QUANTIFYING EVAPORATION AND TRANSPIRATION IN FIELD LYSIMETERS USING THE SOIL WATER BALANCE

by

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Declaration

I declare that the thesis hereby submitted by me for the Philosophiae Doctor in Soil Science degree at the University of the Free State is my own independent work and has not been previously submitted by me to another University/Faculty. I further cede copyright of the thesis in favour of the University of the Free State.

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Date: May 2010

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Notification

All outcomes of the study are written as stand-alone publications. Therefore, a general literature review is not included since each publication contains its own specialized literature review and some repetition may occur between publications.

Abstract

The main aim of this study was to determine the transpiration efficiency coefficient (TEC) for three C_3 crops; canola, wheat and lucerne. TEC relates to the efficiency of water management in crop production. It is defined as the ratio of seed or biomass to the product of transpiration and vapour pressure deficit. Of these variables, transpiration is the most difficult to measure. Two experiments (canola, 2007 and wheat, 2007&2008) were therefore designed with the aim of partitioning evapotranspiration (ET) into its components of evaporation (E) from the soil and transpiration (T) from the plant. These experiments were based on a split plot design, with two soils (Clovelly and Bainsvlei) and two surface treatments which comprised of a bare soil for measuring ET and a 50 mm thick gravel mulch for measuring T using the lysimeter unit of the University of the Free State at Kenilworth near Bloemfontein. These components were measured regularly and E was derived by subtracting T from ET. The results showed that for canola, E was 12% of the total ET (809 mm) and for wheat E was 27% of total ET (639 mm). The percentage contribution of T to ET was high in both crops: 718 mm or 88% of total ET of canola and 489 mm or 63% of total ET of wheat. Conclusive evidence showed that crops should be managed differently with respect to their individual irrigation water demands.

The remaining three experiments were dedicated to factors influencing the TEC of crops. Specific objectives were to establish the effect of growth periods during the reproductive stage on the TEC of canola, the effect of weather on the TEC of wheat and effect of cutting periods on the TEC of lucerne. All experiments were conducted in the lysimeter unit and measurements were based on the soil water balance of both soils. TEC was expressed as grain yield (GY) or seed yield (SY), above-ground biomass (AGB) and total biomass (TB). Soils had no significant effect on TEC. However, TEC of canola was significantly affected by growth periods. For growth periods, TEC_{ABG} varied between 3.82 and 4.95 g kPa mm^{-1} and TEC_{TB} between 3.94 and 5.04 g kPa mm^{-1}. For wheat it was concluded that weather had no influence on the TEC based on AGB, but TEC based on GY was significantly lower in 2008 (TEC = 0.9 g kPa mm^{-1}) compared to 2007

(TEC = 2.3 g kPa mm^{-1}). This was caused by severe frost which occurred in the early reproductive stage. The result revealed a mean TEC_{AGB} of 4.75 g kPa mm^{-1} for the two wheat seasons. The results on lucerne suggested that cutting periods do played a significant role in the TEC_{AGB} of the crop. TEC decreased from 3.86 g kPa mm^{-1} for the first cutting period to 2.22 g kPa mm^{-1} for the sixth cutting period, with a mean TEC value of 2.84 g kPa mm^{-1} for all six cutting periods. TEC values for canola, wheat and lucerne in this study are consistent with values reported for other C_3 crops in the semi-arid environments and are therefore recommended for use in models.

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Chapter one

Introduction, motivation and objectives

1.1 Introduction

Competition for limited fresh water is becoming an increasingly important political issue among nations, segments of society, geographical regions and seemingly disparate causes, including the environment, agriculture, forestry, industry and urban development. This is especially so in arid and semi-arid parts of the world, where water is naturally lacking in supply and the growing needs of industry and urban populations are already clashing with those of agriculture. Water scarcity is reaching crisis proportions now because of skewed supply and demand.

While food surpluses and adequate agricultural production capacity are currently characteristic of many countries with developed economies, for the vast majority of countries in the developing world meeting the needs of their burgeoning populations is an ever present challenge and sometimes an insurmountable one (Borlaug, 2003). With decreasing per capita land area on a worldwide basis, land-use pressure has intensified, posing a severe challenge to management of soil and water resources (Lal, 2000). The threats to ecosystem sustainability and resilience to production intensification depend on the environment, with semi-arid areas being particularly vulnerable (Stewart and Robinson, 1997).

It is often assumed that the most limiting factor in dryland wheat cropping is water. In the absolute sense, this is true but in practice many factors limit the efficient use of water in yield production. The concept of limiting factors, discussed early in the last century by Blackman (1919) who drew on earlier German work, has been the guiding principle for agronomists and farmers in devising cropping systems. In most cases, more than one factor limits yield, and improvements have come from bringing together all the factors that are recognized as limiting in a given situation. Synergisms between the factors often operate such that the response to two factors applied together is much greater than the response to the same two factors applied individually.

In developing countries of the world, the sustained trends of increased population and decreased land availability and increased competition for limited fresh water resources lead to an inescapable conclusion so far as agriculture and food security are concerned. The burden of meeting food demand, while protecting environmentally sensitive lands from detrimental agricultural expansion, will fall increasingly on dryland and irrigation agriculture. To meet this challenge, dryland cropping systems in developed and developing countries alike must use available water as efficiently as possible for food production. Increasing the water use efficiency requires an understanding of how crop production is related to such determining factors as transpiration and evaporative demands, water capture, water retention, and crop management.

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation (E) and on the other hand from the crop by transpiration (T) is referred to as evapotranspiration (ET) (Thornthwaite, 1948). Evapotranspiration from natural surfaces continues to occupy a great deal of research effort in order to characterize the rate of water loss from soil and plant. Evaporation is a key component in the growth of plants and the impact of water deficit can be clearly seen on yield and biomass reductions. Monteith (1986) stated that the progress made to our understanding of ET in the past years has been large and that information is being practically applied today. Jensen and Middleton (1973) and others provided comprehensive reviews of the current state of ET research at that time.

Evapotranspiration is directly inferred from the residual of the soil water balance after all other terms have been measured. This method has been successfully used in a number of hydrologic scale studies where entire drainage basins have been studied. In some field studies, this method has been used to determine the soil water use by crops for periods of 7 to 10 days and beyond (Hatfield, 1988).

The soil water balance requires accurate measurement of all terms and if the estimate is to be expanded to an entire field, then a measure of the spatial variability of the measurements is necessary. Rouse and Wilson (1972) performed a detailed analysis of the errors involved in the water balance approach. They concluded that this method is acceptable at intervals of not less than 4 days if the actual ET is high and without precipitation.

Neutron probes or neutron scattering devices have become acceptable techniques for the measurement of soil water content throughout the soil profile. The neutron probe still remains a labour-intensive procedure. Sinclair and Williams (1979) discussed in detail the errors associated with using the neutron probe and Haverkamp and Vachaud (1984), after a detailed analysis, found that the major component of the total variance was the calibration.

Evaporation and transpiration occur simultaneously and there is a need to separate the two processes in order to study their effects on crop yield. Apart from the water content of the topsoil, the evaporation from soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominantly lost by evaporation from the soil, but once the crop is well developed and completely covers the soil, transpiration becomes the main process. Evaporation losses can be reduced by minimizing frequency of irrigation in the early ground-cover development period (Stegman *et al*., 1976). If the root-zone water content is near the drained upper limit at planting, the early root-zone advance takes place to soil water and a maximum delay of initial irrigation is possible. Once ground cover is complete, many crops enter their reproductive growth stages and irrigations should usually be sufficient to maintain potential transpiration rates (Stegman *et al*., 1976).

Researchers in various dry areas of the world, for example Syria (Allen *et al*., 1998), Western Australia (Yunusa *et al*., 1993) and Niger (Daamen and Simmonds, 1995) have demonstrated that evaporation from the soil surface is largely unaffected by the size of the plant canopy once the canopy is fully formed. When the plant canopy is large, and its duration is long, evaporation losses from the soil surface are often small and transpiration losses are commensurately greater. The choice of crop may also influence effective water use because of species differences in both the pattern and extent of both root and shoot growth. For example, chickpea grown at Jindiress, Syria (Brown *et al*., 1989) extracted water less rapidly than barley (Brown *et al*., 1987) because of smaller leaf area and less extensive root system, with the consequence that more water was 'wasted' through evaporation from the soil surface.

This applies also to Kenilworth near Bloemfontein where the soils for the experiments were sandy and there is a high evaporative demand. In this situation, the 'energy-limited' phase of evaporation continues only for the first few hours of daylight on the first day after irrigation, thereafter evaporation is 'water-limited'. Any differences in evaporation between treatments with different canopy sizes during the 'energy-limited' phase are compensated by faster evaporation during the middle of the day from treatments with a mulched soil surface. Therefore, the estimated value of evaporation is affected only by differences in the water input to the profile by irrigation and not by other management factors which may affect leaf area index (LAI).

Under semi-arid climatic conditions of South Africa, Bennie *et al*. (1994) noted that substantial evaporation losses could be reduced in the short term (less than 14 days after wetting), with a ground cover of 70% or more using mulch. Botha (2006) in separating the components of ET used different mulching techniques such as stone and organic mulch with 50 and 100% coverage as surface treatments against bare surface treatment. He found that the 50% stone mulch reduced evaporation as much as the 50% organic mulch treatment. Mulches reduce soil water evaporation by providing a mechanical barrier to drying forces of wind and they shield the soil from solar radiation. Mulches also buffer the connection between the water vapour in the soil and the air above (Burt *et al*., 2001). Mulching soil surface reduces evaporation and increases the amount of water stored in the soil profile (Gardner, 1959; Bennett *et al*., 1966; Mahrer *et al*., 1984). Peters and Johnson (1962) stated that a reduction of 50% in evaporation water losses was realized using plastic mulch. Many researches reported a significant increase in vegetation yield of different crops using mulch (Clarkson and Frazier, 1957; Chen and Katan, 1980). Surface-applied mulch provide several benefits to crop production through improving water, heat energy and nutrient status in soil, preventing soil from water loss, averting salinity flow to soil and controlling weeds (Bu *et al*., 2002).

Most often, transpiration is estimated from evapotranspiration measurements using: (i) subtraction of an estimated E (usually, E is assumed to be a seasonal constant from the measured seasonal ET (Hanks and Shawcroft, 1969); (ii) daily water balance simulation using empirical functions to separately calculate T from daily calculations (or measurements) of ET using measured plant parameters such as leaf area index or ground cover (Ritchie, 1972; Hanks, 1985; Howell *et al*., 1995) and (iii) measuring E and subtracting it from measurements of ET (Lascano *et al*., 1987). All of these measurement techniques yield indirect estimates of transpiration. Not only the type of crop, but also the crop development, environment and management should be considered when assessing transpiration (Unger *et al*., 2006). Water use efficiency measures the efficiency with which a particular crop can convert the water available to it during a particular growing season into yield. It is generally referred to as yield (biomass or grain) per unit of evapotranspiration or transpiration (Tanner and Sinclair, 1983).

Transpiration efficiency coefficient (TEC) is a product of transpiration efficiency (total biomass per transpiration) and the mean daytime vapour pressure deficit over the growing season (Tanner and Sinclair, 1983). Tanner and Sinclair (1983) and others have concluded that TEC is largely dependent on the photosynthesis pathway (i.e., whether the crop is a C_3 or C_4 species) and is relatively insensitive to the effects of environment and within-species genetics. The use of TEC provides a simple way of partitioning evapotranspiration into its components of evaporation and transpiration.

Water management to achieve maximum yield is frequently the most profitable scheme, particularly when water supply for a given land area is unlimited and application efficiency is relatively high. When these conditions occur, irrigation should usually be sufficient for plants to meet the day-to-day evaporative demand and irrigation (particularly in the most stress-sensitive stages of seed crops) should be at a frequency that maintains high soil water potential, particularly in the upper root zone. This latter requirement relates to studies (Hsiao, 1973; Begg and Tunner, 1976) showing that adequate cell turgor pressure must be maintained to achieve maximum rates of expansive growth. Thus, as high soil water potentials are maintained by frequent irrigation, the daily depression of leaf water potential is minimized and net photosynthesis is optimized within practical limits.

1.2 Motivation

World population projection is that it will grow from 6 billion to 8.3 billion by the year 2030 and this translates to feeding an estimated 2 billion more people by the year 2030. According to the United Nations Food and Agricultural Organization (FAO), world food production needs to increase by 60% in order to feed the growing world population. Agricultural water will play a leading role in meeting the projection by FAO, especially third world countries where water is found to be inadequate. According to FAO (2000), about 800 million people in the third world countries are chronically undernourished and therefore cannot sustain healthy active lives which results in sicknesses and early death as well as immeasurable loss of human potentials and social development around the world.

According to Hsiao and Hendersen (1985), a number of papers have been published reporting separate estimates of soil E and plant T. Before considering these data and judging their reliability, it is necessary to consider the difficulties involved in making these estimates and review the methods used for such estimations. It has been observed that 30-60% of seasonal evapotranspiration can be lost as evaporation (Perry, 1987; Siddique *et al.*, 1990). Wallace (2000) observed that 13-18% of the water resource in irrigated agriculture is used for transpiration, while 8-13% is lost through evaporation from the soil or water surface and the rest in other ways. Quantifying these losses is fundamental to understanding the influence of cropping systems on water use and eventual yield, especially where water is limiting. Rainfed crops tend to have sparser cover and therefore evaporation losses from the soil surface are higher. Evaporation losses equivalent to 30-35% of rainfall have been reported by Wallace and Batchelor (1997) under a millet crop grown at a research station in Niger. They observed from this analysis that water use as transpiration was as low as 15-30% of rain under these conditions and could be much lower in the fields. Other estimates of evaporation reported in literature (Daamen and Simmonds, 1995; Wallace *et al.*, 1995) for semi-arid conditions are 30 – 60% of the seasonal rainfall.

Evaporation of soil water can be reduced by minimizing the amount of energy reaching the soil surface under various cropping systems by stimulating a denser crop canopy. Wallace *et al.* (1990) have demonstrated the potential for using canopy shade to evaporation under *Gravillea robusta* in an agroforestry system with about 50% ground cover in Kenya. Under semi-arid climatic conditions of Southern Africa, Bennie *et al.* (1994) found that the substantial evaporation losses could be reduced in short term (>14 days after wetting) in the presence of a ground cover of 70% and more in the form of mulch.

