to increase yield depends on water supply according to the law of optimum: For higher production, the plant can make better use of the growth factor being in minimum, the more the other growth factors are within the optimum (Claupein, 1993). With increasing water stress, nutrient availability as well as nutrient uptake capacity of the plant are impaired and the marginal return in terms of yield increase per unit of applied nutrient decreases (Ehlers and Goss, 2003). Drought can limit nutrient availability due to reduced mineralization of organic matter and lower transport of nutrients to the root. Both, convective transport of non-adsorbing solutes (e.g. nitrate) as well as diffusive transport of adsorbing nutrients (e.g. phosphate) is reduced with increasing water shortage. Decreasing transpiration flux can cause nutrient deficiency in leaves due to reduced xylem transport of dissolved nutrients from roots to the aboveground plant parts (Alam, 1999).

Nutrient uptake capacity is significantly influenced by root system parameters. Root growth and root distribution are modified by nutrient availability and distribution in the soil (Hodge, 2004). Plants respond to low nutrient availability by enhanced root growth and root exudation. If water use efficiency is related to aboveground biomass or yield, it can even decrease with increasing investment of assimilates and energy into the root system (Raven et al., 2004).

The nutritional status of the crop influences stomatal response and water use efficiency at leaf, whole plant and crop stand scale. Several physiological processes relevant for water use efficiency are affected by nutrient deficiencies, such as osmotic pressure, stomata regulation, photosynthesis and activity of nitrate reductase in plant leaves (Hu and Schmidhalter, 2005; Li et al., 2009).

At the whole plant and crop stand scale, the nutrient status influences growth rate, leaf area and green leaf duration as well as assimilate partitioning (Davis, 1994; Gregory 2004). When relating water use efficiency to total evapotranspiration, improvement by fertilizer input is obtained via increase in early canopy growth so that it shades the surface and thereby reduces the proportion of soil evaporation on total evapotranspiration (Schmidhalter and Studer, 1998; Gregory, 2004). Higher nutrient availability leads to a different rate of increase in water use and crop yield. Early studies already reported that improved nutrient status promoted yield more than water use and therefore resulted in better water use efficiency (Power, 1983; Ritchie, 1983). Also Hatfield et al. (2001) consider fertilization as a principal measure to improve plant growth and yield and thereby increase water use efficiency.

Nitrogen (N) management is one of the major factors to attain higher crop productivity. Nitrogen effects have been described on gas exchange as well as integrative agronomic water use efficiency. Positive effects of nitrogenous fertilizers include increase in leaf area index, green crop duration and dry matter production that ultimately lead to increase in water use efficiency (Latiri-Souki et al., 1998).

Up to 75% of leaf nitrogen is present in the chloroplasts, most of it in the photosynthetic machinery which gives a positive relationship between light-saturated rate of photosynthesis and leaf nitrogen concentration (Evans,1989). Leaf nitrogen is correlated with photosynthetic capacity by influencing Rubisco activity and the capacity of electron transport. Although assimilation is not directly proportional to leaf nitrogen, an enhanced photosynthetic capacity due to better nitrogen-supply can results in higher transpiration efficiency at a given stomatal conductance (Shangguan et al., 2000).

Nitrogen deficiency can reduce mesophyll conductance and to a lesser extent, stomatal conductance (Jacob et al., 1995). Cavaglia and Sadras (2005) analyzed nitrogen effects on the relative response of radiation use efficiency, which is related to both stomatal and mesophyll conductance, and transpiration per unit intercepted radiation, which is related to stomatal conductance. Reduced nitrogen inhibited radiation use efficiency more than water conductance, resulting in reduced transpiration efficiency. Also Ciompi et al. (1996) related lower gas-exchange water use efficiency of nitrogen-deficient sunflower leaves to a more pronounced reduction of mesophyll activity compared to stomatal conductance.

Beside physiological processes, a main effect of nitrogen-deficiency on water use efficiency is found on the whole plant and crop stand level. Restricted development of nitrogen-deficient plants is usually due to a lower rate of leaf expansion rather than to a decline in the rate of photosynthesis per unit leaf area (Sage and Pearcy, 1987). Reduction in leaf expansion and leaf area under low nitrogen supply decreases radiation interception and leads to higher evaporation losses (Davis, 1994). Therefore higher water use efficiency of well fertilized plants is mostly explained by a higher proportion of transpiration in relation to total evapotranspiration. When water use efficiency is related to yield, an additional advantage of nitrogen fertilization is prolonged green leaf area duration and higher harvest index (e.g. Lawlor, 2002). However, ample nitrogen supply could also result in abundant vegetative growth which may induce water shortages during yield formation as well as increased logging (Ehlers and Goss, 2003).

The effect of nitrogen on root water uptake capacity is complex (Li et al., 2009). Rational use of fertilizers can enhance root growth, while high levels of nitrogen tend to reduce root penetration into the soil and restrict formation of fine roots and root hairs, which could increase crop susceptibility to temporal water shortage.

Increased water use efficiency due to nitrogne fertilization was reported for grain sorghum and maize by Varvel (1995) and Ogola et al. (2002). Higher water use efficiency due to increased biomass production with improved nitrogen supply have also been reported for wheat and corn by Campbell et al. (1992) and Varvel (1994), respectively. A 25 % increase in water use efficiency of chickpea has been reported through application of nitrogen fertilizer (Bahavar et al., 2009). In the Sahel, water use efficiency of Pearl millet was improved through the combination of nitrogen management and increased plant densities (Payne, 1997).

The efficiency of nitrogen management to improve water use efficiency is influenced by environmental conditions. Under limited water supply, crop response to higher dose of inorganic fertilizer is restricted (Hatfield et al., 2001). Under such conditions, timing and dose of fertilizer application shall be adjusted based on available soil moisture if positive effects of nitrogen application are to be fully realized (Passioura, 2006).

Phosphorus is required for several physiological processes including storage and transfer of energy, photosynthesis, regulation of some enzymes, and transport of carbohydrates (Hu and Schmidhalter, 2005). Soils in arid Mediterranean areas as well as large areas in the tropics suffer from low phosphate availability. Phosphorus supply to the plant in these regions is further reduced by dry soil conditions that lower diffusion rates to the roots (Simpson and Pinkerton, 1989). Plant phosphorus uptake efficiency is strongly influenced by root traits (Lambers et al., 2006; Lynch, 2007) as well as mycorrhization (Bolan, 1991), while sufficient soil phosphorus can enhance root growth, water uptake and water extraction from deep soil layers (Dang, 1999). Payne et al. (1992) found an increase of transpiration efficiency at the whole plant as well as the leave scale. Increasing phosphorus availability resulted in stronger increase in photosynthetic rate compared to transpiration rate. Phosphorus deficiency was found to lower the level of light saturation which could explain observed inhibition of photosynthetic rate (Payne et al., 1992). On the whole crop level, strong effects of additional phosphorus supply on dry matter production and water use efficiency, particularly under low water availability, have been reported for millet by Brück et al. (2000). Kundu et al. (2008) showed increasing leaf area index and higher water use efficiency of common bean with higher phosphorus supply. Addition of phosphatic fertilizer has been reported to enhance water use efficiency of different crops (Hatfield et al., 2001), such as pearl millet (Payne et al., 1992, 1995) and chickpea (Singh and Bhushan, 1980).

The positive effect of potassium (K) on water stress tolerance is related to several physiological processes (Pettigrew, 2008). Potassium maintains the osmotic potential and turgor of the cells (Hsiao, 1973) and regulates the stomatal functioning (Kant and Kafkafi, 2002; Benlloch-Gonzales et al., 2008). Potassium enhances photosynthetic rate, yield and water use efficiency under stress conditions (Tiwari et al., 1998; Egila et al., 2001; Umar and Moinuddin, 2002). Improvement of potassium nutritional status has also been found to protect plants against oxidative damage during drought stress (Cakmak, 2005). Potassium promotes root growth of plants which in turn leads to a greater uptake of nutrients and water by plants (Saxena, 1985; Rama Rao, 1986). Gerardeaux et al. (2010) described effects of potassium deficiency on cotton. Potassium stress during vegetative development decreases plant dry matter production and leaf area, increased dry matter partitioning to leaves and specific leaf weight. Severe deficiency also reduced partitioning to roots and inhibited leaf photosynthetic rates.

Positive effect of potassium on drought tolerance include enhancement of deep rooting, protection against tissue dehydration, optimization of stomatal opening and closure resulting in better water use efficiency, detoxification of toxic oxygen radicals, and improvement in translocation of photo assimilates (Römheld and Kirkby, 2010). Higher application of potassium such as 125 and 200 kg ha^{-1} increased water use efficiency of barley for dry matter production by 12 % (Anderson et al., 1992). He et al. (1999) conducted experiments to clarify the effects of water, nitrogenous and potassium fertilizer and animal manures on water uee efficiency of potatoes. The results showed that both fertilizer and water supply very significantly increased water use efficiency. Application of farm yard manure and recommended doses of NPK to soybean for three consecutive years increased seed yield and water use efficiency by 103 % and 76 %, respectively, over the unfertilized control (Hati et al., 2006). Effect of fertilizers on water use efficiency is indicated in Table 1.6. These values may vary among crops, regions and with other management practices and shall be interpreted with great care.

Table 1. 6: Effect of fertilizers on water use efficiency

Practice	Increase in water use efficiency (%)	Reference
Nitrogenous fertilizers	20-60	Dordas and Sioulas (2008); Bahavar et al. (2009)
Phosphatic fertilizers	35	Singh and Bhushan (1980)
Potassium fertilizers	12	Anderson et al.(1992)
NPK and farm yard manure	7-76	Gu et al. (2004) ; Hati et al. (2006)

Increased use of chemical fertilizer in dry land farming has doubled grain yields and water use efficiency (Deng et al., 2006). Davis and Quick (1998) suggested that variety selection for improved water use efficiency should be based on an understanding of the role of nutrient management on photosynthetic rate, yield, rooting characteristics, and transpiration. To optimize water use efficiency, variety and nutrient management decisions have to be made together. Nutrient application decisions for a given crop shall be made based on soil fertility tests and use of balanced nutrition at appropriate time of crop growth can help to obtain better crop yields and water use efficiency.

Fertilizer effects on water use efficiency are related to physiological leaf processes, root system dynamics as well as radiation use within a field crop stand. Nutrient supply and crop water status interact in determining the balance of dry matter accumulation to transpiration losses. Most studies were made on nitrogen fertilization. They suggest that high improvement could be expected at the level of the crop stands by the common effect of better radiation use efficiency and reduced soil evaporation due to enhanced leaf growth rate. Improved photosynthetic capacity of plants with optimum nutrition status seems to contribute also to improve transpiration efficiency. Under water stress, potassium is of particular importance for maintenance of tissue water status, cell expansion and sustained water uptake from the drying soil. Phosphorus is limiting growth in several arid and semi-arid regions of the world, particularly in tropical ecosystems. Root properties are essential to improve the phosphorus status of plants which in turn can lead to better water use efficiency.

Appropriate crop management practices contribute to improve several components of agronomic water use efficiency. Substantial increase of water use efficiency by better crop management is documented by Xu and Zhao (2001) in north China where water use efficiency improved threefold during 1949 to 1996. This was due to a combined effect of water conservation facilities, better soil management, extension of new crop varieties and a continuous increase in the use of nitrogen and phosphorus fertilizers. Progress requires a combination of several crop management practices. While improvement via better transpiration efficiency can be achieved by breeding, crop type and variety selection as well as plant nutrition management, reduction of evaporation, drainage and runoff losses can be obtained by proper timing of crop establishment and improved root growth. Optimization of water use efficiency on a system basis can be obtained by crop rotation practices that extended the time of soil coverage and crop growth avoiding prolonged fallow periods. From the farmer's prospective a monetary assessment of costs and benefits will determine which set of management measures for improved water use efficiency should be adopted.

1.3.4.2 Soil management

Following equation 2, overall agricultural water use efficiency for a crop with given transpiration efficiency (M/T) will only increase, if transpiration is maximized in relation to unproductive water losses. While transpiration efficiency set the upper limit, soil management determines whether water resources are allocated optimally to sustain plant growth.

Figure 1.5 gives an overview of relevant soil physical and hydrological properties that might be targeted by management measures to optimize the ratio of transpiration to the sum of soil evaporation, runoff and drainage. Also plant traits influence these hydrological processes as discussed in section 2.1. The efficiency of soil management also depends on non-manageable soil properties such as soil texture as shown by Katerji and Mastorilli (2009) who found a general reduction in water use efficiency on clay soils compared to loam soils.

Tillage operations can influence water use efficiency by (i) changing soil surface properties, (ii) modifying soil hydraulic properties, and (iii) influencing root system formation of crops (Figure 1.5). Tillage therefore influences water dynamics and water use efficiency via mechanical effect of the tillage implements, mulching effects related to the amount of residues cover remaining on the soil surface, and biological effects due to modified root system formation and soil microbiological activity. All relevant components of the water balance framework of Gregory (2004) are potentially influenced by these effects of tillage.

Soil surface roughness is higher under more intense tillage compared to minimum and no-tillage (Lampurlanés and Cantero-Martínez, 2006). Higher surface roughness can reduce surface runoff by better storage of ponded water in the surface micro-relief. However, Gómez and Nearing (2005) found only a minor effect of different surface roughness on runoff. They also showed that increased surface roughness by higher tillage intensity disappeared after the first rainfall.

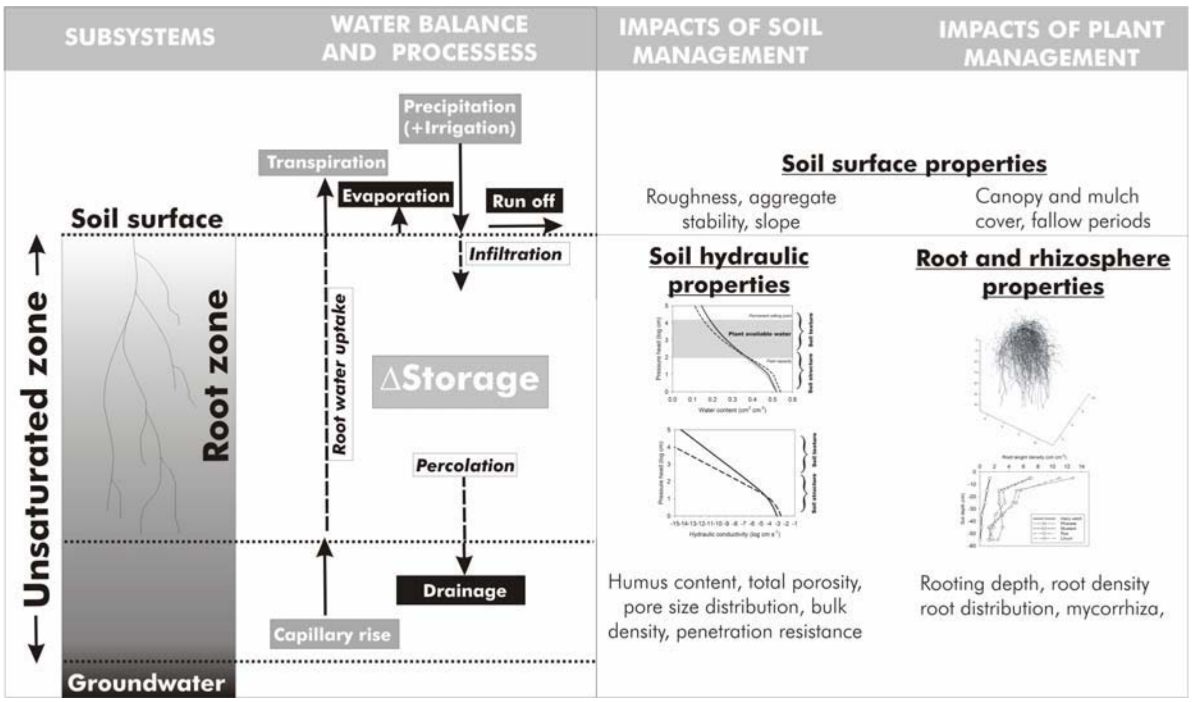


Figure 1.5: Effect of management measures on components of water balance. Modifications in soil surface properties, soil hydraulic properties and root and rhizosphere properties induced by crop and soil management practices affect each component of water balance.

Tillage can influence rainfall infiltration via changes of soil surface structure. Barthés and Roose (2002) reported a significant reduction in surface runoff with increased aggregate stability. After 24 years of conservation tillage, Zhang et al. (2007c) found an increase of 52 % in macro-aggregate stability and a 3.7 times higher infiltration rate in no-tillage compared to conventional tillage which substantially reduced runoff.

Most benefits of reduced tillage can be attributed to higher soil organic matter and the effects of canopy and residue management that protect the soil surface (Arriaga and

Balkcom, 2005). Canopy and mulch coverage protect the soil surface, preventing crust formation and maintaining soil infiltration capacity (Armand et al., 2009). Zuazo and Pleguezuelo (2008) reviewed the effect of plant covers on soil-erosion and runoff prevention. In average a surface cover of 50 % resulted in a reduction of runoff to only 10 %. Particularly during intense rainfall runoff can be greatly reduced with a good (>50 %) residue cover (Silburn and Glanville, 2002).

Also the higher organic matter content in the surface near soil layers under conservation tillage is essential for an enhanced infiltration capacity and thereby reduced runoff losses (Zhang et al., 2007c). Beside enhanced humus content, the conservation of root and earthworm induced continuous biopores in no tillage systems contributes to higher infiltration rates and reduction of runoff (Cresswell and Kirkegaard, 1995).

An essential tillage effect for improved water use efficiency is the reduction of evaporation losses from the soil surface. Aase and Pikul (1995) sustained that decreasing tillage intensity tends to improve water use efficiency because of improved soil water availability through reduced evaporation losses. Evaporation losses can be particularly high when rainfall is contributed by frequent small events during the vegetation period (Sadras, 2003). In Mediterranean-type environments, 30–60% of the seasonal evapotranspiration of wheat may be lost as evaporation from the soil surface (Siddique et al., 1990). Evaporation losses are affected by the water content of the soil surface. Therefore movement of moist soil to the surface may result in higher losses in mouldboard plough systems (Ritchie, 1971). Soil evaporation is influenced by the surface energy balance as well as water transmission properties to the soil surface. Tillage intends to disrupt pore continuity to the soil surface and thereby limit evaporation losses. In case of a fallow soil surface, Moret et al. (2007) found a 20 % higher soil evaporation from a no-tillage soil compared to conventional tillage.

Mulching is regarded as one of the best ways to reduce soil evaporation (Steiner, 1989; Li and Xiao, 1992; Baumhardt and Jones, 2002). Residues and mulches limit evaporation by reducing soil temperature, preventing vapour diffusion, absorbing water vapor on to mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface (Greb, 1966; Lagos et al., 2009). Crop residues extend the duration of the first stage of soil drying and most effectively reduce soil evaporation when the soil surface is wet. Unger et al. (1991) however reported that cumulative evaporation from a residue covered soil may become similar to a bare soil upon prolonged drying as the soil generally remains wetter in the upper layers and therefore sustains water transport to the surface for longer time. Effect of mulching on water use efficiency and components of water balance are presented in Table 1.7. These may vary with residue cover, slope of land, rainfall intensity and region.

Table 1.7: Effect of mulching on water use efficiency and components of water balance

Practice	Effect (range)	Reference
Mulching	Reduction in runoff (10-75 %)	Carsky et al. (1998); Silburn and Glanville (2002); Zuazo and Pleguezuelo (2008)
	Reduction in evaporation (11-36 %)	Mellouli et al. (1998) ; Zhang et al. (2007b)
Overall increase in WUE	**10-45 %**	Zhao et al. (1996); Zhang et al. (2002); Sarkar et al. (2007) ; Zhang et al. (2007b)

Strudley et al. (2008) reviewed tillage effects on soil hydraulic properties. There is no single trend how tillage influences soil hydraulic conductivity and both, increase and decrease in saturated as well as unsaturated hydraulic conductivity have been reported. This indicates a substantial influence of soil texture, crop rotation as well as temporal effects on the measured values (Soracco et al., 2010).

Under reduced and no tillage system, an increase in soil water storage capacity has been found in most studies. e.g. Fernandez-Ugalde et al. (2009) found 32.6 % higher plant water availability under no-tillage compared to conventional tillage in the upper soil layers where also soil organic matter and water retention at field capacity were significantly increased. Increase in organic matter content leads to higher soil porosity (Rasool et al., 2008) and improved water holding capacity (Hatfield et al., 2001). Thus reduced tillage is likely to influence water holding capacity by a combined effect of organic matter and soil structure. Also Bai et al. (2008) found an improvement in plant water availability and in several pore characteristics related to structure after nine years of reduced tillage in the Chinese Loess plateau. Feng et al. (2010) reported up to 25 % higher soil water storage under no tillage with mulching. Effect of different tillage practices on water use efficiency and components of water balance is summarized in Table 1.8. Great care shall be exercised in the interpretation of these values as they may vary among regions as well as with soil types, etc.

An increase in water storage is related with a reduction in drainage losses which could be a relevant loss component in humid areas as well as in irrigated fields. Wallece (2000) estimated drainage losses from farmers' fields in humid West Africa as high as 40 to 50 % of incoming rainfall.

Table 1.8: Effect of tillage practices on water use efficiency and components of water balance

Practice	Effect (range)	Reference
Conventional Tillage	Reduction in evaporation (1-20 %)	Moret et al. (2007)
	Increase in infiltration rates (35-61 %)	Moreno et al. (1997) Lipiec et al. (2005)
	Increase in soil water storage (9-42 %)	Selvaraju and Ramaswami (1997); Jin et al. (2007)
No tillage	Increase in soil water storage (8-33 %)	Chen et al. (2005) ; Fernandez-Ugalde et al. (2009) ; Wang et al. (2010)
Overall increase in WUE	**17-30 %**	Peterson and Westfall (2004); Sarkar et al. (2007)
Reduced tillage	Reduction in evaporation (1-19 %)	Lopez and Arrue (1997)
	Increase in soil water storage (15-24 %)	McHugh et al. (2007)
Overall increase in WUE	7-30 %	Jin et al. (2009)

For semi-arid ecosystem, an increase of the transpiration component can be achieved by better root growth. Besides crop improvement by breeding for higher root water uptake (Richards et al, 2007), tillage can support root growth by (i) conserving continuous macro pores that serve as preferential growth channel for roots to the subsoil (Rasse and

Smucker, 1998), (ii) avoiding soil compaction that restricts root growth (Bengough et al. (2006) and (iii) providing a soil structure where roots and root associated microorganisms can proliferate easily (Hinsinger et al., 2009). In their study, Feng et al. (2010) found higher root length density under reduced tillage treatments which might have contributed to better water extraction and reported yield increase. Soil compaction restricts root growth and increases drought susceptibility of crops (Bengough et al., 2006). Conventional tillage has frequently been reported to cause soil compaction, particularly when tillage operations are performed under wet conditions. However also in long term no-till systems, susceptible soils can show compaction due to natural settling (Tebrügge and Düring, 1999).

Beside tillage effects on water balance components, their concomitant influence on biomass growth and yields has to be considered in order to evaluate their potential to improve water use efficiency. Jin et al. (2009) reported winter wheat yield and related water use efficiency improvement by 6.7 % and 30.1 % with conservation tillage compared to the conventional tillage treatments, and for corn, 8.9 % and 6.8 %, respectively. In the Central Plains of the USA, no-tillage practices have made it possible to intensify cropping from the traditional wheat–fallow system and produce a 30 % increase in water use efficiency (Peterson and Westfall, 2004). No tillage and sub soil tillage with mulching were found to be the optimum tillage systems for increasing water storage and wheat yields, resulting both in enhancing water use efficiency on the Loess Plateau in China (Su et al., 2007). There have been 50 % yield and water use efficiency increases in the North China Plain in winter wheat and maize over the last 20 years associated with combined effect of mulching and improved irrigation scheduling (Zhang et al., 2005). In Australia, Gibson et al. (1992) found that retaining sorghum stubble on the soil increased the sorghum yield by 393 kg ha^{-1} due to increased water use efficiency because of a greater amount of water stored in and extracted from the soil profile compared with conventional tillage.

The role of tillage has been changing and is likely to keep on changing as the advantages of direct-drilling techniques become more widely appreciated, not only for improving crop performance but also for protecting the soil (Passioura, 2006). The highest improvement by conservation tillage and mulch management can be expected in sloping soils where runoff is the predominant component of unproductive water losses. Most reports indicate an exponential reduction in runoff losses with increasing soil coverage. For Mediterranean agro-ecosystems where early season rainfall essentially contributes to crop performance, the reduction of evaporation becomes the central target. Reported efficiencies of tillage and mulching practices are variable, ranging from no effect or even higher cumulative losses, to reductions of 25 to 30 %. Improved water use efficiency by 10–20 % through reduced soil evaporation and consequently increased water available for plant transpiration were reported by Zhao et al. (1996) and Zhang et al. (2002). Improved water storage capacity is often restricted to the upper soil layers where reduced tillage enhances organic matter accumulation. Although moisture availability in upper layers can be essential for crop growth when the root system is concentrated near the soil surface, an enhanced root penetration to deep layer seems to be more effective to increase plant water availability. Deep rooting crops have access to a higher soil volume, effectively reduce drainage losses and can increase uptake of water as well as mobile nutrients such as nitrate. All these effects will increase the affectivity of water use by the crop and optimize yield under water limited conditions.

Most reported increases in water use efficiency by conservation tillage in agronomic literature are based on evapotranspiration calculated via a water balance. Frequently runoff and drainage are ignored and the ratio is given as biomass or yield to total evapotranspiration. We therefore assume that the higher biomass or yield values in these studies are mainly a result of water redistribution from soil evaporation to productive plant use due to the protective effect of a mulch cover. This effect is expressed in Figure 1.6. Thus progress in tillage management will be obtained from its hydrological effects on plant water availability, rather than changes in transpiration efficiency.

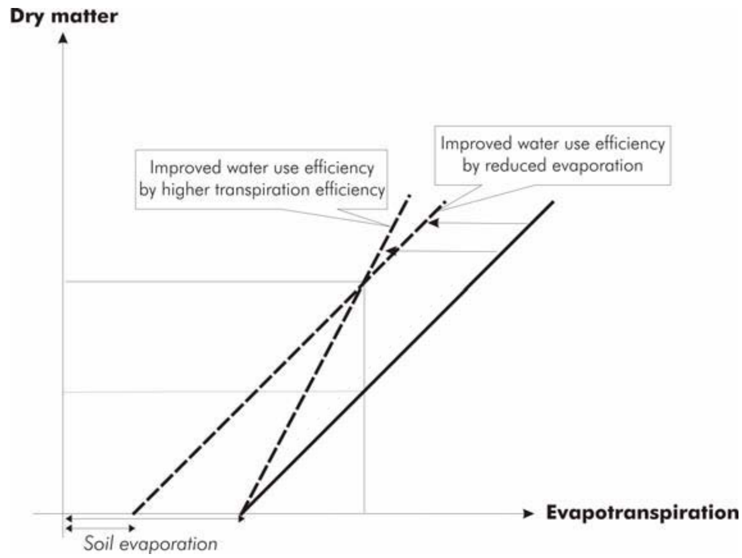


Figure 1.6: Relationship between evapotranspiration and dry matter production. Improvement of water use efficiency can be achieved by reduced soil evaporation or higher transpiration efficiency. The impact of soil management is on evaporation and other loss components of field water balance

1.3.4.3 Irrigation management

Globally 18 % of the cultivated area is irrigated. About 40 % of global food production comes from irrigated agriculture and about 70 % of all freshwater is used in agriculture. Currently low efficiencies in irrigation systems would suggest high potential for improvement in agricultural water use by better irrigation management (Hsiao et al., 2007). Introducing modern irrigation technology usually implies higher costs, which must be compensated by sustainable yields, increases in water use efficiency with resulting water savings. Sub surface drip irrigation is reported to have significantly increased yield and WUE of many crops as revealed by 15 years of research in United States (Ayars et al., 1999). 26 % increase in water use efficiency in cotton was observed due to drip irrigation in comparison with check basin (surface flooding) method of irrigation (Aujla et al., 2005). It was found from a study in California that water use efficiency ranged from 60 % - 85 % for surface irrigation to 70 % - 90 % for sprinkler irrigation and 88 % - 90 % for drip irrigation (Cooley et al., 2008). Irrigating pepper with water pillow method - a novel irrigation method that combines drip irrigation and mulching - at 11 days interval helped to obtain significantly higher water use efficiency compared to conventional furrow irrigation (Gercek et al., 2009).

Potential water savings would be even higher if the technology switch were combined with more precise irrigation scheduling and a partial shift from lower-value, water-intensive crops to higher-value, more water-efficient crops (Cooley et al., 2008). Measurement based irrigation scheduling is generally based on soil parameters such as water content or pressure head. While plant based irrigation scheduling methods would have the advantage to directly respond to a crop water stress parameter, they are still limited by practical problems such as automatization (Jones, 2004b).

Irrigation management increasingly focuses on more effective and rational uses of limited water supplies with increasing water use efficiency (Marouelli et al., 2004; Payero et al., 2009). Improved efficiency can be obtained by reducing drainage, runoff and evaporation losses by using measurement or model assisted irrigation scheduling (Pereira et al., 2002). Also supplemental irrigation at critical growth stages has substantially improved irrigation efficiency (Oweis et al., 1999).

A proper timing of supplemental irrigation is critical for maximizing yield and water use efficiency. Manipulation of pre- and post-flowering water use in crops can be used to increase harvest index and by using methods of controlled irrigation the optimized water use by stomata can lead to an increase in water use efficiency, without a significant decrease in production and eventually with beneficial effects on quality (Chaves and Oliveira, 2004). Examples of some marked increase in water use efficiency by supplemental irrigation are given by Deng et al. (2002), Oweis et al. (2004) and Xue et al. (2006).

Several studies showed that optimizing irrigation not necessarily needs to provide full crop water requirements (English and Raja, 1996; Kirda, 2002). Water use efficiency can be increased if irrigation water is reduced and crop water deficit is intentionally induced (Zwart and Bastiaanssen, 2004). Studies on the effects of limited irrigation on crop yield and water use efficiency show that crop yield can be largely maintained and product quality can, in some cases, be improved while substantially reducing irrigation volume (Kang et al., 1992; Zhang and Oweis, 1999; Zhang et al., 1999). For example, Panda et al. (2004) evaluated the effect of different irrigation methods on root zone soil moisture, growth, yield parameters, and water use efficiency of corn and concluded that under water scarcity conditions irrigation should be scheduled at 45 % of the maximum allowable depletion of available soil water to obtain high yield and high water use efficiency. When irrigation is above the optimum, an excessive shoot growth can occur at the expense of roots and fruits (Zhang, 2004).

Thus, recent efforts in optimizing irrigation have studied practices that intentionally induce slight water deficits to plants such as regulated deficit irrigation and partial root zone drying. When water deficits start to build up, leaf stomatal conductance usually decreases faster than carbon assimilation, leading to increased transpiration efficiency (Chaves et al., 2004).

Regulated deficit irrigation involves the application of irrigation water below the evapotranspiration requirements of crop. It tends to reduce or eliminate drainage and helps to improve water use efficiency (Fereres and Soriano, 2007). The basic principle of regulated deficit irrigation is that water is withheld or reduced during a period when vegetative growth is normally high and fruit growth is low. A normal irrigation regime is resumed during the later period of rapid fruit growth. Successful application of regulated deficit irrigation requires careful attention to the timing of the water deficit period and to the degree of stress that is allowed to develop (Loveys et al., 2004; Geerts and Raes, 2009). This tactic helps to reduce vegetative growth with little effect on fruit development. In fruit crops like peach, apple and pear balance between vegetative and reproductive development is critical as excessive vegetative vigour may result in mutual shading with consequences of long-term fruitfulness. Knowledge about the phenology of vegetative and reproductive development of fruit crops can be used for saving water through regulated deficit irrigation (Chalmers et al., 1981; Chalmers et al., 1986).

Application of regulated deficit irrigation has doubled water use efficiency when compared with standard irrigation practice (Goodwin and Boland, 2002). These improvements are due to improved water use by reducing unproductive losses, reduction in vegetative canopy size, and also due to reduced leaf stomatal conductance during the regulated deficit irrigation period (Boland et al., 1993). Effect of timing, method and scheduling of irrigation practices is summarized in Table 1.9 to demonstrate the importance of irrigation management.

Table 1.9: Effect of irrigation on water use efficiency

Practice	Increase in water use efficiency (%)	Reference
Irrigation scheduling	5-38	Karam (1993); Fare et al. (1993); Tyler et al. (1996); Ismail et al. (2008)
Method of irrigation	7-48	Liu et al. (2003); Aujla et al. (2005) ; Li et al. (2007) ; Cooley et al. (2008) ; Li et al. (2010)
Timing of irrigation	25-57	Guinn et al. (1981); Hu et al. (2002); Buttar et al. (2007)

An irrigation practice that focuses on increasing water use efficiency by controlling stomatal opening is partial root zone drying. Stomatal closure is a common response to root zone stresses including soil drying, soil flooding and soil compaction. Beside hydraulic signals, this response is governed by increased levels of the plant hormone abscisic acid in plant roots and transmitted to leaves especially under dry soil conditions (Loveys et al., 2004). The knowledge about the ability of the particular plant genotypes to sense the onset of changes in moisture availability and fine-tune its water status in response to the environment has lead to the development of partial root-zone drying technique (Wilkinson, 2004). In this irrigation method, each side of the root system is irrigated during alternate periods and the maintenance of the plant water status is ensured by the wet part of the root system, whereas the decrease in water use derives from the closure of stomata promoted by dehydrating roots (Davies et al., 2000). It is recognized that stomatal closure and growth inhibition are likely to be responding simultaneously to different stimuli, some of which may operate through common signal transduction systems (Webb and Hetherington, 1997; Shinozaki and Yamaguchi-Shinozaki, 2000). Physiological data from studies on grapevines under partial root zone drying point to subtle differences between partial root zone drying and deficit irrigation, where the same amount of water is distributed by the two sides of the root system (Souza et al., 2003; Santos et al., 2003). These differences include some reduction of stomatal aperture in partial root zone drying, a depression of vegetative growth, and an increase in cluster exposure to solar radiation, with some potential to improve fruit quality. There is also evidence that partial root zone drying can increase fruit quality in tomato, presumably as a result of differential effects on vegetative and reproductive production (Davies et al., 2000). The root system is also significantly altered in response to partial dehydration, not only in respect to total extension and biomass but also in architecture. Root system tends to grow deeper under partial root zone drying enabling roots to extract water from greater soil depths and provide higher plant water uptake (Dry et al., 2000). It is likely that this alteration in the root characteristics and in the source/sink balance plays an important role in plant performance under partial root zone drying. The technique had been found effective in improving water use efficiency for a wide range of crops in different environments (Kirda et al., 2007, Sadras, 2009) and its large scale implementation had been successful for vineyards (Loveys and Ping, 2002; Souza et al., 2003; Santos et al., 2003) .

Future developments in irrigation technology, better scheduling of timing and amount of water applied as well as new application methods are likely to contribute essentially to improved agricultural water use. Modern irrigation methods like supplemental irrigation, regulated deficit irrigation and partial root zone drying exploit physiological mechanisms to improve instantaneous water use efficiency at the leaf, make use of knowledge on sensitive phonological states of the crop to increase water use efficiency in relation to yield and provide a more effective water use by reducing losses and enhancing root water uptake. Site specific application of proper and efficient irrigation methods can therefore help to improve the overall agricultural water management and save water for other competitive demands (Playan and Mateos, 2006).

1.3.5 Conclusions and challenges

Improvement of water use efficiency has been a focus of extensive agronomic, breeding and water management research. This work has provided the basis for the development of management tools to improve agricultural water management. Most comprehensive studies on agricultural water use come to the conclusion that a set of measures is required to achieve higher water use efficiency, while single measures are of limited use. It is particularly important to evaluate agricultural production systems over the whole crop rotation to determine system water use efficiency instead of focussing on single crops.

Based on practical recommendations of FAO, several agricultural management measures were analysed for their effects on water use efficiency and the underlying plant physiological and soil hydrological processes. Only few measures improve water use efficiency due to higher transpiration efficiency which is a rather conservative plant property. Changes in transpiration efficiency are mainly an effect of the type of photosynthesis. However some effects of plant nutrition management and selection of improved varieties were found. Most studies reporting higher water use efficiency relate dry matter or yield production to total evapotranspiration. Both crop and soil management measures have a huge effect on the components of the water balance, thereby changing the proportion of plant water uptake (transpiration) in relation to losses.

In case of erosion-prone sloping fields, conservation tillage systems and residue management that reduce runoff are most effective. Redistribution of evaporative water fluxes from soil evaporation to plant transpiration is the key of many management measures that improve water use efficiency. Use of proper amount of irrigation water as and when needed based on plant requirements and its application with site specific method can ensure reasonable gains in water use efficiency. Use of regulated deficit irrigation and partial root zone drying also offer enormous potential towards bringing improvement in water use efficiency.

From an agronomic point of view the suggestion of Blum (2009) to plant breeders to focus on an efficient water use rather than on water use efficiency alone has particular relevance. We consider that future efforts on the root system, the hidden half of the plant, still have a substantial potential to improve an efficient agricultural water use. The complex dynamics of root-soil interactions and of communication between aboveground and belowground plant parts require an interdisciplinary approach of agronomists, breeders and soil scientists to achieve what we would call "root system management" for better plant water use.

The challenge to feed the rapidly growing population under present scenario of depleting fresh water resources is big. The problem is further aggravated by erratic impacts of forthcoming climatic change. Particularly developing countries suffer for water and food shortages and generally lack resources for several modern technical measures to overcome the adverse effects of droughts and famines. Challenges for researchers are to improve interdisciplinary approaches to water use efficiency which is a topic that inseparably relates plant, soil and hydrological research. Knowledge about using management practices that are fit for a region based on its environment and its application for improvement of water use efficiency still remain the key concern in some parts of the world as adoption of technology is constrained by cultural and societal issues.

Challenges for policy makers and extension staff are to ensure dissemination and utilization of appropriate production technology packages to the end users. Use of simulation models for decision support can be used to adapt available management tools to local conditions. Still use of models for extension is restricted to developed world. Data bases for model calibration and validation experiments are lacking for many regions of the world, particularly developing countries. Capacity building and technical training of scientists from developing countries for proper application of simulation models is needed (Mathews and Stephens, 2002).
Crop water use is likely to stay a main topic for research and practical agriculture, and will probably even gain importance in future. Still there are large options for improved water use efficiency that can contribute to narrow the "yield gap" that is currently

building up. Better knowledge of processes and effects across all scales, from physiology to farming system design, will lay the grounds for better management and broad adoption of measures for improved agricultural water use.

Chapter 2

Root sampling and analysis in lucerne (*Medicago sativa L.*) field trial

ABSTRACT

Use of reliable method for estimation of root biomass is crucial in organic farming system. The main objective of this study was to compare two common root sampling methods, soil corer (9 cm diameter) and soil monolith (12.5 cm wide), in order to determine their suitability for estimation of root biomass in a lucerne row crop. A randomized block experiment with four replicates was carried out on organically managed fields at Raasdorf, Eastern Austria, for two consecutive years (2007 and 2008). Root biomass of lucerne variety Sitel was determined in the top 30 cm soil layer. With the soil corer, two samples were taken per plot, one sample on the row and one between the rows. Calculations of root biomass were based on the percentage of "on" and "between"-row area. Monolith samples were taken from each of the harvest areas per plot integrating over the whole "on" and "between"-row area. Results revealed that the root biomass differed significantly ($P < 0.05$) due to the sampling method, and it also differed significantly ($P < 0.05$) between the two years. The soil monolith method yielded slightly more root biomass than the soil corer method in both years, suggesting its better suitability for estimation of root biomass in large field experiments.

2.1 Introduction

Roots play a major role in water and nutrient uptake by plants besides the useful effects of root exudates on microbial activities in soil. Organic farming systems usually produce larger root biomass as compared to conventional farming systems because of the basic role of forage legumes for nitrogen delivery and soil fertility enhancement. The use of reliable methods of root biomass estimation is crucial due to the relative importance of roots in organic farming systems. Root samples from field are usually collected using soil corer or soil monolith and roots are then washed out of the soil. In the samples, surface area, biomass, necromass, diameter, length and other root morphological parameters can be determined besides chemical and isotopic analysis (Smucker et al., 1982, 1987; Srivastava et al., 1982; Vogt and Persson, 1991).

The soil corer (9 cm diameter in our study) usually is smaller than the row distance of forage legumes (i.e. 12 cm). Therefore, in these row crops, separate samples need to be taken to determine the amount (and biomass) of roots present on the crop row and between the crop rows. Total root biomass is then calculated regarding the percentage of "on" and "between"-row area. This method requires extra time and labor. The shortcoming can be partly overcome by using the soil monolith (12.5 cm wide) method that regards roots present on the row as well as between the rows. Thus, a reasonable amount of time can be saved by reducing the number of samples to half. Owing to the importance of roots in organic farming systems, it is imperative to use a root sampling method that provides reliable estimates of root residues left in soil with minimum input of efforts. Keeping in view the same objective, soil corer and soil monolith methods were compared to estimate root biomass of lucerne in a field trial.

2.2 Materials and methods

A field experiment with lucerne variety Sitel was laid out on organically managed fields at Raasdorf, Eastern Austria for two consecutive years (2007-2008). The randomized complete block experiment with four replicates, having a plot size of 3 m x 3 m and row spacing of 12.5 cm, received usual management from sowing to harvest. Every year at the time of final harvest, root sampling was done using soil corer (9 cm diameter) and soil monolith (12.5 cm wide) in the top 30 cm soil layer. Using soil corer, one sample was taken on the row and one between the rows from each harvest area of a single Lucerne plot having two distinct harvest areas each of 0.5 m^2 sizes. Monolith samples were taken from sides of each of the harvest areas of each Lucerne plot integrating over the whole "on" and "between"-row area.

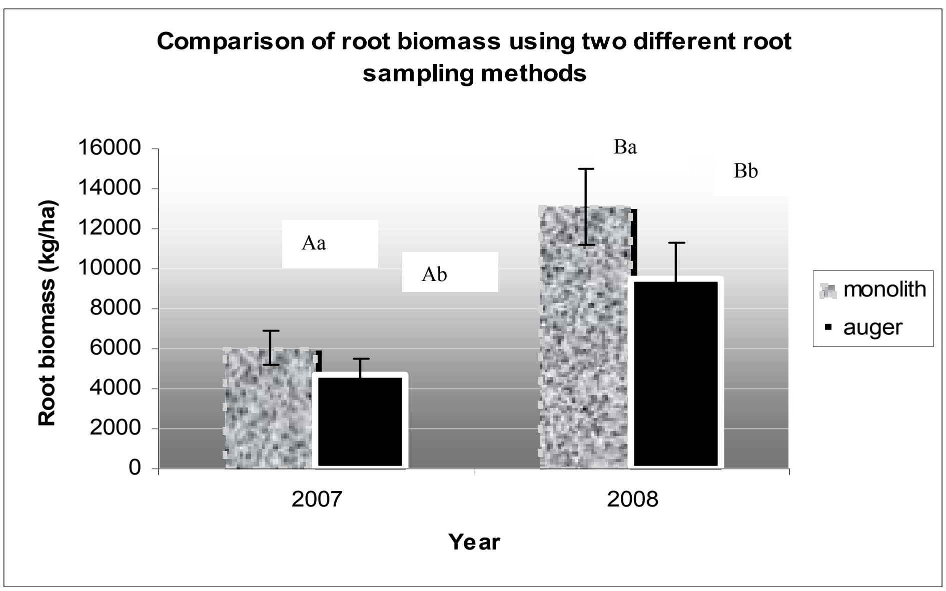
Soil samples were washed using a root washing machine (Gillison´s Variety Fabrication Inc., USA) to separate roots from soil. Separated roots were passed through sieves having a mesh size of 0.75 mm. Collected roots were dried in an oven at 60 ^{0}C for 48 hours for determination of root biomass. For soil corer samples, root biomass was calculated separately for both positions, on the row and between the rows using a correction factor for the percentage of area present on and between the rows. Total biomass was the sum of root biomass found on and between the rows. For calculation of root biomass from the monolith samples, an area percentage factor is not used as the monolith area already regards roots present both on row and between row positions. Data were analyzed using General linear model procedure in statistical software SPSS 15 where year and treatment were used as fixed factors and replicate as random factors.

2.3 Results and Discussion

Interactions among root sampling methods and years were found non-significant. Root biomass differed significantly between the years ($P < 0.05$). Higher root biomass was observed in 2008 as compared to 2007 with both sampling methods. Root biomass also differed significantly ($P < 0.05$) because of the sampling method. Soil monolith yielded more root biomass than soil corer samples in both years (Fig. 2.1). Higher root biomass in 2008 may be attributed to relatively higher rainfall during vegetation period (Fig. 2.2). Findings of higher root biomass using monolith method as compared to core method in our study are in line with those of Ping et al. (2010) .They compared sampling accuracy of core and monolith method for the estimation of root biomass in a grassland (dominated by cool season C_3 grass species) in Inner Mongolia, China in a semi arid climate. Their results indicated that the small core method (3.8-cm-diameter) significantly underestimated total root biomass compared with the large core method (10-cm-diameter), small monolith method (0.25 m^2) and large monolith method (1m^2). Total root biomass estimated from the small core method was about 52 % less than that from the large monolith method (1 m^2). At 95 % confidence interval, 10 % relative precision could be obtained with 5 small monoliths, 15 large cores and 65 small cores. The coefficient of variation for total root biomass decreased logarithmically with increasing sample size for both the monolith and core methods. They reported that compared with the stratified random sampling, core sampling with different fixed positions could not provide reliable estimate of total root biomass. Washing damage and soil lost during extraction might be the major factors controlling the measurement accuracy of total root biomass by core method with small sample size.

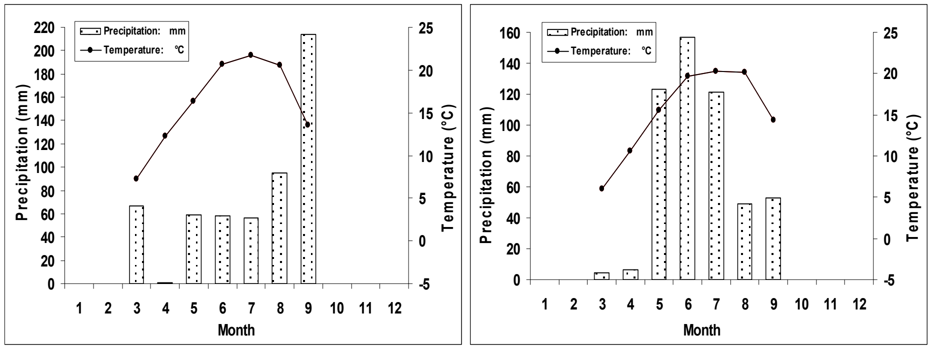
Findings of our study are not in agreement with those of Levillain et al. (2008) who compared these methods for the estimation of fine root biomass in eucalyptus forest plantation in Congo characterized by a tropical climate. They used auger having 8 cm diameter and monolith of 25 x 25 cm.

This contradiction in results may be attributed to differences in nature of plants being studied and diameter of samplers being used in different studies. Root studies are associated with high variability coupled with the variability in the environment and the age of plant being studied (Sheaffer et al., 1988).



Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and methods, respectively.

Figure 2.1: Lucerne dried root biomass (kg DM ha^{-1}) as affected by the method of sampling.



2007 **2008**

Fig. 2.2: Rainfall distribution during the experimental period

It can be concluded from the present study that soil monolith shall be preferred over soil corer for reliable estimation of root biomass in row crops in larger field experiments only. Although, soil monolith provides relatively more reliable estimates of root biomass than soil corer, but it is more destructive than soil corer. This limitation of the method makes it unfeasible for smaller field experiments. Soil monolith was not used for the estimation of root biomass in trial on lucerne varieties (chapter 3) as it was a small field experiment.

Chapter 3

Comparison of performance of lucerne varieties under irrigated and rain-fed conditions

3.1 Introduction

Water is the main factor limiting crop yields in agriculture (Cooper et al., 1987; Zeid and El-Semary, 2001). Water plays an important role in maintaining turgidity of plant cells and transport of assimilates. Expected increase in water scarcity in many areas of world in future is going to constrain further increases in crop yields (Seckler et al., 1998; Fraiture and Wichelns, 2010). It is imperative that this precious natural resource must be utilized efficiently to ensure sustained food supplies. The greatest challenge for agriculture is to develop the technology for improving water use efficiency (Karasov, 1982; Wallace and Batchelor, 1997; Turner, 2004).

Increase in yield and water use efficiency can be achieved by a choice of appropriate crop varieties and use of improved soil and crop management factors (Zhang et al., 2005). Use of appropriate variety in a given site is critical towards bringing improvement in yield and WUE. Under organic farming systems, the choice of crop varieties is constrained by lack of varieties developed specifically for organic farming systems. These systems, being relatively new, usually use varieties originally developed for conventional farming systems. As area under certified organic farming in increasing in world as well as in Europe (IFOAM, 2009), it is desired that number of crops and varieties shall also be increased for these systems. This will increase diversification of the systems and will lead to sustainability of these systems (Ronchi and Nordone, 2003).

Legumes are important crops in organic farming system due to their nitrogen (N) fixation capability and nutrient recycling (Howieson et al., 2000). Among legumes, lucerne (*Medicago sative* L.) is a key crop that ensures sustainability of organic farming systems (Huyghe, 2003, Shen et al., 2009) due to its contribution towards N-fixation as this biologically fixed N is the main source of N in organic farming systems (Pietsch et al., 2007). It can survive longer periods of drought (White, 1967) and can improve soil drainage (Shen et al., 2009). High yielding lucerne varieties that are efficient in water use are needed for organic farming systems. Irrigation can have positive effects on lucerne yield and its components (Abu-Shakra et al., 1969, Taylor and Marble, 1986). It is desired that lucerne varieties shall be screened for their yield potential and water use under both irrigated and rain-fed organic farming conditions.

Keeping in view the importance of finding suitable lucerne varieties for organic farming, a study was designed to compare lucerne varieties for their yield, yield components, physiological traits, and water use under conditions of varying water availability.

3.2 Materials and methods

3.2.1 Experimental set up

The present study comprised of two different experiments, namely irrigated and rain-fed, planted at Gross Enzerdorf and Raasdorf, respectively. These two sites are part of an experimental farm belonging to the University of Natural Resources and Applied Life Sciences (BOKU), Vienna, Austria. Each experiment comprised of 18 lucerne varieties in total. Each experiment was laid out in α–lattice design with two replicates. Sowing of both experiments was done manually in 2006 using seed rate of 25 kg ha^{-1}. Row to row distance was 12.5 cm. Each sub plot having a single lucerne variety was 1.5 m and 2 m long for irrigated and rain-fed site, respectively and 1.5 m wide in both sites. First year was regarded as establishment year and next two years (2007 and 2008) were regarded as experimental years.

From the irrigated site, three lucerne varieties viz. Niva, Mohajaren and Sitel were selected for detailed studies on water use whereas from rain-fed set six lucerne varieties viz. Niva, Mohajaren, Sitel, Vlasta, Ordobad and NS-banat were used for studies. Drip irrigation system was used to irrigate the irrigated set only. Irrigation was applied based on regular monitoring of soil water content (SWC) using FDR (Frequency Domain Reflectometry, ML2x, UMS GmbH, München, Germany) probes. FDR probes were installed in each replicate of three selected lucerne varieties at the depth of 10, 40, 80 and 120 cm. Irrigation was started at 50 % depletion of soil available water (SAW) content

(SAW = Water content difference between field capacity (FC) and permanent wilting point (PWP)) based on FDR probe in 10-15 cm soil depth. The amount of applied irrigation water was calculated for 0-30 cm depth based on soil moisture content up to field capacity.

3.2.2 Site description

Fields used for experimental purpose at Gross Enzersdorf (48º12' N, 16º33' E) and Raasdorf (48º15' N, 16º37' E) belong to research station of BOKU, Vienna, Austria. Both of these sites have organically managed fields. Soils at two sites are silty loam having organic carbon content of 0.4-1.5 % and a bulk density of 1.4-1.6 g cm^{-3}. The amount of precipitation, average temperature and applied irrigation water from March to September in 2007-08 are shown in Figure 3.1.

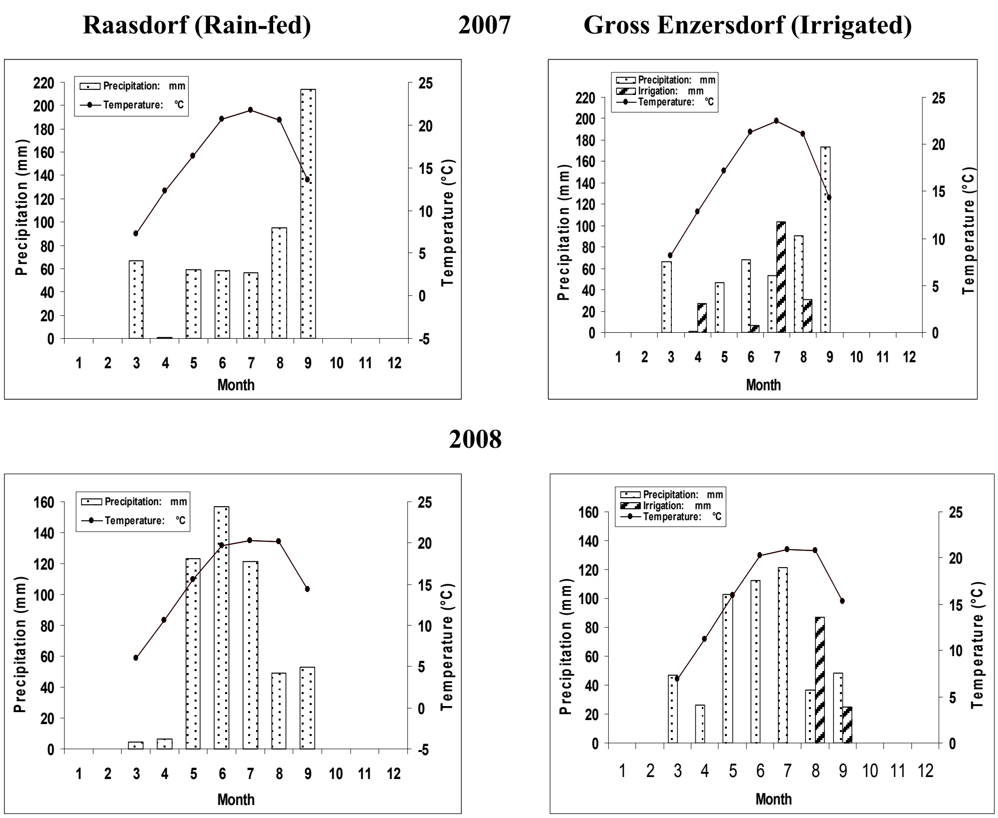


Figure 3.1: Monthly precipitation, average temperature and applied irrigation water from March to September (2007- 2008) (After Moghaddam, 2010).

.3.2.3 Soil sampling – timing and procedure

Soil samples were collected from both experimental sites for the determination of inorganic nitrogen (N) content. Sampling was done from each replicate of lucerne using a mechanical soil auger till the depth of 90 cm. Each sample was further divided into three 30 cm samples so as to determine soil inorganic nitrogen (N) content in 0-30, 30-60 and 60-90 cm. In both years, sampling was done before the start of vegetation period and then at three main harvests. Soil organic carbon (C) contents were determined at the end of experimental period for both sites. Six composite samples for every 30 cm depth till 90 cm were used for said purpose.

Soil samples for the determination of texture, dry density, saturated hydraulic conductivity and retention curves were collected from both experimental sites at the end of vegetation period in 2008. Two representative replicates were selected for sampling from each experimental site. These replicates were selected based on variation in soil texture determined by finger testing method. One soil samples was collected from each replicate from the depth of 15-20, 50-55 and 80-85cm.

3.2.4 Determination of inorganic nitrogen content

Inorganic soil N content (nitrate only) were determined in the laboratory of Division of Organic Farming using N-min analyze method. Ammonium content was not determined as sites had negligible amounts of ammonium due to pH values of 7.6 (Pietsch et al., 2007). Soil samples were homogenized and mixed with a weak calcium chloride ($CaCl_2.2H_2O$) solution (0.0125 mol L^{-1}) in proportion 1 to 4. Then the samples were rotated for an hour and filtered to have extractions. The first 30 ml (approximately) were discarded. 5 ml of extract was mixed with 20ml of calcium chloride extraction solution and 1 ml of sulphuric acid (7 %) and shaken well before conducting analysis. The analyses were performed by means of Spectrophotometer (at 210 nm wavelength).

Nitrate is extracted in $CaCl_2$ and directly measured at 210 nm in a photometer. At this wavelength, humic substances are also measured, so their concentration has to be determined and subtracted from the first value. For this purpose, four zinc granules coated with copper were added to this extract sample and extracts were kept over night before making the second analysis using Spectrophotometer (ONORM L1091).

3.2.5 Determination of organic carbon contents

Soil organic C contents were determined using the following relation**:**

$$\text{Soil organic carbon (\%)} = \text{Total C} - \text{Carbonate C}$$

Total C contents of soil were determined by dry combustion and infra-red detection of CO_2 using C-N 2000 Elemental Analyser (LECO) at the Institute of Agronomy and Plant Breeding, BOKU. Carbonate-C content was determined following Blum et al. (1996) at the Institute of Soil Research, BOKU. The method involves destruction and measurement of carbonates in a known amount of soil sample by using hydrochloric acid and gas volumetric measurement of the amount of CO_2 evolved during this process at a given temperature and air pressure.

3.2.6 Determination of soil texture and bulk density

Texture is a conventional expression of the results of particle size analyses. Particle size analyses are based on determination of percentage of sand (0.063-2 mm), silt (0.063-0.002) and clay (< 0.002) in a soil sample. Particle size analyses involved dry sieving to separate particles > 2mm, wet sieving (for < 2mm) and pipette approach (for < 0.063 mm) (ONORM L1061). Based on relative proportion of sand, silt and clay, textural classes were determined following American textural triangle adopted from American Soil Survey Manual (Soil Survey Staff, 1951).

Bulk density is a measure of the mass of soil per unit bulk (including solid and pores) volume. Metallic cores of known volume were used to collect undisturbed soil samples. Soil mass of undisturbed soil samples was determined by over-drying the soil sample at 105 ^{0}C for 24 hours. Bulk density was determined using the following relation proposed by Blake and Hartge (1986).

$$\text{Bulk density (g cm}^{-3}\text{)} = \text{mass of oven-dried soil sample (g)/ volume of core (cm}^{3}\text{)}$$

3.2.7 Determination of saturated hydraulic conductivity

Undisturbed soil samples were saturated by displacing the air to the top with a rising water table. Then the samples were coupled to automated device for measuring saturated hydraulic conductivity (SHC). SHC was determined by using method of rising head soil core. This method is a modified form of falling head soil core/tank method (Reynolds and Elrick, 2002). Method involves the measurement of speed of water movement in a saturated soil column. Values of saturated hydraulic conductivity were re-calculated and corrected by deleting the clogged needles using MathCad software (personal communications, Kammerer).

3.2.8 Determination of soil water retention characteristics

Soil water retention characteristics were determined by using pressure plate extractor following procedure described by Dane and Hopmans (2002). Soil water content was determined by applying pressure of 0.33, 0.5, 1, 3, 5 and 15 bars. The method is based on simple principle of determining the weight of water present in a fixed volume of soil at a series of defined pressure heads (tensions), to convert these weights into volume of water, and then divide by the volume of soil.

3.2.9 Studies on above ground biomass and its components

Data on above ground biomass and associated characters viz. shoot height, shoot number, leaf to stem ratio, leaf area index (LAI), relative water content (RWC) and chlorophyll content were recorded at three main harvests from both sites. Plots were hand clipped at 30-40 % of flowering using a garden scissor to a 5-cm stubble height. An area of 0.5 m^2 was harvested from each plot at each harvest to determine shoot biomass. Stubble biomass was determined only on final harvest in each year. Shoot and stubble dry matter yield were determined by oven-drying the sub-sample at 60 °C for 48 h. Shoot dry matter (SDM) yield data at final harvest includes value of stubble dry matter yield also.

Number of stems per m^2 and leaf to stem ratio were determined in a sub-sample of 0.25 m^2. Leaf area index was measured using LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE), before each harvest. Chlorophyll contents (mg m^{-2} leaves) were measured using a portable chlorophyll meter, Yara N-tester (Yara international ASA ,Norway, www.yara.com) at main harvests. Chlorophyll content (mg m^{-2} leaves) was measured from 30 fully expanded leaves in the upper 15 cm of plant canopy. Fully expanded leaves from top 15 cm were used to determine RWC following Gonzalez (2003).

RWC= {(fresh weight- dry weight)/ (saturated weight-dry weight)} x 100

3.2.10 Root sampling protocol for root biomass studies and determination of maximum rooting depth

Root samples were taken at first and final harvests from both sites during the experimental period. In 2007, cylindrical augers were used to take root samples till the depth of 90 cm with every 30 cm profile. One sample was taken on the row and two samples were taken between the rows from each lucerne plot, mixed and washed. During the first harvest in 2008, two samples were taken on the row and two between the rows from each lucerne plot and washed separately. Washed roots were separated using a mesh size of 0.75mm. Root samples were dried at 60^0C for 48 hours for determination of root biomass. Root biomass for first harvest of year 2008 was calculated regarding the percentage of area present on and between the rows. Based on these results of root biomass, a correction factor was devised to correct root biomass for year 2007, where percentage of roots present on and between the rows was not regarded. Root sampling at final harvest in 2008 involved use of auger having 7 cm diameter. Sampling was done till the depth of 60 cm with every 10 cm profile. One sample was taken on the row and one between the rows from each lucerne plot and washed separately.

Every year, samples from final harvest of both sites were scanned using a scanner (Epson Expression/STD 1600 extra optimized for root analyses by Regent Instrument, Inc.) following Himmelbauer et al. (2004). On these samples, root characters including root length, root surface area (RSA), root volume (RV) and average diameter (AD) were determined using a commercial software package WinRHIZO 4.1 (Regent Instruments, 2000), prior to drying them for determination of root dry matter yield/root biomass. The entire amount of roots available from each sampling depth in each replicate was scanned. The samples with higher volume of roots were sub-divided into sub-samples to avoid overlapping of roots while spreading them on the tray of scanner. The number of sub-samples for each sample varied among sampling depths and position of sampling (on or between the rows). Root length density (RLD) was determined by dividing the root lengths with volume of respective soil sample. After making the final harvest at both experimental sites in year 2008, maximum rooting depth was determined for each lucerne variety using a 2 m long mechanical auger.

3.2.11 Carbon isotope discrimination

Carbon isotope discrimination (CID)(Δ) based on shoot was determined at three main harvests from both sites during 2007-2008. Additionally, to study difference in (Δ) values between different plant parts, stubble and root samples (0-30 cm) were also used from final harvests in both years. Samples were dried, processed and passed through 1 mm sieve before packing and labelling in special trays for further isotopic analysis. The Δ values (‰) were determined with an isotope ratio mass spectrometer (IRMS-Thermo Quest Finnigan DELTA plus) in the laboratory of the Department of Chemical Ecology and Ecosystem Research, University of Vienna, according to procedures of Farquhar et al. (1989):

$$\Delta = \frac{\delta^{13}C_{air} - \delta^{13}C_{plant}}{1 + \delta^{13}C_{plant}}$$

where $\delta^{13}C$ is the value of stable isotope ratio (air or plant) which is expressed as the $^{13}C/^{12}C$ ratio (R_{sample}) relative to the PeeDee belemnite standard ($R_{standard}$) (Craig, 1957):

$$\delta^{13}C(‰) = \left(\frac{R_{sample}}{R_{standard} - 1} \right) \times 1000$$

$$R_{sample} = \frac{^{13}C}{^{12}C}, \; R_{standard} = \text{-8 ‰}$$

3.2.12 Measurement of soil water content and water balance calculations

Soil water content was measured using FDR probes and Sentek Diviner at irrigated and rain-fed site, respectively. FDR (Frequency Domain Reflectometry, ML2x, UMS GmbH, München, Germany) probes were installed at the depth of 10, 40, 80 and 120 cm whereas SENTEK Diviner 2000 (Sentek Sensor Technologies, Australia) probes were installed at the depth of 120 cm. Soil water content was measured using manual data loggers for both types of probes at weekly to fortnightly intervals. No site specific calibration was performed for both data loggers and original values of water content obtained from these data loggers were used to calculate water balance.

Actual evapotranspiration (ETa) of the lucerne varieties was calculated for each harvest according the climatic water balance (Ehlers and Goss, 2003).

$$N + B = T + E + A + S + \Delta R$$

Where N, B, T, E, A, S and ΔR are precipitation, irrigation, transpiration, evaporation, surface runoff, leaching and change in the water content of the soil profile (0-120 cm), respectively. Precipitation and meteorological data was obtained from weather station of Institute of Meterology, BOKU and Institute of Agronomy and Plant Breeding, BOKU, for irrigated and rain-fed site, respectively. The total amount of applied water was determined for the rain-fed site based on total precipitation and for irrigated site based on summing up the total precipitation and applied irrigation water during the vegetation period for respective harvests in each year. Surface run off was ignored, since the experimental fields were flat (A = 0). It was assumed that no significant amount of leaching occured (S = 0) beyond the root zone during vegetation period based on prevailing precipitation trends and water content data. The following simplified equation was used to calculate ETa.

$$ETa = T + E = N + B - \Delta R$$

3.2.13 Water use efficiency of productivity

Water use efficiecy of productivity (WUE_{P}) is an expression of the unit amount of dry matter (DM) produced per unit of water consumed. It is a useful indicator to describe suitability of genotypes under different environments. WUE_P was calculated using SDM from each harvest for both sites, separately. Respective water consumption (ETa) values were derived from water balance calculations.

$$WUE_P = \text{Shoot dry matter production} / \text{ETa} \ [\text{kg DM m}^{-3} \ H_2O]$$

3.2.14 Statistical analysis

Data from each parameter were analyzed separately for each harvest. Data from three common varieties in both sites were analyzed using general linear model of statistical software SPSS (version 15) where varieties and sites were considered as fixed factors and replicates were considered as random factors. All data sets were treated following randomized complete block design. Data from six varieties in the rain-fed site were analyzed separately using general linear model in SPSS where varieties were used as fixed factor and replicate as random factor. Mean comparison was done using Student Newman Keuls (SNK) test at 5 % level of probability.

3.3 Results

3.3.1 Physio-chemical properties of experimental sites

Soils in Gross Enzersdorf have higher bulk density as compared to soils in Raasdorf and therefore have relatively less SHC as compared to soils in Raasdorf. Bulk density in Gross Enzersdorf varied from 1.57-1.62 in the 15-85 cm profile, whereas soils in Raasdorf have bulk density ranging from 1.37-1.44. Organic carbon contents in the soils of Raasdorf (rain-fed site) are < 1 % below 30 cm depth which can lead to less water holding capacity of these soils. Soils in Gross Enzersdorf have organic carbon contents > 1 % throughout the profile. Detailed results of bulk density, SHC and organic carbon contents in different soil depths are presented in Table 3.1. Soils in both experimental sites were silty loam throughout the profile except Gross Enzersdorf (50-55 cm) where it was found to be loam (Table 3.2). The textural classes were defined following American textural triangle adopted from American Soil Survey Manual (Soil Survey Staff, 1951).

Table 3.1: Physio-chemical properties of experimental sites

Property	Depth (cm)	Gross Enzersdorf	Raasdorf
Bulk density (g cm^{-3})	15-20	1.62	1.37
	50-55	1.57	1.40
	80-85	1.58	1.44
Saturated hydraulic conductivity (cm s^{-1})	15-20	5.05×10^{-5}	1.55×10^{-3}
	50-55	1.25×10^{-4}	3.75×10^{-4}
	80-85	2×10^{-4}	3.05×10^{-4}
Organic carbon content (%)	0-30	1.5	1.5
	30-60	1.4	0.9
	60-90	1.1	0.4
pH($CaCl_2$)	-	7.6	7.6

Table 3.2: Texture of experimental sites

Depth (cm)	Gross Enzersdorf				Raasdorf			
	Sand (%)	**Silt (%)**	**Clay (%)**	**Textural class**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Textural class**
15-20	20	57	23	Silty loam	17	60	23	Silty loam
50-55	33	50	17	Loam	14	69	17	Silty loam
80-85	27	62	11	Silty loam	20	70	10	Silty loam
90-120	5	70	25	Silty loam	41	52	7	Silty loam

3.3.2 Soil water content at field capacity and permanent wilting point

Specification of a water retention curve is essential for most efforts at modeling soil water behavior (Prunty and Case, 2002). Determination of soil water retention characteristics revealed that soils of experimental sites do not differ significantly in tetaining water at field capacity and permanent wilting point. Soils at Raasdorf were found relatively better in retaining soil water as compared to soils of Gross Enzersdorf (Table 3.3).

Table 3.3: Soil water content at field capacity (-0.33 bars) and permanent wilting point (-15 bars)

Depth (cm)	Gross Enzersdorf			Raasdorf		
	Field capacity (m^3 m^{-3})	Permanent wilting point (m^3 m^{-3})	Available soil water (m^3 m^{-3})	Field capacity (m^3 m^{-3})	Permanent wilting point (m^3 m^{-3})	Available soil water (m^3 m^{-3})
15-20	0.310	0.195	0.115	0.287	0.159	0.128
50-55	0.320	0.144	0.176	0.266	0.103	0.163
80-85	0.283	0.083	0.200	0.302	0.064	0.238

3.3.3 Inorganic nitrogen content of experimental sites

The inorganic nitrogen content in the soil profile (0-90 cm) varied from 1-135 kg ha^{-1} and 0-25 kg ha^{-1} for irrigated and rain-fed site, respectively. Soils in irrigated site had relatively higher inorganic N content as compared to soils in rain-fed site only during major part of vegetation period in 2007. During 2008, inorganic nitrogen content of two sites became almost similar as nitrogen was used by lucerne plants in vegetation period of 2007. Mean values of inorganic soil nitrogen content of two experimental sites determined at start of vegetation period and at three main harvests during experimental period are presented in Table 1 and 2 (see Annexure). These variations in inorganic soil nitrogen of two experimental sites can have implications for the performance of lucerne varieties as nitrogen plays a key role in crop growth, yield and WUE (Latiri-Souki et al., 1998).

3.3.4 Biomass and its components

Shoot dry matter yield: Total yearly shoot dry matter yield varied from 8.3 to 18.6 tones ha^{-1}. Interactions among site and varieties were found non-significant for shoot dry matter yield (SDMY) at all harvests in both years except at first harvest in 2007 (See Table 3.4). There were significant differences among irrigated and rain-fed site for SDMY at three main harvests during both years except at second harvest in 2008. Also the two sites differed significantly in producing total yearly SDMY. SDMY of lucerne varieties was higher under irrigated site as compared to rain-fed site in both years. Lucerne varieties differed significantly ($P < 0.05$) in producing SDMY only at first harvest in 2007 and second harvest in 2008. On the overall basis, Sitel was found superior in producing SDMY under both sites followed by Niva and Mohajaren (Fig. 3.2).

Shoot height: Based on yearly averages, shoot height varied from 46-101 cm. Interactions among site and varieties were found non-significant for shoot height (SH) at all harvests in both years except at third harvest in 2007 (Table 3.4). There were significant differences ($P < 0.05$) between irrigated and rain-fed sites for SH at all harvests except at first harvest in 2008. Based on yearly averages, SH was higher in irrigated site (71-101 cm) as compared to rain-fed site (46-84 cm). Differences among lucerne varieties for shoot height were non-significant except at final harvest in 2007 and second harvest in 2008. Based on yearly averages, Mohajaren had relatively higher SH as compared to Sitel and Niva under both sites.

Shoot number m^{-2}: Based on yearly averages, shoot number was in the range of 762-1306 m^{-2}. Interactions among site and varieties were found significant ($P < 0.05$) at all major harvests in 2007 and were found non-significant in 2008. Sites differed significantly ($P < 0.05$) for shoot number (SN) only at second harvest in 2007 and first harvest in 2008. Like SDMY and SH**,** SN was usually higher under irrigated site (773-1306) as compared to rain-fed site (762-1208) in both years. Lucerne varieties differed significantly ($P < 0.05$) for their SN only in 2007 where Mohajaren had the highest shoot number (1061 m^{-2}) followed by Sitel (965) and Niva (773).

Leaf area index: LAI varied from 1.5-4.6 (yearly averages). Interactions among sites and varieties for LAI were found significant ($P < 0.05$) only at first harvest in 2008 (Table 3.4). At the time of first harvest in 2008 in the irrigated site, Niva, Mohajaren and Sitel attained LAI of 4.3, 4.3 and 4.4 respectively, as compared to their LAI of 3.7, 3.5 and 5.4 at the rain-fed site. LAI differed significantly ($P < 0.05$) among sites at main harvests in both years except at first harvest in 2008. LAI was also higher under irrigated site as compared to rain-fed site (see Fig. 3.3) due to optimal amount of irrigation water available at irrigated site. Differences among lucerne varieties were non-significant except at first harvest in 2008. Based on yearly averages, it can be concluded that

Mohajaren > Sitel > Niva in irrigated site while for rain-fed-site, Sitel > Niva > Mohajaren.

Leaf to stem ratio: Based on yearly averages, leaf to stem ratio varied from 0.5-1**.** Interactions among site and varieties were found non-significant except at second harvest in 2007 and first harvest in 2008. Differences between irrigated and rain-fed site were significant (at main harvests in both years) for leaf to stem ratio except at first harvests in both years. In both years, varieties had relatively higher leaf to stem ratio under the rain-fed site when compared with irrigated site. Based on yearly averages, leaf to stem ratio of varieties varied from 0.67-1.02 under rain-fed site as compared to 0.54-0.93 under irrigated site. Lucerne varieties did not differ significantly for this parameter only at second and third harvests in 2007 (Table. 3.4).

Relative water content: Based on yearly averages, varieties had relatively higher RWC under rain-fed conditions (76-93) as compared to irrigated conditions (75-90). Interactions among sites and varieties were found non-significant at all major harvest in both years. There were significant differences between two sites only at first harvest in 2007 and differences among sites and varieties were found non-significant for RWC in both years at all other main harvests. At the time of first harvest in 2007, RWC of varieties was 76-80 and 64-72 for the irrigated and rain-fed site, respectively (see Table 3, 4, 5 in Annexure).

Chlorophyll content (mg m^{-2} leaves): Chlorophyll content varied from 641-752 on the basis of yearly averages**.** Interactions among sites and varieties were found non-significant at all major harvest in both years. Differences among two sites were non-significant based on yearly averages of chlorophyll content. Lucerne varieties differed significantly for this trait only at first harvest and third harvest in 2007 and 2008, respectively (Table. 3.4). At the time of third harvest from irrigated site in 2008, highest chlorophyll contents were found in Sitel (686) followed by Niva (619) and Mohajaren (611) while from rain-fed site, highest chlorophyll content were found in Sitel (684) followed by Mohajaren (657) and Niva (561). At other harvests in both years, differences among varieties were found non-significant. On overall basis, Sitel had the highest chlorophyll content in both sites as well as years (Table 5).

Detailed results on individual component of biomass are presented in Table 3, 4 and 5 (see Annexure) for Niva, Mohajaren and Sitel, respectively. Table 3.4 presents a comprehensive summary of findings from two different sites for SDMY and its components at main harvests as well as yearly averages (2007-2008).