According to Hensley and Bennie (2003), loss of water through evaporation process is known to be the largest in the semi-arid regions. The quantity of water necessary for crop production has been historically important, particularly in the arid and semi-arid regions of the world. Evaporation and transpiration has become a widely used agronomic term implying the water intake and loss by the crops (T) and soil water loss to the atmosphere (E) and their influences on crop yield.

From the above statements, it was therefore considered necessary to quantify evaporation and transpiration separately in order to have effective monitoring of these processes towards improving crop water use. Minimizing losses by evaporation and concomitantly increasing transpiration for the benefit of crops will guide researchers to make firm recommendations on how to effectively control their influences on agriculture in the semi-arid environment.

1.3 Aim and specific objectives

The general aim of the study was to partition water use of crops, normally expressed as evapotranspiration, into its components of soil water evaporation and transpiration. Based on the general aim, specific objectives were derived for selected C_3 crops (canola, wheat and lucerne):

i Evaluate the influence of soils and growth periods on transpiration efficiencies of canola under irrigation (Chapter 2).

ii Evaluate the effectiveness of gravel mulch to plastic mulch in reducing evaporation, partition evapotranspiration for canola into its components of soil water evaporation and transpiration, and establish the contribution of these components to water use efficiencies of canola under water table conditions (Chapter 3).

iii Determine the quantitative relations between water use and yield for winter wheat and the effect of weather changes on the TEC of wheat (Chapter 4).

iv Quantify the transpiration efficiency of irrigated lucerne under semi-arid conditions (Chapter 5).

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Chapter two

Influence of soils and growth periods on transpiration efficiencies of canola under irrigation.

Abstract

Much is reported on the agronomical aspects of canola (*Brassica napus* L.) but there is a distinct lack of information on the crop's transpiration and the efficiency of this process. The objective of this chapter was to evaluate the influence of soils and growth periods on the transpiration (T), transpiration efficiency (TE) and transpiration efficiency coefficient (TEC) of canola under irrigation. Thirty lysimeters (2.5 m^{-2}) were used for the study, half of them filled with a sandy soil and the other half with a sandy loam soil. The experiment was laid out as a split plot design with two soil forms and four growth periods (GP) during the reproductive stage as treatments *viz*. 84 – 98 days after planting (GP1), 98 – 112 DAP (GP2), 112 - 126 DAP (GP3) and 126 – 140 DAP (GP4). Treatments were all replicated three times. Canola was planted 14 June and harvested 2 November 2006. Irrigation was applied weekly through a surface drip system and daily through a sub irrigation system to maintain a constant water table at 1200 mm from the surface. Soil water content was measured three times a week using a neutron soil water meter. TE was calculated as total biomass per unit transpiration and ranged between 2.84 and 2.88 g m^{-2} mm^{-1}. TEC was obtained by normalizing TE to the vapour pressure deficit and resulted in values of 4.21 and 4.30 g kPa mm^{-1}. These efficiencies for canola were consistent with other C_3 crops such as sugar beet, groundnut and common bean. Both TE and TEC were significantly different between growth periods and not amongst soils. During the reproductive stage of canola its efficiency of transpiration increased to 126 DAP and declined thereafter. This phenomenon was observed when the pods developed and fills the upper part of the canopy. Future work should focus on whether physiological changes are responsible for this trend in transpiration efficiency during the reproductive growth stage of the crop.

Keywords: Transpiration efficiency; vapour pressure deficit; transpiration efficiency coefficient

2.1 Introduction

Water sources for irrigation have reached the point of full utilization in South Africa (Backeberg *et al.*, 1996), forcing managers and irrigators to re-evaluate their strategies to maintain growth in the agricultural sector. The situation demands for sound information on water use of irrigated crops, especially alternative crops which could fit into the crop rotation system. One of the crops identified by the Protein Research Trust of South Africa is canola (Seetseng, 2009). Canola is mainly planted in the coastal area of Western Cape as an alternative crop to control diseases and pests associated with mono culture wheat.

Water is frequently considered to be the main factor limiting crop production in arid and semi-arid zones. Therefore, achieving greater yield per unit irrigation is one of the most important challenges in these zones. Enhancing transpiration efficiency (TE), the dry matter produced (g) per unit water transpired (mm), may be an important means of improving canola yield (Sinclair *et al.*, 1984). Hence, it is of utmost importance to view transpiration as part of the soil-plant-atmospheric continuum (SPAC) system, wherein the water component can be expressed in terms of a soil water balance (Bennie and Hensley, 2001):

$$T = P + I - \Delta W - D - R - E \qquad (2.1)$$

Transpiration (T, mm) is the pivoting point in the balance, because it is the only productive loss. The rest of the losses, *viz*. drainage (D, mm), runoff (R, mm) and evaporation (E, mm), needs to be minimized so that transpiration can benefit directly from water gains expressed as precipitation (P, mm) and or irrigation (I, mm). The change in soil water content (ΔW, mm over profile) is a very good indicator to assess conditions in the SPAC system as it indicates the relative position between the two soil water management boundaries, *viz.* the drained upper limit of plant-available water and the lower limit of plant-available water. Maintaining soil water content between these boundaries will ensure optimum transpiration and CO_2 assimilation (van Rensburg, 1988; Bennie *et al.*, 1997).

Irrigation research trials on canola were conducted at the experimental stations of the University of Pretoria (Tesfamariam, 2004) and University of the Free State (Seetseng, 2009) in South Africa. These researchers concluded that the yield of canola grown under such conditions strongly depends on the availability of irrigation. Water use efficiencies, expressed as kg seed or biomass ha^{-1} mm^{-1} ranged between 2.4 and 3.4 in Bloemfontein (Seetseng, 2009) and between 3.62 and 5.4 in Pretoria (Tesfamariam, 2004). Nielsen (1997) reported for the semi-arid zone of north-east Colorado a water use efficiency of 7.73 kg seed ha^{-1} mm^{-1}.

Transpiration efficiency (TE) describes the coupling between whole-plant C and water exchange through stomatal action to the atmosphere (Ludlow and Muchow, 1990). TE is generally expressed as kg biomass ha^{-1} or g m^{-2} mm^{-1} transpiration or kg seed ha^{-1} mm^{-1} water transpired. Unfortunately, not much has been published on the TE of canola, therefore, TE values of 1.0 -1.22 g m^{-2} mm^{-1} are widely used in the canola industry based on field experience that the actual TE is approximately 60% of wheat, a C_3 plant (Grey and Jones, 1995). For rainfed canola at Tatura in Victoria, Australia, the TE calculated from the data of Taylor *et al*. (1991) ranged from 0.7 to 1.4 g biomass m^{-2} mm^{-1}. Musick *et al*. (1994) reported that in the southern High Plains of the USA, TE for irrigated wheat was 0.8 g biomass m^{-2} mm^{-1} compared with 0.4 g biomass m^{-2} mm^{-1} for dryland wheat. From above mentioned results, it seems that TE is not consistent as it varies from region to region.

As a further development, the concept of transpiration efficiency coefficient (TEC) was introduced with the aim that TEC would enable researchers to compare transpiration efficiencies of crops in different weather conditions. TEC is therefore expressed as the product of biomass per unit transpiration and vapour pressure deficit. In literature, TEC has been given different names such as transpiration equivalent (Azam-Ali and Squire, 2002), transpiration efficiency coefficient (e_wD) (Tanner and Sinclair, 1983; Ogindo and Walker, 2004), transpiration coefficient (Seetseng, 2009); m value (de Wit, 1958 as cited by Hanks, 1983) and β coefficient (Stewart *et al*., 1977). Apart from Hanks (1983) who used pan evaporation as a normalizing factor to derive the m value, Tanner and Sinclair (1983), Azam-Ali and Squire (2002), Ogindo and Walker (2004) and Seetseng (2009) used vapour pressure deficit to normalize TE to TEC.

A number of studies have demonstrated genetic variability for the ratio of photosynthesis to stomatal conductance within C_3 species. For example, values of 4.12 – 4.56 g biomass kPa kg^{-1} for sugar beet (Clover, 1999), 1.5 – 5.2 g biomass kPa kg^{-1} for groundnut (Matthews *et al*., 1988; Azam-Ali *et al*., 1989) and 3.02 to 3.15 g biomass kPa kg^{-1} for common beans (Ogindo and Walker, 2004) were reported. According to Seetseng (2009) canola grown under well-watered conditions gave a value of 4.5 g biomass kPa kg^{-1}. All these values were derived after normalizing TE with vapour pressure deficit (VPD). Squire (1990) reported that when crops are grown in the same environment, C_4 tropical crops typically have dry matter to transpired water ratios about twice those of C_3 species. None of the available reports on transpiration efficiency dealt with this parameter at different growth stages for canola. Most reports on transpiration efficiency are only on integrated measurements and not segmented into growth stages. It is envisaged that determining canola's efficiency of transpiration at different growth periods in the reproductive stage will enhance the understanding of its water use and requirements. This research was aimed at evaluating in the reproductive stage the influence of soils and growth periods on the transpiration, transpiration efficiency and transpiration efficiency coefficient of canola grown under irrigation in a semi-arid environment.

2.2 Materials and methods

2.2.1 Lysimeter unit

A lysimeter unit at the Field Research Facility of the Department of Soil, Crop and Climate Sciences, University of the Free State at Kenilworth near Bloemfontein (29^{o}01'00"S, 26^{o}08'50"E) was used for this study. The unit was constructed in 1999 by Ehlers *et al.* (2003) for investigating the contribution of root accessible water tables towards the irrigation requirements of crops. It covers an experimental area of 70 m x 35 m. In the center of the unit, 30 round plastic lysimeters (1.8 m diameter and 2 m deep), are buried in the soil in two parallel rows of 15 each, with their rims 50 mm above the bordering soil surface (Figure 2.1). A 100 mm layer of dolerite gravel (10 mm in diameter) was placed on the bottom of each lysimeter and covered with a plastic mesh. One row of lysimeters was filled with a soil classified as a Clovelly (form) Setlagole (family) according to Soil Classification Working Group (1991) or Quartzipsamment according to Soil Survey Staff (2003). The other row of lysimeters was filled with a soil classified as a Bainsvlei (form) Amalia (family) according to Soil Classification Working Group (1991) or Plinthustalf according to Soil Survey Staff (2003).

Each horizon of both soils was removed separately and packed in the same order into the lysimeters to reconstruct that specific soil. Particle size analysis was carried out on both soils using the pipette method of Day (1965) and the results are shown in Table 2.1. The mean silt-plus-clay content for soil depth 0 - 1800 mm were 8% for the Clovelly (Cv) soil and 18% for the Bainsvlei (Bv) soil. The textures of these soils are representative of about 60% of the irrigated land in South Africa (Barnard *et al.*, 2010).

Figure 2.1 Aboveground view of the lysimeter unit with each lysimeter in row A filled with Clovelly Setlagole soil and in row B with a Bainsvlei Amalia soil. Every lysimeter is equipped with two neutron probe access tubes.

Figure 2.2 Underground chamber of the lysimeter unit showing that each lysimeter has a manometer through which the height of the water table was regulated by recharging from a bucket.

An underground chamber (1.8 m wide, 2 m deep and 30 m long) allows access to the inner walls of the lysimeters (Figure 2.2). An opening at the bottom of each lysimeter is connected to a manometer and a bucket used for recharging and regulating the height of water table. Each lysimeter is equipped with two neutron probe access tubes with lengths of 1900 mm. Five 2500 L reservoirs were used to store irrigation water of a high quality (±20 mS m^{-1}). These reservoirs are mounted aboveground on a 1 m high stand at the eastern end of the unit. A movable shelter with a transparent roof (30 m long, 10 m wide and 4 m high) is available to cover the lysimeter unit to prevent any interference by rain.

Table 2.1 Particle size distribution of both soils for the different depths in the lysimeters (Ehlers *et al*., 2003).

Soil	Soil depth (mm)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
Clovelly	0–300	1.3	10.7	79.0	4.0	5.0
	300–600	1.4	25.6	65.0	3.0	5.0
	600–900	1.4	25.6	65.0	3.0	5.0
	900–1200	1.4	25.6	65.0	3.0	5.0
	1200–1500	1.4	25.6	65.0	3.0	5.0
	1500–1800	1.4	25.6	65.0	3.0	5.0
Bainsvlei	0–300	0.3	6.4	83.3	2.0	8.0
	300–600	0.2	4.1	77.8	4.0	14.0
	600–900	0.1	3.5	78.4	4.0	14.0
	900–1,200	0.1	5.7	76.2	4.0	14.0
	1200–1500	0.1	5.1	70.8	4.0	20.0
	1500–1800	0.2	5.2	70.7	4.0	20.0

2.2.2 Experimental layout

The experiment was laid out as a split plot design with three replications. Treatments were two soils (Cv and Bv) and four growth periods (GP) in the reproductive stage: (GP1 = 84 – 98 days after planting, GP2 = 98 – 112 DAP, GP3 = 112 – 126 DAP and GP4 = 126 – 140 DAP) based on the biomass samplings in 2006 growing season. The biomass was sampled on 98 (21 September), 112 (5 October), 126 (19 October) and 140 (2 November) DAP.

2.2.3 Agronomic practices

Before commencement of the experiment, soils in the lysimeters were leached to remove excess salts, which might have accumulated during previous experiments. Prior to planting, a 4:2:1 (28) fertilizer mixture was manually broadcast at a rate of 60 g m^{-2} after which the soil was tilled with a spade to a depth of 200 mm. Then canola (var: Outback) was planted on 6 May 2006 at a density of 75 plants m^{-2} (280 mm row width with 65 mm in-row spacing. The soil surface was covered with a 50 mm thick mulch layer of 10 mm mesh dolerite gravel during the plant establishing period. After the plant establishment stage, limestone ammonium nitrate (LAN) was applied at a rate of 41 g m^{-2}. The total fertilizer application amounted to 197 kg N ha^{-1}, 96 kg P ha^{-1} and 48 kg K ha^{-1}. Canola was also planted adjacent to the lysimeter unit using the same plant density and fertilizer rates. This canola was irrigated once a week with a sprinkler irrigation system and was used specifically for root measurements. Weeds were manually controlled with hand-hoes and pests were chemically controlled.