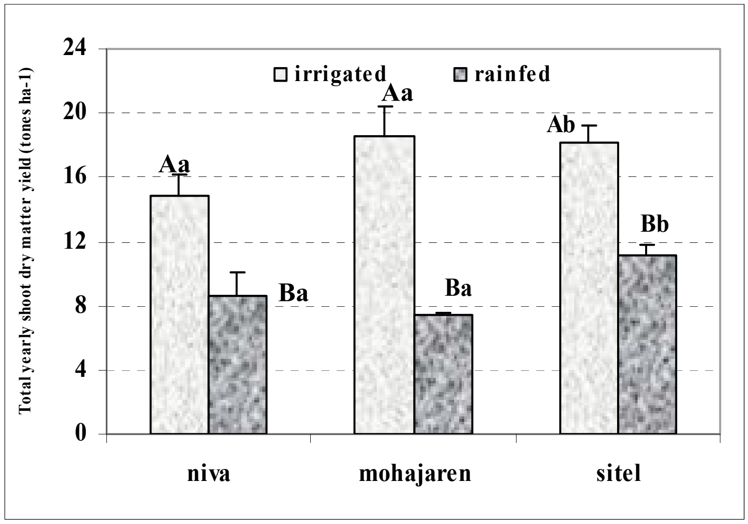
Table 3.4: Significance levels for fixed factors and their interactions for biomass and its components of three lucerne varieties at two sites

Parameter/ Harvest	Effect	2007				2008			
		1	2	3	Yearly Average	1	2	3	Yearly Average
Shoot dry matter	**Site**	*	*	*	*	+	ns	*	*
Yield (tones ha^{-1})	**Varieties**	*	Ns	ns	*	ns	*	ns	ns
§	**Site*Var**	*	Ns	ns	*	ns	ns	ns	ns
Shoot height (cm)	**Site**	*	*	*	*	ns	*	*	*
	Varieties	ns	Ns	*	*	ns	*	ns	ns
	Site*Var	ns	Ns	+	*	ns	ns	ns	ns
Shoot number m^{-2}	**Site**	ns	*	ns	*	+	ns	-	ns
	Varieties	*	*	*	*	ns	ns	-	ns
	Site*Var	*	*	*	+	ns	ns	-	ns
Leaf area index	**Site**	*	*	*	*	ns	*	*	*
	Varieties	ns	Ns	ns	ns	*	ns	ns	ns
	Site*Var	ns	Ns	ns	+	*	ns	ns	ns
Leaf to Stem ratio	**Site**	ns	*	+	*	ns	*	-	*
	Varieties	*	Ns	ns	*	+	+	-	*
	Site*Var	ns	*	ns	+	+	ns	-	ns
Relative water	**Site**	*	Ns	-	+	-	-	ns	ns
content (%)	**Varieties**	ns	Ns	-	ns	-	-	ns	ns
	Site*Var	ns	Ns	-	ns	-	-	ns	ns
Chlorophyll	**Site**	ns	Ns	-	ns	ns	*	ns	ns
content	**Varieties**	+	Ns	-	ns	ns	ns	+	+
(mg m^{-2} leaves)	**Site*Var**	ns	Ns	-	+	ns	ns	ns	ns

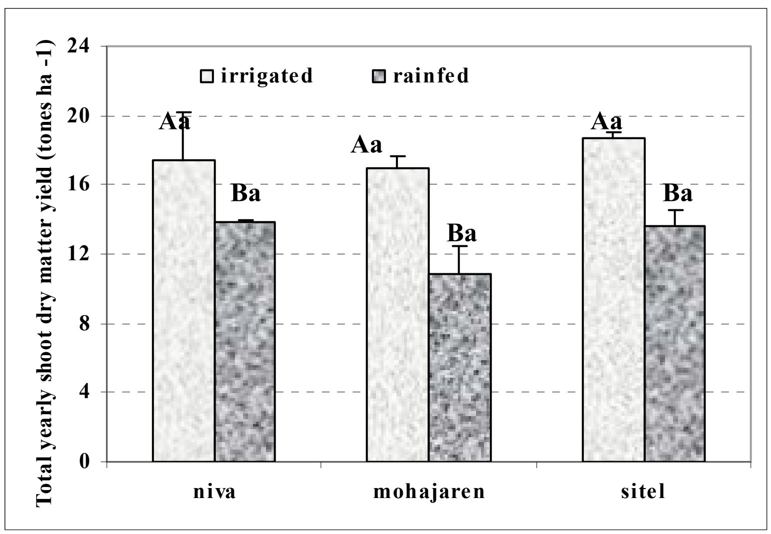
ns- non- significant, *- significant at 5% level of probability, +- significant at 10 % level of probability

§- total yearly shoot DM yield instead of yearly average

2007



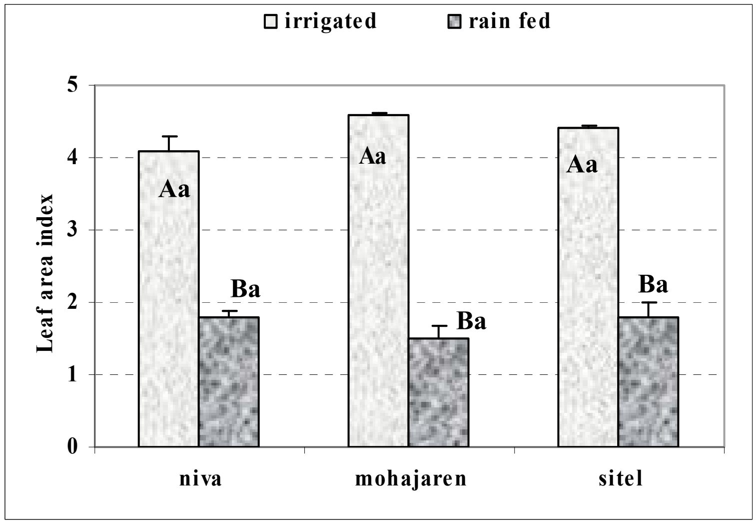
2008



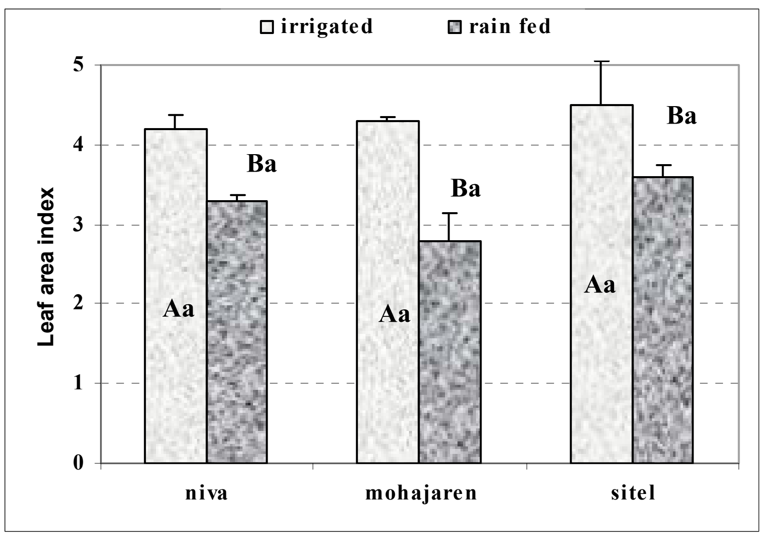
Error bars indicate one standard deviation. Significant differences among sites and varieties are represented by different capital and small alphabets, respectively.

Fig 3.2: Total yearly shoot dry matter yield of lucerne varieties under irrigated and rain-fed conditions (2007-2008).

2007



2008



Error bars indicate one standard deviation. Significant differences among sites and varieties are represented by different capital and small alphabets, respectively

Fig. 3.3: Leaf area index of lucerne varieties under irrigated and rain-fed conditions.

Data from six lucerne varieties in the rain-fed site were analyzed separately to compare their performance for yield and its components. A comprehensive summary of findings for different traits at all major harvests and their yearly averages are presented in Table 3.5. Significant differences (P < 0.05) were found in varieties for their total yearly SDMY in 2007. Total yearly SDMY of lucerne varieties varied from 5.9-11.1 and 10.8-14.3 tones ha^{-1}, in 2007 and 2008, respectively. In 2007, Sitel had the highest total yearly

SDMY (11.17 tones ha^{-1}) and Ordobad had the lowest SDMY (5.9 tones ha^{-1}) and in 2008 NS-banat had the highest SDMY of 14.3 tones ha^{-1} while Ordobad the lowest total yearly SDMY of 10.82 tones ha^{-1}.

Table 3.5: Significance levels for fixed effects for biomass and its components of six lucerne varieties (rain-fed site)

Parameter/Harvest	2007				2008			
	1	2	3	Yearly Averages	1	2	3	Yearly Averages
Shoot dry matter Yield (tones ha^{-1}) §	*	+	ns	*	ns	*	ns	*
Shoot height (cm)	+	ns	ns	*	ns	*	ns	+
Shoot number m^{-2}	*	*	*	+	*	+	-	*
Leaf area index	ns	ns	ns	ns	ns	+	ns	+
Leaf to Stem ratio	*	ns	ns	ns	ns	+	-	ns
Relative water content (%)	ns	ns	ns	ns	ns	ns	ns	ns
Chlorophyll content (mg m^{-2} leaves)	*	ns	ns	ns	ns	ns	+	*

ns- non- significant, *- significant at 5% level of probability, +- significant at 10 % level of probability
§- total yearly shoot DM yield instead of yearly average

Based on yearly averages, varieties differed significantly ($P < 0.05$) for SN in both years. Varieties differed significantly ($P < 0.05$) for SH in 2007. Based on yearly averages, Sitel had the highest SH (52 cm) and Ordobad had the lowest shoot height (41 cm) in 2007. Vlasta produced the tallest shoots (83.8 cm) in 2008 and Mohajaren produced the shortest shoots (75 cm). Mohajaren produced the highest shoot number m^{-2} (859) in 2007 while Ordobad had the lowest shoots m^{-2} (667). In 2008, Vlasta had the maximum shoots m^{-2} (1264) and Ordobad had the minimum shoots m^{-2} (880).

Differences were found non-significant (based on yearly averages) among varieties for their leaf to stem ratio and RWC in both years. In 2007, varieties had generally higher leaf to stem ratio as compared to 2008. Differences in varieties were so minute for said trait that it is difficult to establish a clear ranking for showing superiority of one variety over the others. Lucerne varieties had relatively higher RWC in 2008 as compared to 2007 due to better water availability in 2008 through rains (Fig 3.1), but within one year differences among the varieties were small. In 2007, Mohajaren maintained the highest

RWC (82 %) while Niva was the poorest in terms of maintenance of RWC (76 %) but in 2008, Sitel was found superior as it was able to maintain higher RWC (88 %) while Ordobad had the lowest value of RWC (86 %).

LAI of lucerne varieties did not differ significantly in 2007 but became significant in 2008 ($P < 0.10$). LAI was higher in 2008 as compared to 2007 for all varieties. In 2007, Sitel and Vlasta were the varieties with maximum LAI of 1.9 while Mohajaren had the lowest LAI (1.5) among all other varieties. In 2008, Sitel had the highest LAI of 3.7 while Mohajaren produced the smallest LAI of 2.8.

In 2007, varieties did not differ significantly for their chlorophyll content while in 2008, significant differences ($P < 0.10$) were found among varieties for their chlorophyll content. Based on yearly averages of chlorophyll content, it was found that varieties had higher chlorophyll content in 2007 as compared to 2008. In 2007, highest chlorophyll content was found in Sitel (730 mg m^{-2} leaves) and lowest in Ordobad (668 mg m^{-2} leaves) whereas in 2008, Sitel had the highest chlorophyll content (mg m^{-2} leaves) of 705 while lowest chlorophyll content were observed in Niva (641 mg m^{-2} leaves). Detailed results on SDMY and its components are presented in Table 6 (see Annexure). Results on parameters that differ significantly among varieties are presented in Table 3.6.

Table 3.6: Results on parameters that differ significantly under rain-fed site

Year	Parameter	Niva	Mohajaren	Sitel	NS-banat	Ordobad	Vlasta
2007	Total yearly SDMY (tones ha^{-1})	8.64abc	7.38ab	11.17c	7.73ab	5.9a	10.39bc
2007	Shoot number m^{-2}	762ab	859b	773ab	747ab	667a	741ab
2008		968a	1208b	1136b	1168b	880a	1264b
2007	Shoot height (cm)	49b	46b	52c	47b	41a	51c
2008	Chlorophyll content (mg m^{-2} leaves)	641a	672ab	705b	642a	665ab	646a

3.3.5 Carbon isotope discrimination

CID values ranged from 19.8 to 23.5(‰) in the present study. Interactions among sites and varieties were found non-significant except at third harvest in 2007. Carbon isotope discrimination values differed significantly ($P < 0.05$) between two sites at all main harvest in both years except at harvest 1 and 2 in 2008 (Table 3.7). CID values in the irrigated site varied form 21.4 to 23.5 (‰) while CID values for rain-fed site were in the range of 19.8 to 22.9 (‰). Non-sigficant results in earlier harvests of 2008 can be attributed to better rains in rain-fed site in 2008 (Fig 3.1) and over all better growing conditions for lucerne in 2008. Non- significant differences were found among varieties for their CID at all harvests in both years except at final harvest in 2007 (Table 3.7). At the time of final harvest in 2007, Niva, Mohajaren and Sitel had the CID values of 23.1, 23.3 and 23.5 (‰) in the irrigated site and CID values of 21.5, 21.3 and 21.5 (‰) in the rain-fed site, respectively. Differences in CID values for lucerne varieties were minor so it is difficult to establish a clear ranking for showing superiority of one variety over the other. Detailed results regarding varietal performance for their CID in different sites are presented in Table 7 (see Annexure).

In the rain-fed site, values of CID varied from 19.7 to 23.2 (‰) during the entire study period. Non-significant differences were found among varieties for CID at all main harvests in both years except at the third harvest in 2008 (Table 3.9) where Vlasta had the highest value of CID (23.2) followed by Sitel and Niva (22.4) while NS-Banat and Ordobad had the lowest values (22.1). Values of CID for additional varieties in the rain-fed site are presented in Table 8 (see Annexure).

Table 3.7: Significance levels for fixed factors and their interactions for carbon isotope discrimination of three lucerne varieties at two sites

Effect/Harvest	2007			2008		
	1	2	3	1	2	3
Site	*	*	*	ns	ns	*
Varieties	ns	ns	*	ns	ns	ns
Site* Var	ns	ns	*	ns	ns	ns

ns- non- significant, *- significant at 5% level of probability

CID values for different plant parts ranged from 19.7-23.5 (‰). Significant differences were observed among shoot, stubble and root for their CID in both years at both sites. Root and stubble have relatively lower values of CID as compared to shoots. In 2007, CID values for roots and stubbles were in the range of 19.7-20.8 (‰) while for shoot, CID values were 21.3-23.5 (‰). In 2008, CID for roots and stubbles were in the range of 20.2-23.1 (‰) while shoots had CID values of 22.2-23 (‰). Relatively lower values of CID were observed in rain-fed site as compared to irrigated site. In 2007, CID ranged from 19.7 to 21.5 (‰) for rain-fed site while for irrigated site these values were in the range of 21.3-23.5 (‰). In 2008, CID ranged from 20.2 to 22.3 (‰) for rain-fed site while for irrigated site these values were in the range of 21.3-23.1(‰). Lucerne varieties did not differ significantly for their CID (Table 3.8) except in the rain-fed site in 2008. Varieties in the rain-fed site in year 2008 differed significantly ($P < 0.10$) for CID where CID values for different plant parts among varieties ranged from 20.2-23.2 (‰). Values of CID for site comparison and rain-fed site are presented in Table 9 and 10, respectively (see Annexure). Statistical analysis was carried out for each site and each year separately with the objective to show only if plant parts differ significantly for their CID values or not.

Table 3.8: Significance level of fixed factors and plant parts for carbon isotope discrimination of three lucerne varieties at two sites

Effect/Site	2007		2008	
	Irrigated	Rain-fed	Irrigated	Rain-fed
Plant parts	*	*	*	*
Varieties	ns	ns	ns	+

ns- non- significant, *- significant at 5% level of probability, +- significant at 10 % level of probability

Table 3.9: Significance levels for fixed effects for carbon isotope discrimination values of six lucerne varieties (rain-fed site)

Effect/Harvest	2007			2008		
	1	2	3	1	2	3
Varieties	ns	ns	ns	ns	ns	*

ns- non- significant , *- significant at 5% level of probability

3.3.6 Root biomass, root length density and associated parameters

Root biomass: Roots play an important role in anchoring plants to soil and help plants to absorb water and nutrients from the soil. Root biomass in the 0-60 cm of soil profile ranged from 8252- 16140 kg ha^{-1} at the time of final harvest in 2008 (Table 11). In the present study, interactions among sites and varieties, varieties and depth and sites, varieties and depths were found significant ($P < 0.05$) only at final harvest in 2008. Interactions among sites and depths were found non-significant at all major harvests in both years (Table 3.10). Differences among sites and varieties were found non-significant for root biomass but differences between sampling depths were significant ($P < 0.05$) at all harvest in both years.

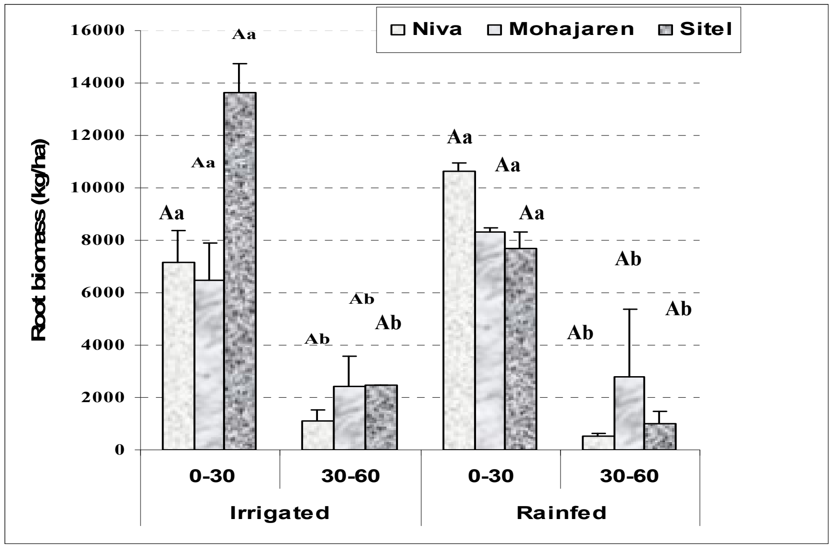
Based on results of final harvest in 2008 in irrigated site, Sitel had the highest biomass (16140 kg ha^{-1}) followed by Mohajaren (8881 kg ha^{-1}) and Niva (8252 kg ha^{-1}) and in rain-fed site, Niva produced the highest biomass (11136 kg ha^{-1}) followed by Mohajaren (11101 kg ha^{-1}) and Sitel (8658 kg ha^{-1}). Results from final harvest in 2008 in every 30 cm profile in both sites are presented in figure 3.4. Detailed results of studies on root biomass from both sites and years at all main harvests are presented in Table 11 (see Annexure).

In the rain-fed site, interactions among varieties and depths were found significant at first harvest in 2007 and third harvest in 2008 (Table 3.11). Differences among varieties were found significant at all major harvests except at first harvest in 2008. Differences among root biomass in different depths were also found significant ($P < 0.05$) at third harvest in both years.

Table 3.10: Significance levels for fixed factors and their interactions for root biomass of three lucerne varieties at two sites

Effect/Harvest	2007		2008	
	1	3	1	3
Site	ns	ns	ns	ns
Variety	ns	ns	ns	ns
Depth	*	*	*	*
Site* Var	ns	ns	ns	*
Site*Depth	ns	ns	ns	ns
Var*Depth	ns	ns	ns	*
Site*Var*Depth	ns	ns	ns	*

ns- non- significant, *- significant at 5% level of probability



Error bars indicate one standard deviation. Significant differences among varieties and depths are represented by different capital and small letters, respectively.

Fig 3.4: Root biomass of lucerne varieties at final harvest (2008) under irrigated and rain-fed conditions.

Detailed results on root biomass from all main harvests in both years are presented in table 11 and 12 (see Annexure). At the final harvest in 2008, Ordobad produced the highest root biomass (16709 kg ha^{-1}) followed by NS-banat (14492 kg ha^{-1}) while Sitel had the lowest biomass (8658 kg ha^{-1}).

Table 3.11: Significance levels for fixed effects and their interactions for root biomass of six lucerne varieties under rain-fed conditions

Effect/Harvest	2007		2008	
	1	3	1	3
Variety	*	+	ns	*
Depth	ns	*	ns	*
Var*Depth	+	ns	ns	*

ns- non- significant, *- significant at 5% level of probability,
+- significant at 10 % level of probability

Maximum rooting depth: Maximum rooting depth of lucerne varieties ranged from 100-190 cm. Differences among sites, varieties and interactions of site and varieties were found non-significant for maximum rooting depth. Differences among varieties in the rain-fed site were also found non-significant for their maximum rooting depth. In the irrigated site, Mohajaren had the maximum rooting depth (190 cm) followed by Sitel (150 cm) and Niva (130 cm). In the rain-fed site, Sitel had the highest rooting depth (145 cm) and Vlasta had the lowest (100 cm). Data on maximum rooting depth is shown in Table 13 (see Annexure).

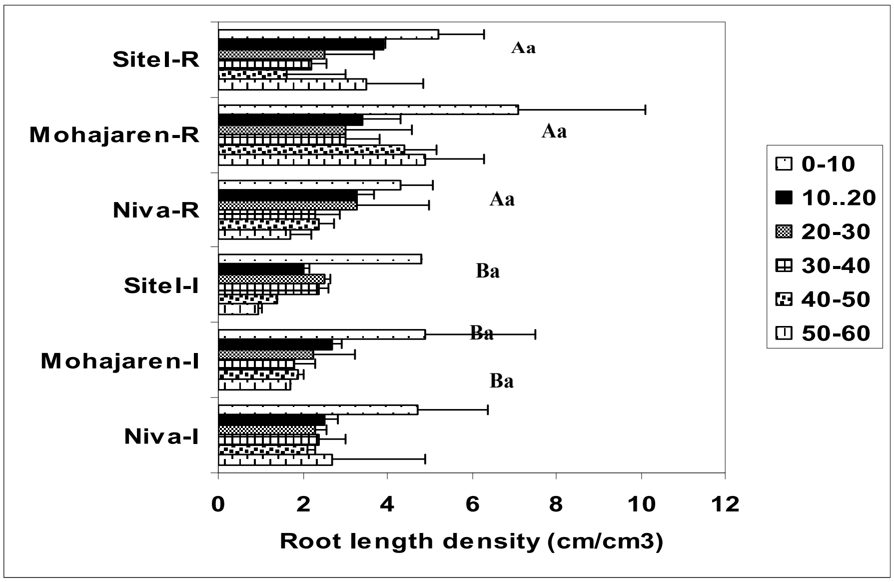
Root length density: RLD describes root length per unit soil volume**.** In the present study, interactions among sites and varieties and sites, varieties and depths were found non-significant in both years. Interactions among sites and depth and among varieties and depths were found significant ($P < 0.05$) in 2007 and found non-significant in 2008 (Table 3.12). RLD usually tended to increase with depth in both sites in the first year of study. Higher values of RLD were observed for rain-fed site (0.5-1.6 cm cm^{-3}) as compared to irrigated site (0.4-1.2 cm cm^{-3}). In 2007, there were significant differences ($P < 0.10$) among sites and varieties for RLD. RLD was also significantly different ($P < 0.05$) among sampling depths like root biomass. In 2008, differences among sites and depths were significant ($P < 0.05$) but differences among lucerne varieties were found non-significant. RLD ranged from 1.6-7.1 cm cm^{-3} and 1.0-4.9 cm cm^{-3} at the rain-fed and irrigated site, respectively. Varieties in rain-fed site have relatively higher RLD like root biomass in both years. RLD of lucerne varieties for every 10 cm profile for both sites is shown in Figure 3.5.

Table 3.12: Significance levels for fixed factors and their interactions for root characteristics of three lucerne varieties at two sites

Effect/Year	2007				2008			
	Root length density	Root surface area	Root volume	Average diameter	Root length density	Root surface area	Root volume	Average diameter
Site	+	+	ns	ns	*	+	ns	ns
Variety	+	*	*	+	ns	ns	ns	ns
Depth	*	*	*	*	*	*	*	ns
Site* Var	ns	+	ns	ns	ns	ns	ns	ns
Site*Depth	*	*	*	ns	ns	ns	*	ns
Var*Depth	*	*	*	*	ns	ns	*	ns
Site*Var*Depth	ns	ns	*	+	ns	ns	+	ns

ns- non- significant, *- significant at 5% level of probability, + significant at 10 % level of probability

In the rain-fed site, interactions among varieties and depths were also found non-significant in both years (Table 3.13). Non-significant differences were found among varieties for their RLD in both years of studies but RLD was significantly different ($P < 0.05$) among different sampling depths in both years. RLD varied from 0.5-1.6 cm cm^{-3}in 2007 and 1.6-7.1 cm cm^{-3} in 2008.



Error bars indicate one standard deviation. Significant differences among sites and varieties are represented by different capital and small letters, respectively.

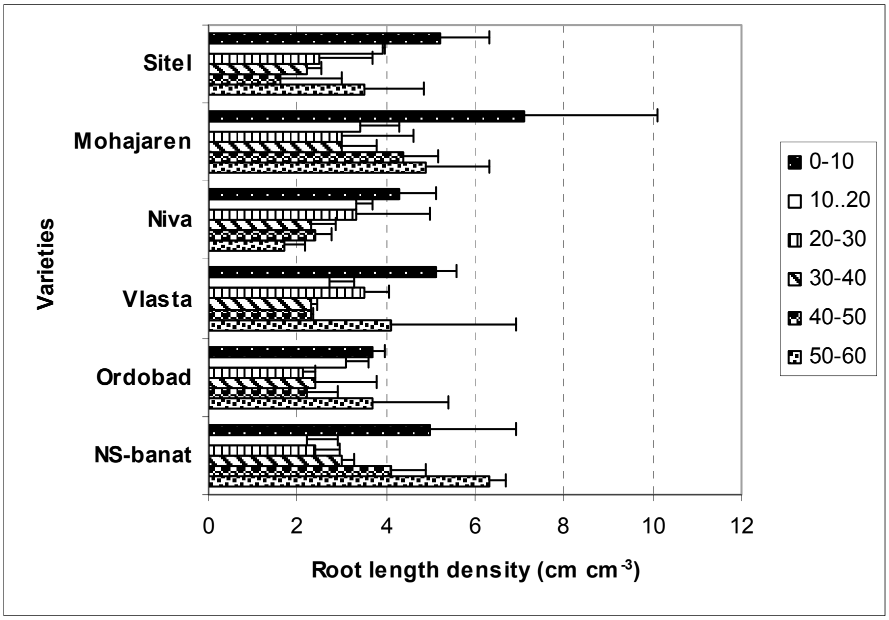
Fig 3.5: Root length density (cm cm^{-3}) of lucerne varieties under rain-fed and irrigated conditions (2008).

In 2008, varieties have usually higher RLD in upper soil layers as compared to lower soil layers. These findings are in line with those of Zahid (2009). RLD of varieties determined at final harvest in 2008 is presented in Figure 3.6.

Table 3.13: Significance levels for fixed effects and their interactions for root chaharcteristics of six lucerne varieties (rain-fed site)

Effect/Year	2007				2008			
	Root length density	Root surface area	Root volume	Average diameter	Root length density	Root surface area	Root volume	Average diameter
Variety	ns	*	*	ns	ns	ns	ns	ns
Depth	*	*	*	*	*	*	*	ns
Var*Depth	ns	*	*	*	ns	*	ns	ns

ns- non- significant, *- significant at 5% level of probability



Error bars indicate one standard deviation.

Fig. 3.6: Root length density of lucerne varieties under rain-fed conditions (2008).

Root surface area (cm^2) : Measurements of RSA are important as root biomass data do not provide information on active root surface area because of bias by large and inactive roots (Box and Ramseur, 1993). RSA influences the kinetics of water and nutrient uptake (Smika and Klute, 1982). RSA ranged from 15-459 cm^2. In the present study, interactions among sites and varieties, sites and depths and varieties and depths were found significant in 2007 and non-significant in 2008. Interaction among site, varieties and depths were found non-significant in both years. There were significant differences (P < 0.10) among sites for RSA in both years. RSA also differed significantly (P < 0.05) among sampling depths. In 2007, RSA varied from 15-82 cm^2 in the irrigated site while RSA values for the rain-fed site varied from 31-72 cm^2 in the 0-90 cm of soil profile. In 2008, RSA values for irrigated site in the 0-60 cm of soil profile were in the range of 56-377 cm^2 while RSA for rain-fed site varied from 119-459 cm^2. Differences among varieties were significant (P < 0.05) in 2007 and non-significant in 2008. This may be due to the fact that in 2007, roots were still actively growing but by 2008, roots might have reached their maximum RSA due to which no significant differences were observed.

Varieties in the rain-fed site had usually higher RSA as compared to irrigated site in both years. These results match with the results of RLD. In 2007, RSA was higher in lower soil depths like RLD but in 2008, trend changes slightly and upper soil layers had generally higher RSA. Based on total RSA (0-60 cm), at the final harvest in 2008, Niva produced the highest RSA followed by Sitel and Mohajaren in the irrigated site while Mohajaren produced the highest RSA followed by Sitel and Niva in the rain-fed site. Detailed results on root parameters viz. RSA, RV and AD are presented in Table 14 and 15 (see Annexure) for year 2007 and 2008, respectively.

In the rain-fed site, RSA of six varieties differed significantly ($P < 0.05$) in 2007 but did not differ significantly in 2008. RSA of varieties ranged from 28-74 cm^2 in the 0-90 cm of soil profile in 2007. Significant differences ($P < 0.05$) were observed among sampling depth for RSA in both years. Interactions among varieties and depths were also found significant ($P < 0.05$) in both years. Detailed results on root parameters (RSA, RV and AD) of three additional varieties in the rain-fed site are presented in Table 16 and 17 (see Annexure) for year 2007 and 2008, respectively. Values of RSA presented in this section were based on mean value of 2 replicates from the auger sample at a given depth for each variety.

Root volume: Interactions among sites and varieties were found non-significant in both years. Interactions among sites and depths, varieties and depths and site, varieties and depths were found significant in both years. Sites do not have a significant effect on root volume in both years but lucerne varieties differed significantly ($P < 0.05$) in their RV in 2007 but did not differ significantly in 2008. In 2007, Niva had the maximum RV of 3.18 cm^3 followed by Mohajaren (2.5 cm^3) and Sitel (1.63 cm^3) in the irrigated site. In the rain-fed site, varieties had the same ranking with Niva having the maximum RV (2.45 cm^3) followed by Mohajaren (2.34 cm^3) and Sitel (1.76 cm^3). There were significant differences ($P < 0.05$) in RV at different depths at both years of study. Higher proportions of RV are concentrated in upper 30 cm of soil profile for both sites. Significant differences among RV in 2007 and non-significant differences in 2008 correspond to results of RSA.

Interactions among six varieties in the rain-fed site and depths were found significant (*P* < 0.05) in 2007 and non-significant in 2008. Six varieties in the rain-fed site differed significantly (*P* < 0.05) in 2007 and did not differ significantly in 2008 for their RV. In 2007, Niva had the highest RV (2.45 cm^3) followed by Mohajaren (2.34 cm^3) and Vlasta (2.33 cm^3) while NS-banat had the lowest RV (0.57 cm^3). Significant differences (*P* < 0.05) among different depths were found also for varieties in both years of experimentation. Upper part of soil profile (0-30 cm) usually had higher RV as compared to lower part (30-90 cm) that might have lead to significant differences among depths (see Table 14, 15 and 16)..

Average diameter: Root diameter influences net ion influx into roots (Barber, 1995). Root with smaller diameters usually exhibit better nutrient and water uptake capacity than larger diameter. Fine roots are assumed to account for the majority of the uptake surface of the plant (Eissenstat and Caldwell, 1988). Interactions among sites and varieties and interactions among sites and depths were found non-significant in both years. Interactions among varieties and depths and interactions among sites, varieties and depths were found significant and non-significant in 2007 and 2008, respectively.

There were no significant differences in AD in both sites in both years and these results are acceptable as fineness of roots is usually not influenced by site. Lucerne varieties differed significantly (*P* < 0.10) for their AD in 2007 and did not differ significantly in 2008. In the irrigated site in 2007, AD of Niva, Mohajaren and Sitel was 0.28-0.59 mm, 0.27-0.33 mm and 0.28-0.34 mm in the 0-90 cm of soil profile, respectively. In the rain-fed-site, AD of Niva, Mohajaren and Sitel was 0.27-0.48 mm, 0.25-0.41 mm and 0.27-0.45mm, respectively. Significant differences (*P* < 0.05) were observed for depths in 2007 and non-significant differences among depths in 2008. This can be attributed to the continual growth of roots in 2007 and probable cessation of growth in 2008. AD varied from 0.24 to 0.35 mm for irrigated site and 0.21 to 0.49 mm in 0-60 cm of soil profile at the time of final harvest in 2008.

Interactions among six varieties in the rain-fed site and depth were also significant in 2007 and non-significant in 2008. Varieties in the rain-fed site did not differ significantly for their AD in both years. Differences in depth were significant ($P < 0.05$) in first year but these differences became non-significant in second year.

3.3.7 Evapotranspiration of lucerne varieties

ETa represents the amount of water used by a crop variety during a given period of time like harvests or vegetation period in a given year. Varieties with higher yield and lower ETa are desirable to obtain better WUE. Values of ETa for varieties under irrigated and rain-fed conditions are given in Table 18 and 19 (see Annexure), respectively. Significant differences ($P < 0.05$) were observed among sites at most of the harvests in both years of experimentation (Table 3.14). Irrigated site usually had higher ETa values (76-495 mm) as compared to the rain-fed site (54-314 mm). Differences among varieties were found non-significant at all harvests in both years except final harvest in 2008. Based on the results of final harvest in 2008, ETa values of Niva, Mohajaren and Sitel are 211, 225 and 226 mm for the irrigated site and 100, 166 and 149 mm for the rain-fed site, respectively. Based on cumulative ETa during the entire vegetation period in 2007 and 2008 in the irrigated site, Mohajaren had the lowest ETa values followed by Niva and Sitel. In the rain-fed site in 2007, Sitel had the lowest ETa followed by Niva and Mohajaren and in 2008 Niva had the lowest ETa followed by Mohajaren and Sitel.

Table 3.14: Significance levels for fixed factors and their interactions for actual evapotranspiration of three Lucern varieties at two sites

Effect/Harvest	2007		2008		
	2	3	1	2	3
Site	*	ns	*	*	*
Varieties	Ns	ns	ns	ns	*
Site* Var	Ns	ns	ns	ns	*

ns- non- significant, *- significant at 5% level of probability

Differences among six lucerne varieties at the rain-fed site were found non-significant at all harvests in both years (Table 3.15). Values of ETa for lucerne varieties at all main harvests in both years are presented in Table 19 (see Annexure).

Table 3.15: Significance levels for fixed effects for for actual evapotranspiration of six lucerne varieties (rain-fed site)

Effect/Harvest	2007		2008		
	2	3	1	2	3
Varieties	Ns	ns	ns	ns	ns

ns- non- significant

3.3.8 Water use efficiency of productivity

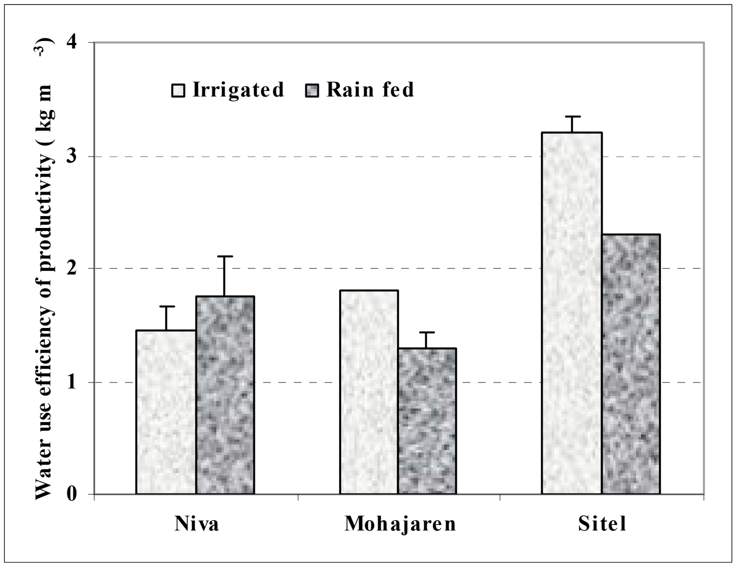
WUEp varied from 0.8-4.6 kg m^{-3} in the present study**.** Interaction among varieties and site were significant at first and final harvests in 2008 (Table 3.16). At the first harvest from irrigated site in 2008, Sitel had the highest WUE (4.6 kg m^{-3}) followed by Niva (3.65 kg m^{-3}) and Mohajaren (3.6 kg m^{-3}) while from rain-fed site, Niva had the maximum WUE (2.25 kg m^{-3}) followed by Mohajaren (2.1 kg m^{-3}) and Sitel (2 kg m^{-3}). Significant differences ($P < 0.05$) were observed between sites for their WUEp at all major harvests except the final harvest in 2008 (see Table 20). Irrigated site usually had higher values of WUEp (1.4-4.6 kg m^{-3}) as compared to rain-fed site (0.8-2.3 kg m^{-3}) at all major harvest in both years. These differences were expected due to higher yields in irrigated site and effect of irrigation. Lucerne is reported to produce higher yields and WUE under light and frequent irrigations (Saeed and El-Nadi, 1997). Differences among varieties were found non-significant at all major harvests in both years. On the overall basis, Sitel had relatively higher WUEp under both irrigated and rain-fed conditions (Table 20). WUEp of lucerne varieties at final harvest in 2008 is presented in Figure 3.7.

Table 3.16: Significance levels for fixed factors and their interactions for water use efficiency of productivity of three lucerne varieties at two sites

Effect/	2007	2008		
Harvest	3	1	2	3
Varieties	Ns	ns	ns	ns
Sites	*	*	*	ns
Site*Var	Ns	*	ns	*

ns- non- significant, *- significant at 5% level of probability

Differences among six varieties at rain-fed site were non-significant except at second harvest in 2008 (Table 3.17) (Table 21). At second harvest in 2008, Sitel and NS-banat had the highest WUE (2.3 kg m^{-3}) followed by Niva (2.15 kg m^{-3}) while Mohajaren had the lowest WUE (1.15 kg m^{-3}).



Error bars indicate one standard deviation.