2.2.4 Measurements and calculations

2.2.4.1 Soil water balance components

Soil water content: Change in soil water content (ΔW) was measured three times per week at 0.3 m depth intervals down to 1.8 m using a *in situ* calibrated Campbell Pacific Neutron Water Meter (Model 503DR).

Irrigation and precipitation**:** Two methods of irrigation were applied, *viz*. surface drip and sub irrigation for water table recharge. The surface drip irrigation (IRsd) was applied manually through 25 litre containers connected to dripper lines installed at the surface of the soil. The discharge rates of the drippers were 4 litre h^{-1}and 60 drippers were equally spread at the surface of each lysimeter to enhance a uniform application and redistribution. Each lysimeter was drip irrigated on a weekly basis at fixed rates for all treatments. The sub irrigation (IRs) was based on water application through a bucket fitted above the water table to recharge water loss from it on a daily basis. Precipitation was zero because the rain shelter was used to prevent water from entering the system during incidence of rainfall.

Drainage and runoff**:** Drainage was zero as the water table was monitored and kept constant at 1.2 m from the surface. Runoff was also zero because of the lysimeter rims that prevented water spillage.

Evaporation**:** Evaporation from gravel covered lysimeters was negligible when plastic covered lysimeters served as control (see Section 3.3.1 for details).

Transpiration**:** Transpiration was calculated with Equation 2.1 taking irrigation and change in soil water content into account.

2.2.4.2 Soil water management boundaries

From an irrigation point of view, crops can experience water stress when the supply of water to the roots does not meet the demand induced by the atmosphere. Hence, water stress can be avoided by managing the allowable depletion level (ADL) of the SPAC. In the absence of *in situ* measured soil water management levels, the following approach was used to estimate ADL. ADL was defined as the soil water content at 50% between the permanent wilting point (PWP) and the drained upper limit (DUL). The PWP was calculated with the equation of van Rensburg (1996), *viz*. PWP = 0.0385 (silt % + clay %) + 0.0125, where silt-plus-clay represents the percentage of soil particles smaller than 0.05 mm. These values were 0.047 mm mm^{-1} or 85 mm for the Cv profile (1800 mm) and 0.083 mm mm^{-1} or 151 mm for the Bv profile (1800 mm). Unlike the PWP, DUL was determined *in situ* under water table conditions. It was necessary to do this because a water table was maintained at 1200 mm from the soil surface in the experiments. After saturation, the soil was allowed to drain towards the 1200 mm level. During drainage, the soil surface was covered with a white plastic sheet to prevent evaporation from the soil. The soil water content was measured as described earlier with a neutron soil water meter at 0.3 m intervals to 1.8 m depth. The mean values were 0.236 mm mm^{-1} or 425 mm for the Cv profiles and 0.260 mm mm^{-1} or 468 mm for the Bv profiles. Literature showed that when water tables are closer than 750 mm from the surface, oxygen may become the restricting factor in plant growth as it impacts negatively on the respiration process of crops (Lal and Shukla, 2004; Surya *et al*., 2006). Hence, the ADL was calculated and found to be 0.142 mm mm^{-1} or 255 mm for the Cv profile and 0.172 mm mm^{-1} or 310 mm for the Bv.

2.2.4.3 Plant components

Roots**:** Root samples were manually collected from the field adjacent to the lysimeter complex using a 1 litre core sampler towards the end of each growing period by taking 4 x 1 litre samples per 300 mm soil layer over the total rooting depth. Roots were separated from soil by hand washing with a 0.5 mm screen. Rooting density (mm mm^{-3}) was calculated by dividing the root length of each sample with the volume of a segment (mm^{-3}). Root mass was obtained by weighing it after oven drying at 65^{o}C for 48 hours. Root length was determined with a modified infrared root line interception counter as described by Rowse and Phillips (1974).

Leaves: Plants were sampled at the end of each growth period by cutting them as close to the soil surface as possible. Only a half of the lysimeter's area was used. Leaves were removed and then measured with a LICOR 3000 leaf area meter calibrated using a standard method before each leaf cutting. Leaf area was then expressed in relation to the soil surface area, i.e. the leaf area index (LAI). Due to technical problems with the leaf area meter it was not possible to measure the leaf area during the end of GP3. There were no green leaves present in any of the plots at the end of GP4 and consequently the LAI was taken as zero. In order to obtain mean LAI values for the middle of the different growth periods, the LAI were regressed against days after planting using a second order polynomial function. The coefficients are given in Table 2.2 as a note.

Biomass**:** All plant material was dried at 65^{o}C for 72 hours in a ventilated oven. The plants used for leaf area, plus the plants harvested from the other half of the lysimeter were added to obtain the above-ground biomass. The total biomass was calculated from above-ground biomass and root mass obtained from the adjacent commercial field.

2.2.4.4 Weather components

Weather data was extracted from the records of the automatic weather station located at Kenilworth research station. Calculations were done using the relationship outlined in FAO 56 (Allen *et al*., 1998) and summarized as follows:

Mean temperature: Equation 2.2 was used to calculate the mean temperature

$$t_{mean} = \frac{t_{\max} + t_{\min}}{2} \qquad (2.2)$$

Where t_{mean} is the mean temperature; t_{max}, the maximum temperature; t_{min}, the minimum temperature.

Saturation vapour pressure: Equation 2.3 was used to determine the saturation vapour pressure.

$$e_s = \frac{e^\circ(t_{\max}) + e^\circ(t_{\min})}{2} \tag{2.3}$$

Where e_s is the saturation vapour pressure; $e^o(t_{max})$, saturation vapour pressure at maximum temperature; $e^o(t_{min})$, the saturation vapour pressure at minimum temperature.

Ambient vapour pressure (e_a): This was calculated using Equation 2.4.

$$e_a = \frac{e^\circ(t_{\min})\frac{RH_{\max}}{100} + e^\circ(t_{\max})\frac{RH_{\min}}{100}}{2} \tag{2.4}$$

Where $e^o(t_{min})$ is the saturation vapour pressure at minimum temperature (kPa); RH_{max}, the maximum relative humidity (%); $e^o(t_{max})$, the saturation vapour pressure at maximum temperature (kPa); RH_{min}, the minimum relative humidity (%).

Slope of vapour pressure curve**:** The slope of vapour pressure curve (Δ) for different temperatures (t) was determined using Equation 2.5.

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27t}{t+237.3}\right)\right]}{(t+237.3)^2} \tag{2.5}$$

Vapour pressure deficit: The mean vapour pressure deficit (vpd) expressed in kPa was calculated as the difference between the period during which the crop is actively transpiring (07:00 - 17:00 – South African standard time).

Vpd = $e_{s} - e_a$ (2.6)

2.2.4.5 Calculation of transpiration efficiencies

Transpiration efficiency**:** Transpiration efficiency (g m^{-2} mm^{-1}) was calculated as above-ground biomass (AGB) or total biomass (TB) (g m^{-2}) per unit transpiration (mm) using Equation 2.7.

TE = AGB/T or TB/T (2.7)

Transpiration efficiency coefficient**:** Tanner and Sinclair (1983) stated that atmospheric water vapour pressure deficit is a better measure of atmospheric evaporative demand when relating crop growth to transpiration as represented in Equations 2.8 and 2.9.

$$Y = mT/(vpd) \quad (2.8)$$

$$m = Y/T(vpd) \quad (2.9)$$

Where Y is the yield in the form of AGB or TB (g m^{-2}); m, the crop coefficient (g kPa mm^{-1}); T, the transpiration (mm); vpd, the vapour pressure deficit (kPa).

In this study, Equations 2.8 and 2.9 were rewritten and TEC was computed using the relationship:

$$TEC = BM/T(vpd) \quad (2.10)$$

Where TEC is the transpiration efficiency coefficient (g kPa mm^{-1})**.**

2.2.5 Statistical analysis

Analysis of variance was conducted to establish significant differences amongst soils and growth period treatments using the GLM Procedure of SAS System (Local, XP_PRO) (SAS Institute Inc., 1999). Variables such as biomass, transpiration, transpiration efficiency and transpiration efficiency coefficient were statistically tested and Fisher's least significant difference (LSD) procedure for means comparison was applied (Fisher, 1935).

2.3 Results and discussion

Results on the soil water regime, i.e. irrigation application, soil water content, daily transpiration rate and cumulative transpiration during each of the four growth periods of canola are presented in Figure 2.3 for the Clovelly soil and in Figure 2.4 for the Bainsvlei soil. Means of irrigation applications, plant components and transpiration efficiencies for the main effects (soils and growth periods) are summarized in Table 2.2. analysis of variance revealed no significant interaction between soils and growth periods for any of the variables. However, there were significant differences amongst soils and also growth periods, which will be discussed in subsequent sections.

Table 2.2 Means of irrigation applications, plant components and transpiration efficiencies per soil form and growth period.

Variable	Soil form		LSD	Growth period				LSD
	Cv	Bv		GP1	GP2	GP3	GP4	
Surface drip (mm)	47.2	47.2	nd	47.2	47.2	47.2	47.2	nd
Sub irrigation (mm)	51.3	51.1	nd	44.9	52.5	58	49.4	nd
Total irrigation (mm)	98.5	98.3	nd	92.1	99.7	105.2	96.6	nd
Leaf area index[*]	nd	nd	nd	1.28	3.63	3.52	2	nd
Above ground biomass (g m^{-2})	244.9^{b}	284.8^{a}	38.1	250.8^{ab}	280.7^{ab}	297^{a}	231^{b}	53.9
Root mass (g m^{-2})	6.2	6.2	nd	8.9	5.8	5.3	4.7	nd
Total biomass (g m^{-2})	251.1^{b}	291^{a}	38.9	259.7^{ab}	286.5^{ab}	302.3^{a}	235.7^{b}	56.9
Transpiration (mm)	92.3^{a}	95.4^{a}	3.2	89.6^{c}	84.4^{d}	103.3^{a}	98.0^{b}	4.53
TE_{AGB} (g m^{-2} mm^{-1})[**]	2.66^{a}	3.02^{a}	0.42	2.81^{ab}	3.32^{a}	2.88^{ab}	2.36^{b}	0.6
TE_{TB} (g m^{-2} mm^{-1})[***]	2.72^{a}	3.05^{a}	0.48	2.90^{ab}	3.38^{a}	2.92^{ab}	2.41^{b}	0.71
Vapor pressure deficit (kPa)	1.49	1.49	nd	1.36	1.49	1.46	1.64	nd
TEC_{AGB} (g kPa mm^{-1})[**]	3.96^{a}	4.46^{a}	0.63	3.82^{b}	4.95^{a}	4.20^{ab}	3.82^{b}	0.88
TEC_{TB} (g kPa mm^{-1})[***]	4.10^{a}	4.55^{a}	0.73	3.94^{b}	5.04^{a}	4.30^{ab}	3.95^{b}	0.98

Means in any one column followed by the same letters are not significant at $P = 0.05$.
LSD = least significant difference
nd = not determined.
[*] LAI was estimated for the middle of each GP using a polynomial function: $y= -0.0045x^2 + 1.0252x - 54.752$, $r^2 = 0.89$, where x = days after planting and y = LAI.
[**] TE & TEC based on above-ground biomass (AGB).
[***] TE & TEC based on total biomass (TB).

2.3.1 Soil water regime

Several researchers showed that the transpiration efficiency of crops can be modified by environmental factors of which water stress is the most common (Richards and Thurling, 1978; Parameswaren *et al.*, 1981; Onken and Wendt, 1989; Champolivier and Merrien, 1996). Thus, it is important to assess the irrigation scheduling approach. As indicated in Figures 2.3a and 2.4a, both soils received two irrigations per growth period through surface drip (IRsd), giving a total of 47.2 mm per growth period (Table 2.2). These fixed or main irrigation events were supported by smaller sub irrigations to ensure that the crop's daily water demand was met. The amount irrigated daily this way cumulated irrespective of growth period to between 2 and 26.9 mm per week (Figure 2.3a and 2.4a). However, total sub irrigation (IRs) varied between 49 and 58 mm per growth period (Table 2.2). The total irrigation (IRsd + IRs) therefore increased from 92 mm in GP1 to 105 mm in GP3. In comparison to GP3, irrigation was lower in GP4 (96 mm) due to less IRs. The irrigation scheduling approach also resulted in very low fluctuations in soil water content from 84 to 140 DAP, *viz*. between 332 and 363 mm for the Cv soil (Figure 2.3b) and between 397 and 412 mm for the Bv (Figure 2.4b). During this period for example, the coefficient of variation (CV) for the soil water content in the saturated zone (SWCsz = 1200 - 1800 mm) was <0.7% in both soils. The variation of the soil water content in the unsaturated zone (SWCuz = 0 – 1200 mm) of both soils was slightly higher (CV <3.7%) because of the weekly surface drip irrigation.

This variation is almost negligible, which indicates that the irrigation scheduling approach was very effective in meeting the crop water demand. The mean total soil water content during the four growth periods was 346 mm for the Cv soil and 404 mm for the Bv soil which are much higher than the estimated allowable depletion of 233 and 313 mm for the two soils, respectively. Bennie *et al*. (1994) showed with several field crops on similar soils and atmospheric conditions that the crops do not experience water stress if the soil water level remains above the 50% ADL. From the results it can be deduced that it is most unlikely that the plants in both soils could have experienced water stress during the measuring period.

2.3.2 Transpiration

According to the daily transpiration rates depicted in Figures 2.3c and 2.4c, transpiration varied between 3.5 and 10 mm day^{-1}, which is typical for canola (Seetseng, 2009) and other field crops (Bennie *et al*., 1997) grown under irrigation in the area. Very interesting results with respect to the individual contribution of the saturated and unsaturated zones towards the transpiration rates from the total profile were obtained. During periods of surface irrigation, the transpiration rates from the unsaturated zone were consistently higher than that from the saturated zone and the opposite occurred in the periods without surface irrigation. This phenomenon can be attributed to the deep taproot system of canola that proliferates well over depth as indicated in Figure 2.5.