Fig. 3.7: Water use efficiency of productivity of lucerne varieties at final harvest in 2008**.**

Table 3.17: Significance level for water use efficiency of productivity for six lucerne varieties under rain-fed conditions

Effect/ Harvest	2007	2008		
	3	**1**	**2**	**3**
Varieties	ns	ns	*	ns

ns- non- significant , *- significant at 5% level of probability

3.4 Discussion

Significant differences were observed between two sites for SDMY, SH, SN and LAI at most harvests in both years. Relatively higher values for SDMY, SH, SN and LAI were observed at irrigated site as compared to rain-fed site. This may be due to the fact that optimal amount of water was available for maintaining plant growth under irrigated site throughout the vegetation period through supplemental irrigation. These differences can also be attributed to relatively lower organic carbon contents in 30-90 cm of soil profile for soils of rain-fed site (Table 3.1) that led to their lower water holding capacity. Soils in the rain-fed site were slightly better in terms of soil available water as revealed by retention curves data (Table 3.3) but this did not seem to have much effect on better yield performance of lucerne varieties under rain-fed site probably because this was superseded by the effect of irrigation. No supplemental irrigation was provided to rain-fed site thereby creating a water deficit at this site when compared to irrigated site where supplemental irrigation was provided. This water deficit leads to a reduction in SDMY for lucerne as reported in earlier studies (Carter and Sheaffer, 1983). Higher values of leaf to stem ratio are observed usually under rain-fed site as compared to irrigated site. This may be due to the fact that water deficit causes a cessation of stem growth while leaf growth continues thereby leading to a higher leaf to stem ratio. Increase in leaf to stem ration under water deficit conditions has also been reported in earlier studies (Carter and Sheaffer, 1983; Halim et al., 1989).

Non-significant differences among varieties for RWC depict that varieties had very small differences for this parameter and even site/irrigation effect did not bring major change. RWC has been shown to correlate well with drought tolerance (Jamaux et al., 1997; Altinkut et al., 2001; Colom and Vazzana, 2003). Non-significant differences among varieties for their chlorophyll content may explain us that these varieties may not differ in their drought tolerance under stress conditions and it is justified as site is not going to alter chlorophyll content of a variety as this character is in built and fixed for a given variety. On the overall basis, higher values of chlorophyll content for Sitel are justified as it is a local well-adapted variety.

Differences in CID values at two sites can be attributed to differences in water regime of two sites and these findings are supported by earlier studies of Xu et al. (2007) who reported that CID can vary with plant part being studied, stage of sampling, environment and water regime. Non-significant differences among varieties for CID coincide with results of other physiological parameters (RWC and chlorophyll content) in the present study. As CID is also related to drought tolerance (Condon et al., 2004) , it explains that narrow genetic diversity exists among studied varieties for their suitability under drought, that is why they do not produce significantly different results for drought sensitive parameters.

CID varied with plant parts being studied and these findings are in line with earlier studies (Araus et al., 2002; Xu et al., 2007). Root and stubble have relatively lower values of CID as compared to shoots. These findings partly coincide with those of Johnson and Rumbaugh (1995) who reported lower values of CID for lower parts of plants.

Differences among varieties and differences among sites were found non-significant for root biomass. Differences in root biomass in different depths at different sites were found significant and it can be due to the fact that as the roots grow deeper, their distribution pattern becomes different. Rain-fed site have relatively higher biomass as compared to irrigated site. Under water limited conditions, roots tend to grow more in search of water. Contrasting and inconclusive results have been reported by earlier workers (Jodar-Karimi et al., 1983; Luo et al., 1995) dealing with research on lucerne roots due to difficulties associated with traditional methods of studying roots in the field as these methods require more labour , time and equipment. Root studies are associated with high variability coupled with the variability in the environment and the age of plant being studied (Sheaffer et al., 1988).

RLD varied significantly only with depth in both years of study. In 2007, RLD is higher in lower soil layers as compared to upper soil layers. Contrasting results have also been reported earlier for lucerne root studies (Jodar-Karimi et al., 1983; Luo et al., 1995). Possible causes of higher RLD in lower soil layers can be colliding of branches of roots in middle to lower soil layers (30-90 cm) due to relatively narrow row spacing, mixing of on the row and between the row samples, small number of replications and small diameter of augers used in root sampling. Heterogeneity in root distribution studies even with higher number of replicates is well known besides this root distribution itself is highly variable (Bengough et al., 2000). In 2008, varieties have higher RLD in upper soil layer (0-30 cm) as compared to lower soil layer (30-60 cm). These findings coincide with those of Zahid (2009). Results of RLD in second year of studies seem more reliable due to use of auger of larger diameter (7 cm) and washing and analysis of on the row and between the row samples separately.

ETa of varieties was found non-significant at most of the harvests and it depicts that varieties do not differ drastically in their water requirements for transpiration. The same trend follows for WUEp as it was based on ETa values where differences among varieties were found non-significant. Differences among sites for WUEp seem largely due to differences in irrigation and water holding capacity of the sites. Higher values of WUEp in the irrigated site as compared to rain-fed site are associated with higher SDMY.

In the rain-fed site, significant differences among varieties for SDMY (based on yearly averages) can not be considered as an indicator of variation among varieties as varieties did not differ significantly for SDMY at most of the harvests in both years of study (Table 3.5). Also the varieties did not differ significantly for SH, LAI, leaf to stem ratio, RWC and chlorophyll content at most of the harvest in both years of experimentation.

On the overall basis, varieties tended to produce relatively higher SDMY in 2008 as compared to 2007 due to higher precipitation during vegetation period of 2008 (see Fig. 3.1). Based on total yearly SDMY in the rain-fed site, Ordobad was consistently low yielding variety in both years and not fit for use under rain-fed conditions. NS-banat, Sitel and Niva seem to perform better under rain-fed conditions and can be suitable choice for rain-fed conditions due to their relatively higher yields and WUEp. In the rain-fed site, NS-banat had relatively higher WUEp during all main harvests mainly because it had lower ETa values. Non-significant differences among varieties for their ETa and WUEp indicate that there exists narrow physiological and genetic diversity among varieties under study.

Varieties tended to perform better under irrigated conditions as compared to rain-fed conditions in both years of study. Differences among dry matter yield and associated morphological parameters seem to be caused by irrigation, site and year instead of varietal effect. This is reflected in the physiological parameters like relative water content, chlorophyll content and relative water content that do not seem to be much different among sites as well as among varieties. This holds true for comparison of varieties in two sites as well as for comparison of six varieties in the rain-fed site.

Based on total yearly shoot dry matter yield from comparison of three varieties at two sites, Sitel is the best variety followed by Niva and Mohajaren. In the rain-fed site NS-banat, Sitel and Niva seem to perform better and can be suitable choice for rain-fed conditions due to their relatively higher yields and WUEp. As roots are equally important especially under organic farming conditions, we found that under irrigated conditions, Sitel is the leading variety as it produced the highest root biomass followed by Mohajaren and Niva. In the rain-fed site, Ordobad had the maximum root yields followed by NS-banat and Sitel.

Chapter 4

Effect of lucerne utilization system on yield, biological nitrogen fixation and water conservation

4.1 Introduction

Utilization systems strongly affect the amount of nitrogen (N) supplied by the legume crops. In a cutting regime, most of the fixed N_2 is removed by harvesting the forage legumes, and the benefit to the subsequent crops is reduced. On the contrary, with green manure use where the cut material is returned to the soil as mulch, also fixed N_2 will be returned to the soil with the legume residues. Nitrogen fixation is likely to be affected by the additional mineral N released from the decomposing residues. Nitrogen dynamics are likely to be very different when the cut herbage is returned to soil (Cuttle et al., 2003). The grass yield in a mulched red clover/ryegrass-mixture was promoted by the foliage, which acted apparently as an N fertilizer (Schmitt and Dewes, 1997).

In northern Germany, Loges et al. (1999; 2000) determined a reduced N_2 fixation of mulched green manure legumes compared with the forage utilization (lucerne/grass forage use: 320 kg ha^{-1}, lucerne/grass green manure: 136 kg ha^{-1}). The returned herbage may also delay the regrowth of the legume by temporarily smothering their stubbles and thus reducing nitrogen fixation (Cuttle et al., 2003). There exists a possibility that when soil moisture content is sub-optimal for the mineralization process, the foliage will not be mineralized within the vegetation period. Thus, at fertile but dry sites, like in the pannonian region, green manure legume crops may fix the same amount as in a forage utilization system. The effect of mulching on the yield performance and nitrogen fixation process of forage legumes especially lucerne has not been investigated intensively under semi-arid conditions.

Mulching is regarded as one of the best ways to improve water retention in the soil and to reduce soil evaporation (Steiner, 1989; Li and Xiao, 1992; Baumhardt and Jones, 2002). Mulching tends to reduce runoff and increase infiltration (Papendick et al., 1990).

Mulching is known to affect water storage through moisture conservation under field conditions (Baumhardt and Jones, 2002). Greb (1966) found that residue and mulches reduce soil water evaporation by reducing soil temperature, impeding vapor diffusion, absorbing water vapor on to mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface.

Simulation models like CropSyst (Stöckle et al., 2003) can be used to compare the effect of utilization system (no mulch versus mulch) on yield and soil water conservation. Initial data on lucerne shoot dry matter yield is required for the purpose of application of mulch using model. These data need to be generated through field experimentation in the semi-arid regions like Raasdorf, Austria. A study was designed with the following objectives:

- To compare the effect of the utilization system (no mulch versus mulch) on lucerne yield and its components under semi-arid conditions
- To test if mulching increases nitrogen fixation and water use efficiency and decreases soil temperature
- To generate data sets on lucerne shoot dry matter yield under different utilization systems for use with simulation model, CropSyst.

4.2 Materials and methods

4.2.1 Experimental details and site description

A field experiment with lucerne variety Sitel was laid out on organically managed fields at Raasdorf, Eastern Austria for two consecutive years (2007-2008). The randomized complete block experiment with four replicates, having a plot size of 3 m x 3 m and row spacing of 12.5 cm, received usual management from sowing to harvest. Every year in April, sowing was done with machine on a different field using a seed rate of 25 kg ha^{-1}. Reference crop used for the estimation of nitrogen fixation comprised of mixture of four grasses in equal proportion. Species in the grass mixture included Perennial Ryegrass, False Oat, Cock's Foot and Red Fescue. Adjustments in seed rate were made based on germination percentage of seeds. The soil was labelled with ^{15}N at the beginning of the vegetation period in April 2007 and 2008 by using 0.1 kg ^{15}N ha^{-1} (N as 1 kg potassium nitrate ha^{-1}, 10 at% ^{15}N).

The trial site in Raasdorf is located in the Marchfeld, an area of about 100,000 ha approx. 5 km east of Vienna ($48^0 14^/$N, $16^0 35^/$E) at an altitude of 150–160 m above sea level. The Marchfeld is mainly devoted to intensive farming and the climate is characterized by hot, dry summers with little dew, and cold winters with little snow The mean daily temperature is 11.1 ^{0}C and the average annual precipitation is 539 mm (based on data from 1980-2009). Soils are Calcaric Phaeozems (WRB, 1998) from fine alluvial sediments with a silty loam texture, organic carbon contents of 2.2% in the Ap horizon, and a pH_{CaCl2} value of 7.6 (Pietsch et al., 2007).

4.2.2. Data recording on yield and its components

Data on yield was recorded at two main harvests in each year. Harvesting was done at 30-40 % of the flowering. Lucerne and reference crop (grass mixture) plots were hand clipped with a garden scissor at about 5 cm above the ground level. An area of $1m^2$ was harvested from each plot at each harvest to determine shoot biomass. Each plot had two distinct harvest areas of 0.5 m^2. Every year first harvest was used to apply no mulch and mulch treatments (data not shown). At second harvest, detailed studies on yield and its components were made to compare the effect of treatments and data on shoot height (SH), shoot number (SN), leaf area index (LAI) and chlorophyll content were recorded. Stubble biomass was determined only on second harvest in each year. Shoot and stubble dry matter yield were determined by oven-drying the sub-sample at 60 °C for 48 h. Total dry matter yield (TDMY) data at second harvest includes value of shoot, stubble and root dry matter yield (RDMY). Data on dry matter yield of reference crop (not shown) was used to estimate biological nitrogen fixation (BNF). Number of stems per m^2 was determined in a sub-sample of 0.20 m^2.

Leaf area index (LAI) was measured using LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE), at second harvest. Chlorophyll content (mg m^{-2} leaves) was measured using a portable chlorophyll meter, Yara N-tester (Yara international ASA, Norway, www.yara.com) at second harvest. Chlorophyll content (mg m^{-2} leaves) was measured from 30 fully expanded leaves in the upper 20 cm of plant canopy. Data from second harvest in each year is presented in the results and discussion section.

4.2.3 Soil and root sampling

Soil sampling was done to determine soil inorganic nitrogen (nitrate content) from experimental sites of both years. Ammonium content was not determined as sites had negligible amounts of ammonium (Pietsch et al., 2007). Sampling was done from each lucerne plot till 90 cm with every 30 cm profile. Every year, soil samples were collected before sowing the experiment in April and after making the first and second harvest in July and September, respectively.

Root samples were collected after second harvest in both years. Root sampling was done using soil corer having a diameter of 9 cm till the depth of 60 cm with every 15 cm profile for lucerne and every 30 cm profile for reference crop. Sampling strategy involved collection of one sample on the row and one sample between the row from each of the two harvest areas of each plot of lucerne and reference crop (grass mixture). Root samples were washed and roots were separated using a sieve having mesh size of 0.75 mm for the determination of RDMY by oven drying at 60 ^{0}C for 48 hours.

At the end of vegetation period in each year, undisturbed soil samples were collected in two replicates for the determination of soil texture, bulk density, retention curves and saturated hydraulic conductivity.

4.2.4 Measurement of soil water content and calculation of water balance and water use efficiency of productivity

Soil water content was measured using SENTEK Diviner 2000 (Sentek Sensor Technologies, Australia) probes that were installed at the depth of 120 cm in each lucerne plot. Soil water content was measured using manual data logger at weekly to fortnightly intervals. No site specific calibration was done and original values of water content obtained from the data logger were used to calculate water balance. Actual evapotranspiration (ETa) for treatments was calculated according the climatic water balance (Ehlers and Goss, 2003).

$$N + B = T + E + A + S + \Delta R$$

Where N, B, T, E, A, S and ΔR are precipitation, irrigation, transpiration, evaporation, surface runoff, leaching and change in the water content of the soil profile (0-120 cm), respectively. Precipitation and meteorological data was obtained from weather station of Institute of Agronomy and Plant Breeding, BOKU. The total amount of applied water was determined based on total precipitation and irrigation. Surface run off was ignored, since the experimental fields were flat (A = 0). It was assumed that no significant amount of leaching occurred (S = 0) beyond the root zone during vegetation period based on prevailing precipitation trends and water content data. The following simplified equation was used to calculate ETa.

$$ETa = T + E = N + B - \Delta R$$

ETa values presented in this chapter are calculated following the application of treatments (no mulch versus mulch) and include the period between first and second harvests in both years of experimentation. Water use efficiency of productivity (WUE_P) was calculated using TDMY from second harvest for each year. Respective water consumption values were derived from water balance calculations.

$$WUE_P = \text{Total dry matter yield / water consumption [kg DM m}^{-3}\text{ H}_2\text{O]}$$

4.2.5 Measurement of soil temperature

Soil temperature was measured using a manual and digital thermometer till the depth of 5 cm. Soil temperature measurements started after making treatment application at the time of first harvest in July each year. Temperature readings were taken for 2-3 weeks between the lucerne crop rows to compare the effect of treatments on soil temperature. Temperature readings were terminated as the LAI tended to increase as with increase in LAI, effect of mulching on soil temperature tends to disappear (Chen et al., 2007).

4.2.6 Samples for isotopic analysis

Shoot samples from first harvest and shoot, stubble and root samples from second harvest in both years were collected for the estimation of biological nitrogen fixation (BNF). Values of atom % N and atom % $^{15}N/^{14}N$ were determined on same sample that was used for determination of carbon isotope discrimination (Δ) by using isotope ratio mass spectrometer. Values of water use efficiency of photosynthesis/carbon isotope discrimination (Δ) were calculated from shoot samples of second harvest in both years. Samples were dried, processed and passed through 1 mm sieve before packing and labelling in special trays for further isotopic analysis. The Δ values (‰) were determined with an isotope ratio mass spectrometer (IRMS-Thermo Quest Finnigan DELTA plus) in the laboratory of the Department of Chemical Ecology and Ecosystem Research, University of Vienna, according to procedures of Farquhar et al. (1989):

$$\Delta = \frac{\delta^{13}C_{air} - \delta^{13}C_{plant}}{1 + \delta^{13}C_{plant}}$$

where $\delta^{13}C$ is the value of stable isotope ratio (air or plant) which is expressed as the $^{13}C/^{12}C$ ratio (R_{sample}) relative to the PeeDee belemnite standard ($R_{standard}$) (Craig, 1957):

$$\delta^{13}C(‰) = \left(\frac{R_{sample}}{R_{standard} - 1} \right) \times 1000$$

$$R_{sample} = \frac{^{13}C}{^{12}C}, \ R_{standard} = \text{-8 ‰}$$

4.2.7 Estimation of biological nitrogen fixation

Biological nitrogen fixation was estimated by the ^{15}N isotopic dilution method (Chalk, 1985). This method provides direct evidence for N_2 fixation since the ^{15}N concentration in plants exposed to ^{15}N becomes greater than the 0.3663% (amount of ^{15}N present at natural abundance). BNF changes atom % $^{15}N/^{14}N$ as it tends to increase the concentration of ^{14}N while it decreases the concentration of ^{15}N. This change can be measured to determine atom % $^{15}N/^{14}N$ for use in calculations of BNF. The percentage of legume N_2 content derived from the air (N_{dfa}) is then calculated using the isotopic differences between the legume and reference crops (McAuliffe et al., 1958).

^{15}N isotope dilution method is used when both N_2 fixing (legume) and reference plants (grass mixture) are grown in soil to which the same amount of fertilizer having the same ^{15}N enrichment has been applied. In the absence of any supply of N other than soil and ^{15}N labelled fertilizer, a fixing plant and a non-fixing reference plant will contain the same ratio of $^{15}N/^{14}N$, since they are taking up N of the same $^{15}N/^{14}N$ composition, but not necessarily the same total quantity of N in both plants. The $^{15}N/^{14}N$ ratio within the plant is lowered by the N_2 absorbed from the atmosphere by the N_2 fixing legume. The extent to which the $^{15}N/^{14}N$ ratio in the fixing plant (legume) is decreased, relative to the non-fixing plant can be used to estimate N_2 fixed in the field.

In preliminary work at the experimental site (Pietsch et al. 2007), it was found that the $\delta^{15}N$-value of the plant-available N pool is below 5 ‰. Therefore, in the present study, the plant-available soil N_2 pool was enriched with ^{15}N by spraying ^{15}N fertilizer at the soil surface, thereby artificially increasing the difference between the $^{15}N/^{14}N$ ratio of the air and that of the soil N_2 pool. The soil was labelled with ^{15}N at the beginning of the vegetation period in April 2007 and April 2008 using 0.1 kg ^{15}N ha^{-1} (N as 1 kg potassium nitrate ha^{-1}, 10 at% ^{15}N). A legume (lucerne) and reference crop (grass-mixture) was grown on the ^{15}N-labelled soil.

BNF and % Ndfa was estimated using the ^{15}N dilution method. The total amount of N fixation was determined using the following relations:

$$\text{Atom \% } ^{15}N \text{ excess} = \text{atom \% } ^{15}N/^{14}N - 0.3663\ \%$$

$$N_{dfa\,\%} = [1-(\text{atom \% } ^{15}N \text{ excess legume / atom \% } ^{15}N \text{ excess reference crop})] * 100\%$$

$$\text{N yield (kg ha}^{-1}) = \{(\text{Dry matter yield}/100)\} * \text{atom \% N}$$

$$\text{N fixation (kg ha}^{-1}) = \{(N_{dfa\,\%}/100)\} * \text{N yield (kg ha}^{-1})$$

The total amount of BNF was derived by adding N fixation of shoot, stubble and roots. A respective value of Ndfa %, N yield and N fixation were determined separately for on and between the row root samples in every 30 cm of soil profile and total amount of N fixation was derived by adding the N fixed by roots in 0-60 cm of soil profile.

4.2.8 Determination of soil texture, bulk density, soil water retention characteristics, saturated hydraulic conductivity, nitrate content and organic carbon contents

Particle size analyses are based on determination of percentage of sand (0.063-2 mm), silt (0.063-0.002) and clay (< 0.002) in a soil sample. Particle size analyses involved dry sieving to separate particles > 2 mm, wet sieving (for < 2 mm) and pipette approach (for < 0.063 mm) (ONORM L1061). Based on relative proportion of sand, silt and clay, textural classes were determined following American textural triangle adopted from American Soil Survey Manual (Soil Survey Staff, 1951).

Bulk density was determined using the following relation proposed by Blake and Hartge (1986).

Bulk density (g cm^{-3}) = mass of oven-dried soil sample (g)/ volume of core (cm^{3})

Saturated hydraulic conductivity (SHC) was determined by using method of rising head soil core. This method is a modified form of falling head soil core/tank method (Reynolds and Elrick, 2002). Method involves the measurement of speed of water movement in a saturated soil column. Values of SHC were re-calculated and corrected by deleting the clogged needles using MathCad software.

Soil water retention characteristics were determined by using pressure plate extractor following procedure described by Dane and Hopmans (2002). The method is based on simple principle of determining the weight of water present in a fixed volume of soil at a series of defined pressure heads (tensions), to convert these weights into volume of water, and then divide by the volume of soil.

Nitrate content in soil samples were determined using N-min analyze method (ONORM L1091). Nitrate is extracted in $CaCl_2$ and directly measured at 210 nm by a photometer (reading 1). At this wavelength, humic substances are also extracted and measured in the given soil sample. The concentration of humic substances is determined (reading 2) and subtracted from reading 1 to determine nitrates. This is done in a second measurement by putting the solution over night after adding copper-plated zinc granules that reduce nitrate to N_2 Ammonium content was not determined as sites had negligible amounts of ammonium due to a pH value of 7.6 (Pietsch et al., 2007).

Soil organic carbon (C) contents were determined on a composite sample for every 30 cm of soil profile till the depth of 0-90 cm for both treatments. Following relation was used to calculate organic C contents.

$$\text{Soil organic carbon (\%)} = \text{Total C} - \text{Carbonate C}$$

Total C contents of soil were determined by dry combustion and infra-red detection of CO_2 using C-N 2000 Elemental Analyser (LECO) at the Institute of Agronomy and Plant Breeding, BOKU. Carbonate-C content was determined following Blum et al. (1996) at the Institute of Soil Research, BOKU. The method involves destruction and measurement of carbonates in a known amount of soil sample by using hydrochloric acid and gas volumetric measurement of the amount of CO_2 evolved during this process at a given temperature and air pressure.

4.2.9 Statistical analysis

Data were analyzed using general linear model of statistical software SPSS (version 15) where treatments and years were considered as fixed factors and replicates were considered as random factors.

4.3 Results

4.3.1 Results of laboratory studies

The soil of experimental site in 2007 was silty loam throughout the profile (0-120 cm) with relatively higher sand content in lower part of profile (60-120 cm) than upper part of soil profile (0-60 cm). The soil of experimental site in 2008 was loam in middle to lower part of soil profile (30-90 cm) while its upper most (0-30 cm) and lower most layer (90-120 cm) was silty loam. Results of detailed texture analysis of experimental sites in both years are presented in Table 4.1.

Table 4.1: Texture of experimental site

Year	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class (American triangle)
2007	**0-30**	15.2	60.4	24.4	Silty loam
	30-60	11.8	65.7	22.5	Silty loam
	60-90	17.2	70	12.8	Silty loam
	90-120	33.1	60.55	6.35	Silty loam
2008	**0-30**	22.7	57.6	19.7	Silty loam
	30-60	34.25	53.45	12.25	Loam
	60-90	47.2	48.05	4.75	Loam
	90-120	33.2	58.2	8.5	Silty loam

Bulk density varied from 1.37-1.44 and 1.32-1.45 in 0-90 cm of soil profile for sites of 2007 and 2008, respectively (Table 4.2). For 2007 site, SHC values tend to decline with increasing depth of soil profile as lower part of profile has slightly higher bulk density than upper part of soil profile. In 2008, values of SHC are also affected by bulk density and SHC tended to decline with increase in bulk density in the profile (Table 4.2).

Differences in water retention of experimental sites at field capacity and permanent wilting point do not seem pronounced in upper part of soil profile (0-60 cm) but water retention values at field capacity in lower part of profile (60-90 cm) become drastically lower for 2008 site due to relatively higher sand content (47 %). Results are presented in Table 4.3.

Table 4.2: Bulk density and saturated hydraulic conductivity

Year	Depth (cm)	Bulk density ($g\ cm^{-3}$)	Saturated hydraulic conductivity ($cm\ s^{-1}$)
2007	**15-20**	1.37	1.55×10^{-3}
	50-55	1.40	3.75×10^{-4}
	80-85	1.44	3.05×10^{-4}
2008	**15-20**	1.45	5.8×10^{-4}
	50-55	1.32	8.3×10^{-4}
	80-85	1.39	1.33×10^{-3}

Table 4.3: Soil water content at field capacity (-0.33 bars) and permanent wilting point (-15 bars)

Depth (cm)	2007			2008		
	Field capacity ($m^3\ m^{-3}$)	Permanent wilting point ($m^3\ m^{-3}$)	Available soil water ($m^3\ m^{-3}$)	Field capacity ($m^3\ m^{-3}$)	Permanent wilting point ($m^3\ m^{-3}$)	Available soil water ($m^3\ m^{-3}$)
15-20	0.287	0.159	0.128	0.290	0.177	0.113
50-55	0.266	0.103	0.163	0.217	0.104	0.113
80-85	0.302	0.064	0.238	0.168	0.054	0.114

In 2007, organic C content varied from 0-2.2 % and 0-1.1 % in lucerne no mulch and mulch plots, respectively. In 2008, organic C content varied from 0.1-1.4 % and 0.1-1.8% in lucerne no mulch and mulch plots, respectively. Organic C contents tended to decline with increasing soil depths in the profile (see Table 25).

The nitrate content of experimental sites in 0-90 cm of soil profile varied from 0-54 and 1-36 kg ha^{-1} in 2007 and 2008, respectively. Fields have usually higher nitrate at the start of vegetation period that tended to decline over time. Upper soil layers (0-30 cm) have usually higher nitrate content than lower soil layers (30-90 cm). Detailed results on nitrate content are presented in Table 22 (see Annexure).

4.3.2 Effect of mulching on yield and its components

Shoot height (cm): In the present study, shoot height of lucerne varied from 18- 78 cm. Interactions among treatments and years were found non-significant. Differences among treatments were found non-significant for SH. Differences among years were significant ($P < 0.01$) for SH. In 2007, SH for lucerne mulch (M) was 24.7 cm as compared to SH of 18 cm for no mulch (NM). In 2008, SH for both treatments was similar (78 cm).

Shoot number (m^{-2}): Shoot number varied from 506-720 m^{-2}. Interactions among treatments and years were found non-significant. Differences among treatments were found non-significant for SN. Differences among years were significant ($P < 0.05$) for SN. In 2007, SN for M was higher (720 m^{-2}) as compared to NM (693 m^{-2}). In 2008, SN for NM was higher (581 m^{-2}) as compared to M (506 m^{-2}).

Leaf area index: In the present study, LAI varied from 0.5-2.6. Interactions among treatments and years were found non-significant. LAI was not significantly affected due to treatments. Differences in LAI were found significant ($P < 0.01$) among years. In 2007, LAI was 0.52 for NM and 0.75 for M while in 2008, LAI was 2.6 for NM and 2.2 for M (Table 23).

Chlorophyll content: Chlorophyll content varied from 458-642 mg m^{-2} of leaves. Interactions among years and treatments were found non-significant. Chlorophyll content was not significantly affected due to treatments. Years had significant ($P < 0.01$) effect on chlorophyll content. In 2007, chlorophyll content was 493 mg m^{-2} of leaves and 458 mg m^{-2} of leaves while in 2008; it was 585 mg m^{-2} of leaves and 642 mg m^{-2} of leaves for NM and M, respectively.

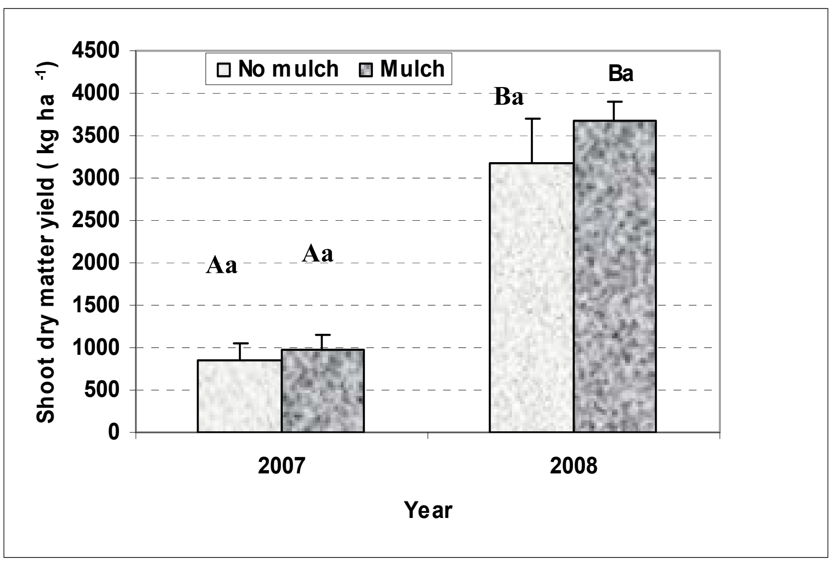
Shoot dry matter yield: Shoot dry matter yield (SDMY) ranged from 855-3665 kg ha^{-1}. Interactions among treatments and years were found non-significant. Differences among treatments were found non-significant for SDMY. Years differed significantly ($P < 0.01$) on SDMY. In 2007, SDMY was 855 and 983 kg ha^{-1} while in 2008 SDMY was 3184 and

3665 kg ha^{-1} for NM and M, respectively (Fig. 4.1). Lower SDMY in 2007 can be attributed to yearly effect and damage by rats and rabbits.

Table 4.4: Summary of results on yield and its components

Parameter	Treatment	Year	Treatment x Year
Shoot height (cm)	ns	*	ns
Shoot number (m^{-2})	ns	**	ns
Leaf area index	ns	*	ns
Chlorophyll content	ns	*	ns
Shoot dry matter yield (kg ha^{-1})	ns	*	ns
Root dry matter yield (kg ha^{-1}), 0-60 cm	ns	*	ns
Total dry matter yield (kg ha^{-1})	ns	*	ns
Total N yield (kg ha-^{1})	ns	*	ns
Total Ndfa (%)	ns	*	ns
Biological nitrogen fixation (kg ha^{-1})	ns	*	ns
Actual Evapotranspiration (mm)	+	*	ns

ns- non- significant, *- significant at 1 % level of probability, **- significant at 5 % level of probability
+- significant at 10 % level of probability

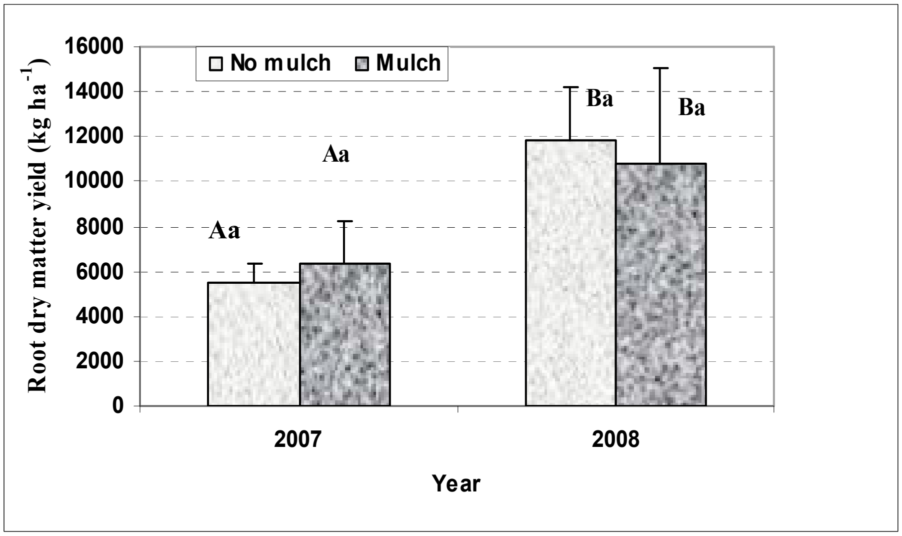


Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and treatments, respectively.

Figure 4.1: Shoot dry matter yield at second harvest under different lucerne utilization systems.

Root dry matter yield: RDMY ranged from 5526-11823 kg ha^{-1} in 0-60 cm of soil profile in the present study. Interactions among years and treatments were found non-significant. Effect of treatments was found non-significant on RDMY. Years differed significantly (P < 0.01) for RDMY. In 2008, RDMY in 0-60 cm of soil profile was

10830-11823 kg ha^{-1} as compared to RDMY of 5526-6370 kg ha^{-1} in 2007. RDMY in 0-60 cm of soil profile under different lucerne utilization systems in both years of experiments is shown in figure 4.2.

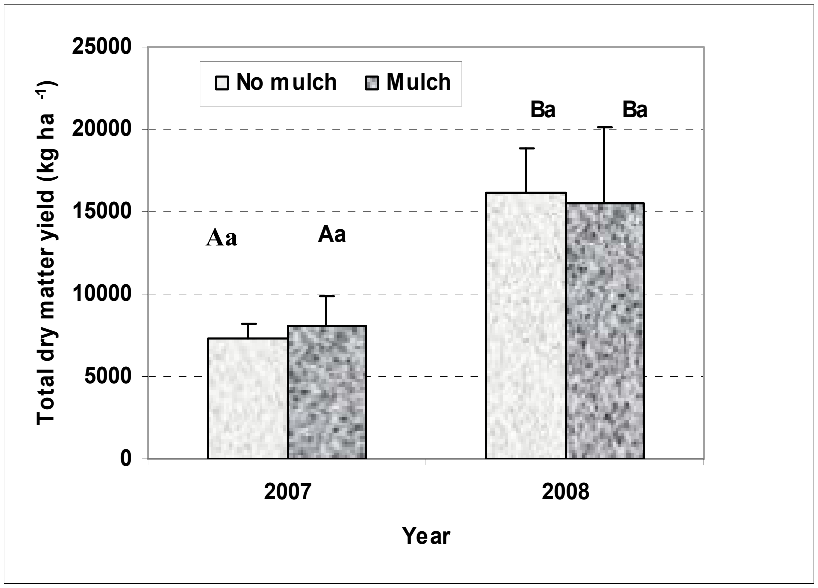


Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and treatments, respectively.

Figure 4.2: Root dry matter yield at second harvest under different lucerne utilization systems.

Total dry matter yield: In the present study, TDMY ranged from 7260-16095 kg ha^{-1}. Interactions among treatments and years were found non-significant. Treatments did not differ significantly in producing TDMY. TDMY differed significantly ($P < 0.01$) among years. In 2007, TDMY was 7260-8030 kg ha^{-1} while in 2008 TDMY was 10830-11823 kg ha^{-1}. TDMY under different lucerne utilization in both years of experimentation is shown in figure 4.3.

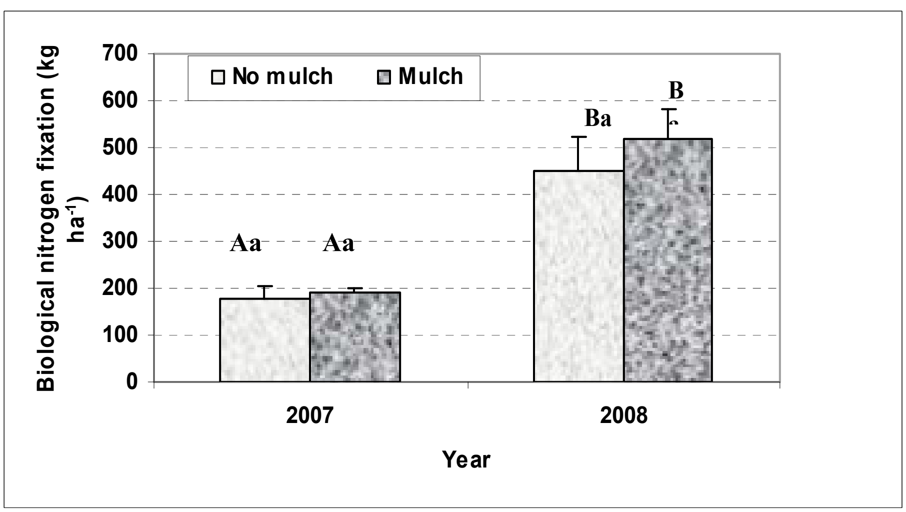
Biological nitrogen fixation: Interactions among treatments and years were found non-significant for total N yield and Ndfa %. Treatments also did not differ significantly for total N yield and Ndfa %. Significant ($P < 0.01$) differences were observed among years for both total N yield and Ndfa % (Table 4.4). In 2007, N yield was 340 kg ha^{-1} and 387 kg ha^{-1}, for M and NM, respectively. In 2008, N yield was 686 kg ha^{-1}and 724 kg ha^{-1} for M and NM, respectively. In 2007, Ndfa under M was 46.75 % as compared to 47.25 % under NM. In 2008, Ndfa under M was 57.75 % as compared to 62.5 % under NM.



Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and treatments, respectively.

Figure 4.3: Total dry matter yield at second harvest under different lucerne utilization systems.

Interactions among treatments and years were found non-significant for BNF. Treatments did not differ significantly in BNF. Years had significant ($P < 0.01$) effect on BNF. In year 2008, the amount of total BNF was more than two times as high as in 2007 (see figure 4.4).



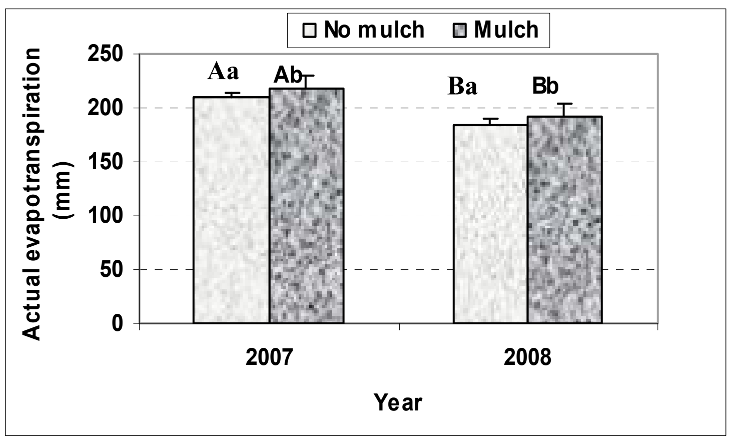
Error bars indicate one standard deviation

Figure 4.4: Total biological nitrogen fixation under different lucerne utilization systems.