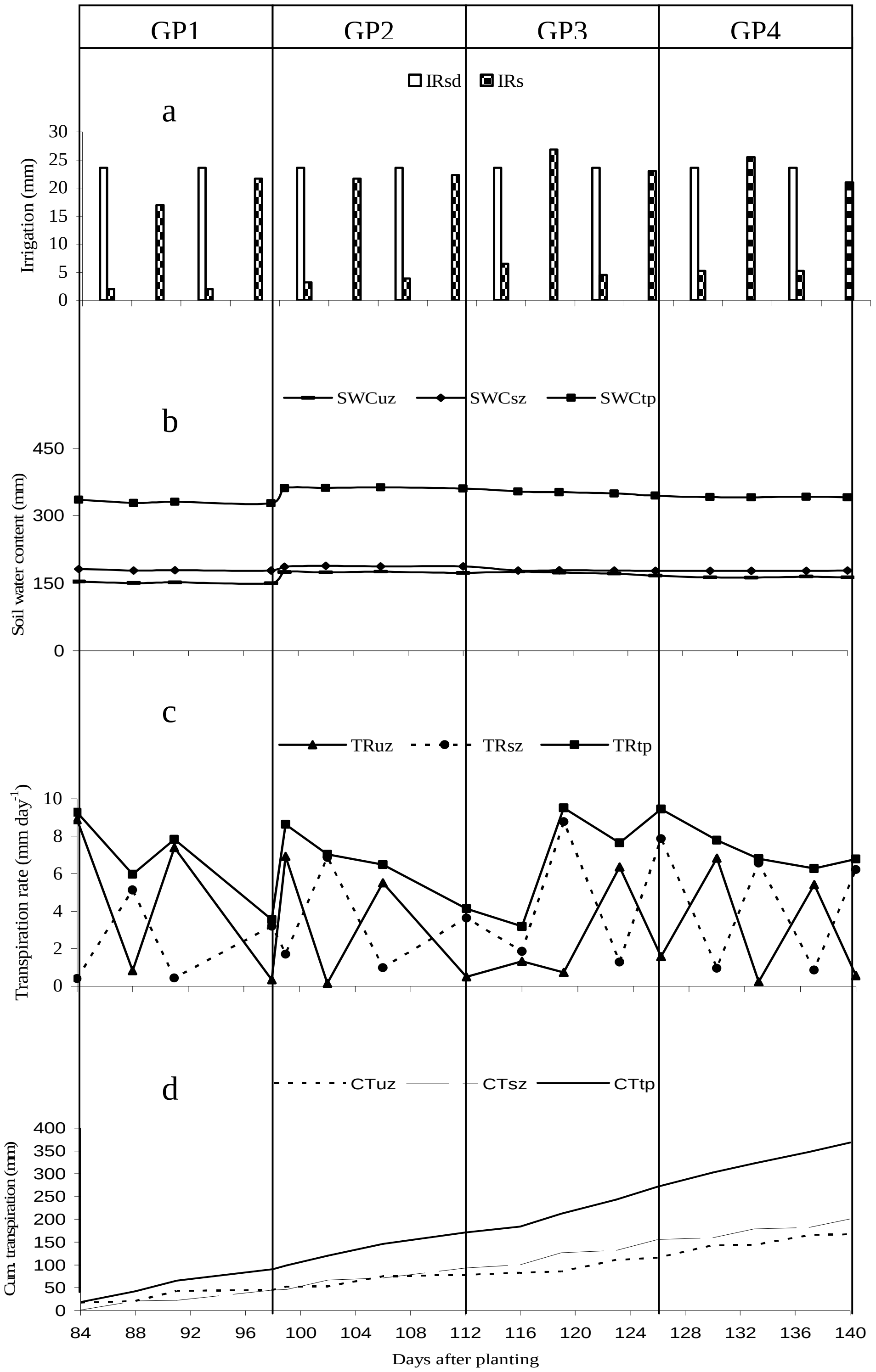

Figure 2.3 Soil water balance components during four growth periods of canola on the Clovelly soil: (a) irrigation (IR), (b) soil water content (SWC) (c) transpiration rate (TR) and (d) cumulative transpiration (CT). sd = surface drip; s = sub irrigation; uz = unsaturated zone; sz = saturated zone; tp = total profile.

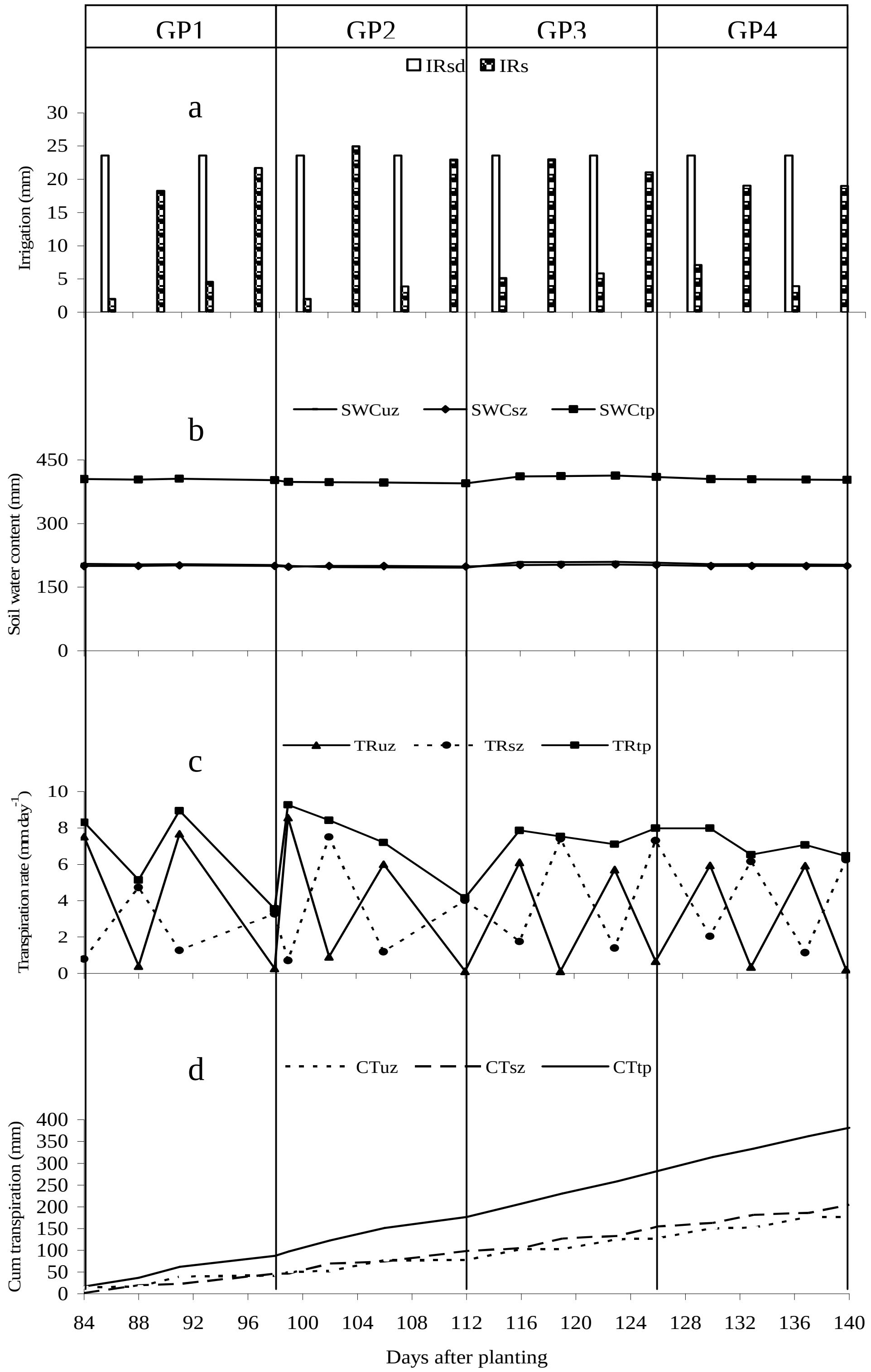

Figure 2.4 Soil water balance components during four growth periods of canola on the Bainsvlei soil: (a) irrigation (IR), (b) soil water content (SWC) (c) transpiration rate (TR) and (d) cumulative transpiration (CT). sd = surface drip; s = sub irrigation; uz = unsaturated zone; sz = saturated zone; tp = total profile.

Root densities varied between 0.5 and 6.1 mm $mm^{-3}x10^{-3}$ in the 0 – 1200 mm soil depth and decreased gradually in the deeper soil (1200 - 1500 mm). Seetseng (2009) observed similar rooting characteristics on the same soil during the previous year. It is assumed that the deeper roots will not be present in the lysimeters due to the water table. Roots do not grow in the saturated zones unless there is sufficient oxygen (Ehlers *et al.*, 2003). However, there are ample roots in the unsaturated zone to extract the easily available water from the topsoil during surface irrigation. Once the available water is depleted, the zone of extraction moves down to the subsoil. Due to the daily refilling of the water table, water is continuously supplied to the subsoil through capillary rise and hence the water is easily available in the first half meter above the water table.

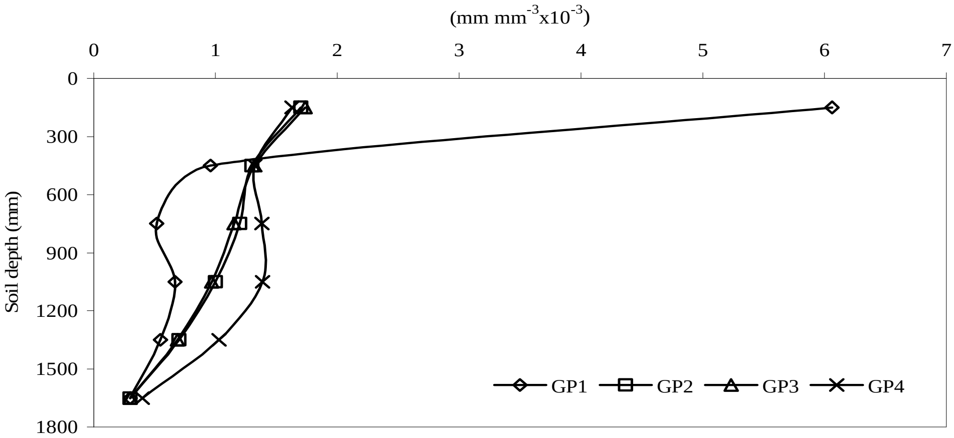

Figure 2.5 Root length densities (RLD) of canola in the Bainsvlei soil for each growth period in the absence of a water table.

The importance of the saturated zone becomes evident when its contribution is expressed as a percentage of the cumulative transpiration from the total profile. Results indicated further that the water table supplied between 50 and 62% of the transpiration of canola during the growth periods. In both soils, the cumulative transpiration from the saturated zone is slightly higher than from the unsaturated zone. These results are in conformity with the findings of Ehlers *et al*. (2003) for field crops that used the same lysimeter unit. They reported that cumulative uptake from the water table over the growing season ranging between 38 and 63% for wheat, 25 and 53% for maize, 30 and 55% for peas and 21 and 45% for groundnuts.

Transpiration was significantly different amongst growth periods, but not for soil forms (Table 2.2). It varied between 84.4 mm for GP2 and 103.3 mm for GP3. Of interest is that the plants maintained a relatively high transpiration during the last growth period, despite sharp decrease in LAI (Table 2.2). Visual observations during GP4 indicated that the pods dominated the canopy and probably shaded the leaves as most of the pods occurred in the upper third of the canopy. Thus, it can be deduced that the pods were involved in transpiration. Walton *et al*. (1991) stated that the green pod walls and stems can photosynthesize actively. Seetseng (2009) reported an average LAI of 3.6 for full and moderate irrigated canola when the plants transpired at maximum rates. Clarke and Simpson (1978) reported that crop growth rates were related to a LAI slightly above 3 which results almost in full interception of radiation.

2.3.3 Biomass production

Table 2.2 shows the contribution of above-ground and below-ground biomass (measured only in the Bv soil) components to the total biomass of the plant. Below-ground biomass was measured only in the Bv soil adjacent to the lysimeter unit and its contribution to total biomass was an insignificant 2.3%. From the analysis of variance, it is clear that soil forms affected biomass yield significantly (P = 0.05). Yields from the Bv were 16% higher than from the Cv soil, which is difficult to explain from a water supply and demand point of view. As discussed earlier, the possibility of water stress induced by irrigation in both soils is highly improbable. Biomass yields were significantly different (P = 0.05) between growth periods, because it is usually strongly related to the growth cycle of a crop. As expected increased biomass from GP1 (260 g m^{-2}) to GP3 (302 g m^{-2}) and then declined to GP4 (236 g m^{-2}). The decline in GP 4 is probably due to the high temperatures associated with the onset of summer. Seetseng (2009) made similar observations for irrigated canola and other winter crops (wheat and peas) are subjected to the same phenomenon (Bennie *et al*., 1994). Grain filling is highly sensitive to prevailing temperatures in October and November for the central parts of South Africa (Bennie *et al*., 1988; van Rensburg, 1996).

2.3.4 Transpiration efficiency

Results on transpiration efficiency based on above-ground biomass (TE_{AGB}) and total biomass (TE_{TB}) are shown in Table 2.2. These means were not significantly different between soil forms, but significantly different ($P = 0.05$) amongst growth periods. Due to the addition of root mass, TE_{TB} is slightly higher than TE_{AGB} in all the four growth periods. However, both TE_{AGB} and TE_{TB} showed the same trend in that they increased from GP1 to GP2, and then decreased to GP4. This decline could be attributed to leaf senescence with ageing and that neither the green pods nor the green stems are as efficient in transpiration as the leaves. Walton *et al*. (1991) noted that stomatal density is not as high on the pods and stems as in the case of leaves. During pod filling, significant amounts of energy may be mobilized from the leaves before they are being shed to either the stem and pod walls and then used in grain filling (Walton *et al*., 1991).