A summary of statistical analysis of results is shown in Table 4.4. Data on yield and its components under different lucerne utilization system are presented in Table 23 (see Annexure-1).

4.3.3 Effect of utilization system on actual evapotranspiration of lucerne

ETa values in the present study varied from 184-218 mm during the period between first and second harvest (July-September). Interactions among treatments and years were found non-significant. Differences among treatments were found significant ($P < 0.10$) for ETa. M usually had slightly higher values of ETa as compared to NM in both years of study. Effect of years on ETa was also significant ($P < 0.01$). In 2007, ETa values varied from 210 mm (NM) to 218 mm (M) while in 2008 ETa varied from 184 mm (NM) to 192 mm (M). ETa under different utilization systems are presented in Figure 4.5.



Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and treatments, respectively.

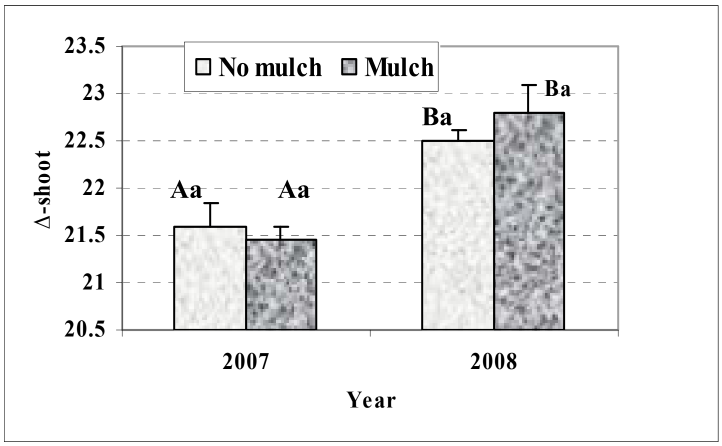
Figure 4.5: Actual evapotranspiration (between first and second harvest) under different lucerne utilization systems.

4.3.4 Effect of utilization system on soil temperature

Mulching with lucerne was found effective in lowering the soil temperature by 1-5 ^{0}C and differences among treatments were found significant. Results regarding effect of utilization system on soil temperature are presented in Table 24.

4.3.5 Effect of utilization system on water use efficiency

CID values ranged from 21.4 to 22.7 ‰ in the present study. Differences among treatments and interactions among treatment and years were found non-significant for WUE of photosynthesis/CID. Differences among years for CID were found significant ($P < 0.001$). CID values were lower (21.4-21.5 ‰) in 2007 as compared to CID values in 2008 (22.5-22.7 ‰). Results on CID from utilization system experiment are presented in Figure 4.6.



Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and treatments, respectively

Figure 4.6: Δ-shoot (‰) of lucerne under different utilization systems at second harvest.

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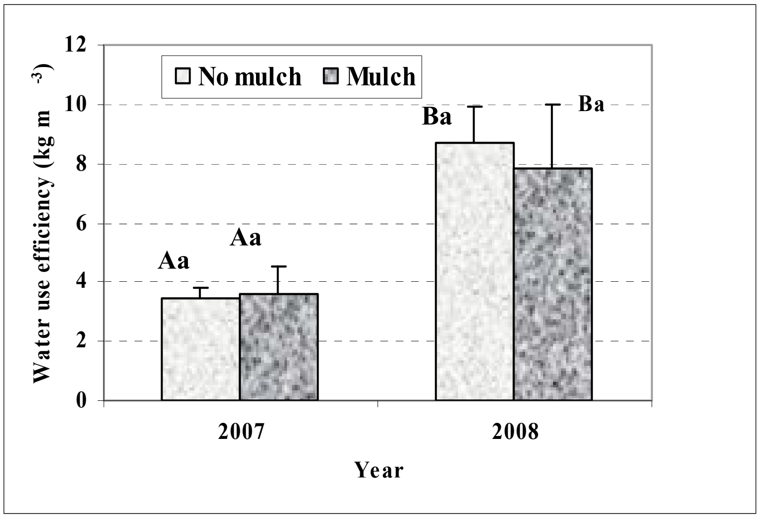
WUEp ranged from 3.4-8.7 kg m^{-3} in the present study. Effect of treatments on WUEp was found non-significant. Interactions among treatment and years were also found non-significant. Significant differences were observed among years for WUEp. Higher values (7.8-8.7 kg m^{-3}) of WUEp were obtained in 2008 as compared to 2007 (3.4-3.6 kg m^{-3}). These differences can be attributed to higher SDMY in 2008 as compared to SDMY in 2007 (see Figure 4.1). Results on WUEp are presented in figure 4.7.



Error bars indicate one standard deviation. Different capital and small letters indicate significant differences among years and treatments, respectively

Figure 4.7: Water use efficiency of productivity of lucerne under different utilization systems from first to second harvest.

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4.4 Discussion

Interactions among treatments and years were found non-significant for yield and its components (Table 4.4). Utilization system (no mulch and mulch) had no significant effect on lucerne yield and its components in both years of experimentation. These findings are in line with those of Hatch et al. (2007) who concluded from a two year study at two sites in south west and north east of England that mulching did not affect dry matter yield of red clover. Our findings in the present study are also in agreement with those of Pietsch et al. (2007) who concluded from a two year study in eastern Austria that utilization system and crop composition (pure lucerne crops versus lucerne-grass mixtures) had no marked influence on above ground dry matter yield of lucerne. In the present study, there was a tendency of slightly higher SDMY under M than under NM (Fig. 4.1).

Previous studies indicate that straw mulch can increase crop yield of sorghum and maize (Unger, 1978; Wicks et al., 1994; Lal, 1995) probably because of higher soil moisture (Tolk et al. 1999). But mulch has not always increased yields (Tolk et al., 1999) because many factors determine the effect on crop development. Crop response is influenced by a complex interaction that could vary from year to year. Important factors are mulch mass, irrigation frequency, evaporative potential and soil texture (Tolk et al., 1999). Crop residue mulches reduce evaporation of soil water primarily by shading the soil surface from the sun. Mulch will reduce evaporation most effectively early in the drying cycle when the surface soil is wet and early in the growing season when the leaf area is small (Bond and Willis, 1970; Ji and Unger, 2001; Tao et al., 2006). In the present study, mulch was applied in July when soil surface was becoming drier and crop re-growth after first harvest was relatively faster. This might have lead to non-significant increase in SDMY due to mulching.

Years had a significant effect on lucerne yield and its components as 2008 seems more suitable for lucerne production than 2007 as yield and most of the associated components have relatively higher values in 2008 as compared to 2007 (Table 23 in Annexure). This yearly effect seems largely due to higher amount of rainfall from May-July in 2008 (see Fig. 3.1). Besides the effect of rainfall, year 2008 was more suitable for lucerne production and results from other experiments in the same site indicate higher yields of lucerne varieties in 2008 as compared to 2007 (Moghaddam, 2010). Another reason for much lower SDMY in 2007 was sudden and heavy attack by rats and rabbits in the field that caused unrecoverable loss to SDMY.

Utilization systems also have non-significant effect on root dry matter yields in both years of experimentation. These findings can be supported with the argument that utilization system treatments (no mulch and mulch) were applied after first harvest in both years and by that time lucerne root system had already established to the extent where application of treatment for a short period of 8-10 weeks (gap between first and second harvest) is not going to affect the root biomass development. These findings are in line with those of Pietsch et al. (2007) who reported that utilization system had no marked influence on above- and below-ground dry matter yield. Other studies indicate that mulching has not always been shown to increase crop yields, and its effectiveness depends on crop, soil and climate (Wicks et al., 1994; Gajri et al., 1994).

Utilization system had no significant effect on BNF in the present study. These findings are in line with those of Pietsch et al. (2007) who reported that utilization system had no marked influence on BNF under semi-arid site conditions. There exists a possibility that when soil moisture content is sub-optimal for the mineralization process, the foliage will not be mineralized within the vegetation period. Thus, at fertile but dry sites, like in the pannonian region, green manure legume crops may fix the same amount as in a forage utilization system. But in both years of experimentation, BNF under M tended to have higher values as compared to NM (Fig 4.4). Our findings in 2008 coincide with those of Hatch et al. (2007) who reported that BNF was 60 kg ha^{-1} higher under mulching as compared to harvesting. Higher values of BNF under M can be attributed to overall better SDMY of M as compared to NM (see Fig. 4.1).

In northern Germany, Loges et al. (1999; 2000) determined a reduced N_2 fixation of mulched green manure legumes compared with the forage utilization (lucerne/grass forage use: 320 kg ha^{-1}, lucerne/grass green manure: 136 kg ha^{-1}). The returned herbage may also delay the regrowth of the legume by temporarily smothering their stubbles and thus reducing nitrogen fixation (Cuttle et al., 2003).

Mulching with lucerne was found effective in lowering the soil temperature and differences among treatments were found significant. Mulching lowered the soil temperature by 1-5 ^{0}C as compared to no mulch in the present study. This can be due to the fact that mulch cover present on the soil surface acts as a barrier between sun rays and soil surface , thereby, reducing the temperature of soil as compared to the soil that is bare and directly exposed to sun rays (no mulch treatment). These findings are in line with those of Sarkar et al. (2007) who reported that mulching with rice straw can reduce soil temperature. Zhang et al. (2009) found similar results of reduction in temperature by using wheat straw mulch at the application rate of 0.8 kg m^{-2}. The magnitude of the changes in soil temperature due to mulching varies between studies and can be attributed to the mulch application rates or climatic conditions.

Differences among years for CID (Δ) were found significant and these results coincide with other results of the experiments where years had a significant effect on yield and its associated components. These variations in Δ might be due to differences in rainfall in two years of experimentation (see Fig. 3.1). Johnson and Rumbaugh (1995) reported that negative relation exists between Δ and WUE. This relationship is found in the results from present study as well. In 2007, higher values of Δ correspond to lower WUE for NM while lower values of Δ relate to higher value of WUE for M. In 2008, lower values of Δ correspond to higher WUE for NM while higher values of Δ relate to lower value of WUE for M (see Fig. 4.6 and Fig.4.7).

Results revealed that utilization system does not seem to have marked influence on WUEp and these findings are in line with those of Pietsch et al. (2007) who reported similar results for lucerne under similar experimental conditions as were for the present study. Chen et al. (2007) reported that in China, mulching with maize did not improve the WUE of following wheat crop because mulching did not increase the yield of wheat crop. Marked influences of mulching on WUEp can be either due to significant increase in SDMY or decrease in water consumption (ETa) but in the present study, mulching neither significantly increased SDMY nor it decreased ETa significantly. Due to this reason, mulching did not differ significantly from no mulch in improving the WUEp. Effect of years on WUEp was significant and higher values of WUEp in 2008 are associated with higher SDMY in 2008 as compared to 2007.

Mulching had no marked effect on increasing the above and below ground dry matter yield, WUE and BNF of lucerne in the present study. Mulching tended to lower the soil temperature by 1-5 ^{0}C. Positive effects of mulching are usually reflected in long duration experiments under irrigated conditions where soils are kept fallow for few months in the season. Under the conditions of present study, there was a small gap of about 2-3 weeks for the treatment effect to take place. Because lucerne crop in the no mulch treatment started regrowth simultaneously, thereby, nullifying the minor effect of mulching. Mulching initially lowered the soil temperature but as the leaf area started to increase, its effect was removed. The smaller duration of treatment application and dry site conditions did not cause significant increase in above and below ground yields and same trend is reflected in BNF and WUE as their calculations are dependant on above and below ground yields. The minor differences among treatments seem merely an effect of soil heterogeneity rather than treatment effect. Long term studies are required to explore the effect of mulching with lucerne on subsequent wheat or other winter season crops under the present site conditions.

Chapter 5

A comprehensive experimental study with modeling to investigate the impact of plant traits on water balance variables

5.1 Introduction

Lucerne (*Medicago sativa* L.) is an important crop especially under organic farming systems as it fixes nitrogen (Bruulsema and Christie, 1987), improves soil structure (due to deep root systems), increases soil organic matter content and improves water infiltration (Bourgeois, 1990; Campbell et al., 1990; Meek et al., 1990). Lucerne has a reputation as a fairly drought-tolerant crop and can survive longer periods of drought (White, 1967; Sheaffer et al., 1988). It can extract water from deeper soil depth up to 2 m and helps to reduce losses of soil water by deep drainage (Pollock et al., 2009). Use of lucerne in crop rotations with shallow rooted cereals and pulses helps to improve WUE of the entire cropping system (Latta et al, 2001; Ridley et al*.,* 2001). Water can be a limiting factor for growth and yield in dry climates. It is imperative to study the complex relations between crop management, crop growth and environmental issues for intensive forage systems in order to maximize the economic returns. Economic returns can be increased by increasing yields and WUE. Yield and WUE are linked following Viets (1962) definition of WUE and any factor that increases yield will lead to an increase in WUE (Gregory, 2004; Machado et al., 2008). Yield is a complex trait affected by soil, crop, variety, management, irrigation regimes and climatic factors (Peterson and Westfall, 2004; Fernandes-Silva et al., 2010). It is relevant to study the effect of varieties and irrigation regimes on yield of lucerne to make rational decisions about choice of varieties and amount of irrigation that can give maximum economic gains.

Direct estimation of WUE is extremely difficult under field conditions as we have to measure the components of water use like evaporation, transpiration, drainage and runoff. The components of water use can be assessed using properly calibrated simulation models. Yield, WUE and components of water use may be affected by plant traits like leaf area index, stem leaf partitioning coefficient, specific leaf ratio and rooting depth. It is imperative to find which of these plant traits can bring a major improvement in yield and WUE. The selective parameter can then be referred to breeders for use in the improvement of germplasm for higher WUE and yield.

CropSyst (Stöckle and Nelson, 1999; Stöckle et al., 2003) is a process-based simulation model. It is a generic crop simulator, which uses the same approach to simulate the growth and development of a wide range of herbaceous crops, including meadows. It can simulate rotations and is continuously being developed. It has been widely applied to cereals and other cropping systems (Stöckle et al., 1994; Pala et al., 1996; Donatelli et al., 1997; Stöckle and Debaeke, 1997; Giardini et al., 1998; Pannkuk et al., 1998). Few published results exist to describe the performance of this model when used with perennial crops like lucerne (Confalonieri and Bechini, 2004). Simulation model CropSyst was used in the present study as it includes morphological and physiological processes at the level of plant components. It can be of great scientific interest to compare the effect of plant parameters on components of water use at field level mainly transpiration, evaporation and drainage. Simulation model CropSyst will be used as it has not already been used for lucerne in Austria. The model will improve our understanding on the contribution of plant traits towards bringing an improvement in the yield and WUE and will help to identify the traits that can be targeted for further use in breeding programmes.

The objectives of present study were:

- To calibrate and validate the simulation model CropSyst in simulating lucerne growth in Austria, Europe
- To analyze the impact of different plant traits on the accumulation of above ground biomass and components of field water dynamics
- To identify the potential of these plant traits to contribute an improvement of lucerne performance under water limiting conditions of rain-fed production.
- To identify the irrigation strategy that can bring maximum increase in lucerne yield

5.2 Materials and methods

5.2.1 Experimental data

The data were collected from experiments laid out at Gross-Enzersdorf (irrigated site) and Raasdorf (rain fed site). Experimental site at Gross-Enzersdorf had a drip irrigation facility for timely and controlled application of irrigation. Irrigation was applied at 50 % depletion of soil available water (SAW) content (SAW = Water content difference between field capacity (FC) and permanent wilting point (PWP)) based on FDR probe in 10-15 cm soil depth. The amount of applied irrigation water was calculated for 0-30 cm depth based on soil moisture content up to field capacity.

Fields used for experimental purpose at Gross-Enzersdorf (48º12' N, 16º33' E) and Raasdorf (48º15' N, 16º37' E) belong to research station of BOKU, Vienna, Austria. Data were collected over two growing seasons (2007 and 2008) from experiments established in 2006. Soils at two locations are silty loam having organic carbon content of 1.5 % in A-horizon (0-20 cm) and a bulk density of 1.4-1.6 g cm^{-3}. Soil water retention characteristics were determined at field capacity and permanent wilting point on two representative profiles from each experimental site (Table 5.1).

Table 5.1: Soil water content at field capacity (-0.33 bars) and permanent wilting point (- 15 bars)

Depth (cm)	Gross Enzersdorf			Raasdorf		
	Field capacity (m^3 m^{-3})	Permanent wilting point (m^3 m^{-3})	Available soil water (m^3 m^{-3})	Field capacity (m^3 m^{-3})	Permanent wilting point (m^3 m^{-3})	Available soil water (m^3 m^{-3})
15-20	0.300	0.185	0.115	0.338	0.187	0.151
50-55	0.272	0.162	0.110	0.269	0.114	0.155
80-85	0.317	0.176	0.141	0.230	0.050	0.180

Daily meteorological data on temperature (maximum, minimum), rainfall, wind speed, global solar radiation and relative humidity (maximum, minimum) were obtained from weather station located at the irrigated and rain fed site, respectively. The climate is characterized by hot, dry summers with little dew, and cold winters with little snow. The mean daily temperature is 11.1 ^{0}C and the average annual precipitation is 539 mm (based on data from 1980-2009).

The experiment compares the performance of three lucerne varieties viz. Niva, Mohajaren and Sitel in irrigated and rain fed conditions for two consecutive years (2007-2008). Both these experiments were laid out in randomized complete block design with two replicates. Sowing of both experiments was done manually in 2006 using seed rate of 25 kg ha^{-1}. Row to row distance was 12.5 cm. Each sub plot having a single lucerne variety was 2 m long and 1.5 m wide. From both sites, lucerne was cut twice in the first year of the experiment (2006) and thrice in each of the later years (2007-2008). Management practices for both experimental sites are presented in Table 5.2.

Data on above ground biomass (AGB) and leaf area index (LAI) were recorded at all three harvests from both experiments in each year. LAI was measured using LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE). Plots were hand clipped at 30-40 % of flowering using a garden scissor to a 5-cm stubble height. An area of 0.5 m^2 was harvested from each plot at each harvest to determine shoot biomass. Stubble biomass was determined only on final harvest in each year. Shoot and stubble dry matter yield were determined by oven-drying the sub-sample at 60 °C for 48 h. Shoot dry matter (SDM) yield data at final harvest includes value of stubble dry matter yield also. Maximum rooting depth was determined at the time of final harvest in 2008 using a mechanically compressed auger. Visual observations regarding the presence of fine roots were used to note the maximum rooting depth. Very rare fine roots were found down to 1.9 m only for lucerne variety Mohajaren in the irrigated site. Root samples were collected at the end of vegetation period in 2008 from irrigated site (non-stressed conditions) using an auger having 7 cm diameter. Sampling was done till the depth of 60 cm with every 10 cm profile. After washing and cleaning, the samples were analyzed to determine root length and root surface area using WinRhizo 4.1 (Regent Instruments, 2000), following Himmelbauer et al. (2004), prior to drying them for determination of root dry matter. Soil water content (SWC) was measured using FDR probes and Sentek Diviner at irrigated and rain fed site, respectively. FDR (Frequency Domain Reflectometry, ML2x, UMS GmbH, München, Germany) probes were installed at the depth of 10, 40, 80 and 120 cm whereas SENTEK Diviner 2000 (Sentek Sensor Technologies, Australia) probes were installed at the depth of 120 cm. Soil water content was measured using manual data loggers for both types of probes at weekly to fortnightly intervals. No site specific calibration was performed for both data loggers and original values of water content obtained from these data loggers were used as such for the purpose of calculation of profile SWC for comparison with simulation results.

Table 5.2: Management operations

Date	Operation
	Irrigated site at Gross-Enzersdorf
12-05-2006	Ploughing with hand driven machine till the depth of 20 cm
30-05-2006	Sowing
01-06-2006	Irrigation (20 mm)
14-06-2006	Irrigation (20 mm)
28-06-2006	Irrigation (20 mm)
12-07-2006	Irrigation (20 mm)
26-07-2006	Irrigation (20 mm)
30-07-2006	Ist cut
30-09-2006	2nd cut
02-04-2007	Irrigation (30 mm)
16-04-2007	Installation of FDR probes
02-05-2007	Irrigation (30 mm)
31-05-2007	Ist cut
01-06-2007	Irrigation (30 mm)
28-06-2007	Irrigation (6.22 mm)
02-07-2007	Irrigation (10.58 mm)
04-07-2007	Irrigation (6.22 mm)
09-07-2007	Irrigation (9.33 mm)
13-07-2007	Irrigation (9.33 mm)
17-07-2007	Irrigation (6.22 mm)
19-07-2007	Irrigation (15.56 mm)
22-07-2007	Irrigation (12.44 mm)
26-07-2007	Irrigation (24.89 mm)
29-07-2007	Irrigation (9.33 mm)
31-07-2007	2nd cut
02-08-2007	Irrigation (6.22 mm)
06-08-2007	Irrigation (12.44 mm)
08-08-2007	Irrigation (12.44 mm)
05-10-2007	3rd cut
12-06-2008	Ist cut
05-08-2008	2nd cut
05-08-2008	Irrigation (18.67 mm)
11-08-2008	Irrigation (18.67 mm)
21-08-2008	Irrigation (18.67 mm)
26-08-2008	Irrigation (18.67 mm)
29-08-2008	Irrigation (12.44 mm)
08-10-2008	3rd cut
	Rain fed site (Raasdorf)
13-05-2006	Ploughing with hand driven machine till the depth of 20 cm
30-05-2006	Sowing
01-06-2006	Irrigation (20 mm)
14-06-2006	Irrigation (20 mm)
28-06-2006	Irrigation (20 mm)

12-07-2006	Irrigation (20 mm)
26-07-2006	Irrigation (20 mm)
31-07-2006	Ist cut
30-09-2006	2nd cut
11-06-2007	Ist cut
13-06-2007	Installation of Diviner probes
01-08-2007	2nd cut
01-10-2007	3rd cut
17-06-2008	Ist cut
05-08-2008	2nd cut
09-10-2008	3rd cut

5.2.2 Brief model description

The model is intended for crop growth simulation over a unit field area (m^2). Growth is described at the level of whole plant and organs. Integration is performed with daily time steps using the Euler's method. A complete description of the model is given in the user's manual (Stöckle and Nelson, 1994), which is updated (Stöckle and Nelson, 1996). The nitrogen and water submodels in CropSyst, and a general description of growth simulation have been presented (Stöckle et al., 1994). A new approach to determine crop nitrogen demand has been also developed (Stöckle and Debaeke, 1997). A finite difference solution of Richards equation to simulate water transport (as an alternative to existing cascading approach), and crop response to salinity has been also added.

The water budget in the model requires precipitation and irrigation inputs as well as basic soil properties. It calculates redistribution of water in the soil profile using different methods. Water flow in the soil is by Richards equation with options of Penman-Monteith model, the Priestley-Taylor model, and a simpler implementation of the Priestley-Taylor model. Evapotranspiration is determined from a crop coefficient at full canopy and ground coverage determined by canopy leaf area index.

Crop development is simulated based on thermal time required to reach specific growth stages. The accumulation of thermal time may be accelerated by water stress. Thermal time may be also modulated by photoperiod and vernalization requirements whenever pertinent. Daily crop growth is expressed as biomass increase per unit ground area. The model accounts for four limiting factors to crop growth: light, water, nitrogen and temperature. Given the common pathway for carbon and vapor exchange of leaves, there is a conservative relationship between crop transpiration and biomass production.

Crop transpiration dependent biomass production (G Tr) (kg m^{-2} day^{-1}) is calculated using (Tanner and Sinclair, 1983):

G Tr = Tr act · BTR/VPD [Eq. 1]

where BTR ((kg m^{-2} · kPa) m^{-1}) is the above ground biomass-transpiration coefficient crop parameter, Tr act (m) is the actual transpiration, VPD (kPa) is the daily mean vapor pressure. Tanner-Sinclair relationship has the advantage of capturing the effect of site but this relationship becomes unstable at low VPD; indeed it would predict infinite growth at near zero VPD. To overcome this problem, a second estimate of biomass production is calculated following Monteith (1977):

$B_L = e\ I_{PAR}$ [Eq. 2]

where B_L is the light-dependent biomass production (kg m^{-2} day^{-1}), e is the light-use efficiency (kg MJ^{-1}) and I_{PAR} is the daily amount of crop-intercepted photosynthetically active radiation (MJ^{-1} m^{-2} day^{-1}). Each simulation day, the minimum of B_T and B_L is taken as the biomass production for the day. The calculation of actual transpiration follows closely the approach proposed by Stöckle et al. (1992).

Although the parameter e (Eq. 2) includes the effect of the temperature regime prevailing during its experimental determination, temperature limitations during early growth are not captured and a single value is determined for the vegetative period or, more usually, for the entire growing season. However, more detailed measurements will show a decrease of e during early growth due to low temperature. Not accounting for this temperature effect may result in over prediction of biomass production during early growth, particularly in the case of winter crops. A temperature limitation factor is included in CropSyst to correct the value of e during this period, which is assumed to increase linearly from zero to one as air temperature fluctuates from the base temperature for development to an optimum temperature for early growth.

The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, LAI), is calculated as a function of biomass accumulation, specific leaf area, and a partitioning coefficient. Leaf area duration, specified in terms of thermal time and modulated by water stress, determines canopy senescence. Root growth is synchronized with canopy growth, and root density by soil layer is a function of root depth penetration. The prediction of yield is based on the determination of a harvest index (grain yield/aboveground biomass). Although an approach based on the prediction of yield components could be used, the harvest index seems more conservative and reliable for a generic crop simulator. The harvest index is determined using as base the unstressed harvest index, a required crop input parameter, modified according to crop stress (water and nitrogen) intensity and sensitivity during flowering and grain filling. A detailed description of model, its components and modeling approach, data requirements and model evaluation are given by Stöckle et al. (2003).

5.2.3 Perennial crops

For perennial crops, CropSyst simulates the start of dormancy when, starting from a day in autumn (SD), *T*a falls below a threshold (*T*dormancy) for 7 consecutive days. In spring, the crop restarts when the reverse occurs (*T*a > *T*dormancy for 7 consecutive days), starting from a date in spring.The model simulates LAI and biomass after dormancy and after cuttings. LAI for the day after dormancy (LAIi) is calculated as:

LAIi = SLA x AGBi [Eq. 3]

where AGBi is the biomass after dormancy (0.005 kg ha^{-1}) and SLA is specific leaf area. Accumulation of carbohydrates in the crown is not simulated by CropSyst, and therefore the crown cannot affect crop growth rate after cuttings and after dormancy. For perennials, CropSyst considers LAI = GAI (Green area index). Everyday a pair of values consisting of the daily increment of GAI and the corresponding increment of biomass is appended to a list which serves as a history for the crop to remember the GAI/biomass pairs for everyday of its life. In the case of perennials, all these pairs are removed at the beginning of dormancy. When the meadow is cut, CropSyst determines the amount of biomass to be removed (percentage on total AGB) and removes the latest pairs of values starting from the more recent ones, until the amount of biomass to be removed is reached; in this way, it is possible to recalculate a value of LAI after the cut which is coherent with the amount of AGB after the cut (Confalonieri and Bechini, 2004).

Regrowth after clippings can be obtained by ensuring that clipping resets active growth option is enabled in each clipping file. Reserve biomass and minimum GAI to be retained can be adjusted to obtain proper growth dynamics under a given set of conditions. Last clipping option is enabled only for last clipping in each year while ensuring that terminate crop is disabled except for last clipping in last year. First date to start looking for dormancy and first date to start looking for restart after dormancy needs to be specified besides the value of average temperature for 7 consecutive days to induce dormancy (Personal communications, Roger Nelson).

5.2.4 Model parameterization

CropSyst version 4.09.00 was used. Potential evapotranspiration was calculated with Penmann-Monteith equation. Soil water dynamics were simulated solving Richards equation with the finite difference method. It was assumed that no run off occurs, the experimental sites being flat. Crop biomass was simulated using default crop input parameter set of CropSyst and measured values for selective parameters for each lucerne variety under study. After sensitivity analysis, some parameters were further calibrated to find their optimum value to obtain a good fit of measured and simulated above ground biomass (AGB) for lucerne varieties under study. These selective parameters are indicated as calibrated (C), while measured parameters used in place of default value are indicated by M and default crop input parameters from CropSyst are indicated by D. Values taken from literature and local experience are represented by L and E, respectively. Values of crop input parameters used in the present study are presented in Table 5.3.

Table 5.3: Crop model parameters for lucerne

Parameter	Determination	Value	Units
Photosynthetic pathway	-	C3	-
Above ground biomass transpiration coefficient	D	5	kPa kg m^{-3}
Unstressed light to above ground biomass conversion (Radiation use efficiency)	D	3	g MJ^{-1}
Actual to potential transpiration ratio that limits leaf are growth	D	0.8	-
Actual to potential transpiration ratio that limits root growth	D	0.5	-
Optimum mean daily temperature for growth	C	15	^{0}C
Maximum water uptake	C	12	mm day^{-1}
Leaf water potential at the onset of stomatal closure	D	-1300	J kg^{-1}
Wilting leaf water potential	D	-2100	J kg^{-1}
Maximum rooting depth (Sitel, Niva and Mohajaren)	M	1.5,1.3, 1.9	M
Maximum expected leaf area index (Sitel, Niva and Mohajaren)	M	4.5, 4.2, 4.5	-
Root length per unit root mass ((Sitel, Niva and Mohajaren)	M	30.92,43.5 ,39	km kg^{-1}
Surface root density (Sitel, Niva and Mohajaren)	M	5.56,4.72, 4.96	cm cm^{-3}
Curvature of root density distribution (Sitel, Niva and Mohajaren)	M	0.029,0.02 2,0.026	-
Fraction of maximum LAI at physiological maturity	D	0.8	-
Specific leaf area (Sitel, Niva and Mohajaren)	C	24, 20,23	m^2 kg^{-1}
Stem/leaf partition coefficient (Sitel, Niva and Mohajaren)	D	3, 3, 3	-
Extinction coefficient for solar radiation	D	0.5	-
Et crop coefficient at full canopy	C	0.8	-
Degree days emergence	D	100	^{0}C-days
Degree days flowering	C	800	^{0}C-days
Base temperature	L	5	^{0}C
Cutoff temperature	L	30	^{0}C
Adjustment factor for phenological response to water stress	D	0	-
Average temperature for 7 consecutive days to induce dormancy	E	10	^{0}C
First date to start looking for dormancy	E	10 November	-
First date to start looking for restart after dormancy	E	20 February	-

C- calibrated, D- default, M- measured, L- literature, E- local experience

Biomass calibration for each lucerne variety was done separately using the set of parameters mentioned in Table 5.3. Crop biomass was initially calibrated by finding an optimum temperature for growth and further improvements in calibration of biomass were made by calibrating specific leaf area. Values of base temperature and cutoff temperature were taken from literature (Confalonieri and Bechini, 2004). These are temperatures below and above which thermal time does not accumulate. Local experiences indicate that lucerne does not accumulate significant amount of biomass during the period from early November to end of February. The dates to start looking for dormancy and first date to start looking for dormancy were set accordingly. Data on root parameters of lucerne varieties assessed using WinRhizo software were used to calculate root length per unit of root mass, surface root density and curvature of root density distribution (input for CropSyst) using curve fitting approach.

The Richards equation based finite difference model was used to describe water fluxes in the soil profile. Finite difference model was preferred over cascade model as finite difference is more detailed and can transport both up and down in comparison with cascade model which only shows downward movement of water.

Two year data (2007-2008) from the irrigated site was used to calibrate the model while two year data (2007-2008) from rain-fed site was used to validate the model. Above ground biomass and soil water content were compared for the purpose of calibration and validation of model. The agreement between measured and simulated values was evaluated by using different indices proposed by Loague and Green (1991). The indices included root mean squared error (RMSE), coefficient of determination (CD), modeling efficiency index (EF) and coefficient of residual mass (CRM). The CD indicates whether the model reproduces the trend of measured values or not and its minimum value is 0 and optimum is 1. The optimum value for EF is 1 and if positive, it indicates that the model is a better predictor than the average of measured values. The CRM ranges from 0-1 and its optimum value is 0 and if found positive, it indicates model under estimation. The indices were calculated using statistical software IRENE (Integrated Resources for Evaluating Numerical Estimates) (Fila et al., 2003).

5.2.5 Scenario Analysis

After calibration and validation of model, the model can be used to analyze the impact of different plant traits that vary among available lucerne varieties, viz. maximum rooting depth (MRD), specific leaf area (SLA) and stem leaf partitioning coefficient/ stem to leaf ratio (SLR) on the yield and components of water balance equation. This will help to identify the parameter that can bring maximum increase in yield under water limited conditions. Additionally, it will generate information on changes in components of water balance viz. cumulative actual transpiration, cumulative actual soil evaporation and cumulative soil water drainage/capillary rise during the vegetation period which underly potential yield effects in water-limited environments. These components of water balance are sometimes difficult to assess under field conditions but with the modeling, we can study them even by using additional scenarios while using a range of plant parameters for lucerne. The validated model was used for this purpose where individual plant parameters were subject to change one by one while keeping the others constant.

The impact of each above mentioned parameter was analyzed for a standard lucerne variety. For this standard lucerne variety, we used average values of measured and calibrated sensitive parameters viz. MRD (1.6 m), LAI (4.4), SLR (3), SLA (22 m^2 kg^{-1}), root length per unit root mass (37.8 km kg^{-1}), surface root density (5.08 cm cm^{-3}) and curvature of root density distribution (0.025). These scenarios had an objective to find the value of MRD, SLA and SLR where we can have maximum AGB under the given experimental conditions. This type of information can be of significance for breeders. Impact of MRD was analyzed by varying it from 1-3 m (Shen et al., 2009). SLA was varied from 15-30 (Sheehy and Popple, 1981; Erice et al., 2010) while SLR was varied from 1-3.5 (Confalonieri and Bechini, 2004). Impact of plant traits on components of water balance was calculated for entire vegetation period for each year and values presented in the tables are for vegetation period. Results from scenario analysis were further consolidated by calculating mean (using two years simulation results) to assess overall effect of different values of plant parameters on components of water balance.

Effect of varying levels of irrigation was evaluated on cumulative AGB for a two years simulation period taking examples of rainfall extremes from previous 30 years rainfall data. Years 2007-2008 were regarded in high rainfall scenarios as annual rainfall was 773 and 612 mm in 2007 and 2008, respectively .Rainfall data from 2003-2004 was taken as example for low rainfall year scenarios as annual rainfall in 2003 and 2004 was 409 and 540 mm, respectively. Irrigation levels tested were control (no supplemental irrigation), 10 mm, 20 mm, 30 mm, 40 mm and 50 mm at the intervals of 10, 15 and 20 days. The supplemental irrigation were applied during the period from June - September in each of the two experimental years as at this time of year, rain-fed lucerne usually suffers from water stress under the Raasdorf site conditions. Objective of these scenarios was to find a suitable irrigation strategy for lucerne at Raasdorf for low and high rainfall years.

5.3 Results

5.3.1 Experimental results

Cumulative AGB for three lucerne varieties during 2007-2008 are presented in Table 5.4. Sitel produced the highest AGB under both irrigated and rain-fed conditions. Mohajaren produced the lowest AGB under rain-fed conditions. All varieties performed better under irrigated conditions as compared to rain-fed conditions. Soil water content in the profile (0-120 cm) varied between 216-420, 212-383 and 190-378mm for the calibration of Sitel, Niva and Mohajaren, respectively. Soil water content for the validation of varieties varied between 142-305, 111-332 and 146-313 mm for Sitel, Niva and Mohajaren, respectively.

Table 5.4: Cumulative above ground biomass (tones ha^{-1}) of lucerne varieties

	Niva	Mohajaren	Sitel
Calibration	32.31±4.24	35.67±2.42	36.82±1.49
Validation	22.49±1.30	18.32±1.40	25.27±0.28

5.3.2 Model results

5.3.2.1 Calibration

Calibrated crop parameters are shown in Table 5.3. Some parameters were commonly adjusted for all lucerne varieties investigated in the experiment such as optimum mean daily temperature and maximum water uptake. These parameters showed a pronounced effect on biomass accumulation in lucerne as revealed by sensitivity analysis of CropSyst. Example of calibration for optimum temperature for lucerne already exists in literature (see Confalonieri and Bechini, 2004). Wide variation exists in optimal temperature for growth and AGB accumulation by lucerne ranging from 12-30

^0C due to cultivation of diverse germplasm in different agro-ecologies (Arbi et al., 1979; Confalonieri and Bechini, 2004). Optimum mean daily temperature calibrated for use in present study (15^0 C) falls within lower limits of range. Calibrated value of maximum water uptake (12 mm day^{-1}) is close to default value (10 mm day^{-1}). These two parameters were initially calibrated to make a close agreement between measured and simulated AGB. Variety specific calibration was done for SLA to find its optimum value for fine tuning of measured and simulated AGB. The calibrated values of SLA for three lucerne varieties ranged from 20-24 m^2 kg^{-1} those are again close to the default value of 22 m^2 kg^{-1}.

The base and cut-off temperatures are taken from literature (Confalonieri and Bechini, 2004). Dates related to dormancy were adjusted based on local experience which shows that no substantial above ground biomass accumulation occurs during the period from start of November to end of February.

The agreement between simulated and measured AGB is shown in Fig. 5.1, 5.2 and 5.3 and in Table 5.5. The values of the indices presented in Table 5.5 are an indicative of goodness of the model performance. The agreement between simulated and measured AGB is quite satisfactory for all three varieties at most of the cuts. The overall agreement between measured and simulated cumulative AGB is very good.

Table 5.5: Indices of agreement between simulated and measured above ground biomass after calibration

Variety	RMSE	EF	CRM	CD
Niva	1.29	0.98	0.009	0.81
Mohajaren	1.49	0.97	0.05	0.99
Sitel	0.58	0.99	0.006	0.95

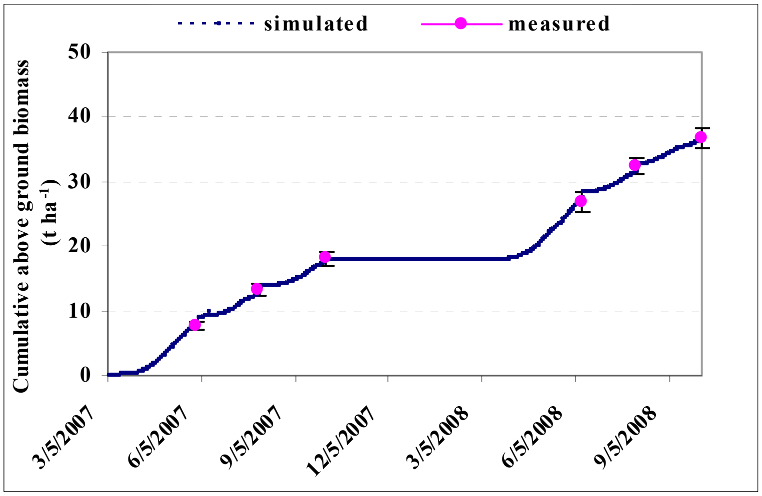


Figure 5.1: Cumulative above ground biomass of Sitel after calibration

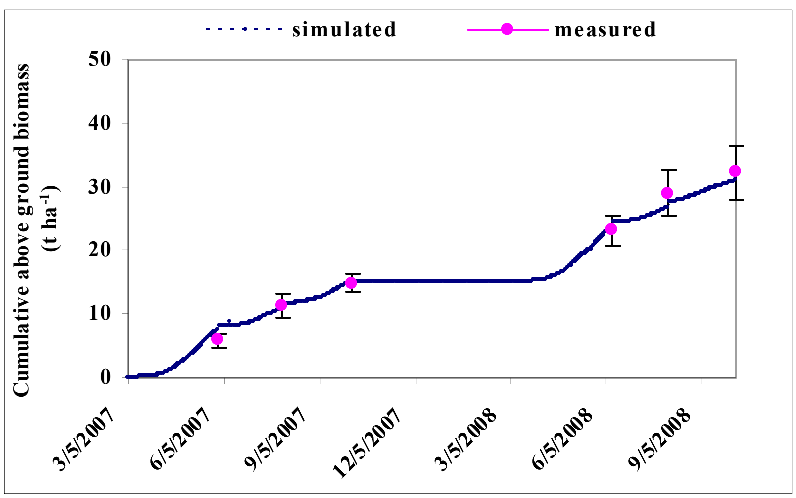


Figure 5.2: Cumulative above ground biomass of Niva after calibration

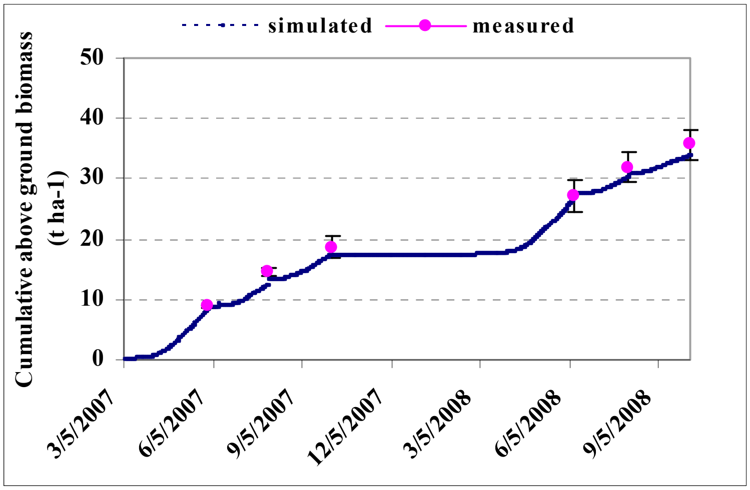


Figure.5.3: Cumulative above ground biomass of Mohajaren after calibration

A fine tuning between measured and simulated profile SWC was achieved by calibrating the saturated hydraulic conductivity. Values of 0.044, 0.108 and 0.173 m day^{-1} were used for A, AC and C horizon, respectively in the irrigated site. The agreement between measured and simulated profile SWC (0-120 cm) is shown in Fig. 5.4, Fig. 5.5 and Fig. 5.6 and Table 5.6. The model seems quite accurate in simulating soil water content especially during the vegetation period for Sitel and Niva. The values of RMSE are low and CD is close to 1. Initially, model slightly over estimates profile SWC in case of Mohajaren, but later on agreement between measured and simulated values becomes good (Fig. 5.6).

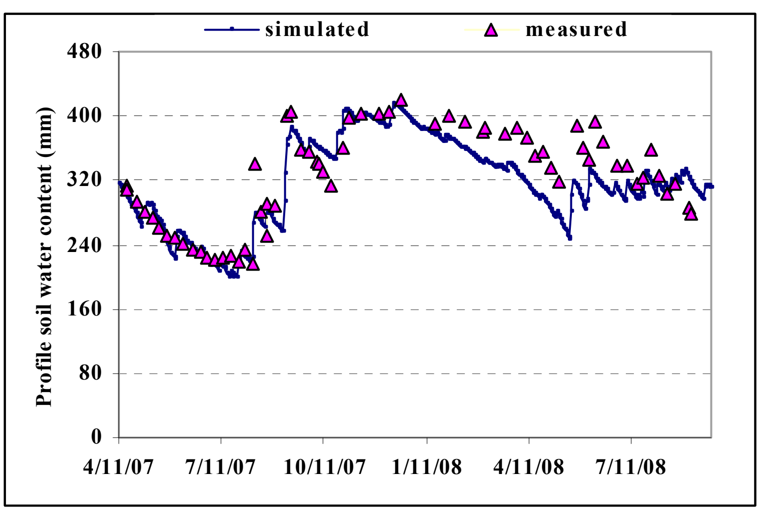


Figure 5.4: Profile soil water content for Sitel after calibration

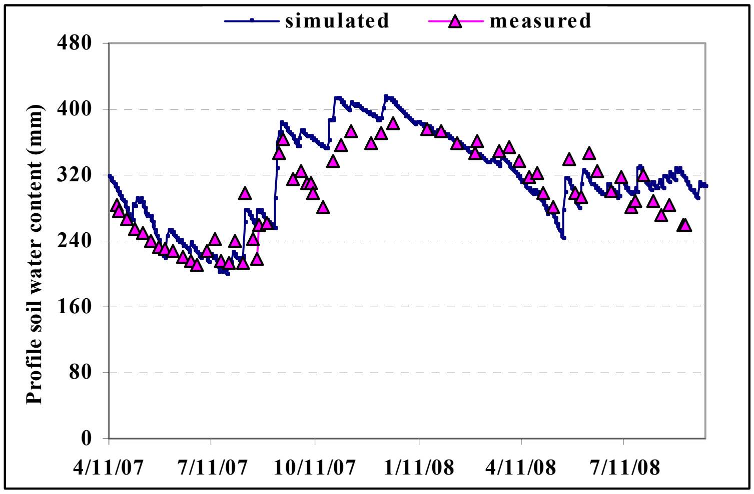


Figure 5.5: Profile soil water content for Niva after calibration

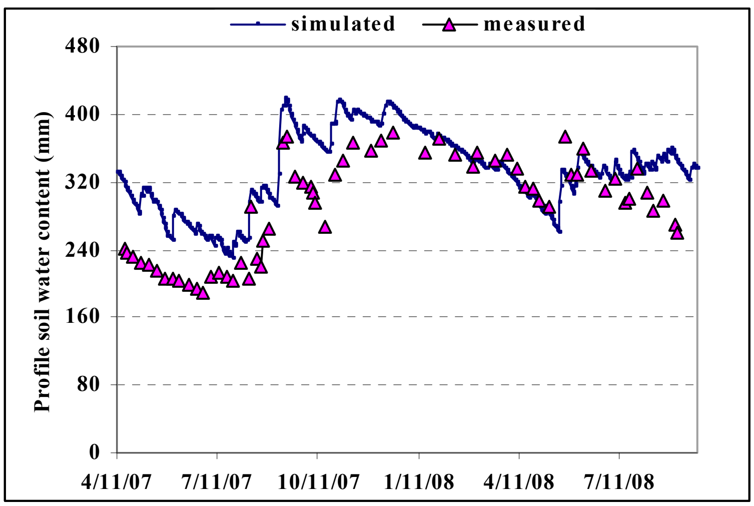


Figure 5.6: Profile soil water content for Mohajaren after calibration

Table 5.6: Indices of agreement between simulated and measured profile soil water content after calibration

Variety	RMSE	EF	CRM	CD
Niva	31.20	0.61	-0.04	1.24
Mohajaren	50.62	0.25	-0.13	1.03
Sitel	31.33	0.72	0.04	0.87

5.3.2.2 Validation

Results on agreement between simulated and measured cumulative AGB of lucerne varieties are presented in Fig. 5.7, Fig. 5.8 and Fig. 5.9 and Table 5.7. On the overall basis, model performance seems quite satisfactory. It simulates AGB of Sitel quite well (Fig. 5.7) except for the last two cuts in 2008. Model slightly under estimates the AGB of Niva during the last two cuts in 2008 (Fig. 5.8). Model over estimates the AGB of Mohajaren (Fig.5.9).The indices of agreement between simulated and measured AGB seem quite reasonable for Sitel and Niva as RMSE is low, and CD and EF are close to 1.

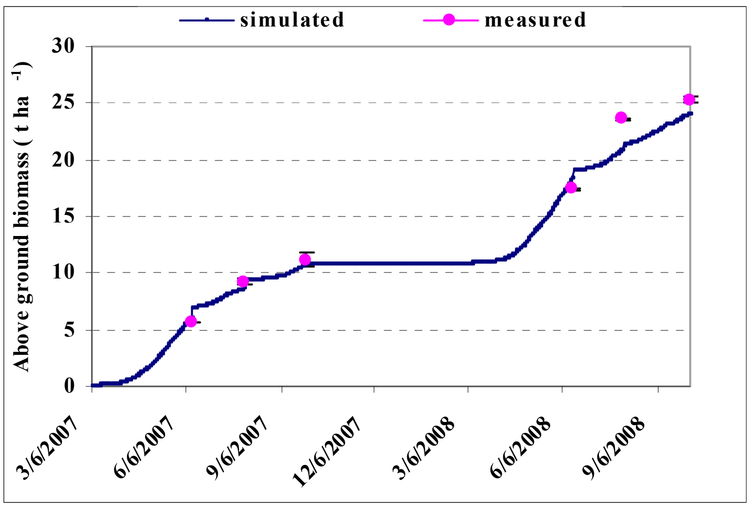


Figure 5.7: Cumulative above ground biomass of Sitel after validation

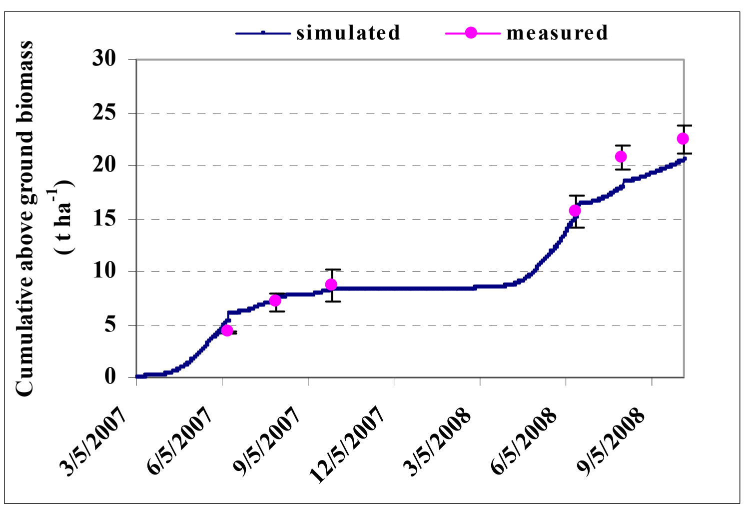


Figure 5.8: Cumulative above ground biomass of Niva after validation

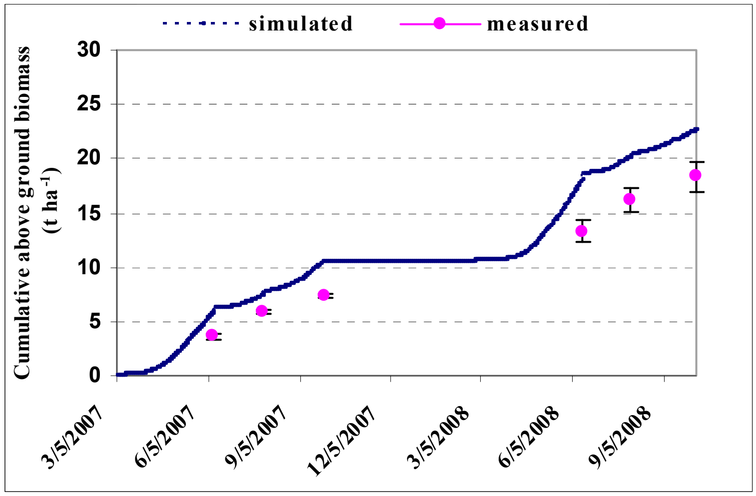


Figure 5.9: Cumulative above ground biomass of Mohajaren after validation

Table 5.7: Indices of agreement between simulated and measured above ground biomass after validation

Variety	RMSE	EF	CRM	CD
Niva	1.50	0.95	0.05	0.69
Mohajaren	3.52	0.58	-0.30	1.77
Sitel	0.65	0.99	-0.005	1.02

A fine tuning between measured and simulated profile SWC was achieved by calibrating the saturated hydraulic conductivity. Values of 0.400, 0.320 and 0.500 m day^{-1} were used for A, AC and C horizon, respectively in the rain-fed site. Agreement between measured and simulated profile SWC after validation is shown in Fig.5.10, Fig. 5.11 and Fig. 5.12 and Table 5.8. The model performance seems quite satisfactory for simulating profile SWC for Niva, Sitel and Mohajaren where RMSE is low and CD and EF are close to 1.

Table 5.8: Indices of agreement between simulated and measured profile soil water content after validation

Variety	RMSE	EF	CRM	CD
Niva	20.92	0.86	-0.02	0.79
Mohajaren	20.90	0.77	-0.04	1.09
Sitel	26.10	0.64	0.01	1.30

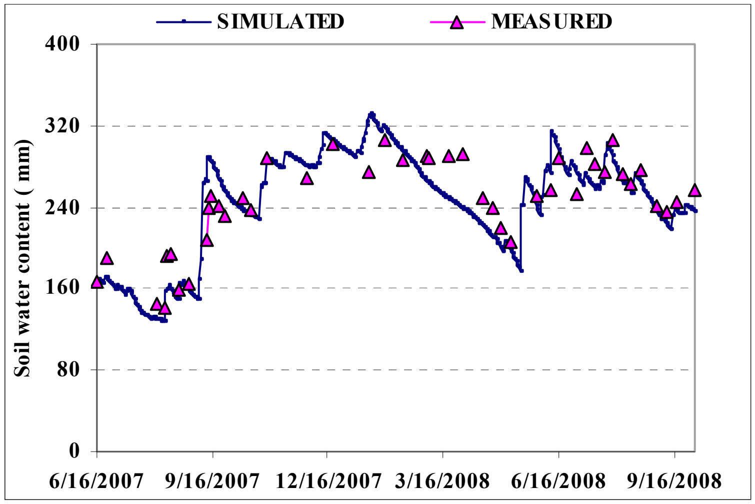


Figure 5.10: Profile soil water content for Sitel after validation

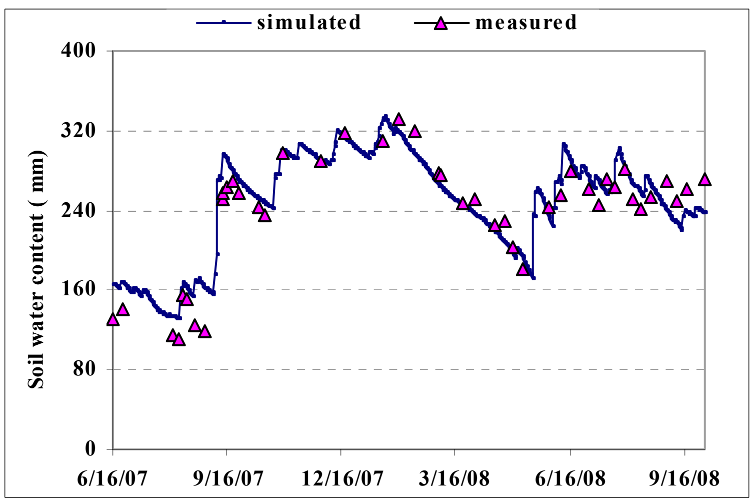


Figure 5.11: Profile soil water content for Niva after validation

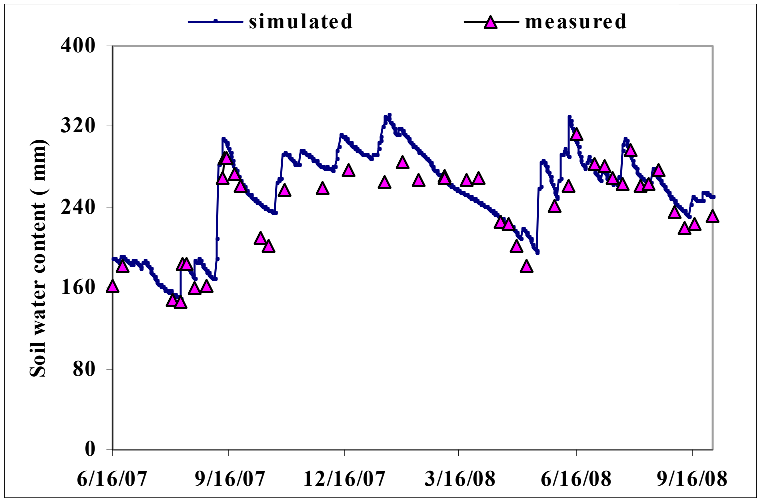


Figure 5.12: Profile soil water content for Mohajaren after validation

5.3.2.3 Results from scenario analysis

5.3.2.3.1 Impact of maximum rooting depth

As shown previously in chapter 3, lucerne varieties revealed a large variability in maximum rooting depth varying from 1.0-1.9 m (see Table 13). Lucerne roots can grow 3 m deep (Shen et al., 2009). Rooting depth plays an important role in water uptake by plants and therefore directly affects water availability to the plants. On the other hand, root water uptake from deeper soil layers has the potential to reduce ground water recharge under medium rainfall environments (Crawford and Macfarlane, 1995).

The effect of varying rooting depths (1-3 m) on biomass accumulation and components of water balance was evaluated in scenarios after validating the model for rain-fed site. The results are presented in Table 5.9. Effect of varying MRD on AGB accumulation varied among years probably due to different amounts of rainfall received during these years (see figure 2.2). Results indicated that highest biomass was achieved with MRD 2.5 m (11624 kg ha^{-1}) in 2007 and with MRD 1.3 (12549 kg ha^{-1}) in 2008. In 2008, increasing MRD beyond 1.3 did not produce substantial increase in AGB accumulation. Effect of varying MRD on cumulative yearly evaporation also varied slightly among years and seems to be linked to the water availability through different rainfall amounts and distribution in study years. In 2007, increasing MRD from 1-1.9 tended to decrease

Table 5.9: Impact of maximum rooting depth on above ground biomass and components of water balance

Year	MRD (m)	Yearly cumulative AGB (kg ha^{-1})	Cumulative actual transpiration (mm)	Cumulative actual soil water evaporation (mm)	Cumulative soil water capillary rise (mm)
2007	1.0	6860	146	338	11
	1.3	8452	192	328	11
	1.6	10697	224	312	34
	1.9	11595	248	299	32
	2.5	11624	248	304	26
	3.0	11624	248	307	22
2008	1.0	12445	236	321	33
	1.3	12549	239	323	28
	1.6	12549	239	324	20
	1.9	12549	239	325	16
	2.5	12549	239	326	6
	3.0	12549	239	326	4

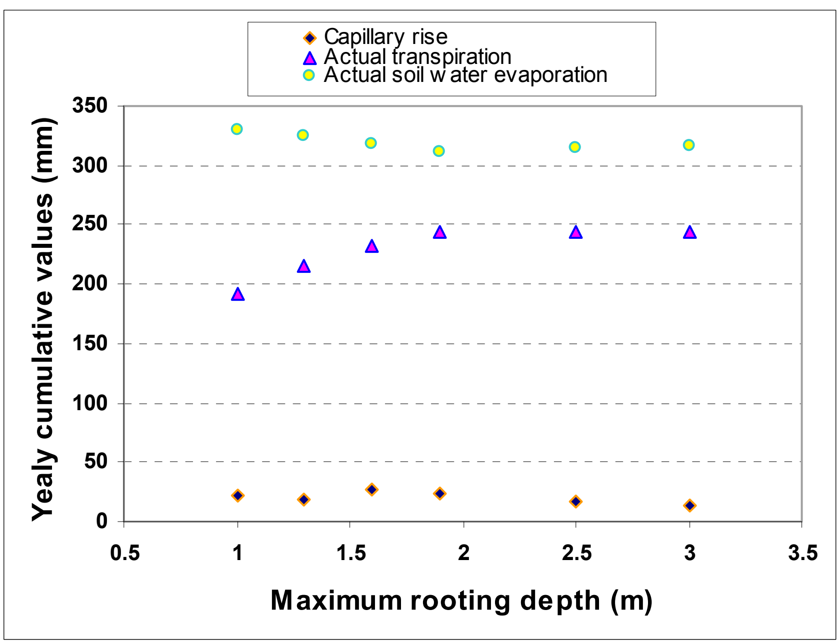


Figure.5.13: Effect of maximum rooting depth on components of water balance

evaporation from 338-299 mm but increasing MRD beyond 1.9 m slightly increased evaporation up to 307 mm. In 2008, there was no substantial effect of varying MRD on cumulative yearly evaporation as with increasing MRD from 1 to 3 m, evaporation increased from 321 to 326 mm. Effect of varying MRD on evaporation is also linked to biomass accumulation. With lower MRD biomass accumulation and ground cover is less and evaporation usually tends to increase. Cumulative yearly actual transpiration varied among years and at varying levels of MRD 1-3 m, transpiration ranged from 146-248 and 236-239 in 2007 and 2008, respectively. Effect of MRD on capillary rise varied among years and its values ranged from 11-34 and 4-33 mm in 2007 and 2008, respectively (see Table 5.9).

Based on two years average, it was found that cumulative yearly transpiration increased from 191-243 mm when rooting depth was increased from 1 to 1.9 m while increasing MRD beyond 1.9 m did not increase transpiration. Increasing MRD from 1 to 1.9 m resulted in a reduction in cumulative yearly evaporation from 329 to 312 mm and increasing MRD beyond 1.9 m does not seem to affect evaporation greatly as evaporation values were found to be 315 and 317 mm at MRD of 2.5 m and 3m, respectively. Highest capillary rise (27 mm) was observed at MRD of 1.6 m while lowest capillary rise (13 mm) was observed at MRD of 3 m (see Fig. 5.13).

5.3.2.3.2 Impact of specific leaf area

SLA represents leaf area per unit of leaf mass. Higher SLA means that higher leaf area and this higher leaf area tends to absorb more radiation and ensures its conversion to biomass but it can have consequences for water losses by transpiration and evaporation. Usually varieties with higher SLA tend to cover more soil and may reduce water losses by evaporation. In breeding programs, higer values of SLA are desirable (Rebetzke et al., 2004).

Results from scenario analysis indicated that SLA has a linear relation with AGB accumulation as increasing SLA increased AGB in both years. Increasing SLA from 15 to 30 m^2 kg^{-1} increased yearly AGB from 8705 to 12023 kg ha^{-1} and 9247 to 15214 kg ha-[1], in 2007 and 2008, respectively. Similar trend was observed for cumulative yearly actual transpiration as with an increase in the value of SLA, transpiration tended to increase in both years. Values of cumulative yearly transpiration ranged from 179 to 253 and 171 to 296 in 2007 and 2008, respectively. Evaporation losses tended to decrease by increasing SLA. This trend was observed in both experimental years. It seems quite logical that when SLA increases, it means more soil surface is covered by plant leaves and it may reduce water losses by evaporation. Increasing SLA from 15 to 30 decreased cumulative yearly soil water evaporation from 349 to 276 mm and 386 to 265 mm in 2007 and 2008, respectively.

The effect of varied values of SLA on cumulative yearly capillary rise was not pronounced, although it varied among years. In 2007, capillary rise varied from 32 to 35 mm in comparison with capillary rise of 17 to 20 mm in 2008. There was no drainage losses found in simulation results during the entire vegetation period in both experimental years. These findings are in agreement with those of Diaz-Ambrona et al. (2005) who used CropSyst to investigate the impact of crop rotations and management practices in a 5 year study on the water balance of farming systems in a semi-arid region of south-eastern Australia.

The optimum values of SLA shall be selected with care. The optimum value is of course one at which model accumulates maximum biomass. The results regarding impact of SLA on biomass and components of water balance equation are presented in Table 5.10.

Based on mean values of results from two years of simulations, it was found that increasing SLA from 15 to 30 usually increased transpiration and decreased evaporation. Capillary rise due to changes in SLA seem to be the least affected (Fig. 5.14).

5.3.2.3.3 Impact of stem/leaf partitioning coefficient

Stem/leaf partitioning coefficient is an important component of yield. It is desired that more assimilates are partitioned to leaves than to stem as these assimilates are needed there for photosynthesis.

Table 5.10: Impact of specific leaf area on above ground biomass and components of water balance

Year	SLA (m^2 kg^{-1})	Yearly cumulative AGB (kg ha^{-1})	Cumulative actual transpiration (mm)	Cumulative actual soil water evaporation (mm)	Cumulative soil water drainage/ capillary rise (mm)
2007	15	8705	179	349	35
	20	10245	217	319	33
	22	10697	224	312	34
	23	10914	229	307	34
	24	11179	232	304	34
	30	12023	253	276	32
2008	15	9247	171	386	17
	20	11721	221	342	20
	22	12549	239	324	20
	23	12937	247	316	20
	24	13307	255	307	19
	30	15214	296	265	17

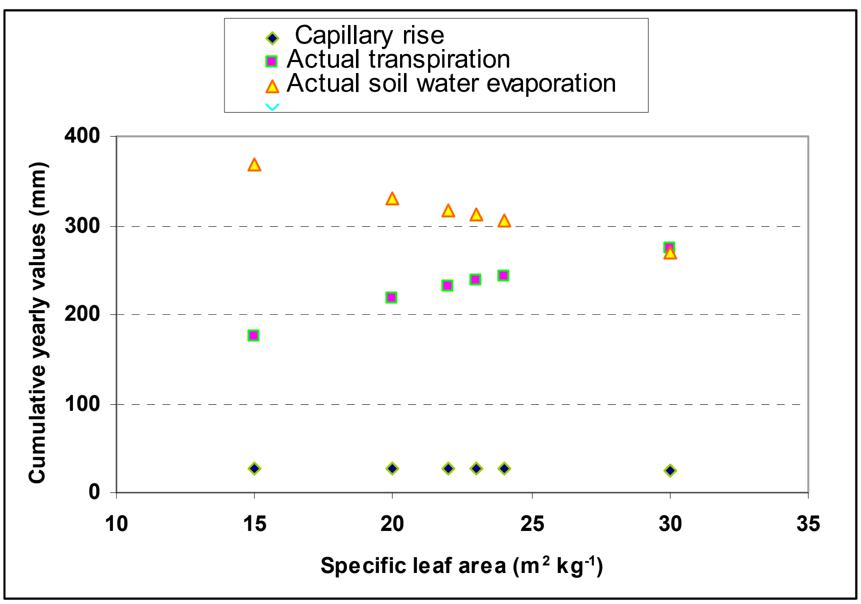


Figure 5.14: Effect of specific leaf area on components of water balance

Finding an optimum value of SLR is crucial for a given situation as if SLR value is either too low or too high, it may lead to inefficient utilization of resources especially water in the system. If SLR is too high, there exists a possibility that water requirements of plants with too much leaves are not fulfilled. But if SLR values are low, there may be extra water losses by evaporation due to less ground cover. Analyzing the impact of SLR on yield and components of water balance is especially important under water limited rain-fed conditions.

The effect of varying SLR on AGB accumulation varied slightly among years. In 2007, the highest cumulative yearly AGB (11356 kg ha^{-1}) was obtained at SLR of 1.5 while in 2008, the highest cumulative yearly AGB (16183 kg ha^{-1}) was obtained with SLR of 1.0. This slight variation might be due to relativey drier conditions in 2007 due to which model was unable to accumulate enough biomass during third cut in scenario with SLR value of 1.0. Increasing values of SLR from 1 to 3.5 tended to increase cumulative yearly evaporation and decrease cumulative yearly transpiration in both years (see Table 5.11). There was an increase in cumulative capillary rise with increase in SLR values and it seems demand driven as more leaves need more water to meet their transpiration requirements.

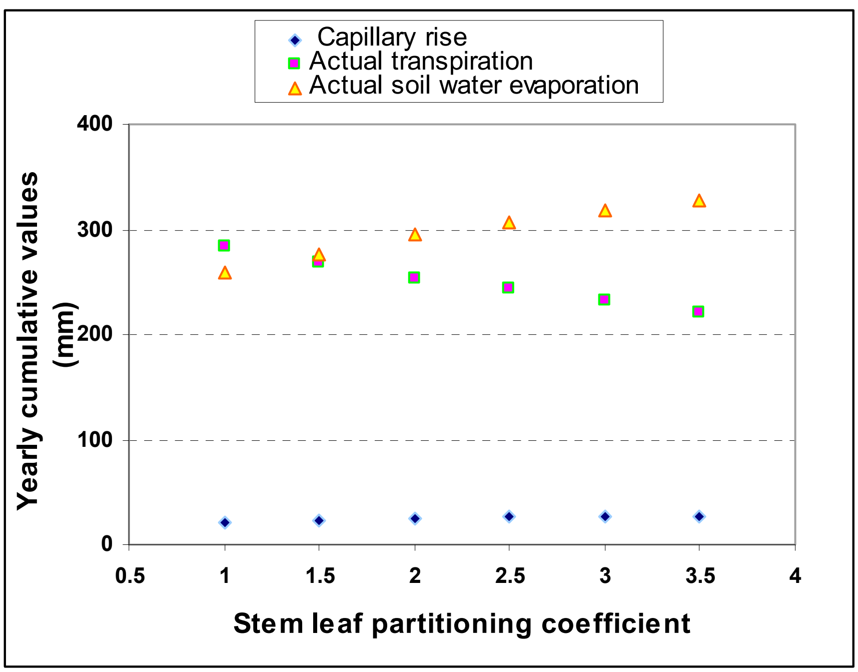
Based on mean values of results from two years of simulations, it was found that increasing SLR from 1.0 to 3.5 usually decreased transpiration and increased evaporation. Capillary rise due to changes in SLR seem to be affected slightly (see Fig. 5.15). These results on the overall effect of SLR on the components of water balance shall be interpreted with care as too lower values of SLR (1) are usually reported under stress conditions and models usually do not produce nice results under stress conditions.

5.3.2.3.4 Effect of supplemental irrigation

Irrigation brought a remarkable increase in biomass under the present site conditions. In low rainfall scenarios, an increase of 5.7 tones ha^{-1} was recorded due to irrigation over the control. In high rainfall scenarios, an increase of 1 ton ha^{-1} was recorded over control.

Table 5.11: Impact of stem/leaf partitioning coefficient on above ground biomass and components of water balance

Year	SLR	Yearly cumulative AGB (kg ha^{-1})	Cumulative actual transpiration (mm)	Cumulative actual soil water evaporation (mm)	Cumulative soil water drainage/ capillary rise (mm)
2007	1	9828	249	281	26
	1.5	11356	246	287	27
	2	11185	238	298	31
	2.5	10906	231	307	33
	3	10697	224	312	34
	3.5	10504	219	315	34
2008	1	16183	320	238	16
	1.5	14925	292	267	17
	2	13919	269	292	17
	2.5	13339	256	306	19
	3	12549	239	324	20
	3.5	11869	224	339	20



. **Figure 5.15**: Effect of stem/leaf portioning coefficient on components of water balance

Under low rainfall conditions, highest AGB of 24.2 tones ha^{-1} can be achieved if 40 mm of irrigation is applied at 20 days interval. i.e. 200 mm of supplemental irrigation can help to bring an increase of 5.7 tones in AGB. In case of high rainfall scenarios, highest AGB of 24.2 tones ha^{-1} can be achieved if 20 mm of irrigation is applied at 20 days interval. i.e. 100 mm of supplemental irrigation can help to bring an increase of 1 ton in AGB. Detailed results from scenario analysis on the effect of various levels of irrigation at various intervals on the accumulation of AGB during two years simulation period are presented in Table 5.12.

Table 5.12 Effect of amount and frequency of irrigation on above ground biomass (tones ha^{-1})

Interval	Control	10 mm	20 mm	30 mm	40 mm	50 mm
Low rainfall scenarios (Annual rainfall 409-540 mm)						
10 days	18.5	21.3	24.2	24.2	24.2	24.2
15 days	18.5	19.3	23.8	24.2	24.2	24.2
20 days	18.5	18.9	21.8	24.0	24.2	24.2
High rainfall scenarios (Annual rainfall 612-773 mm)						
10 days	23.2	24.2	24.2	24.2	24.2	24.2
15 days	23.2	23.9	24.2	24.2	24.2	24.2
20 days	23.2	24.0	24.2	24.2	24.2	24.2

5.4 Discussion

The model performance seems quite satisfactory especially during calibration under irrigated conditions for radiation-limited potential crop growth and soil water dynamics as revealed by indices of agreement between simulated and measured AGB and profile SWC (see Table 5.5 and Table 5.6). Low values of RMSE, close to zero values of CRM, and EF and CD close to 1 confirm the goodness of model performance. It indicates the sufficiency of set of default crop parameters of CropSyst for lucerne and accuracy of measured parameters on soil hydraulic properties and root characteristics. The fit for biomass for all varieties and fit for profile SWC for Niva and Sitel is good. For Mohajaren, fit of measured and simulated profile SWC is less satisfactory. It may be due to the over estimation of SWC by model during 2007 and end of vegetation period in 2008 (see Fig. 5.6). This variation in SWC might have resulted from higher input value of

MRD of Mohajaren (1.9 m) as compared to other varieties (1.3-1.5 m). With increasing MRD, model assumes to extract water from deeper depths, while in reality SWC in Mohajaren plots did not vary greatly from those of other varieties in the study. It can also be due to error in measurement on MRD of Mohajaren or can be due to effect of spatial variability on profile SWC that lead to slight under estimation of SWC in the profile by the measurement devices.

Under rain-fed site, AGB was reproduced quite well by the model for Niva and Sitel as revealed by indices of agreement between simulated and measured values (see Table 5.7) where EF and CD are close to 1, CRM is close to zero and RMSE is low. These findings are in line with those of Confalonieri and Bechini (2004) who evaluated CropSyst for lucerne in northern Italy and found good agreement between measured and simulated AGB with EF and CD close to 1 and CRM close to 0. The model slightly under estimated the biomass for last two cuts in 2008 for both Sitel and Niva. These findings are in agreement with those of Confalonieri (2003) who also found that CropSyst under estimated AGB for last 2 cuts of lucerne in northern Italy during the validation of model.

The over estimation in biomass accumulation for Mohajaren seems to be associated with variation in measured MRD of this variety under two different sites. The model assumes that Mohajaren had MRD of 1.9 m for rain-fed site as well but measurements revealed that roots of this variety were able to grow only till 1.1 m deep under the rain-fed site. When MRD was reduced from 1.9 m to 1.1 m, the cumulative AGB from six harvests in two year simulation period (2007-2008) reduced from 23 to 19 tones ha^{-1} and it was close to the measured value of cumulative AGB i.e. 18.3 tones ha^{-1}. These variations in AGB biomass are acceptable because the model was calibrated using values of SLA and SLR that are usually achieved under non-stressed irrigated conditions. Under water stress conditions, SLA and SLR may decrease (Lemaire et al., 2005; Erice et al., 2010), thereby, leading to a reduction in AGB accumulation. The reduction in MRD from 1.9 m to 1.1 m resulted in profile SWC that was usually below the values resulting from MRD of 1.9 m and it did not improve the fit between measured and profile SWC greatly. A comparison of measured and simulated profile SWC under two rooting depths is presented in Figure 5.16.

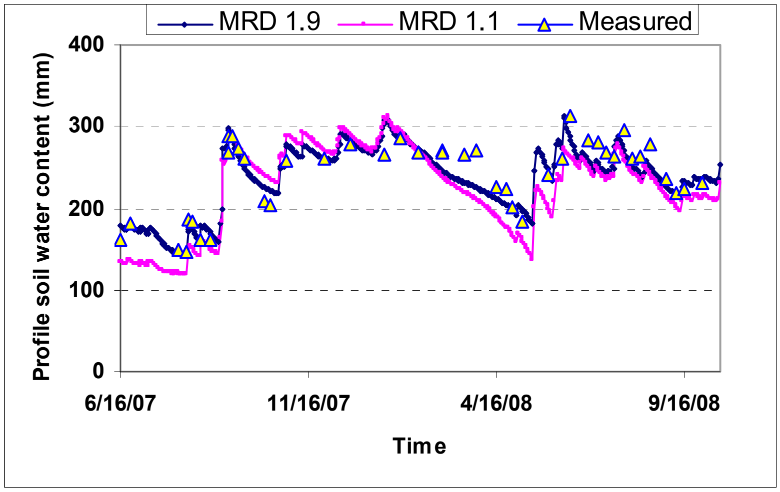


Figure 5.16: Effect of varying rooting depth (m) on profile soil water content

The model performance for simulating profile SWC under the rain-fed site is not too bad as indicated by indices of agreement between measured and simulated profile SWC (see Table 5.8). SWC is one of the most difficult parameter to be simulated accurately by the models as the differences between measured and simulated SWC may result from different factors. These differences may be due to the water retention curve parameterization, to the time discretization of precipitation input, to the upper boundary condition during precipitation and to the lower boundary condition (Scanlon et al., 2002), Parameterization of evapotranspiration and root growth shows to be the most relevant factor affecting models performance (Eitzinger et al., 2004). Parameters related to evapotranspiration and root growth are difficult to assess. Sensitivity analysis regarding effect of rooting depth explains how model performance in terms of AGB accumulation and components of water balance can be affected by varying only one parameter related to roots (see table 5.9).