A maximum TE_{ABG} of 3.32 g m^{-2} mm^{-1} was observed during GP2 (Table 2.2). This is much higher than the TE values of 1 – 1.2 g m^{-2} mm^{-1} widely used in the canola industry. Values of this nature are based on the field experience that the actual TE for canola is approximately 60% of that for wheat (Grey and Jones, 1995). For rainfed canola at Tatura in Victoria, Australia, the TE calculated from data of Taylor *et al*. (1991) ranged from 0.7 to 1.4 g m^{-2} mm^{-1}. According to Hocking *et al*. (1997), a potential TE value of 1.3 g m^{-2} mm^{-1} was derived for canola based on the biosynthetic cost of seed production. Zaheer *et al*. (2000) reported a TE value of 2.8 g biomass m^{-2} mm^{-1} for canola in Western Australia. A potential transpiration efficiency of 2 g m^{-2} mm^{-1} has been observed to apply in a number of glasshouse and field studies in Australia (Passioura, 1976; Gregory *et al*., 1992; Zhang *et al*., 2004).

Squire (1990) reported that when crops are grown in the same environment, C_4 tropical crops typically have dry matter to transpired water ratios about twice those of C_3 species. Ritchie (1983) concluded that improving crop management, i.e. practices under the control of the farmer, can lead to an increased TE. According to Polley (2002), another factor that can lead to increased TE is the increase of atmospheric CO_2 concentration.

2.3.5 Transpiration efficiency coefficient

TEC differed significantly amongst growth periods but not between soils (Table 2.2).

Both TEC_{ABG} and TEC_{TB} increased from GP1 to GP2 and decreased to GP4. The lower values of TEC at GP4 are attributed to lower efficiencies associated with leaf senescence and transpiration by either green pods or stems as described earlier.

For growth periods, TEC_{ABG} varied between 3.82 and 4.95 g kPa mm^{-1}, while TEC_{TB} fluctuated between 3.94 and 5.04 g kPa mm^{-1}. These values compared well with that of sugar beet, a C_3 crop with values of 4.12 to 4.56 g kPa mm^{-1} reported by Clover *et al*. (2001). Mathews *et al*. (1988) and Azam-Ali *et al*. (1989) found values of 1.50 to 5.20 g kPa mm^{-1} for groundnuts (also a C_3 crop) under varying conditions of vapour pressure deficit. Ogindo and Walker (2004) working on common beans, another C_3 crop, determined TEC values of 3.02 and 3.15 g kPa mm^{-1}. Based on the reported TEC values, it can be concluded that the TEC values obtained in this study with canola for the different growth periods are in the same order as that of other C_3 crops and hence supported the general observations of Tanner and Sinclair (1983) and others. However, the results on canola suggested that TEC change during the reproductive growth stage and these changes should be taken into account in future applications. The transpiration efficiency coefficient has found wide application in modeling to separate ET into its components of E and T (Chapman *et al*., 1993; Howard *et al*., 1995).

2.4 Conclusions

Three main conclusions can be drawn from the study which involved detail measurements on the soil water balance of canola in its reproductive growth phase, planted in 30 lysimeters, equally divided into a sandy and sandy loam soil. Firstly, the results demonstrated the significance of a water table in the rooting zone towards supplying water for transpiration. The saturated zone or water table supplied between 50 and 62% of total transpiration during the reproductive stage, irrespective of soil. For fields that have water tables near or in the root zone of crops, it means that about 50% less water needs to be supplied through the irrigation system. Secondly, the research proved that the transpiration efficiency (TE) and transpiration efficiency coefficient (TEC), irrespective whether it is expressed on above-ground biomass or total biomass, are both not influenced by soil types, provided that the crops are not subjected to water stress. TE and TEC based on total biomass (above- plus below-ground biomass) were consistently higher than those based on above-ground biomass alone. Thirdly, both TE and TEC changed during the reproductive stage of the crop, irrespective whether it is expressed as above-ground biomass or total biomass. It was speculated that the increase to 126 days after planting with a decline thereafter was caused by morphological changes that occur as the pods fills the upper third of the canopy. This aspect should be researched further to find physiological proof for the phenomenon.

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Chapter three

Partitioning evapotranspiration for canola under irrigation using the soil water balance method

Abstract

Key to effective partitioning of evapotranspiration in the semi-arid environment is a mechanistic understanding of how biological and non-biological processes influence water loss in agroecosystems. A field trial was designed to better understand how evapotranspiration is partitioned into its components of soil evaporation and plant transpiration. Evapotranspiration and transpiration were measured from bare soil treatment and gravel mulch treatment respectively. The research was conducted at the Field Research Facility of the University of the Free State at Kenilworth near Bloemfontein. The experiment was laid out as a split plot design with two soil forms and two treatments replicated three times. Canola was planted on 30 May and harvested on 16 November 2007. Irrigation was applied weekly through a surface drip system and daily through sub irrigation from a constant water table. Soil water content was measured three times a week using the neutron soil water meter and manually on weekdays from under the underground chamber of the lysimeter. The soil water balance equation was used to calculate evapotranspiration from bare treatment and transpiration from gravel mulch treatment before evaporation could be determined as the difference between evapotranspiration and transpiration. Results revealed that the difference between plastic and gravel mulches in reducing evaporation is between 2 and 3% in a controlled environment which proved that gravel mulch can be used in place of plastics and is as effective in reducing evaporation as plastic mulch. Thirty percent of the total productive water loss was converted to grain yield, while 70% of productive water loss was converted to crop biomass. Analysis of water use based on soil forms and treatments revealed that Canola grown on Clovelly soil used more water than those on Bainsvlei soil and bare surface treatment also recorded more water use than gravel mulch treatment.

Keywords: Evapotranspiration; partitioning; soil water balance; semi-arid.

3.1 Introduction

In most arid and semi-arid regions of the world there is increasing pressure to improve the efficiency of irrigation farming with regard to water use. A crucial issue in this matter is a better understanding of the evapotranspiration (ET) process. This process resulted in water loss from soil through evaporation (E) and from plant through transpiration (T). The former is not essential for plant growth and should be minimized if its contribution to ET is significant. Therefore it is of ultimate importance to determine the contribution of individual component of E and T.

Most often, transpiration is estimated from evapotranspiration measurements using indirect methods: (i) subtraction of an estimated E usually assumed to be a seasonal constant from the measured seasonal ET as suggested by Hanks and Shawcroft (1969); (ii) daily soil water balance simulation using empirical functions to separately calculate T from daily measurements or measurements of ET using plant parameters such as leaf area index or ground cover (Ritchie, 1972; Tanner, 1981; Hanks, 1985; Howell *et al.*, 1995); (iii) measuring E and subtracting it from measurements of ET (Lascano *et al.*, 1987).

Probably the most accurate and direct method of measuring soil water balance is the use of a lysimeter (Wright, 1991). Although large weighing lysimeters involve considerable expense, they can give very precise measurements (Howell *et al.*, 1995). An excellent review of the use of weighing lysimeters is given by Howell *et al.* (1991). Careful design, installation, and operation will overcome many of the serious problems reported with some lysimeters. Areas that need attention are soil disturbance during initial preparation of the profile (less with monolithic lysimeters), interruption of deep percolation and horizontal flow components and uneven management of lysimeters compared with field soil (Grebet and Cuenca, 1991; Ritchie *et al.*, 1996). Microlysimeters are small enough to be installed and removed by hand for weighing daily or more often as illustrated by Hoffman (1997). They can give good precision but are sensitive to spatial variability. Lascano and Hatfield (1992) showed that 182 microlysimeters were required to measure field average E with precision of 0.1 mm d^{-1} at a 90% confidence level when the soil was wet; but only 39 when dry. This was due to the greater variability of E for wet soil. The field lysimeters of Ehlers *et al.* (2003) used for this study are large (2500 litres each) but simple to manage and monitor. The main advantages of the field lysimenters are that the water table can be manually controlled, runoff can be controlled through the use of rims, influence of rain can be controlled using a movable rain shelter and soil water measurements can be taken with the neutron water meter as desired. The main problems of the field lysimeters are high cost of procurement and installation. The problem of uneven distribution of irrigation has been eliminated by surface drip irrigation system.

A few studies have been conducted to determine the effect of plastic film, straw and gravel mulch on wheat production (Li and Lan, 1995; Niu *et al*., 1998; Li *et al*., 2004; Xie *et al*., 2004). These studies showed that mulched wheat resulted in higher grain yield than unmulched wheat. The main causative reasons for mulch increasing yield are soil and water conservation, improved soil physical and chemical properties, and enhanced soil biological activity (Tumulhairwe and Gumbs, 1983; Tindall *et al*., 1991; Deng *et al*., 2006; Ramakrishna *et al*., 2006).

Research on ET partitioning of canola is scarce, both local and international. Walton *et al.* (1999) reported that total ET varies from 160 to 180 mm in low rainfall areas and from 400 to 500 mm in high rainfall areas. According to Tesfamariam (2004) who conducted field trials in Pretoria, ET of canola ranged from 238 mm to 438 mm for the water stressed treatments in 2002 and from 552 mm to 709 mm in 2003 for the water unstressed treatments. None of these researchers considered the partitioning aspect of ET, hence the importance of this study to partition ET into its components of evaporation and transpiration in order to ascertain individual proportion in terms productive and unproductive losses.

Apart from Seetseng (2009) who used Hanks (1992) method to separate ET by incorporating the β value, no other work on separating ET on canola has been found.

One of the most important challenges of transpiration efficiency studies is to design the experiment in such a way that evaporation from the soil is approximately zero during transpiration. In most transpiration studies the surface area of the soil is covered with plastic to restrict evaporation, but there is always a risk of interfering with gas exchange between the soil-root system and the atmosphere. Therefore it was argued that gravel mulches will not impede gas exchange and hence if it can restrict evaporation from the soil to negligible levels then it can replace the plastic cover on the surface. Hence the first objective of this study was to test whether gravel mulch is as effective as plastic mulch in reducing evaporation from the soil so that it can be used with confidence in evapotranspiration partitioning studies. A second objective was to determine the yield, water use and water use efficiency of canola under irrigation with and without a gravel mulch for the ultimate partitioning of the crop's water use into transpiration and evaporation.

3.2 Materials and methods

3.2.1 Lysimeter unit

The lysimeter unit described earlier (Section 2.2.1) was used also for this study. This unit comprises 30 lysimeters whereof half are filled with a sandy Clovelly (Cv) soil and half with a sandy loam Bainsvlei (Bv) soil. Only 6 of the lysimeters were used to achieve the first objective (Experiment 1), while 12 of the lysimeters were used to achieve the second objective (Experiment 2). The remaining 12 lysimeters were used for an experiment on wheat which will be dealt with in the next chapter.

3.2.2 Experiment one

Three surface treatments were applied to each soil without any replication. They were (i) no cover at all to obtain evaporation from bare soil, (ii) a 50 mm thick gravel mulch (dolerite with a mesh size of 10 mm) uniformly spread over the soil surface and (iii) a white plastic that covered 100% of the soil surface (Figure 3.1). This plastic was mounted on a frame which was installed 100 mm above the soil surface. The experiment started on 3 August 2007 and ran for 120 days until it was terminated on 30 November 2008. During this period the soil water balance components in the lysimeters, *viz.* change in soil water content (ΔW), irrigation (I), precipitation (P), evaporation (E) and drainage (D) were determined as described in Section 2.2.4.1. The irrigation through surface drip to create drying circles in the unsaturated zone of the lysimeters was at a longer interval, namely every fortnight instead of weekly. However, recharging of the water table in the lysimeters through sub irrigation was still daily. Transpiration was zero in this experiment because no plants were allowed to grow in the lysimeters. Therefore evaporation from the lysimeters was calculated between soil water measurements with Equation 3.1.

$$E = (-\Delta W) + I - D \qquad (3.1)$$

Analysis of variance on evaporation from the different treatments was impossible because there was no replication. Comparison of evaporation between treatments was thus based on cumulative water losses over a long period by expressing the evaporation from either the plastics or gravel mulch treatments as a percentage of the bare soil treatments.

Figure 3.1 Illustration of the surface treatments on the Clovelly soil of experiment one, *viz.* (A) the bare soil surface for the reference evaporation, (B) a 50 mm thick gravel mulch (dolerite with a mesh size of 10 mm) and (C) a white plastic for 100% soil surface cover, all equipped with neutron probe access tubes and a surface drip irrigation system. The same layout was repeated for Bainvlei soil.

3.2.3 Experiment two

In this experiment canola was planted in 12 lysimeters using a split plot design with three replications. Two soil surface treatments were applied on each of the Cv and Bv soils. They comprised of (i) a bare soil for measuring the actual evapotranspiration and (ii) a 50 mm thick gravel mulch to prevent evaporation and thus obtaining transpiration. The gravel mulch was similar for experiment 1, but applied after the crop was established.

In the lysimeters and adjacent field (northern side of lysimeters) similar agronomic practices were used as described in Section 2.2.3, except that the canola was planted on 30 May 2008 and harvested on 16 November 2008.

The water balance components were measured as described in Section 2.2.4.1. ET from the bare surface treatment between soil water measurements was calculated with Equation 3.1, where E was replaced with ET on the left side of the equation. This equation by replacing E with T was also used to calculate T from the gravel mulch treatments between soil and water measurements. In this case it was assumed that E is negligible as shown in Section 3.3.1. Separation of ET into E and T was thus possible by subtracting transpiration (measured on the gravel mulch treatment) from evapotranspiration (measured at the bare surface treatment).

The soil water management boundaries was similarly determined and used as described in Section 2.2.4.2.

The canola was harvested 168 days after planting (DAP) by cutting all plants in each lysimeters at their base. Pods were then removed from the plants and both were oven dried for 72 hours at 65°C before weighing. The pods were threshed and seeds weighed to obtain seed yield. Then total biomass yield was calculated by summation of the plant, pod and root masses. Root and leaf samples were collected at 57, 93, 121, and 154 DAP in the area adjacent to the lysimeter unit for the determination of root mass and leaf area index (LAI) as described in Section 2.2.4.3. The harvest index (HI) was expressed as the ratio of the seed yield to total biomass yield.

$$WUE = Y/ET \tag{3.2}$$

Where Y is either total biomass (TB) or seed yield (S) and ET water loss through evaporation (E) from the soil surface and transpiration (T) through stomata of the plants. This most frequently used relationship by researchers according to Tanner and Sinclair (1983) is traceable back to de Wit (1958) as cited by Hanks (1983) who showed that plant yield and transpiration are linearly related in areas with high solar radiation. For this study, Equation 3.2 was rewritten to Equation 3.3 or 3.4 depending on the treatment:

$$WUE = Y/WU_B \tag{3.3}$$

Where WU_B is water use on bare surface treatment.

$$WUE = Y/WU_G \tag{3.4}$$

Where WU_G is water use on gravel mulch treatment.