On the overall basis, model performance seems quite satisfactory for simulating AGB and profile SWC under both irrigated and rain-fed sites and fluctuations between measured and simulated AGB and profile SWC are acceptable as modeled and measured results are never on one line. Also the models do not perform quite well under water limited conditions (Evett and Tolk, 2009).

The adequacy of model to simulate AGB and profile SWC offered opportunity to analyze the impact of plant traits including MRD, SLA and SLR on AGB accumulation and components of water balance. Results revealed that effect of MRD on AGB accumulation may vary among years. As in the present study, in 2008, model produced the highest AGB at MRD of 1.3 while in 2007 model produced the highest AGB with MRD value of 2.5 m. This differential behaviour from model can be attributed to difference in rainfall distribution in two years. Year 2008 seems to have relatively better water availability due to high rainfall as compared to 2007 (see Figure 2.2). Deeper roots are, of course, required under water limited conditions to extract water from deeper soil layers. Analysis of results from scenarios on the effect of MRD on AGB indicates that a value of 1.6 m seems quite satisfactory in terms of biomass accumulation in both years as increasing MRD beyond 1.6 m does not bring a major increase in AGB accumulation (Table 5.9).

SLA value of 30 m^2 kg^{-1} seems quite reasonable for AGB accumulation under the conditions of experiment. Modeling results from scenario analysis indicated that effect of varying SLR can be different in different years particularly in context of moisture availability through rainfall. SLR between 2-2.5 gave reasonably good yields under the conditions of present experiment, although yields at this value of SLR were not the highest but the differences from highest yield recorded at SLR of 1 and 1.5 were not great. As too low values of SLR like 1 or 1.5 are usually observed under stress conditions, as were the conditions of the rain-fed set of experiment, it can be that under the given conditions, we may assume that results produced by the model in scenario analysis are quite reasonable. For practical purposes like breeding for drought tolerance, too low values of SLR are not desirable. Scenario analysis under varied levels of SLA and SLR indicated that gains in AGB accumulation were associated with increased transpiration rates and decreased evaporation (see Table 5.9, Table 5.10 and Table 5.11).

Apparently, leaf related traits seem to have more impact on AGB accumulation as compared to rooting depth. But these results shall be interpreted with care. Leaf parameters have direct link with AGB as leaves absorb radiation and convert it to biomass. Finding an optimum value by sensitivity analysis is always crucial before making any recommendations. It must be considered that CropSyst has a transpiration dependant biomass accumulation function (Stöckle et al., 2003). Variation in leaf parameters may be made in conjunction with rooting parameters because if values of leaf parameters are set too high, then the transpiration rates increase and evaporation usually decreases due to a better ground cover and vice versa. Higher transpiration rates create a gradient and allow the system to extract more water from deeper soil layers to meet the crop demands for water. If system does not have a deep root, there exists a possibility that crop may undergo water stress. It explains that a combination of optimum values of leaf and root parameters shall be selected and one shall not try to bring a drastic change in lucerne yields by changing only one parameter either related to roots or leaves. Finding an optimum value of SLA, SLR and MRD and using these optimum values in combination may allow us to obtain better yields.

Scenario analysis indicated that increase in lucerne yield can be achieved by using a combination of parameters where MRD shall be between 1.5-2 m, SLA between 22-24 m^2 kg^{-1} and SLR shall be 2-3. From plant breeding point of view, an ideotype to be developed for the Raasdorf site conditions shall possess the plant traits in these specified ranges. The range of parameters specified here fall close to the default values of said traits in CropSyst. Default value of MRD in CropSyst is 1.5 m and it is not recommended to use MRD value below 1m or above 2m as there are chances of crop failures due to water stress if MRD is kept below 1m. Suggesting MRD beyond 2m has the disadvantage that too much assimilates will be partitioned to root as compared to shoot while gains from minor increase in water extraction from deeper roots do not contribute a lot towards AGB accumulation.

Although, a linear relationship was observed among SLA and AGB accumulation but again, it is not logical to suggest too high value of SLA around 30 m^2 kg^{-1} as under the given site conditions, soil fertility and water availability factors may not allow to gather a SLA of 30 m^2 kg^{-1} practically, so a relatively higher value of 24 m^2 kg^{-1} seems sufficient for given site conditions. We suggest using a SLR value of 2-3 as too low values of SLR such as 1 are practically not feasible. As yield and WUE have a direct relationship (Viets,1962), if yields are increased, we shall expect an increase in WUE as well.

Previous studies indicate that crop growth models have excellent potential for proposing and hypothesizing plant ideotypes for target environments and can partially reproduce genotype by environment interactions when considered across broad ranges of weather and sites. More physiological insight into primary processes such as source–sink relationships and morphological development will be needed for enhanced application of the models in breeding programmes (Kropff et al., 1995; Aggarwal et al., 1997; Boote et al., 2001).

Effect of supplemental irrigation on AGB can vary with the amount and distribution of rainfall during the years as was revealed from the results of scenario analysis. Effect of supplemental irrigation is more pronounced in low rainfall years and irrigation with 40 mm of water at 20 days interval during the period from June-September can help to achieve about 6 tones ha^{-1} of additional biomass. The positive effects of supplemental irrigation in high rainfall years are less pronounced as only 1 ton ha^{-1} of additional biomass was achieved when 20 mm of supplemental irrigation was applied at 20 days interval. Decisions about irrigation management shall be made with great care especially under high rainfall years keeping in view their cost benefit ratio. Assessing the proper irrigation requirements using simulation model helps to save precious water and enhances yields (Greenwood et al., 2010).

With this modeling exercise, the potential of simulation model, CropSyst, to simulate biomass and soil water content for lucerne production under two sites in Austria is demonstrated. We learnt how plant traits can contribute to bring an improvement in yields from breeding point of view. Modeling helped to define irrigation requirements of lucerne under different rain fall scenarios.

Chapter 6

Evaluation of CropSyst for studying effect of mulching with lucerne

6.1 Introduction

Water is a limiting factor for crop production in many parts of the world. Its efficient utilization remains the key concern for researchers. Different soil and crop management practices can help to obtain better WUE. The aim of management practices shall be to either increase transpiration efficiency or to decrease non–productive water losses. Mulching is regarded as one of the best ways to improve water retention in the soil and to reduce soil evaporation (Steiner, 1989; Huang et al., 2005).

Residues and mulches limit evaporation by reducing soil temperature, preventing vapour diffusion, absorbing water vapor on to mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface (Greb, 1966; Lagos et al., 2009). Presence of mulch on soil surface tends to increase water infiltration into the soil and cumulative effect of increase in infiltration and reduction in evaporation is overall better retention of water under mulch (Li and Xiao, 1992; Baumhardt and Jones, 2002). However, mulch effects depend on the soil type, rainfall and evaporative demand (Wicks et al., 1994; Tolk et al., 1999; Ji and Unger, 2001; Lampurlanes et al., 2002). Incerti et al. (1993) found small gains in water storage attributable to stubble retention in long-fallow periods, with no advantage in crop yield. Greater and more consistent responses to stubble retention were reported for the wetter regions having heavier soils in Australia (Cantero-Martınez et al., 1995).

Evaluation of management practices under field conditions involves high cost and time and due to uncertainty and variability in weather and field conditions, results may vary among years. Alternatively, it can be evaluated much more cheaply and quickly using simulations. Models can be used for long term predictions and their results can be extrapolated if they are calibrated and validated for a management intervention in a given location. Simulation model, CropSyst, (Stöckle et al., 2003) is a SPAC model which has options for biomass fate where we may opt to harvest the biomass and specify a percentage of biomass to be left in the field as mulch or we may harvest and designate it for beneficial use. These options make the model a suitable choice for comparing results on different lucerne utilization system (no mulch versus mulch). The present study was designed to evaluate the efficacy of CropSyst under different lucerne utilization systems.

6.2 Materials and Methods

6.2.1 Experimental details

A field experiment with lucerne variety Sitel was laid out on organically managed fields at Raasdorf, Eastern Austria for two consecutive years (2007-2008). The randomized complete block experiment with four replicates, having a plot size of 3 m x 3 m and row spacing of 12.5 cm, received usual management from sowing to harvest. Every year in April, sowing was done with machine on a different field using a seed rate of 25 kg ha^{-1}. The trial site in Raasdorf is located in the Marchfeld, an area of about 100,000 ha approx. 5 km east of Vienna (48^{0}14$^{/}$N, 16^{0}35$^{/}$E) at an altitude of 150–160 m above sea level. The Marchfeld is mainly devoted to intensive farming and the climate is characterized by hot, dry summers with little dew, and cold winters with little snow. The mean daily temperature is 11.1 ^{0}C and the average annual precipitation is 539 mm (based on data from 1980-2009). Soils are Calcaric Phaeozems (WRB, 1998) from fine alluvial sediments with a silty loam texture, organic carbon contents of 2.2% in the Ap horizon, and a pH_{CaCl2} value of 7.6 (Pietsch et al., 2007).

Data on yield was recorded at two main harvests in each year. Harvesting was done at 30-40 % of the flowering. Lucerne plots were hand clipped with a garden scissor at about 5 cm above the ground level. An area of 1m^{2} was harvested from each plot at each harvest to determine shoot biomass. Each plot had two distinct harvest areas of 0.5 m^{-2}. Every year first harvest was used to apply no mulch and mulch treatments. At second harvest, data on biomass was recorded to compare the effect of treatments. Stubble biomass was determined only on second harvest in each year. Shoot and stubble dry matter yield were determined by oven-drying the sub-sample at 60 °C for 48 h. Values of shoot and stubble dry matter yield at second harvest were added to present the data on above ground biomass for comparison with model results. A summary of management operations during the experimental period is presented in Table 6.1.

Soil water content was measured using SENTEK Diviner 2000 (Sentek Sensor Technologies, Australia) probes that were installed at the depth of 120 cm in each lucerne plot. Soil water content was measured using manual data logger at weekly to fortnightly intervals. No site specific calibration was done and original values of water content obtained from the data logger were used to calculate profile SWC for comparison with simulation results. Precipitation and meteorological data were obtained from weather station of Institute of Agronomy and Plant Breeding, BOKU.

Table 6.1: Management operations in the utilization system experiment

Management operation	2007	2008
Sowing	10th april	11th april
Irrigation	12th april (75 mm)	13th april (15 mm)
Irrigation	18th april (50 mm)	20th april (15 mm)
Installation of SENTEK probes	16th may	28th april
Harvest 1	9th July	9th July
Harvest 2	18th september	9th september

At the end of vegetation period in each year, undisturbed soil samples were collected in two replicates for the determination of soil texture, bulk density, retention curves and saturated hydraulic conductivity. Particle size analyses are based on determination of percentage of sand (0.063-2 mm), silt (0.063-0.002) and clay (< 0.002) in a soil sample. Particle size analyses involved dry sieving to separate particles > 2 mm, wet sieving (for < 2 mm) and pipette approach (for < 0.063 mm) (ONORM L1061). Based on relative proportion of sand, silt and clay, textural classes were determined following American textural triangle adopted from American Soil Survey Manual (Soil Survey Staff, 1951).

Bulk density was determined using the following relation proposed by Blake and Hartge (1986).

Bulk density (g cm^{-3}) = mass of oven-dried soil sample (g)/ volume of core (cm^3)

Saturated hydraulic conductivity (SHC) was determined by using method of rising head soil core. This method is a modified form of falling head soil core/tank method (Reynolds and Elrick, 2002). Method involves the measurement of speed of water movement in a saturated soil column. Values of SHC were re-calculated and corrected by deleting the clogged needles using MathCad software. Soil water retention characteristics were determined by using pressure plate extractor following procedure described by Dane and Hopmans (2002). The method is based on simple principle of determining the weight of water present in a fixed volume of soil at a series of defined pressure heads/tensions, to convert these weights into volume of water, and then divide by the volume of soil.

6.2.2 Model parameterization and calibration

CropSyst version 4.09.00 was used. Potential evapotranspiration was calculated with Penmann-Monteith equation. Soil water redistribution was simulated solving Richards equation with the finite difference method. Finite difference model was preferred over cascade model as finite difference is more detailed and can transport both up and down in comparison with cascade model which only shows downward movement of water. It was assumed that no run off occurs, the experimental sites being flat. Crop biomass was simulated mainly by using default crop input parameter set of CropSyst. Few selective parameters were subject to sensitivity analysis to find their optimum value to obtain a good fit of measured and simulated above ground biomass (AGB) for Sitel under non-stress conditions (it relates to irrigated site in chapter 3 and 5). These selective parameters are indicated as calibrated (C), while measured parameters used in place of default value are indicated by M and default crop input parameters from CropSyst are indicated by D. Values taken from literature and local experience are represented by L and E, respectively. Values of crop input parameters used in the present study are presented in Table 6.2.

Simulation scenarios for two different utilization systems were created separately in each year to predict the model behaviour towards the utilization system (no mulch versus mulch). Under the biomass fate option for clipping file of first harvest of each year, 95 % of the clipped biomass was left as residue on the surface to implement mulch treatment using the model. In case of no mulch treatment, model was set to remove 95 % of the accumulated AGB from the field and designate it for beneficial use

Table 6.2: Crop model parameters for lucerne

Parameter	Determination	Value	Units
Photosynthetic pathway	-	C3	-
Above ground biomass transpiration coefficient	D	5	kPa kg m^{-3}
Unstressed light to above ground biomass conversion (Radiation use efficiency)	D	3	g MJ^{-1}
Actual to potential transpiration ratio that limits leaf are growth	D	0.8	-
Actual to potential transpiration ratio that limits root growth	D	0.5	-
Optimum mean daily temperature for growth	C	15	^{0}C
Maximum water uptake	C	12	mm day^{-1}
Leaf water potential at the onset of stomatal closure	D	-1300	J kg^{-1}
Wilting leaf water potential	D	-2100	J kg^{-1}
Maximum rooting depth	M	1.5	M
Maximum expected leaf area index	M	4.5	-
Root length per unit root mass	M	30.92	km kg^{-1}
Surface root density	M	5.56	cm cm^{-3}
Curvature of root density distribution	M	0.029	-
Fraction of maximum LAI at physiological maturity	D	0.8	-
Specific leaf area	C	24	m^2 kg^{-1}
Stem/leaf partition coefficient	D	3	-
Extinction coefficient for solar radiation	D	0.5	-
Et crop coefficient at full canopy	C	0.8	-
Degree days emergence	D	100	^{0}C-days
Degree days flowering	C	800	^{0}C-days
Base temperature	L	5	^{0}C
Cutoff temperaure	L	30	^{0}C
Adjustment factor for phenological response to water stress	D	0	-

Crop parameter calibration file for irrigated Sitel from chapter 5 was used to run simulations. Data on AGB and SWC obtained from field experiment (Chapter 4) were compared with model results to study the efficacy of model. The agreement between measured and simulated values was evaluated by using different indices proposed by Loague and Green (1991). The indices included root mean squared error (RMSE), coefficient of determination (CD), modeling efficiency index (EF) and coefficient of residual mass (CRM). The CD indicates whether the model reproduces the trend of measured values or not and its minimum value is 0 and optimum is 1. The optimum value for EF is 1 and if positive, it indicates that the model is a better predictor than the average of measured values. The CRM ranges from 0-1 and its optimum value is 0 and if found positive, it indicates model under estimation. The indices were calculated using statistical software IRENE (Integrated Resources for Evaluating Numerical Estimates) (Fila et al., 2003).

6.3 Results

6.3.1 Comparison of experimental results with model results

The model does not seem to produce an effect on the accumulation of AGB under different utilization systems in both years of experimentation. Results from simulations revealed that there were no differences among treatments regarding their effect on accumulation of AGB. Based on experimental resutls, minor differences were found in AGB under different treatments of utilization system. Results on AGB under different utilization systems are compared (measured versus simulated) in each year separately and presented in figure 6.1 and 6.2.

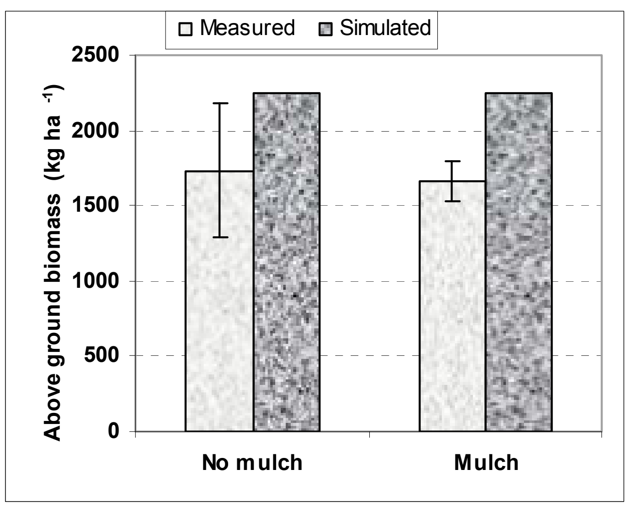


Figure 6.1: Above ground biomass under different utilization systems in 2007 (data from second harvest)

Values of AGB from second harvest under both treatments in both years were compared with simulated values to assess the efficacy of model for prediction of biomass on statistical grounds. Results revealed the EF value of 0.83, CD value of 0.36 and CRM value of -0.0184. As the EF and CD values are below the optimum value of 1, it is an indicative of inadequacy of model to accurately predict biomass accumulation under different utilization systems.

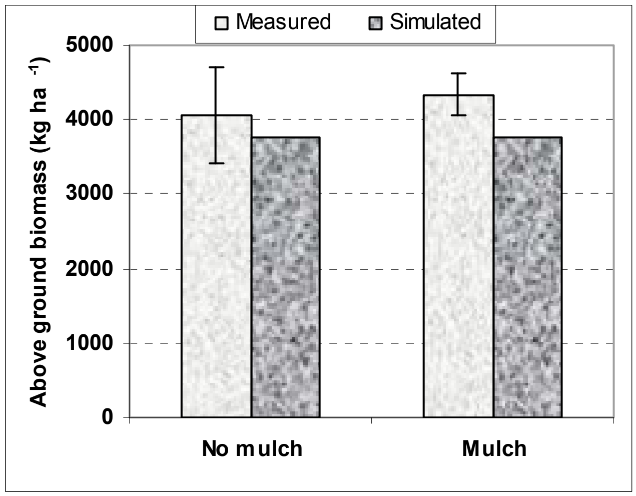


Figure 6.2: Above ground biomass under different utilization systems in 2008 (data from second harvest)

Results on profile soil water content (0-120 cm) were also compared for each treatment separately in each year and statistical indices are presented in table 6.3 and data are shown in figure 6.3. Model tends to apply the mulching treatment and it seems to conserve more moisture under mulching compared to no mulching as is evident from figure 6.3 where in both years profile SWC becomes higher following the application of treatments on July 10. The model slightly over estimated the profile soil water content as is evident from the figure 6.3. However, only in 2008 in mulch treatment, the measured values of profile SWC were found higher than simulated values and it could be due to the plot effect. A good agreement was not found among measured and simulated profile SWC that is also reflected in indices of agreement where values of EF and CD are not close to 1 (see table 6.3). This indicates the inadequacy of model to simulate soil water distribution in the profile under different utilization systems. Mulching usually had effect on retention of water in upper 10 cm soil layer. An increase in soil water content was observed in both years for simulated values of soil water content in upper 10 cm soil layer as is evidet from data shown in figure 6.4. Based on measurements of soil water content, it was difficult to clearly establish an effect of mulch on conservation of water in upper 10 cm soil layer following the application of treatments.While comparing the effects of treatement in upper 10 cm soil layer, we found that soil water content was slightly higher in mulched plots even before the application of treatements.

Table 6.3: Indices of agreement for profile soil water content

Year	Treatment	RMSE	EF	CRM	CD
2007	No mulch	39.5	0.17	-0.16	1.84
	Mulch	61.5	0.88	-0.28	2.61
2008	No mulch	45.7	0.24	-0.17	1.38
	Mulch	37.7	0.24	0.09	0.77

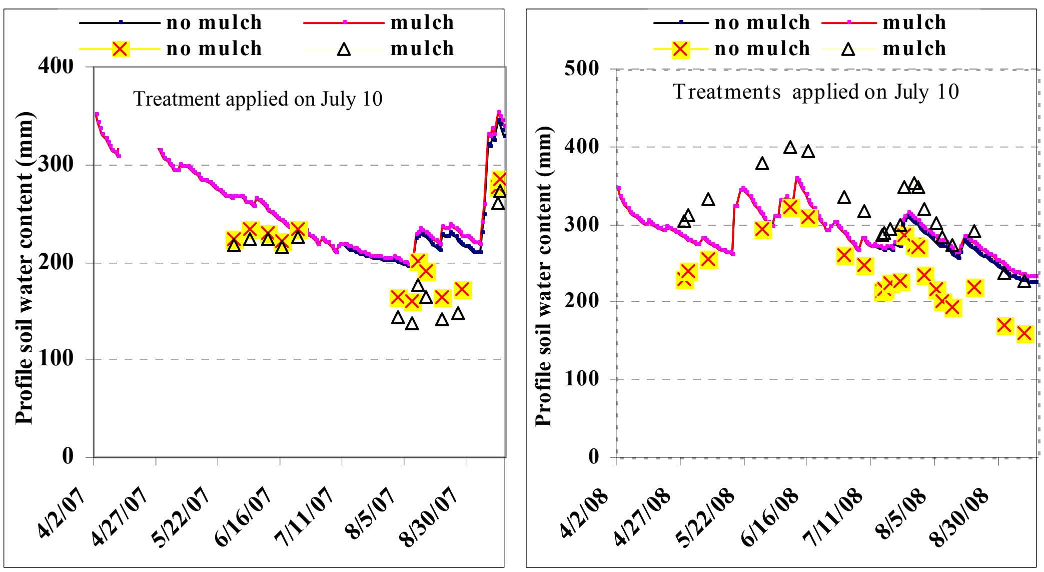


Figure 6.3: Profile soil water content (0-120 cm) under different utilization systems

6.4 Discussion

Principal effect of mulching with crop residues is to reduce soil evaporation and this effect usually takes place if residues are applied during a wet period for a longer duration of at least few months. Reduction in evaporative losses of water under mulching tends to improve soil water retention with consequences of improved plant growth and increase in overall accumulation of biomass**.** Mulch will reduce evaporation most effectively early in the drying cycle when the surface soil is wet and early in the growing season when the leaf area is small (Ji and Unger, 2001; Tao et al., 2006).

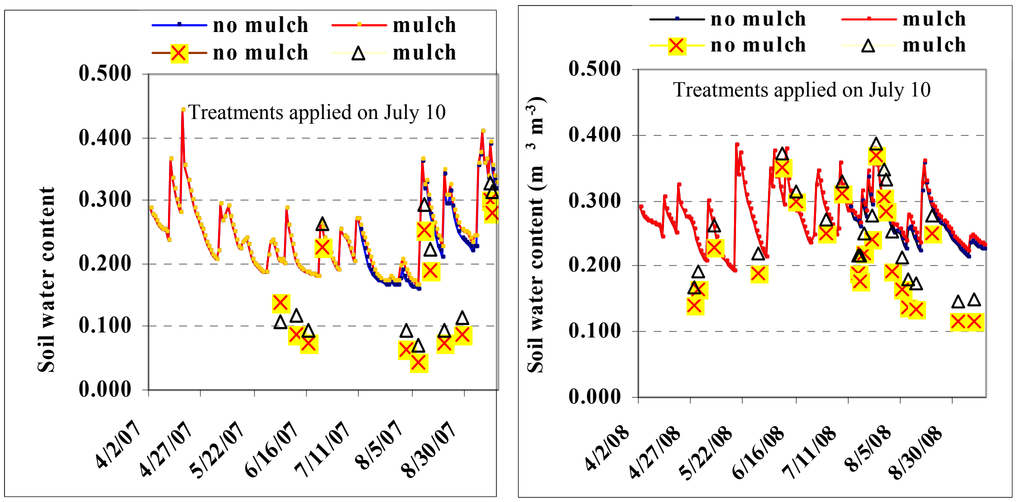


Figure 6.4: Soil water content under different utilization systems in 0-10 cm

In the present study, mulch was applied in July when soil surface was becoming drier and crop re-growth after first harvest was relatively faster. This might be the reason that smaller amounts of water are conserved under mulch treatment in the present study and these smaller amounts of water conserved at the time when soils were becoming drier under hot summer conditions were unable to bring a significant increase in AGB accumulation due to mulching under both years of experimentation.

The simulation model, CropSyst, does not seem to produce an effect on the accumulation of AGB under the scenario of different utilization systems in both years of study. This can be explained based on the behaviour of model towards estimation of profile soil water content after the application of mulch and no mulch treatmens on 10th July in each year. Ideally the model shall show an increase in profile soil water content in mulching scenario following the application of treatment, but the model does not show any major change in profile soil water content (see figure 6.3). This effect is also translated into the accumulation of biomass and model predicts the same amounts of biomass under both scenario of no mulch and mulch under both years of study (see figure 6.1 and 6.2). Results from previous studies with CropSyst indicate that effect of mulching varies among years. Donateli et al. (1997) found from a six year study in Italy that only in some years, mulching with barley residues had positive effect on yield of subsequent soybean crop due to reduced evaporation. Crop response to mulching is influenced by a complex interaction that could vary from year to year (Unger, 1978; Zhang et al., 2007b). Besides effect of year, other factors such as mulch mass, irrigation frequency, rainfall, evaporative potential and soil texture can also affect the response to mulching (Tolk et al., 1999; Ji and Unger, 2001; Lampurlanes et al., 2002; Mupangwa et al., 2007).

In the present study, the masses of mulch used were 4311 and 6253 kg ha^{-1} in 2007 and 2008, respectively. Although, these amounts are reasonable but timing of mulch application, drier soil conditions and short duration of mulching may be the probable reasons for no effect of mulch on soil water conservationa and biomass accumulation. Chen et al. (2007) compared effect of different mulch masses of chopped maize straw on the reduction of evaporation during subsequent wheat season in northern China. They found from a five year study that mulch reduced soil evaporation by 21% under less mulching (3000 kg ha^{-1}) and 40% under more mulching (6000 kg ha^{-1}) compared with control (no mulching). In India, Kar and Kumar (2007) compared the effect of number of irrigations (1-4) with and without rice straw mulch applied at the rate of 6 tones ha^{-1} on the yield of potato. Based on two years pooled data, mulch application increased the potato tuber production by 24-42% depending on the irrigation treatments. The variation in yield of potato under different number of irrigatins indicates how the effect of same mass of mulch may vary with the irrigation frequency. In the present study, one mass of mulch was applied and no additional irrigations were applied during the treatment period, so the magnitude of variation among treatments of mulch and no mulch was expected to be less.

Previous modeling studies to evaluate the effect of mulching indicate that duration of experiments usually lasts for 4-6 years on the same piece of land and residues are left over in the field either for entire duration of fallow period or subsequent growing season (Donateli et al., 1997; Zhang et al., 2007b). This enables the mulch material to settle in the field with consequences of increase in the amount of water entering the soil.The residue cover reduces non-productive water losses through evaporation and increases soil water content to enhance crop growth and yield of subsequent crop (Mupangwa et al., 2007). In the present experiment, location of experiment was changed every year that might have lead to production of no major effect on water content and yield.

The effects of residue mulching on water retention through reduced evaporation are usually smaller in drier or semi-arid environments than in wetter or humid environments. Previous long term studies using CropSyst has already demonstrated that in environments with low rainfall and coarse-textured soil, contribution of stubble to gains in water storage is often smaller than in wetter environments with heavier soil (Monzon et al., 2006). The present study was carried out in a semi-arid environment where mulch is left over the soil surface for a short duration of 2 months. This might be another reason for no big effect of mulch on soil water content and AGB accumulation.

Modeling results demonstrated that mulching tended to improve soil water content in upper 10 cm soil layer as well as slightly improved profile SWC but the amount of water conserved was not so big to bring a drastic change in AGB accumulation under two different treatments. This can be the reason for no differences in AGB accumulation under mulch and no mulch treatments. Effect of mulching with crop residues needs to be further evaluated using data from long term experiments under different locations as well as under different crops to draw reliable conclusions on the effect of mulching on retention of water in soil.

Conclusions

Conclusions drawn from different chapters of thesis are outlined below:

Root sampling methods

- Root sampling methods differed significantly ($P < 0.05$) in the estimation of lucerne root biomass. Soil monolith estimated relatively higher root biomass than soil corer during both years. ***Soil monolith can be preferred over soil corer for reliable estimation of root biomass of row crops in large field experiments only.***

Comparison of lucerne varieties under irrigated and rain-fed conditions

- Non-significant differences were observed among varieties for shoot and root dry matter yield and water use efficiency. The two sites differed significantly ($P <$ 0.05) in producing shoot dry matter yield. Cumulative shoot dry matter yield during two years of experimental period was in the range of 32.3-36.8 tones ha^{-1} and 18.3-25.2 tones ha^{-1}under irrigated and rain-fed site, respectively. Significant differences ($P < 0.05$) were observed between sites for water use efficiency of productivity at all major harvests except the final harvest in 2008. Water use efficiency of productivity at major harvests varied from 1.4-4.6 kg m^{-3} under irrigated site and 0.8-2.3 kg m^{-3} under rain-fed site.

- There exists narrow genetic variability as differences in physiological parameters such as relative water content, chlorophyll content and carbon isotope discrimination were found non-significant among the varieties and sites.

- ***Based on total yearly shoot dry matter yield and water use efficiency from comparison of three varieties at two sites, Sitel is the best variety followed by Niva and Mohajaren.***

- ***For rain-fed conditions, NS-banat, Sitel and Niva can be suitable varieties due to their relatively higher yields and water use efficiency.***

Effect of lucerne utilization system on yield and biological nitrogen fixation

- Lucerne utilization system did not significantly affect shoot dry matter yield, root dry matter yield, biological nitrogen fixation and water use efficiency while years had a significant ($P < 0.01$) effect on studied parameters. Shoot dry matter yield at second harvest varied from 0.85-0.98 tones ha^{-1} and 3.1-3.6 tones ha^{-1} in 2007 and 2008, respectively. Root dry matter yield at second harvest ranged from 5.5-6.3 tones ha^{-1} and 10.8-11.8 tones ha^{-1} in 2007 and 2008, respectively. Total biological nitrogen fixation varied from 177-191 kg ha^{-1} in 2007 and 450-517 kg ha^{-1} in 2008. Water use efficiency determined for the period between first and second harvest was 3.4-3.6 kg m^{-3} in 2007 and 7.8-8.7 kg m^{-3} in 2008.

- Mulching with lucerne was found effective in lowering the soil temperature by 1-5 ^{0}C and differences among treatments were usually found significant.

- ***Mulching does not significantly affect shoot and root dry matter yield, water use efficiency and biological nitrogen fixation.***

Modeling the impact of plant traits on yield and water balance variables

- ***Simulation model CropSyst has the potential to accurately predict the above ground biomass and soil water content under varying levels of water availability.*** Goodness of model performance is demonstrated by desirable values of statistical indices as modeling efficiency index and coefficient of determination were usually found close to 1 and coefficient of residual mass was found close to 0.

- Scenario analysis revealed that an ideotype to be developed for the Raasdorf site conditions shall have maximum rooting depth between 1.5-2m, specific leaf area between 22-24 m^2 kg^{-1} and stem/leaf partitioning coefficient of 2-3.

- While assessing the supplemental irrigation requirements for rain-fed lucerne in high and low rainfall years, it was found that the effect of supplemental irrigation is more pronounced in low rainfall years and irrigation with 40 mm of water at 20 days interval during the period from June-September can help to achieve about 6 tones ha^{-1} of additional above ground biomass.

Modeling the impact of mulching with lucerne

- ***Based on modeling results, mulc hing tends to increase soil water c ontent in upper 10 cm soil layer as well as in the profile under the present site conditions.*** This effect is not translated into biomass accumulation probably due to the smaller amounts of water conserved as well as due to the smaller duration of field experiments.

CropSyst has a limitation that it is obviously difficult to apply for perennials like lucerne especially regrowth after clippings is not adequately described in model. Model is in the continuous process of development and usually only latest versions are available for download from website of model but its user manual is not updated since 1999, it makes its use slightly difficult for beginner users.

Findings from the project provide avenues for further research:

- Can we get more reliable estimates of root yields of lucerne varieties from larger field experiments using soil monolith?

- Can mulching improve yield and water retention in large duration field experiments, if it is practiced using different lucerne varieties, different mulch masses and different levels of irrigation during peak summer months? What is the effect of lucerne mulch on yield of subsequent winter crop? Can these scenarios be addressed adequately using modeling approaches?

- Can we extend the modeling results from variety trial to other sites in Austria? How the lucerne varieties will behave in different regions of Austria? What will be the ideal combination of plant traits for hypothesizing an indeotype for other regions of Austria?

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Curriculum vitae

AMIR RAZA

Personal Profile

Father's Name	Zulfiqar Ali
Date of birth	August 10, 1976
Nationality	Pakistani
Religion	Islam
Passport No:	AV 9896651
Blood group	B+
Postal address	Room 321 , Vetmedheim apartments, Josef Baumann Gasse-8a, A-1220, Wien ,Austria, Central Europe.
Phone	00436505209435
E-mail address	amir_boku@yahoo.com

Academic record

Degree	Year	Board/University	Div/Grade	%age
M.Sc Hons (Agric)	1999	University of Arid Agriculture, Rawalpindi, Pakistan	1^{st} (A)	84.05
B.Sc Hons (Agric)	1997	University of Arid Agriculture, Rawalpindi, Pakistan	1^{st} (A)	84.55
F.Sc (Pre-Medical)	1993	BISE Islamabad, Pakistan	1^{st} (B)	62.00
Matric (Science)	1991	BISE Islamabad, Pakistan	1^{st} (A)	82.00

Professional Career:

Position held	From	To	Organization
Scientific Officer	14.05.2001	31.11.2003	Nuclear Institute of Agriculture, Tandojam, Sindh, Pakistan
Senior Scientist	01.12.2003	To date	-do-

Professional Training

Training	Sponsor	Duration	Venue
Laser Land leveling	NIA, Tandojam, Sindh Pakistan	10-11 August, 2004	Agricultural Engineering Workshop, Tandojam,Sindh, Pakistan

CropSyst Training Course	Division of Organic Farming, University of Natural Resources and Applied Life Sciences, Vienna, Austria	16-20 July, 2007	Centre for Development Research, University of Bonn, Germany

Awards/Distinctions

- Received a ***Gold-medal*** for securing 1st position in B.Sc: Hons: (Agri)
- Received ***certificate of merit*** for securing 1st position in Agronomy Department during M.Sc Hons. (Agri)
- Received ***Honorarium*** in recognition to dedicated wok for Farm management
- Received Honorarium as employee of the institute on overall better performance

Technical Assignments/experience

Project 1 : Transfer of disease resistance in bread wheat

Capacity : Associate investigator
Duration : 5 years

Assignments :

- Screening of germplasm for biotic and abiotic stresses
- Assistance in plantation and handling of wheat germplasm including breeding material, local and exotic lines and screening nurseries
- Agronomic trials for evaluation of yield and yield components and determination of fertilizer requirements in wheat
- Assistance in technical report writing on quarterly to yearly basis and preparation of technical proposal for varietal release through concerned committees at regional and national level

Achievement:

- ***Associate investigator in project that developed wheat variety SASSUI***

Project 2: Farmers participatory saline agriculture project

Capacity : Associate investigator
Duration : 1 year

Assignments:

- Assistance in preliminary surveys for site selection and soil sampling
- Assistance in setting up office at project site
- Assistance in nursery raising of salt tolerant trees species and transplantation to field sites

- Assistance in technical report writing

Project 3 : Farm management

Capacity: Farm manager/convener, farm management committee
Duration: 5 years and 7 months

Assignments:

- Efficient utilization of available farm resources for field experimentation, seed production, orchard management and income generation
- Handling of wheat seed production and processing
- Preparation of farm budgets and periodical reports on farm activities
- Procurement of farm related inputs and machinery
- Assistance in organizing field / farmers days on seasonal basis

Achievement:

- Received honorarium in recognition to dedicated work for farm management
- Improved record keeping and over came audit related issues of farm management

Project 4 : Water Relations of lucerne under organic farming conditions

Capacity : PhD student
Duration : 4 years

Assignments

- Project planning and execution
- Conduction of field experiments and collection of data on plant and soil parameters describing growth and changes in soil water content over time, respectively
- Preparation of plant samples for use in laboratory for the determination of carbon and nitrogen isotope discrimination
- Laboratory work for the determination of soil nitrate content, total carbon and nitrogen, organic matter, soil texture, bulk density, hydraulic conductivity and retention curves
- Data analysis, use of simulation model Cropsyst to describe water use of lucerne
- Report writing and presentation of results

Publications/Articles

Raza, A. (1999) Influence of L-trytophan on the growth of sunflower (M.Sc. Thesis). University of Arid Agriculture, Rawalpindi

Khanzada S.D., Rashid A., Naser M., Rattu A. R., Raza A. (2004) Effectiveness of Yellow Rust Resistance Genes in Pakistani Wheat. Proceedings of 2nd Regional Yellow Rust Conference from 22-26 March 2004, National Agriculture Research Council, Islamabad.

Raza A., Ahmed S., Mehmood T., Imtiaz M. (2005) Effect of L-Tryptophan on the growth of sunflower. Soil Environ.. 24(1):23-26.

Raza A., Rashid A., Naqvi M.H., Asif M. (2006) Water crisis and strategies for wheat production. Farming outlook. 5(3):19-22.

ArdakanI M.R., Teimuri S., Rezvani M., Fatollahi H., Khorasani A., Rejali F., Raza A., Zafarian F. (2009) Evaluation of Mycorrhizae Symbiosis Efficiency with Barley through ^{32}P uptake under Soils Contaminated with Heavy Metals. Int. J. Bot. 5 (3): 236-243.

Ardakani M.R., Pietsch G., Moghaddam A., Raza A., and Friedel J. K. (2009) Response of Root Properties to Tripartite Symbiosis between lucerne, Rhizobia and Mycorrhizae under Dry Organic Farming Conditions. American J. Agric. Biol. Sci. 4 (4):266-277.

Raza A., Friedel J.K., Bodner G. (2011) Increasing water use efficiency for sustainable agriculture. Agron. Sustain. Dev. Vol. 8 (In press).