Analysis of variance was conducted to establish significant differences among the treatments using the GLM Procedure of SAS System (Local, XP_PRO) (SAS Institute Inc., 1999). Variables such as water use, seed yield, total biomass yield, harvest index and water use efficiency were statistically tested and Fisher’s least significant difference (LSD) procedure for means comparison was applied (Fisher, 1935).

3.3 Results and discussion

3.3.1 Experiment one

The cumulative evaporation over 120 days from the bare, gravel and plastics treatments are presented in Figure 3.2a for the Cv soil and in Figure 3.2b for the Bv soil. In comparison to the bare treatment, the white plastic mulch reduced evaporation by 80% and 81% in Clovelly and Bainsvlei soils, respectively. Evaporation from the gravel mulch was only 3% higher than from the plastic mulch, irrespective of soil types. Similar results were obtained for example by Xie *et al.* (2004) in comparing different mulching techniques in China. They stated that gravel mulch is as good as plastic mulch in reducing evaporation from agricultural fields. However, the benefit of gravel mulch is low because it is labour-intensive to apply and maintain on large areas. They recommended plastic mulching techniques which according to them is easy to apply and maintain. According to Hide (1954), Adams (1966), Fairborn (1973), Kemper *et al.* (1994), Poesen and Lavee (1994), van Wesemael *et al.* (1995), Roundy *et al.* (1997), Nachtergaele *et al.* (1998) and Li *et al.* (2000), gravel mulch was effective in reducing E and runoff, improving infiltration and soil temperature and maintaining soil fertility.

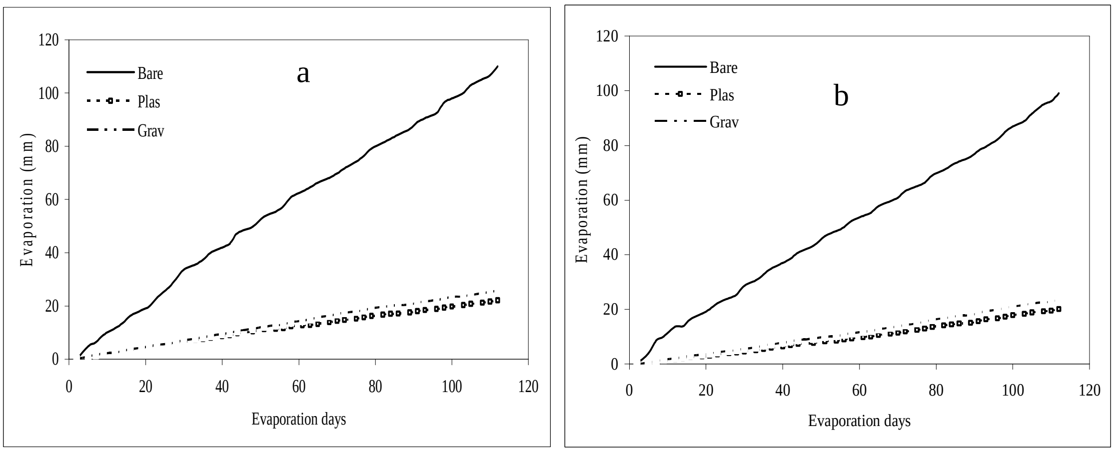

Figure 3.2 Cumulative evaporation from (a) the Clovelly (Cv) and (b) from the Bainsvlei (Bv) soil with bare surface (Bare), plastics (Plas) and (Grav) gravel mulch as treatment.

Thus, it can be concluded that the results in Figure 3.2 concurs with international literature and that gravel mulch is as effective as plastic mulch in reducing evaporation from the soil. The implication is that plastic mulch, which is usually placed between crop rows to prevent evaporation in transpiration studies (Ogindo and Walker, 2004) can be substituted by gravel mulch. One of the disadvantages of using plastic mulch is its potential threat of reducing gas exchange between the atmosphere and the soil. The gravel mulch will not interfere with gas exchange because the soil and atmosphere are connected by pores.

3.3.2 Experiment two

The analysis of variance revealed no significant interaction between soils and surface treatments for any of the variables measured, but there were significant differences between soils and also surface treatments. These differences are summarized in Table 3.1 for the variables associated with irrigation, water use, yield and water use efficiency and will be discussed in the following sections.

3.3.2.1 Managing irrigation to avoid water stress

The way in which irrigation was managed led to variable amounts of water applied to either the soil and surface treatments (Table 3.1). Each lysimeter received a total of 408 mm water through surface drip since a fixed amount was applied every week to wet the unsaturated zone. Water used from the water table was recharged by sub irrigation on a daily basis. Substantial amounts were applied which varied between 42 and 45% of the total irrigation. Very stable soil water contents were measured during the season as a result of the irrigation scheduling approach used. Mean soil water contents were 392 mm for the Cv soil and 448 mm for the Bv soil with coefficients of variation of 3.8 and 6.9%, respectively. The mean soil water content was 412 mm (CV = 7.7%) for the bare soil treatment and 421 mm (CV = 5.7%) for the gravel mulch treatment. From these statistics it is clear that the soil water content to 1800 mm depth never drops below the pre-selected allowable depletion values in any of the treatments. The preselected allowable depletion values were 233 mm per 1800 mm for the Cv soil and 313 mm per 1800 mm for the Bv soil. Thus, it is highly unlikely that the canola crop could have experience water stress under such high soil water levels. On the other hand, the water levels were never so high that it moves beyond the pre-determined drained upper limits of both soils.

Table 3.1 Means of irrigation, water use, seed yield (S), total biomass yield (TB), harvest index (HI), water use efficiency (WUE_S) and water use efficiency (WUE_{TB}) for soil and surface treatments.

Variable	Soil		LSD	Surface treatment		LSD
	Cv	Bv		Bare	Gravel	
Surface drip (mm)	408	408	nd	408	408	nd
Sub irrigation (mm)	339	298	nd	362	275	nd
Total irrigation (mm)	747	706	nd	770	683	nd
Seed yield (kg ha^{-1})	2516^a	2670^a	155	2449^b	2737^a	155
Total biomass (kg ha^{-1})	7965^a	8605^a	652	8034^a	8536^a	652
Harvest index	0.31^a	0.32^a	0.011	0.30^a	0.32^a	0.011
Water use (mm)	767^a	758^a	24	808^a	717^b	24
WUE_S (kg ha^{-1}mm^{-1})	3.28^a	3.52^a	0.71	3.03^b	3.82^a	0.71
WUE_{TB} (kg ha^{-1}mm^{-1})	10.40^a	11.41^a	1.04	9.94^b	11.91^a	1.04

Means in any one column followed by the same letters are not significant at $P = 0.05$.
LSD = least significant difference.
nd = not determined

According to Ehlers *et al.* (2003) the optimum water table depth for these soils is 1200 mm for most field crops. Waterlogging is associated with water tables shallower than 500 mm (Lal and Shukla, 2004; Surya *et al.*, 2006). It is against this background that it can be assumed that such a risk is implausible.

3.3.2.2 Yields and harvest index

With respect to the analysis of variance on grain yield, total biomass yield and harvest index (Table 3.1), the effect of soils and surface treatments were inconclusive. On the one hand, there is a trend that the variables are generally higher in the sandy loam soil (Bv) than in the sandy soil (Cv), which is difficult to explain from an irrigation perspective. Seed and total biomass yields in the Bv soil were both 4% higher than Cv soil. On the other hand, there is a trend that the variables are generally higher in the gravel mulch treatment than the bare surface treatment, but the effect was only significant for seed yield. Seed and total biomass yield for the gravel mulch treatment were respectively 6 and 4% higher than the bare surface treatment. The mean seed (2593 kg ha^{-1}) and biomass (8285 kg ha^{-1}) yields of the experiment are within the range of values reported by other authors. The Canola Council of Canada (2005) reported a seed yield of 2463 kg ha^{-1} and for total biomass they reported 9587 and 8683 kg ha^{-1} for the two cultivars tested under full irrigation. Seed yields of 2233 and 2567 kg ha^{-1} were also reported by Faraji *et al*. (2008). In Bloemfontein, Seetseng (2009) reported a seed yield of 2554 kg ha^{-1} and a biomass yield of 5838 kg ha^{-1}. Tesfamariam (2004) reported seed yields of 2662 and 3831 kg ha^{-1} in Pretoria. The mean harvest index of 0.31 for canola in this experiment falls also in the range reported by other researchers for different species and cultivars of this crop. Rao and Mendham (1991) reported HI values of 0.28 to 0.33, while values of 0.16 to 0.22 were reported by Richards and Thurling (1978).

3.3.2.3 Root and leaf characteristics

The results on root development of canola as depicted in Figures 3.3 and 3.4, reflect the general perception that the crop has a well developed rooting system. Roots were sampled in the 1500 – 1800 mm soil layer as early as 57 DAP, which gives a mean vertical penetration rate of 28 mm day^{-1}. This is higher than the rates reported by van Antwerpen (1988) for groundnuts (14 mm day^{-1}), wheat (17 mm day^{-1}) and maize (24 mm day^{-1}) under local irrigation conditions, probably because the plant has a tap root system. According to the root length density (RLD) results, the roots proliferated well in the profile with values as high as 3 mm mm^{-3}x10^{-3} in the topsoil (150 mm) and 0.2 mm mm^{-3}x10^{-3} in the deep subsoil (1650 mm). This root length density distribution profile compares well with crops known for their proliferation abilities such as groundnuts. The general root growth pattern measured in the experiment corresponds with that reported by Grimes and El-zik (1990), Ashraf and Ahmed (1995) and Ashok *et al.* (1999), namely that the onset of flowering is the point that root growth starts to decline.

A deep and conductive root system is crucial for a plant's ability to transport water to the leaves for maintaining water status. Thus there is often a relationship between root length index (RLI, mm mm^{-2}) and LAI (van Rensburg, 1996), as indicated by the trends of the two parameters in Figure 3.4. The RLI increased over the season and reached a peak of 260 mm mm^{-2} at 121 DAP, whereafter it declines to 224 mm mm^{-2}. Likewise, the mean LAI followed the same trend as the roots and peaked on 121 DAP with an index of 3.8 and then declined to an index of 2.6. A highly positive coefficient of correlation (r = 0.97) was obtained between the two parameters. LAI values from this experiment are consistent with values reported in other experiments. Clarke and Simpson (1978) reported that crop growth rates were related to a LAI of just above 3 which corresponds almost to full interception of radiation.

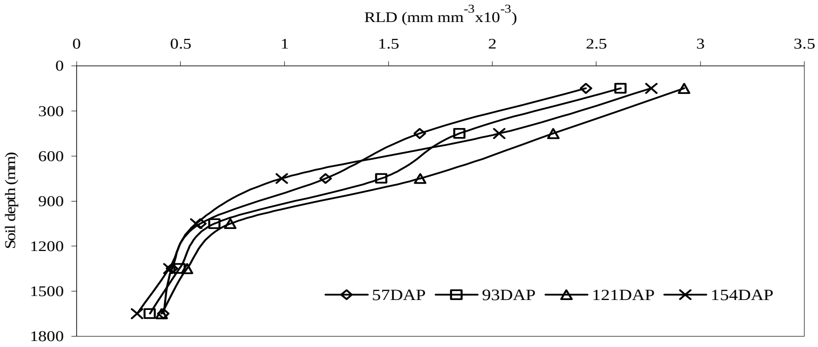

Figure 3.3 Root length densities (RLD) of canola at different soil depths

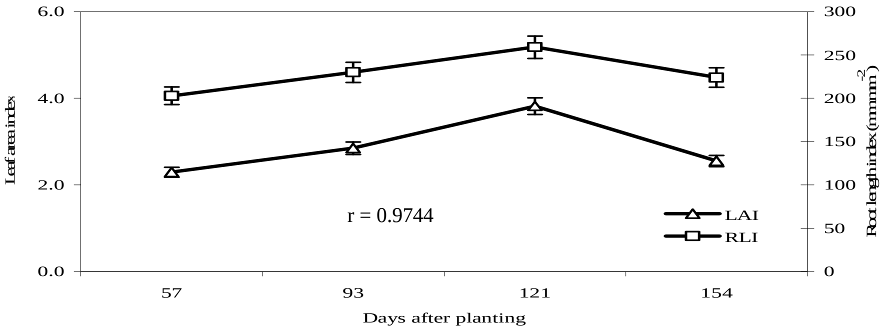

Figure 3.4 Root length index (RLI) and leaf area index (LAI) relationship

Seetseng (2009) reported an average LAI of 3.6 for full and moderately irrigated canola fields in Bloemfontein. According to Walton *et al.* (1999), a leaf area index of 3 to 4 is required for the crop canopy to intercept about 90% of the incoming solar radiation.

3.3.2.4 Water use and its efficiencies

Analysis of variance revealed that the two soils neither influenced water use nor water use efficiency (Table 3.1). However, both variables were significantly influenced by the surface treatments. The water use of canola from the bare surface was significantly higher than from the gravel mulch. This can be explained by the gravel suppressing the evaporation component of evapotranspiration. It seems that water conserved this way has led to significantly improved water use efficiencies as indicated by WUE_S and WUE_{TB}. The mean water use efficiency of the experiment, *viz*. 3.19 kg seed $ha^{-1}mm^{-1}$ and 10.85 kg biomass $ha^{-1}mm^{-1}$ compare well with values of other studies elsewhere. Taylor *et al*. (1991) reported a WUE of 4 to 7 kg biomass ha^{-1} mm^{-1} in South-eastern Australia. In Canada, Johnson *et al*. (1996) found a WUE of 8.3 to 11.4 kg biomass $ha^{-1}mm^{-1}$. Grey (1998) reported a WUE of 2 kg seed $ha^{-1}mm^{-1}$ and 10 kg biomass $ha^{-1}mm^{-1}$ in the Victoria, Australia. In the semi-arid zone of north-east Colorado a WUE of 7.73 kg seed ha^{-1} mm^{-1} was observed by Nielsen (1996). Water use efficiencies of between 6.4 and 6.62 kg biomass $ha^{-1}mm^{-1}$ were reported by the Canola Council of Canada (2005). Seetseng (2009) found in Bloemfontein a WUE of between 9.3 and 12.7 kg total biomass ha^{-1} mm^{-1}. According to Nielsen (1997), WUE is partly a function of canola adaptation to environmental conditions, so favourable agronomic management practices are of great importance.