Poster Presentations

Raza A., Pietsch G., Moghaddam A., Loiskandl W., Himmelbauer M., Ardakani M. R., Friedel J. K. (2009): Root sampling and analysis in lucerne (*Medicago sativa* L.) field trial In: Institute of Hydraulics and Rural Water Management, Department of Water, Atmosphere and Environment, University of Natural Resources and Applied Life Sciences, Vienna (Hrsg.) Himmelbauer M L, Loiskandl W, (Eds.), Short Paper Abstracts, 23-7 (Short Paper on CD, SESSION 7)

Ardakani M.R., Friedel J.K., Pietsch G., Schweiger P., Moghaddam A., Raza A.. (2009) Root area index of lucerne affected by rhizobia and mycorrhiza under dry organic farming conditions In: Institute of Hydraulics and Rural Water Management, Department of Water, Atmosphere and Environment, University of Natural Resources and Applied Life Sciences, Vienna (Hrsg.) Himmelbauer M L, Loiskandl W, (Eds.), 7th ISRR Symposium 'Root Research and Applications' (RootRAP), Short Paper

Abstracts, 12-3 (Short Paper on CD, SESSION 3)

Ardakani M.R., Pietsch G., Friedel J.K., Schweiger P., Moghaddam A., Raza A. (2009) Effect of co-inoculation with rhizobia and mycorrhiza on root parameters of lucerne (*Medicago sativa* L.) under dry organic farming conditions In: Institute of Hydraulics and Rural Water Management, Department of Water, Atmosphere and Environment, University of Natural Resources and Applied Life Sciences, Vienna (Hrsg.) Himmelbauer M L, Loiskandl W, (Eds.), 7th ISRR Symposium 'Root Research and Applications' (RootRAP), Short Paper Abstracts 13-1.

Moghaddam A., Pietsch G., Raza A., Vollmann J., Friedel J.K. (2009) Root biomass of 18 alfalfa (*Medicago sativa* L.) varieties in two different environements under organic management In: Institute of Hydraulics and Rural Water Management, Department of Water, Atmosphere and Environment, University of Natural Resources and Applied Life Sciences, Vienna (Hrsg.) Himmelbauer M L, Loiskandl W, (Eds.), Short Paper Abstracts, 14-5 (Short Paper on CD, SESSION 5) PUBLIZIERTER Beitrag für wissenschaftliche Veranstaltung , 7th ISRR Symposium on Root Research and Applications (RootRAP).

Raza A., Moghaddam A., Loiskandl W., Friedel J K., Himmelbauer M., Bodner G. (2010): Root characters of lucerne (*Medicago sativa* L.) under rain-fed and irrigated conditions In: European Geosciences Union, Geophysical Research Abstracts Vol. 12, EGU2010-9608.

Participation in Seminars

Delivered seminars on ‘Biofortification, water crisis and strategies for wheat production and impact of climatic changes on crop production as a part of weekly seminar series of the institute.

Delivered seminars on ‘Evaluation of bread wheat germplasm for yield and yield components’ and farm management activities during In- House review of research on yearly basis.

Attended ‘National Seminar on ”Role of Agriculture and Forestry in Mitigating the adverse effects of climatic change’ held at University of Arid Agriculture, Rawalpindi on June 27-28, 2005

Attended Seminar on” Efficient use of water for agriculture’ held at Sindh Agriculture University, Tandojam on March 4, 2006

Attended a seminar on “Dynamic soil dampness - measurements for the determination of important key factors planting - soil water atmosphere of continuum for commercial irrigation control “held at Institute of Meterology, University of Natural Resources and Applied Life Sciences, Vienna, Austria on march 9, 2007

Annexure

Table 1: Nitrate content (kg ha^{-1}) of soils of experimental site

Variety	Depth (cm)	2007 Start of vegetation period	2007 After harvest 1	2007 After harvest 2	2007 After harvest 3	2008 Start of vegetation period	2008 After harvest 1	2008 After harvest 2	2008 After harvest 3
Gross-Enzersdorf									
Niva	0-30	31±30†	25±8	22±26	6±1	6±3	5±4	7±1	8±1
	30-60	135±72	88±27	67±29	9±8	3±0	4±1	12±13	2±2
	60-90	39±31	65±6	18±16	22±14	4±5	3±0	32±42	2±2
	0-90	205±70	178±41	107±39	37±21	13±2	12±3	51±54	12±6
Mohajaren	0-30	17±15	15±10	10±6	6±1	3±0	4±5	6±6	9±0
	30-60	26±25	124±10	14±11	3±2	3±1	5±3	4±0	2±3
	60-90	57±35	55±8	12±3	4±2	7±2	3±0	1±1	1±1
	0-90	100±75	194±9	36±15	13±1	13±3	12±8	11±5	12±2
Sitel	0-30	7±0	11±1	1±1	6±2	6±1	4±2	5±2	4±5
	30-60	47±42	61±15	82±96	2±1	4±3	4±0	2±0	1±1
	60-90	88±10	53±24	59±28	9±11	3±2	4±2	2±1	2±3
	0-90	142±51	125±38	142±124	17±10	13±3	12±0	9±3	7±6
Raasdorf									
Niva	0-30	3±2	11±3	8±2	5±1	2±0	17±3	10±1	6±2
	30-60	0±0	2±3	15±18	4±3	2±0	4±3	5±4	4±6
	60-90	21±11	7±3	1±0	15±18	3±0	6±3	4±2	6±7
	0-90	24±9	20±3	24±19	24±20	7±0	27±4	19±4	16±1
Mohajaren	0-30	1±0	17±3	8±1	6±0	3±1	11±9	6±3	0±0
	30-60	1±2	17±21	12±15	6±4	4±5	3±1	3±2	8±1
	60-90	6±7	7±2	3±1	6±4	0±0	3±2	3±0	8±4
	0-90	8±8	41±22	23±17	18±0	7±7	17±8	12±5	16±4
Sitel	0-30	3±2	4±6	13±9	3±2	4±4	21±4	15±6	7±9
	30-60	0±0	3±2	3±1	4±5	1±0	5±0	2±2	8±2
	60-90	2±1	6±2	2±2	6±1	0±0	3±3	1±2	3±4
	0-90	5±1	13±6	18±6	13±4	5±4	29±7	18±2	18±11

† mean ± standard deviation

Table 2: Nitrate content (kg ha^{-1}) of soil in Raasdorf (data from three additional varieties)

Variety	Depth (cm)	2007 Start of vegetation period	2007 After harvest 1	2007 After harvest 2	2007 After harvest 3	2008 Start of vegetation period	2008 After harvest 1	2008 After harvest 2	2008 After harvest 3
Vlasta	0-30	7±0†	7±10	10±3	9±0	3±2	21±2	13±7	7±2
	30-60	0±0	2±1	1±0	2±2	1±1	4±1	4±1	9±1
	60-90	2±1	10±5	1±1	4±4	1±0	4±0	3±0	3±3
	0-90	9±1	19±4	12±4	15±6	5±1	29±3	20±8	19±0
Ordobad	0-30	6±3	13±1	7±2	4±1	4±0	18±5	13±6	10±13
	30-60	0±0	3±0	2±0	2±1	1±1	6±6	3±1	7±2
	60-90	1±1	7±1	1±1	2±3	10±13	14±16	1±2	5±1
	0-90	7±4	20±1	10±0	8±4	15±14	38±17	17±3	22±11
NS-banat	0-30	6±1	19±12	21±11	10±1	5±2	10±7	11±3	9±3
	30-60	6±9	10±7	25±30	6±1	2±1	7±7	3±1	9±4
	60-90	28±39	13±7	4±5	11±9	1±1	3±3	4±1	11±4
	0-90	40±49	42±39	50±55	27±19	8±1	20±17	18±3	29±5

† mean ± standard deviation

Table 3: Performance of Niva under irrigated and rain fed conditions

Location (Year)	Harvest	Shoot dry matter yield (tones ha^{-1})	Shoot height (cm)	Shoot number m^{-2}	Leaf area index	Leaf to Stem ratio	Relative water content (%)	Chlorophyll content (mg m^{-2} leaves)
Irrigated (2007)	**1**	5.87±1.08†	96±2.8	880±22	4.7±0.22	0.49±0.12	79±3	705±41
	2	5.43±0.7	67±2.8	912±68	3.7±0.67	0.87±0.03	71±7	747±29.7
	3	3.58±0.41	50±0	528±28	3.9±0.17	1.18±0.04	-	-
	Yearly average	14.88±1.36§	71±1.9	773±53	4.1±0.2	0.93±0.11	75±5	714±42.8
Rain fed (2007)	**1**	4.28±0.08	71±0.71	992±45	2.6±0.44	0.77±0.16	64±10	654.5 ±30.4
	2	2.8±0.97	34±2.1	624±22	0.74±0.29	1.35±0.03	76±5	741±41.7
	3	1.56±0.56	40±2.8	672±45	2.09±0.44	0.96±0.08	-	-
	Yearly average	8.64±1.47§	49±1.4	762±7	1.8±0.09	1.02±0.08	76±6	680±7.5
Irrigated (2008)	**1**	8.31±0.93	115±7	960±0	4.3±0.2	0.62±0.03	-	688±31
	2	5.77±1.34	107±3.5	1472±45	4.2±0.47	0.55±0.04	-	680±32
	3	3.3±0.6	81±1.4	-	4.3±0.18	-	90.7±6	619±17
	Yearly average	17.4±2.8§	101±4	1280±3.8	4.2±0.16	0.65±0.02	90.7±6	662±5.9
Rain fed (2008)	**1**	7±0.09	106±1.4	784±113	3.7±0.37	0.56±0.08	-	666±47
	2	5.16±0.42	88±2.1	1152±181	4.1±0.03	0.77±0.06	-	695±64
	3	1.68±0.16	55±0.7	-	1.9±0.5	-	92.5±0.78	561±55
	Yearly average	13.85±0.15§	83±0.49	968±147	3.3±0.07	0.67±0.01	-	641±12.9

§ Values represent total yearly shoot dry matter yield instead of average of 3 cuts
† mean ± standard deviation

Table 4: Performance of Mohajaren under irrigated and rain fed conditions

Location (Year)	Harvest	Shoot dry matter yield (tones ha^{-1})	Shoot height (cm)	Shoot number m^{-2}	Leaf area index	Leaf to Stem ratio	Relative water content (%)	Chlorophyll content (mg m^{-2} leaves)
Irrigated (2007)	**1**	8.86±0.19†	104±2.8	1152±45	4.9±0.72	0.35±0.007	80±0.84	694.5±37.3
	2	5.78±0.46	67±0.7	1392±68	4.3±0.45	0.57±0.014	75±2.5	734±82
	3	4±1.2	64±4.9	640±45	4.5±0.33	0.85±0.07	-	-
	Yearly average	18.6±1.88§	79±0.43	1061±53	4.6±0.02	0.59±0.03	77.6±0.85	721±51.6
Rain fed (2007)	**1**	3.67±0.28	62±8.5	897±45	2.6±0.53	0.55±0.14	72.6±2.4	680±53.7
	2	2.23±0.43	35±6.4	736±90	0.51±0.08	1.39±0.03	83±1.8	752±73.5
	3	1.49±0.38	41±1.4	944±22	1.3±0.16	1.03±0.16	-	-
	Yearly average	7.38±0.22§	46±1.27	859±38	1.5±0.19	0.98±0.09	82±0.87	671±3.9
Irrigated (2008)	**1**	8.39±0.78	117±17.7	1120±90	4.3±0.87	0.46±0.03	-	695±32
	2	4.9±0.09	101±4.9	1456±107	4.4±0.89	0.53±0.05	-	675±34
	3	3.7±0.15	78±2.1	-	4.1±0.17	-	90.5±5.6	611±1.4
	Yearly average	17±0.54§	99.2±4.9	1306±92	4.3±0.04	0.54±0.04	-	660±21.5
Rain fed (2008)	**1**	5.92±1.24	101±1.4	1008±23	3.5±0.26	0.65±0.02	-	647±81
	2	2.87±0.08	74±1.4	1408±68	3.3±0.03	0.75±0.14	-	710±61
	3	2.14±0.3	52±4.2	-	1.8±0.74	-	91±1.3	657±37
	Yearly average	10.9±1.6§	75.6±0.5	1208±45	2.8±0.33	0.7±0.08	-	672±19

§ Values represent total yearly shoot dry matter yield instead of average of 3 cuts
† mean ± standard deviation

Table 5: Performance of Sitel under irrigated and rain fed conditions

Location (Year)	Harvest	Shoot dry matter yield (tones ha^{-1})	Shoot height (cm)	Shoot number m^{-2}	Leaf area index	Leaf to Stem ratio	Relative water content (%)	Chlorophyll content (mg m^{-2} leaves)
Irrigated (2007)	**1**	7.69±0.69†	101±10.6	784±22	4.3±1.3	0.48±0.06	75.9±2.3	758.5±61.5
	2	5.55±0.31	63±4.9	1040±68	3.7±0.4	0.87±0.17	77.7±10.6	682±31.8
	3	4.94±0.07	61±1.4	1072±68	4.1±0.1	1.15±0.02	-	-
	Yearly average	18.17±1.07§	75±2.4	965±53	4.4±0.05	0.83±0.03	76.8±4.1	720±14.8
Rain fed (2007)	**1**	5.66±0.02	71±2.2	784±22	3.2±0.18	0.82±0.12	71.5±7.6	786.5±43.1
	2	3.58±0.33	39±1.4	832±45	0.77±0.26	1.3±0.02	78±2.89	742±53
	3	1.93±0.33	45±2.8	704±90	1.6±0.55	0.99±0.15	-	-
	Yearly average	11.17±0.63§	52±0.22	773±53	1.8±0.21	1.03±0.007	78.6±2.3	730±29
Irrigated (2008)	**1**	8.66±0.37	112±10.6	1072±204	4.4±1	0.71±0.11	-	700±0
	2	5.6±0.22	100±4	1264±197	4.4±0.89	0.58±0.02	-	635±49
	3	4.38±0.27	80±0.7	-	4.7±0.29	-	89.6±3.8	686±33
	Yearly average	18.64±0.41§	97.6±1.9	1045±149	4.5±0.55	0.71±0.007	-	667±5.4
Rain fed (2008)	**1**	6.23±0.59	109±0.7	896±85	5.4±0.18	0.66±0.02	-	690±28
	2	6.1±0	68±0	1280±0	3.5±0	0.98±0	-	747±0
	3	1.7±0.23	56±5.6	-	1.9±0.89	-	92.9±1	684±25
	Yearly average	13.59±1§	81.1±6.8	1136±110	3.6±0.14	0.79±0.03	-	705±3.8

§ Values represent total yearly shoot dry matter yield instead of average of 3 cuts
† mean ± standard deviation

Table 6: Performance of three additional varieties under rain fed conditions

Variety (Year)	Harvest	Shoot dry matter yield (tones ha^{-1})	Shoot height (cm)	Shoot number m^{-2}	Leaf area index	Leaf to Stem ratio	Relative water content (%)	Chlorophyll content (mg m^{-2} leaves)
Vlasta (2007)	**1**	5.32±0.24†	70±1.4	544±90.5	2.6±0.2	0.68±0.1	73±0.55	724±12.7
	2	3.29±0.01	38±2.8	768±0	0.66±0.05	1.3±0.1	77±1.6	675±3.5
	3	1.78±0.03	46±2.8	912±67.9	2.3±0.5	1.14±0.15	87..9±3.3	681±20.5
	Yearly average	10.39±0.24§	51±1.4	741±52.8	1.8±0.1	1.04±0.13	79±0.37	693±12.2
Vlasta (2008)	**1**	5.86±0.07	106±5.6	1136±158	4.5±0.28	0.45±0.1	88±1.6	678±17.67
	2	4.64±0.36	89±1.4	1392±67.8	3.9±0.64	0.79±0.04	83±3	696±72.8
	3	1.98±0.15	56±2.1	-	2.4±0.01	-	93±0.07	564±46
	Yearly average	12.49±0.14§	83.8±1.6	1264±113	3.6±0.12	0.62±0.03	88±1.5	646±14.8
Ordobad (2007)	**1**	2.54±0.28	57±2.1	704±90.5	2.6±0.2	0.58±0.08	61±5.1	609±8.5
	2	1.73±0.12	26.5±2.1	496±67.8	0.5±0.007	1.2±0.1	76±2	775±48.7
	3	1.62±0.38	40±7	800±0	1.69±0.07	0.92±0.1	92±3.3	620±27.5
	Yearly average	5.9±0.79§	41±0.85	667±7.5	1.6±0.05	0.92±0.03	76.7±0.07	668±9.9
Ordobad (2008)	**1**	5.21±0.59	105±2.8	784±113	4.1±0.55	0.47±0.09	83±1.4	690±0
	2	3.94±0.57	77±0	976±113	3±0.18	0.81±0.04	83±3	729±12
	3	1.66±0.02	-	47±7	1.4±0	-	90±6.7	577±6.3
	Yearly average	10.82±0.01§	76±3.3	880±0	2.8±0.24	0.64±0.07	85.7±3.7	665±1.9
NS-banat (2007)	**1**	3.47±0.06	66±5.6	912±67.8	2.6±0.6	0.9±0.01	70±1.8	668±32.5
	2	2.38±0.48	32.5±3.5	592±22.6	0.64±0.16	1.2±0.1	78±5.2	814±33.9
	3	1.88±0.72	43±2.1	736±45.2	2.1±0.34	0.96±0.007	90±1.8	639±33.9
	Yearly average	7.73±0.39§	47±0	747±45.2	1.78±0.03	1.03±0.03	79±2.9	707±33.5
NS-banat (2008)	**1**	6.6±0.07	108±0	960±79	4.5±0.93	0.59±0.04	84±2.6	637±41
	2	5.74±0.32	80±0.71	1376±90.5	3.5±0.28	0.78±0.02	85±0.68	722±2.8
	3	1.9±0.36	57±0.7	-	1.5±0.32	-	90±0.28	568±0
	Yearly average	14.31±0.04§	82±0	1168±84.8	3.1±0.32	0.69±0	86±0.75	642±14.6

§Values represent total yearly shoot dry matter yield instead of average of 3 cuts
† mean ± standard deviation

Table 7: CID (‰) values of varieties under rain-fed and irrigated conditions

Year	Harvest	Irrigated			Rain-fed		
		Niva	Mohajaren	Sitel	Niva	Mohajaren	Sitel
2007	**1**	21.4±0.46†	22.3±0.07	22.3±0	20.5±0.42	20.7±0.07	20.8±0.63
	2	21.7±0.07	22.4±0.14	21.9±0.21	19.8±0.77	20.2±0.49	20.2±0.42
	3	23.1±0.14	23.3±0	23.5±0.07	21.5±0	21.3±0	21.5±0.07
2008	**1**	21.5±0.84	21.8±0.07	22.1±0.28	22±0	21.7±0.7	22±0.35
	2	22.9±0.21	22.9±0	23.3±0.07	22.9±0.14	22.5±0.56	22.5±0
	3	23±0.14	22.9±0.21	23±0.14	22.4±0.28	22.2±0.14	22.4±0.42

† mean ± standard deviation

Table 8: CID (‰) values of three additional varieties in the rain-fed site at different harvests

Variety/Harvest	2007			2008		
	1	**2**	**3**	**1**	**2**	**3**
Vlasta	20.8±0.21†	19.7±0.49	22±0.7	21.8±0.07	23.1±0.07	23.2±0.14
Ordobad	20.1±0.14	20.5±0.9	21.2±0.56	22±0.07	22.8±0.28	22.1±0.14
NS-banat	20.8±0.42	20.2±0.07	21.4±0.14	21.6±0.35	22.5±0.56	22.1±0.21

† mean ± standard deviation

Table 9: CID (‰) values based on different plant parts under rain-fed and irrigated conditions

Year	Plant part	Irrigated			Rain fed		
		Niva	Mohajaren	Sitel	Niva	Mohajaren	Sitel
2007	**Shoot**	23.1±0.14†	23.3±0	23.5±0.07	21.5±0	21.3±0	21.5±0.07
	Stubble	21.4±0.21	21.4±0.49	21.6±0.7	19.7±0.77	20.5±0.21	20.4±0.56
	Root	21.3±0.35	21.8±0.2	21.6±0.4	19.7±0.14	19.7±0.7	19.9±0.28
2008	**Shoot**	23±0.14	22.9±0.21	23±0.14	22.4±0.28	22.2±0.14	22.4±0.42
	Stubble	22.5±0.14	23.1±0.28	22.6±0.07	21.9±0.35	21.9±0.35	22.3±0.21
	Root	21.3±0.42	21.6±0	21.5±0.29	20.2±0.35	20.5±0.49	20.8±0.6

† mean ± standard deviation

Table 10: CID (‰) values of different plant parts of three additional varieties in the rain-fed site

Variety/Harvest	2007			2008		
	Shoot	Stubble	Root	Shoot	Stubble	Root
Vlasta	22±0.7†	20.3±0.56	20.1±0.28	23.2±0.14	22.7±0.35	20.8±0.4
Ordobad	21.2±0.56	19.3±0.56	19.7±0.07	22.1±0.14	21.7±0.42	20.3±0.35
NS-banat	21.4±0.14	20.4±0.42	19.9±0.14	22.1±0.21	22.3±0.28	20.8±0.21

† mean ± standard deviation

Table 11: Root biomass (kg ha^{-1}) of lucerne varieties under rain fed and irrigated conditions

Variety	Year	Harvest	Irrigated			Rain fed		
			0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm
Niva	**2007**	**I**	819±19.79†	325±240.4	179±140.7	679±233	530±108.8	393±67.8
		3	4638±1164.6	779±141	693±54.4	2330±38.8	459±263	506±5.6
	2008	**1**	6804±604	890±378	818±198	5806±1611	1714±118	1110±320
		3	7162±1187	1090±455	-	10630±343	506±133	-
Mohajaren	**2007**	**I**	499±38.8	303±79	295±21	1425±930	1217±41	1028±321
		3	3362±4632	988±1258	835±91	2018±1461	385±177	2021±1535
	2008	**1**	6478±3086	2074±605	1445±602	6632±5253	1603±165	669±156
		3	6483±1430	2398±1207	-	8315±136	2786±2571	-
Sitel	**2007**	**I**	1347±1342	212±70	200±13.4	365±45	331±19	409±6
		3	3969±314	1112±786	915±152	1622±1572	476±72	443±120
	2008	**1**	6128±642	1923±2426	1110±876	7493±4305	749±298	630±67
		3	13652±1079	2488±11	-	7676±642	982±492	-

† mean ± standard deviation

Table 12: Root biomass (kg ha^{-1}) of three additional varieties in rain-fed site

Year/ Harvest	Vlasta			Ordobad			NS-banat		
	0-30 cm	30-60cm	60-90cm	0-30 cm	30-60cm	60-90cm	0-30 cm	30-60cm	60-90cm
2007/1	1477±122†	339±160	516±225	1251±48	597±171	555±101	305±251	267±206	202±37
2007/3	6167±2232	646±27	502±218	3368±748	727±227	450±15	4822±1538	1104±280	623±4
2008/1	6499±3755	889±164	1125±227	5894±86	1540±314	1271±22	9834±3411	1777±95	1645±1482
2008/3	7740±570	1040±97	-	15775±971	934±348	-	12685±1540	1807±449	-

† mean ± standard deviation

Table 13: Maximum rootng depth (cm) of Lucerene varieties

Variety	Rain fed	Irrigated
Niva	115±21†	130±28
Mohajaren	110±0	190±14
Sitel	145±63	150±14
NS-banat	115±7	-
Ordobad	110±0	-
Vlasta	100±14	-

† mean ± standard deviation

Table 14: Root parameters of lucerne varieties under rain fed and irrigated conditions in 2007

Variety	Parameter	Irrigated			Rain fed		
		0-30 cm	**30-60 cm**	**60-90 cm**	**0-30 cm**	**30-60 cm**	**60-90 cm**
Niva	**Root length density (cm cm^{-3})**	0.65±0.014†	0.44±0.21	1.22±0.19	0.8±0.01	1±0.16	1.6±0.1
	Surface area (cm^2)	82±3.5	20±11	35±4	72±2	38±3.5	38±1.4
	Average diameter (mm)	0.59±0.04	0.31±0.02	0.28±0.04	0.48±0.05	0.27±0.01	0.29±0
	Root volume (cm^3)	2.6±0.02	0.16±0.09	0.21±0.05	1.77±0.007	0.29±0.028	0.39±0.15
Mohajaren	**Root length density (cm cm^{-3})**	0.37±0.03	0.50±0.18	1.09±0.17	0.54±0.13	1±0.28	1.5±0.05
	Surface area (cm^2)	53±0.7	15±2.8	26±4	42±4.2	35±4.2	45±0.7
	Average diameter (mm)	0.33±0.12	0.27±0.02	0.27±0	0.41±0.07	0.25±0.02	0.34±0
	Root volume (cm^3)	2.3±0.31	0.1±0.03	0.18±0.02	1.29±0.29	0.38±0.12	0.67±0.39
Sitel	**Root length density (cm cm^{-3})**	0.55±0.21	0.41±0.02	0.78±0.12	0.66±0.18	1±0.33	1.3±0
	Surface area (cm^2)	51±0.7	17±1.4	19±3.5	45±6.3	38±14.1	31±0.7
	Average diameter (mm)	0.34±0.01	0.29±0.01	0.28±0	0.45±0.007	0.27±0.007	0.27±0.01
	Root volume (cm^3)	1.37±0.74	0.13±0.01	0.13±0.02	1.3±0.11	0.25±0.10	0.21±0.007

† mean ± standard deviation

Table 15: Root parameters of lucerne varieties under rain fed and irrigated conditions in 2008

Variety	Parameter	0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm	50-60 cm
		Irrigated					
Niva	**Root length density (cm cm^{-3})**	4.7±1.7†	2.5±0.35	2.3±0.28	2.4±0.6	2.1±0.2	2.7±2.2
	Surface area (cm^2)	347±80	186±21	148±2.8	154±45.2	130±1.4	146±102
	Average diameter (mm)	0.3±0.014	0.29±0.05	0.26±0.02	0.26±0.01	0.25±0.02	0.25±0.04
	Root volume (cm^3)	5.9±0.9	3±1.4	1.4±0.27	1.3±0.77	0.9±0.2	0.9±0.26
Mohajaren	**Root length density (cm cm^{-3})**	4.9±2.6	2.7±0.2	2.25±1	1.8±0.49	1.9±0.14	1.7±0
	Surface area (cm^2)	322±80.6	173±48.7	122±46.6	114±21	128±3.5	108±9.1
	Average diameter (mm)	0.27±0.07	0.25±0.04	0.24±0.05	0.25±0.02	0.27±0.03	0.27±0.03
	Root volume (cm^3)	6.8±0.8	1.8±1.2	0.7±0.2	1±0.5	1.5±0.6	0.7±0.1
Sitel	**Root length density (cm cm^{-3})**	4.8±0	2±0.14	2.5±0.14	2.4±0.21	1.4±0	0.95±0.07
	Surface area (cm^2)	377±6.3	171±31.8	158±12.7	144±33.9	89±8.4	56±0.7
	Average diameter (mm)	0.33±0.007	0.35±0.07	0.26±0.02	0.24±0.03	0.26±0.02	0.24±0.02
	Root volume (cm^3)	12.6±0.57	5.1±3.2	1.8±1	1.3±0.9	0.78±0.36	0.35±0.02
				Rain fed			
Niva	**Root length density (cm cm^{-3})**	4.3±0.8	3.3±0.4	3.3±1.7	2.3±0.56	2.4±0.35	1.7±0.49
	Surface area (cm^2)	320±29	272±60	238±140	156±71.4	161±70	125±52.3
	Average diameter (mm)	0.34±0.09	0.34±0.02	0.29±0.01	0.28±0.04	0.27±0.08	0.28±0.06
	Root volume (cm^3)	4.9±1.9	2.8±1.4	1.9±0.9	1.1±0.7	1.1±0.7	0.9±0.4

Mohajaren	**Root length density (cm cm^{-3})**	7.1±3	3.4±0.9	3±1.6	3±0.8	4.4±0.77	4.9±1.4
	Surface area (cm^2)	459±138.6	202±43.8	155±81.3	182±21.2	236±31.4	263±47.3
	Average diameter (mm)	0.3±0.07	0.25±0.02	0.21±0	0.26±0.05	0.22±0.02	0.22±0.02
	Root volume (cm^3)	6.1±0.49	1.7±0.6	0.8±0.35	1.2±0	1.3±0.5	1.5±0.14
Sitel	**Root length density (cm cm^{-3})**	5.2±1.1	3.9±0.07	2.5±1.2	2.2±0.35	1.6±1.4	3.5±1.34
	Surface area (cm^2)	427±113.8	300±24	195±73.5	171±26.1	119±101.8	253±89.8
	Average diameter (mm)	0.28±0.09	0.3±0.02	0.32±0.028	0.32±0.007	0.49±0.26	0.3±0.014
	Root volume (cm^3)	6.7±3.1	3±1.2	1.7±0.07	1.45±0.07	1.05±0.6	1.9±0.5

† mean ± standard deviation

Table 16: Root parameter of three additional varieties in the rain fed site in 2007

Variety	Parameter	0-30 cm	30-60 cm	60-90 cm
Vlasta	**Root length density (cm cm^{-3})**	0.88±0.19†	1.28±0.01	1.18±0.07
	Surface area (cm^2)	63±11.3	50.5±7.7	32±4.2
	Average diameter (mm)	0.40±0.049	0.28±0.04	0.31±0.05
	Root volume (cm^3)	1.7±0.18	0.38±0.13	0.25±0.07
Ordobad	**Root length density (cm cm^{-3})**	0.85±0.05	1.1±0.49	1.3±0.1
	Surface area (cm^2)	74.5±6.3	38.5±19	35.5±6.3
	Average diameter (mm)	0.43±0.007	0.26±0.007	0.27±0.007
	Root volume (cm^3)	1.6±0.03	0.24±0.14	0.35±0.2
NS-banat	**Root length density (cm cm^{-3})**	0.55±0.04	0.7±0.3	1.3±0.14
	Surface area (cm^2)	31.5±0.7	28±11.3	41±7
	Average diameter (mm)	0.28±0.01	0.27±0	0.34±0.028
	Root volume (cm^3)	0.3±0.09	0.19±0.07	0.35±0.08

† mean ± standard deviation

Table 17: Root parameter of three additional varieties in the rain-fed site in 2008

Variety	Parameter	Depth (cm)					
		0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**
Vlasta	**Root length density (cm cm^{-3})**	5.1±0.5†	2.7±0.56	3.5±0.56	2.3±0.14	2.3±0.07	4.1±2.8
	Surface area (cm^2)	377±127	190±24.7	185±29.6	132±13.4	130±29.6	243±82
	Average diameter (mm)	0.29±0.1	0.32±0.13	0.23±0	0.24±0.03	0.23±0.07	0.28±0.11
	Root volume (cm^3)	5.9±5.1	1.9±0.9	1.1±0.16	1±0.27	0.85±0.48	1.7±0.2
Ordobad	**Root length density (cm cm^{-3})**	3.7±0.28	3.1±0.5	2.1±0.28	2.4±1.4	2.2±0.7	3.7±1.7
	Surface area (cm^2)	214±11.3	226±56.5	156±33.2	163±82.7	151±51.6	263±120.9
	Average diameter (mm)	0.24±0.01	0.3±0.007	0.3±0.01	0.29±0.04	0.27±0.01	0.29±0
	Root volume (cm^3)	1.6±0.38	3.3±0.6	1.4±0.6	1.1±0.45	1±0.34	2±0.6
NS-banat	**Root length density (cm cm^{-3})**	5±1.9	2.2±0.7	2.4±0.56	3±0.28	4.1±0.8	6.3±0.4
	Surface area (cm^2)	435±141	201±49.4	183±55.8	211±18.3	344±58.6	449±163
	Average diameter (mm)	0.37±0.02	0.47±0.14	0.32±0.02	0.29±0.007	0.34±0.007	0.28±0.07
	Root volume (cm^3)	7.5±0.16	3.7±0.19	1.7±0.8	1.8±0.5	3.1±0.3	3.5±2.1

† mean ± standard deviation

Table 18: Actual evapotranspiration (mm) of varieties under irrigated conditions

Year	Harvest	Niva	Mohajaren	Sitel
2007	**1**	92.4±0.8†	76.1±10.3	105±8.6
	2	467.3±45.6	443.3±20.9	495.4±4.1
	3	152.6±12.4	142.8±25.8	151.5±26.4
2008	**1**	238.9±27.8	199.3±16.8	212±34.2
	2	141.3±6.7	159.5±5	158.5±41.9
	3	210.7±10.2	225±9.8	226.2±12.4

† mean ± standard deviation

Table 19: Actual evapotranspiration (mm) of varieties under rain fed conditions

Year	Harvest	Niva	Mohajaren	Sitel	NS-banat	Ordobad	Vlasta
2007	**2**	54.9±3.5†	53.9±10.7	55.3±0.15	56.4±12.7	45.3±14.4	49.4±2.2
	3	152.2±1.4	175.9±23.2	132.1±43.5	147.7±7	146±18.2	157.6±8.1
2008	**1**	313.7±5.5	279.5±0	314±0	274.7±0	276.1±36.6	279.4±12.8
	2	241.7±36.9	249±0	268.3±0	247.1±0	264.3±19.3	263.5±51.3
	3	100.5±32.2	165.8±0	148.6±0	148.4±0	158.6±31.8	151.5±2.1

† mean ± standard deviation

Table 20: WUEp (kg m^{-3}) of varieties under irrigated and rain fed conditions

Variety	Year	Harvest	Irrigated	Rain fed
Niva	**2007**	**3**	2.6±0.14†	1.05±0.35
	2008	**1**	3.65±0.21	2.25±0.07
		2	4.25±1.34	2.15±0.21
		3	1.45±0.21	1.75±0.35
Mohajaren	**2007**	**3**	2.45±0.77	0.85±0.35
	2008	**1**	3.6±0.14	2.1±0.43
		2	3.35±0.21	1.15±0.07
		3	1.8±0	1.3±0.14
Sitel	**2007**	**3**	3.45±0.77	1.55±0.77
	2008	**1**	4.65±0.21	2±0.14
		2	3.2±0.14	2.3±0
		3	1.95±0.07	1.15±0.21

† mean ± standard deviation

Table 21: WUEp (kg m^{-3}) of varieties under rain fed conditions

Year	Harvest	Niva	Mohajaren	Sitel	NS-banat	Ordobad	Vlasta
2007	**3**	1.05±0.35†	0.85±0.35	1.55±0.77	1.3±0.56	1.1±0.42	1.15±0.07
2008	**1**	2.25±0.07	2.1±0.43	2±0.14	2.4±0	1.9±0	2.05±0.07
	2	2.15±0.21	1.15±0.07	2.3±0	2.3±0.14	1.5±0.28	1.85±0.49
	3	1.75±0.35	1.3±0.14	1.15±0.21	1.3±0.28	1.05±0.21	1.3±0.14

† mean ± standard deviation

Table 22: Nitrate content (kg ha^{-1}) of experimental site of utilization system experiment

Depth (cm)/ Treatment	Pre-sowing		Harvest 1		Harvest 2	
	Harvest	Mulch	Harvest	Mulch	Harvest	Mulch
			2007			
0-30	24±10†	20±9	5±4	6±6	12±7	7±3
30-60	54±23	41±6	4±6	7±8	5±6	3±3
60-90	13±7	10±8	0±1	0±0	3±3	2±2
0-90	91±32	71±15	9±18	13±12	20±15	12±6
			2008			
0-30	30±11	36±21	1±1	2±2	11±4	6±5
30-60	18±13	15±14	3±5	1±1	6±8	3±2
60-90	10±7	9±7	7±8	4±5	4±2	4±2
0-90	58±26	60±36	11±12	7±5	21±10	13±8

† mean ± standard deviation

Table 23: Yield and its components in utilization system experiment (Post-mulch)

Parameter	2007		2008	
	No mulch	Mulch	No mulch	Mulch
Shoot height (cm)	18.5±2†	24.7±6.4	78±2.8	78±5.4
Shoot number (m^{-2})	693±84	720±152	581±128	506±82.6
Leaf area index	0.52±0.12	0.75±0.23	2.6±1	2.2±0.24
Chlorophyll content	493±125	458±115	585±68	642±30
Shoot dry matter yield (kg ha^{-1})	855±202	983±167	3184±522	3665±233
Root dry matter yield (kg ha^{-1}), 0-60 cm	5526±827	6370±1893	11823±2395	10830±4186
Total dry matter yield (kg ha^{-1})	7260±909	8030±1819	16095±2758	15555±4583
Total N yield (kg ha^{-1})	387±32	340±27	724±180	686±103
Nitrogen derived from air (%)	47±4	47±9	62±8	58±8
Biological nitrogen fixation (kg ha^{-1})	177±26	191±11	450±73	517±66

† mean ± standard deviation

Table 24: Effect of utilization system on soil temperature

Date	No mulch	Mulch	Remarks
10-07-2007	Application of treatments		
17-07-2007	33.7±1.7†	33.2±1.7	ns
19-07-2007	39.2±1.2	34.7±0.9	*
20-07-2007	36.7±0.5	33.5±1	*
23-07-2007	33.2±0.5	30.5±0.57	*
24-07-2007	29±0.8	27.2±0.5	*
25-07-2007	23±0.8	22.2±0.5	+
26-07-2007	35.5±0.5	29.5±1.2	*
27-07-2007	31.7±0.5	27.5±0.57	*
30-07-2007	21±0	20.7±0.5	ns
01-08-2007	26.2±0.9	20.7±2.5	*
03-08-2007	24.2±0.5	22.5±0.5	*
07-08-2007	33.7±0.5	30.5±0.5	*
08-08-2007	35±0.8	32±0.8	*
10-08-2007	21±0	21±0	ns
10-07-2008	Application of treatments		
16-07-2008	27±0.8	27±1.4	*
18-07-2008	24±0	23.2±0.5	+
24-07-2008	18±0	18±0	ns
29-07-2008	27.7±0.5	26.7±0.5	+
01-08-2008	26.2±0.5	26±0	ns
08-08-2008	21.7±0.5	21.7±0.5	ns
12-08-2008	19.5±0.5	19.7±0.5	ns

ns – non significant , * - significant at 5 % level of probability
+ - significant at 10 % level of probability
† mean ± standard deviation

Table 25: Organic Carbon Contents (%) from utilization system experiment

Year	Depth (cm)	No mulch	Mulch
2007	0-30	2.2	1.1
	30-60	1.3	0.5
	60-90	0	0
2008	0-30	1.4	1.8
	30-60	0.7	0.9
	60-90	0.1	0.1