3.3.3 Partitioning of water use (ET) into evaporation (E) and transpiration (T)

The water used by canola in the gravel mulch treatments can be attributed solely to transpiration (T) as evaporation (E) was insignificant. This was proved by Experiment 1, the results of which are presented and discussed in Section 3.3.1. However, water used by canola in the bare surface treatments resulted from evapotranspiration (ET). Thus by subtracting canola's water use in the gravel mulch treatment from that in the bare surface treatments evaporation was obtained. The results for each soil are summarized on a weekly basis in Table 3.2. The weekly water use (ET) on both soils demonstrates the crops water demand in semi-arid regions like Bloemfontein. In weeks, it starts with an ET of 27 mm $week^{-1}$ in the Cv soil and 32 mm $week^{-1}$ in the Bv soil. Then ET increases gradually to a peak in week 15, *viz.* 73 mm $week^{-1}$ in the Cv soil and 61 mm $week^{-1}$ in the Bv soil. Thereafter ET ranged from 44 to 60 mm $week^{-1}$ in the Cv soil and 37 to 64 mm $week^{-1}$ in the Bv soil. The total water use was about similar for both soils and amounted to 767 mm for the Cv soil and 758 mm for the Bv soil. Transpiration was 719 mm on the Cv soil and 716 mm on the Bv soil and accounted for 93.7 and 94.5% of the total ET, respectively. It means that the evaporation component was less than 7% of the total ET.

Table 3.2 Weekly partitioning of water use (WU, mm) or evapotranspiration (ET, mm), transpiration (T, mm) and evaporation (E, mm) for canola grown on the Clovelly and Bainsvlei soils.

Weeks after planting	Clovelly (Cv)					Bainsvlei (Bv)				
	WU or ET (mm)	T (mm)	% T	E (mm)	%E	WU or ET (mm)	T (mm)	% T	E (mm)	%E
5	27.3	23.9	87.7	3.1	11.2	32.0	29.5	92.0	2.6	8.0
6	28.8	25.6	89.1	3.1	10.9	36.1	33.2	91.8	3.0	8.2
7	39.1	36.7	93.7	2.5	6.3	34.8	32.5	93.5	2.3	6.5
8	32.7	29.2	89.3	3.1	9.5	38.3	35.9	93.6	2.4	6.4
9	41.8	38.9	93.1	2.9	6.9	41.4	38.6	93.1	2.4	5.9
10	30.7	28.6	93.0	2.1	7.0	41.3	39.0	94.6	2.2	5.4
11	31.9	29.5	92.6	2.4	7.4	32.3	30.0	92.9	2.3	7.1
12	42.7	39.8	93.2	2.3	5.4	35.2	32.6	92.6	2.3	6.5
13	52.3	49.7	95.0	2.6	5.0	50.0	47.3	94.6	2.5	5.0
14	51.3	48.5	94.4	2.5	4.8	48.6	46.1	95.0	2.4	5.0
15	72.6	69.3	95.5	3.1	4.2	61.0	58.6	96.0	2.4	4.0
16	52.0	49.7	95.7	2.3	4.3	47.0	44.4	94.6	2.5	5.4
17	48.4	45.2	93.4	3.1	6.4	39.4	37.2	94.3	2.2	5.7
18	59.7	56.7	94.9	3.0	5.1	61.2	58.5	95.5	2.5	4.2
19	54.8	51.5	94.0	2.3	4.2	64.2	61.7	96.1	2.5	3.9
20	56.7	53.5	94.4	3.2	5.6	58.1	56.1	96.6	2.0	3.4
21	44.2	41.7	94.3	2.5	5.7	37.0	34.7	93.7	2.3	6.3

By disaggregating total evaporation into weekly evaporation shows that its contribution to evapotranspiration decreased for the Cv and Bv soils from 12% and 8% in week 5 to 5% for both soils in week 13 just prior to when peak water demand started. This decrease in evaporation is due to leaf shading of the soil surface by the crops with a high LAI which reduced the energy reaching the soil surface to an insignificant level. Furthermore, during peak water demand the contribution of evaporation to evapotranspiration remained at this level. This is probably due to the wetting of the soil surface during irrigation. Following several rain events, Dugas *et al.* (1996) found that T/ET ratios ranged from 40 – 80% over several different chihuahuan shrub sites in New Mexico which translates to 20 - 60% losses as evaporation. In their field experiment with sprinkler irrigated maize in Kansas, Klocke *et al.* (1985) found that as much as 20 - 30% of total evapotranspiration is due to evaporation from the soil surface. They also demonstrated that crop residues reduced evaporation from soil in half. Hatfield *et al.* (2001) found in the USA that mulching of the soil with wheat residue modified the microclimate, which increased transpiration to 79% and reduced evaporation to 21% of the total evapotranspiration. Fereres and Villalobos (1990) from their tomato experiment in Spain found that evaporation losses contributed 15 - 17% of ET.

3.4 Conclusions

The results of two experiments were reported. In the first experiment the effectiveness of white plastic mulch and dolerite gravel mulch in preventing evaporation from a sandy Clovelly soil and a sandy loam Bainsvlei soil was tested. The white plastic mulch reduced evaporation by 80% from the Clovelly soil and 81% from the Bainsvlei soil when bare soil surfaces served as reference. Evaporation from the dolerite gravel mulch was only 3% higher than from the white plastic mulch irrespective of soil. Thus dolerite gravel mulch can be used with confidence to reduce evaporation in evapotranspiration partitioning studies.

In the second experiment the yield, water use and water use efficiency of irrigated canola with and without dolerite gravel mulch were measured for partitioning the crop’s water use into evaporation and transpiration. The yield of canola on the Clovelly and Bainsvlei soils were similar. A slightly higher yield was measured on the gravel mulch treatments than on the bare surface treatments. Canola’s water use from the bare surface treatments was significantly higher than from the gravel mulch treatments. This is because the gravel mulch prevented water loss through evaporation. Evaporation contributed in the Clovelly soil between 4% and 12% and in the Bainsvlei soil between 4% and 8% to evapotranspiration. This contribution declined as the growing season proceeded because of better shading.

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Chapter four

Effect of seasons on the transpiration efficiency coefficient of irrigated wheat

Abstract

Wheat is one of the most important grain crops in South Africa. The crop responds well to irrigation but this is mainly practised in semi-arid zones where there is a chronic scarcity of water due to harsh weather conditions. These conditions have a huge impact on soil water evaporation (E), transpiration (T) and grain yield, which relates directly to water use efficiency (WUE). Therefore, an experiment was laid out in the field lysimeter unit at Kenilworth over two wheat production seasons (2007 and 2008) with the objectives: (i) to evaluate the effect of soils and seasons (weather) on E, T and yield, and (ii) to relate these variables to transpiration efficiency coefficient. A split plot design was used with two soils (sandy and sandy loam) and two surface treatments (bare soil and gravel mulch), replicated three times. Irrigation was applied weekly through a surface drip system and daily through a sub irrigation system. Soil water content was measured three times a week using a neutron soil water meter. The water balance equation was used to calculate evapotranspiration from the bare surface treatment and transpiration from gravel mulch treatment. Expressing T and E as a percentage of ET revealed that neither soils nor seasons are important determinants in the partitioning of ET since T varied between 74 and 76% of ET and E varied between 24 and 26% of ET. The two soils did not influence any yields in both seasons. Surface treatments caused significant differences in grain yield in both seasons and aboveground biomass in 2008. Seasons affected the mean grain yield, but not above-ground biomass yield. Grain yield in the 2008 season was severely hampered by frost that occurred in the early reproductive stage. This effect was transferred to the corresponding transpiration efficiency coefficient values.

Keywords: Evaporation; transpiration; water use efficiency; transpiration efficiency coefficient.

4.1 Introduction

Wheat (*Triticum aestivum* L.) is the second most important field crop grown in South Africa and is used for a variety of purposes. Together with secondary processing industries it provides a large number of job opportunities. Statistics obtained from the National Department of Agriculture (2007), revealed that the industry has approximately 3800 to 4000 commercial wheat growers, providing work opportunities to about 28000 people. Accordingly, South Africa consumes about 3 million tons of wheat per year of which 2 million are grown locally and the other million imported. In large parts of the country, water is the most important limiting factor for wheat production in this region and to achieve higher grain yields, farmers rely in many instances on irrigation to grow wheat (Bennie *et al.*, 1997). Approximately 80% of wheat is currently produced under dryland and 20% under irrigation conditions (National Department of Agriculture, 2007).

Conversely, irrigation is mainly practiced in semi-arid zones that chronically experience water scarcity due to harsh weather conditions. These conditions are caused by low and erratic rainfall together with high atmospheric evaporative demand. As a result weather has a huge impact on water losses such as soil water evaporation (E) and transpiration (T). These losses need to be quantified in order to determine the impact thereof on water use efficiency (WUE) of wheat. The problem is that it is difficult to measure the sole effect of E and T under field conditions.

Many studies from different parts of the world showed that the relationship between seasonal ET and wheat yield is linear, provided that the bio-physical conditions were optimal (Singh, 1981; Mogenson *et al.*, 1985; Steiner *et al.*, 1985; Musick *et al.*, 1994; Zhang and Oweis, 1999; Zhang *et al.*, 1999). These relationships, also referred to as crop-water production functions (CWPF), were very popular in the eighties and nineties in South Africa. During this period they were used to determine the seasonal crop water demand for a specific target yield. For example, Bennie *et al.* (1988) established the following relationship on farms in the Sandvet, Ramah and Vaalharts Irrigation schemes:

$$Y = 11.38X - 340 \qquad (4.1)$$

where Y is grain yield (kg ha^{-1}) and X the evapotranspiration (ET, mm).

It was argued that the slope of the line represents water use efficiency (WUE) or transpiration efficiency (TE) of the crop, while the point where the line crosses the x-axis represents the total soil water evaporation (E) of the season (Hanks, 1976). The WUE of wheat is therefore, 11.38 kg ha^{-1} mm^{-1} and the total or seasonal evaporation is 30 mm (340/11.38, where y = 0).

The CWPF in Equation 4.1 was evaluated by Bennie *et al.* (1997) at the experimental site of the University of the Free State at Kenilworth near Bloemfontein. They found that both the slope and the intercept differed significantly from that of Equation 4.1. Accordingly, the CWPF should have a 23% greater slope. The estimated cumulative evaporation amounted to 190 mm in this study. From the aforementioned, it was concluded that the CWPF is an empirical function which might differ from season to season and from place to place, depending on the weather conditions and agronomical practices. Similar conclusions were made by French and Schultz (1984). The outcome was that the CWPF's in both the BEWAB (Bennie *et al.*, 1988; van Rensburg and Zerizghy, 2008) and SWAMP models were replaced with a so called universal approach captured in the Doorenbos and Kassam (1979) equation:

$$1-(Y_{aB}/Y_{mB}) = \beta(1-(ET_a/ET_m)) \quad (4.2)$$

Where Y_a represents the actual ($_a$) biomass yield ($_B$) in kg ha^{-1}, Y_m is the maximum ($_m$) biomass yield (kg ha^{-1}), ET_a is the actual evapotranspiration (mm) and ET_m is the maximum evapotranspiration (mm).

According to Hanks and Rasmussen (1982), Equation 4.2 can be rearranged so that ET_a can be apportioned into its components of actual soil water evaporation (E_a) and actual transpiration (T_a) if the β-value is known:

$$E_a = (1-(1/\beta))ET_a \quad (4.3)$$

$$T_a = ET_a/\beta \quad (4.4)$$

De Wit (1958) as cited by Hanks (1983) proposed that there is a linear relationship between transpiration (T) and biomass (Y_{AGB}) production and the slope of the line represents the so called crop coefficient (*m*-value) that gives the transpiration efficiency (TE) of the crop:

$$Y_{TB} = m\,(T/E_o) \quad (4.5)$$

Tanner and Sinclair (1983) modified Equation 4.5 to normalize the evaporative demand by replacing E_o with the vapour pressure deficit:

$$m = (Y_{TB}/T)e^* - e \quad (4.6)$$

Where e* is the saturated vapour pressure deficit at mean temperature and e is the vapour pressure and the *m* value was renamed as the transpiration efficiency coefficient (TEC) in this study. Wheat's *m* or *k* values used in the SWAMP model were adapted from Hanks and Rasmussen (1982) and those values were not normalized to vapour pressure deficit as is the case with TEC. At that stage it was not possible to evaluate the TEC value because of the lack of a lysimeter unit. A field lysimeter unit erected by Ehlers *et al*. (2003) is now available for this purpose.

Therefore, an experiment was laid out in the field lysimeter unit with the objectives: (i) to evaluate the effect of soils and seasons (weather) on E, T and yield of wheat, and (ii) to relate these variables to the water use efficiency and transpiration efficiency coefficient.

4.2 Materials and methods

The lysimeter unit erected by Ehlers *et al*. (2003) was described in Section 2.2.1. For this study wheat was planted in 12 of the 30 lysimeters during the 2007 and 2008 seasons. Half of the lysimeters were filled with a sandy Clovelly (Cv) soil and the other half with a sandy loam Bainsvlei (Bv) soil. Thus, the experiment was laid out as a split plot design with two soils and two surface treatments, replicated three times. The surface treatments comprised of (i) a bare soil for measuring the actual evapotranspiration and (ii) a 50 mm thick gravel mulch for preventing evaporation and to obtain transpiration. The gravel was applied four weeks after planting when the plants were already established. During rain events the lysimeters were covered by the rain shelter (Figure 4.1) which was removed just after rain events to ensure as far as possible field conditions. Wheat was planted in the field adjacent to the lysimeter, except in the northern side where canola was planted.

In the lysimeters and area adjacent to them similar agronomic practices were used as described in Section 2.2.3. The wheat was planted on 30 May 2007 for the first season and 24 April 2008 for the second seasons. In the lysimeters, prior to planting a 4:2:1 (28) fertilizer mixture was manually broadcast at a rate of 800 kg ha^{-1} and then mixed with the soil to 200 mm depth using a spade. Thereafter wheat (var: SST 826) was manually planted at a rate of 100 kg seed ha^{-1} in a row width of 300 mm, resulting in a final plant density of about 200 plants m^{-2}.

Figure 4.1 Wheat under the movable shelter (30 m long, 10 m wide and 4 m high), covering the lysimeter unit to prevent the influence of rain.

After the plant established, urea was applied at the rate of 220 kg ha^{-1} resulting in a total fertilizer application of 229 kg N ha^{-1}, 64 kg P ha^{-1} and 32 kg K ha^{-1}. The same wheat variety was planted in the area adjacent to the lysimeter unit with a precision planter at a rate of also 100 kg ha^{-1}. In this case the 4:2:1 (28) fertilizer mixture was band placed during planting with the precision planter. The urea was still manually applied after plant establishment. Fertilization rates in this adjacent area were similar to that in the lysimeters. Weeding was done manually with hand hoes and no pests or diseases were observed in either the lysimeter unit or field plot.

The water balance components were measured as described in Section 2.2.4.1. ET from the bare surface treatment between soil water measurements was calculated with Equation 4.7:

$$ET = (-\Delta W) + I - D \qquad (4.7)$$

Where ΔW is the change in soil water content, I is irrigation and D drainage. This equation by replacing ET with T was also used to calculate T from the gravel mulch treatments between soil water measurements. In this case it was assumed that E is negligible as shown in Section 3.3.1. Partitioning of ET into E and T was thus done by subtracting transpiration (measured on the gravel mulch treatment) from evapotranspiration (measured at the bare surface treatment).

The water contents for the soil profiles that correspond with the pre-selected allowable depletion level (ADL) and drained upper limit (DUL) were obtained in a similar way as described in Section 2.2.4.2.

The wheat in the lysimeters was harvested on 21 November 2007 for the first season and on 23 October 2008 for the second season by cutting the plants at their base. All heads were removed from the plants and then dried at 65°C for 72 hours. The dried heads were counted and threshed whereafter the grain and head residue were weighed separately. Other plant residues, *viz*. leaves and stems were also dried at 65°C for 72 hours before being weighed. Grain yield (GY) and above-ground biomass (AGB) yield (grain plus all remains) were then calculated.

The harvest index (HI) was expressed as the ratio of the grain yield to above-ground biomass yield.

Data on precipitation, evaporation and temperature for 2007 and 2008 were obtained from the automatic weather station about 300 m from the lysimeter unit that has records only since 1998. Therefore long-term data of this nature was extracted from a climate report by Botha (2006). This report is based on data of the weather station at Glen that has records for more than 80 years. The distance between the two weather stations is about 30 km.

The water use efficiency (WUE, kg ha^{-1} mm^{-1}) of wheat in the lysimeters was calculated with Equation 4.8:

$$WUE = Y/ET \tag{4.8}$$

Where Y is either in grain or above-ground biomass yield. This equation by substituting ET with T was used also to calculate WUE of wheat in the lysimeters with gravel mulch. Likewise, the transpiration efficiency coefficient (TEC, g kPa mm^{-1}) was calculated with Equation 4.9:

$$TEC = Y/ET(VPD) \tag{4.9}$$

Where VPD is vapour pressure deficit which was calculated as described in Section 2.2.4.4 using data from the nearby weather station. This equation by replacing ET with T was used also to calculate TEC of wheat in the lysimeters with gravel mulch. The mean VPD was 1.16 kPa for the 2007 season and 0.98 kPa for 2008 season.

Analysis of variance was conducted to establish significant differences amongst soils, surface treatments and years using the GLM Procedure of SAS System (Local, XP_PRO) (SAS Institute Inc., 1999). Variables such as grain yield, above-ground biomass yield, harvest index, water use, water use efficiency and transpiration efficiency coefficient were statistically tested and Fisher’s least significant difference (LSD) procedure for means comparison was applied (Fisher, 1935).

4.3 Results and discussion

4.3.1 Meteorological conditions

The weather during both the 2007 and 2008 wheat production seasons was favourable when the long-term climate serves as a reference (Table 4.1). For example the mean aridity index (AI) for June to November is 0.14. The AI for the same period was 0.24 in the 2007 season and 0.39 in the 2008 season.

Table 4.1 Long-term monthly and annual climate data from Glen meteorological station (ARC-ISCW); rain and temperature 1922 – 2003; evaporation 1958 – 2000 as reported by Botha (2006). Weather data (rain, temperature and evaporation) for the 2007 and 2008 growing seasons was obtained from the Kenilworth meteorological station (ARC-ISCW).

						Measurement period								
Variable	Period	Jan	Feb	Mar	Apr	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	Dec	Mean / total
Max. Temp. (°C)	LT	30.8	29.5	27.4	23.9	20.5	17.9	17.8	20.6	24.4	25.4	28.3	30.2	24.8
	2007	32.3	32.9	28.9	24.5	20.9	16.5	17.5	21.0	27.4	24.3	27.2	28.5	25.2
	2008	29.6	29.7	26.0	23.3	20.2	17.1	17.8	19.4	23.5	29.0	28.6	31.2	24.6
Min. Temp. (°C)	LT	15.3	14.8	12.6	7.8	2.8	-1.1	-1.6	0.9	5.2	9.2	12.0	14.0	7.5
	2007	15.3	15.6	12.4	10.5	3.6	1.6	2.4	3.2	9.2	11.1	11.6	14.7	9.3
	2008	16.2	16.1	13.4	7.2	8.2	3.2	2.2	2.9	5.2	11.5	13.7	15.5	9.6
Mean Temp. (°C)	LT	23.0	22.1	19.9	15.8	11.6	8.2	8.1	10.7	14.8	17.5	20.1	22.0	16.2
	2007	23.8	24.3	20.7	17.5	12.3	9.1	10.0	12.1	18.3	17.7	19.4	21.6	17.2
	2008	22.9	22.9	19.7	15.3	14.2	10.2	10.0	11.2	14.4	20.3	21.2	23.4	17.1
Precip. (mm)	LT	83.4	77.6	80.7	49.3	19.9	9.0	8.1	11.6	19.3	49.0	68.2	66.6	542.7
	2007	31.9	8.8	36.6	17.3	12.0	48.6	42.8	11.7	22.7	10.7	70.2	42.9	356.2
	2008	11.1	71.3	59.0	67.1	67.9	20.2	21.3	37.4	23.6	6.9	4.4	2.4	392.6
Evapo. (mm)	LT	276.5	207.7	177.1	126.1	110.6	81.9	93.5	140.6	197.5	239.1	256.0	291.6	2198.2
	2007	121.2	102.0	258.3	260.4	234.7	208.9	146.7	132.0	92.0	114.7	140.1	170.0	1981.0
	2008	147.5	80.0	106.6	96.9	101.6	123.2	98.0	41.7	67.1	79.5	106.6	128.0	1176.7
Aridity index	LT	0.30	0.37	0.46	0.39	0.18	0.11	0.09	0.08	0.10	0.21	0.27	0.23	0.25
	2007	0.26	0.09	0.14	0.03	0.05	0.23	0.29	0.09	0.25	0.10	0.50	0.25	0.19
	2008	0.08	0.89	0.55	0.70	0.67	0.16	0.22	0.90	0.35	0.09	0.04	0.02	0.39

LT = long term; Max = maximum; Min = minimum; Temp = temperature; Precip. = precipitation; Evapo = evaporation. Aridity index = precipitation / evaporation.

This suggests that growth conditions were better in the second than first season. However, rainfall amounted to 207 mm in the 2007 season and 177 mm in the 2008 season. This rain had no influence on the wheat in the lysimeter unit as it was covered with a rain shelter during rain events (Figure 4.1). There was one incidence on 1 May 2008 when it hailed that the shelter failed to cover the unit. However, the plants recovered fully because it occurred in the plant establishment phase of crop development. Temperature probably affected the yield in the 2008 season. The mean temperature in the 2008 season was 1^{o}C lower than in the 2007 season namely 13.4^{o}C versus 14.4^{o}C. There was also on 6 August 2008 severe frost during the reproductive phase which damaged some of the ears. Thus, it can be concluded that the weather differed between the two seasons which provides a platform to evaluate the effect thereof on wheat's transpiration efficiency for which it is often hypothesized that weather has no influence (Botha, 2006).

4.3.2 Irrigation management

The total amounts irrigated in the 2007 and 2008 growing seasons via either surface drip or sub irrigation and the resulting measured mean soil water contents (SWC) for the two soils and their two surface treatments are summarized in Table 4.2. Comparing the total water application in the 2007 with that in the 2008 season confirms the effect of weather described in the previous section. The atmospheric demand was considerably higher in the 2007 season than the 2008 season, hence explaining why irrigation in the 2007 season was on average 113 mm more than in the 2008 season. Partitioning of total irrigation into the contribution of the two methods revealed further that the 2007 season received on average 97 and 16 mm more water through the surface drip and sub irrigation systems, respectively, than the 2008 season.

Surface treatments affected the total water applied, irrespective of soil types. Total irrigation on the gravel mulch treatment was on average 22% lower than the bare surface treatment. This aspect will be dealt with in more detail in the following sections.

The water management approach adopted in this study resulted in very stable SWC in the profiles as indicated by very low coefficients of variation (CV's). A mean SWC over both growing seasons of 411 mm per 1800 mm (CV = 3%) for the Cv soil and 425 mm per 1800 mm for the Bv soil were recorded (CV = 3.4%). Further analysis indicated that the mean SWC were more stable in the 1200 – 1800 mm saturated zone (Cv soil: SWC = 205 mm and CV = 0.4%) and Bv soil: SWC = 207 mm and CV = 0.5%) than in the 0 –

1200 mm unsaturated zone (Cv soil: SWC = 206 mm and CV = 2.5% and Bv soil: SWC = 223 mm and CV = 8.6%). This phenomenon can be attributed to the daily recharge of the water table. Based on the mean SWC of the profiles and their low variation over seasons it can be stated that with the irrigation scheduling approach SWC was managed within the pre-selected drained upper limit and allowable depletion level values. The DUL and ADL were 425 mm and 255 mm per 1800 mm for the Cv soil and 468 mm and 310 mm per 1800 mm for the Bv soil, respectively.

Table 4.2 Mean seasonal irrigation and soil water content on Clovelly (Cv) soil and Bainsvlei (Bv) soil under bare and gravel mulch surface treatments for 2007 and 2008 seasons.

Variables	Year	Clovelly		Bainsvlei	
		Bare	Gravel	Bare	Gravel
Surface drip (mm)	2007	471	471	471	471
	2008	374	374	374	374
	Mean	423	423	423	423
Sub irrigation (mm)	2007	340	170	275	148
	2008	314	140	294	118
	Mean	327	155	285	133
Total irrigation (mm)	2007	811	641	746	619
	2008	688	514	668	492
	Mean	750	578	707	556
Soil water content θunsat zone 0-1200 (mm)	2007	197	221	224	248
	2008	198	207	191	228
	Mean	198	214	208	238
Soil water content θsat zone 1200-1800 (mm)	2007	204	204	208	206
	2008	204	206	205	206
	Mean	204	205	207	206
Soil water content Total profile 0 - 1800 (mm)	2007	401	421	416	454
	2008	403	419	396	434
	Mean	402	420	406	444

Bennie *et al.* (1994) and Ehlers *et al*. (2003) showed that irrigated wheat on similar soils does not experience water stress if the soil water level remains between ADL and DUL. According to Ehlers *et al*. (2003) the optimum water table level for these soils is 1200 mm for most field crops. Waterlogging is associated with water table levels shallower that 750 mm (Lal and Shukla, 2004). Thus, it can be concluded that it is highly unlikely that the plants could have experienced water or oxygen stress during either of the seasons.

4.3.3 Partitioning of evapotranspiration

The measured seasonal water use, namely mean evapotranspiration (obtained from bare surface treatment), transpiration (obtained from gravel mulch treatment) and evaporation (obtained by subtracting T from ET) for the 2007 season and the 2008 season are summarized per soil type in Table 4.3. Based on the differences in the weather between the two seasons, the slightly higher ET (3%) in the 2007 season than the 2008 season was expected. Interesting results were obtained amongst soils, where the ET values of the Cv soil were consistently higher than that of the Bv soil in both seasons. A closer evaluation revealed that the differences were not induced by E but rather T since E was similar for the two soils in both seasons while T was higher for the Cv soil than the Bv soil in both seasons.

Expressing T and E as a percentage of ET revealed that neither seasons nor soils are important determinants in the partitioning of ET since T varied between 74 and 76% of ET and E varied between 24 and 26% of ET, irrespective of soils and seasons (Table 4.3). Unfortunately, no other partitioning research on the wheat's ET could be found for comparison. The contribution of E to ET for wheat seems high as it was only 7% for canola (Chapter 3). On the other hand, Klocke *et al*. (1985) measured comparable E losses (20 to 30% of ET) for sprinkler irrigated maize in Kansas, USA. Similarly, E was also between 15 and 17% of ET for tomatoes in Spain (Fereres and Villalobos, 1990).

Data sets for seasons and soils were pooled because none of them affect the relative contribution of either E or T towards ET. As a result, the mean weekly ET, T and E values measured (data not shown) were expressed relative to the maximum weekly ET which was 49 mm week^{-1}. The resulting values were depicted in Figure 4.2 against the background of the four major growth stages, *viz*. the plant establishment stage, vegetative stage, reproductive stage and physiological maturing stage. This figure shows a close relationship between E, T and ET within growth stages. They all increased gradually in the vegetative stage and reached a peak during the reproductive stage, whereafter they gradually declined in the maturity stage.

Table 4.3 Partitioning of seasonal evapotranspiration (ET, mm) into its components of transpiration and evaporation for wheat grown on Clovelly (Cv) and Bainsvlei (Bv) for the 2007 and 2008 seasons

Season	Soil	ET (mm)	T (mm)	E (mm)	T (%)	E (%)
2007	Cv	715	536	178	75	25
	Bv	644	479	166	74	26
	Mean	680	507	172	75	26
2008	Cv	691	523	168	76	24
	Bv	635	470	165	74	26
	Mean	663	497	167	75	25
Mean (2007&2008)		671	502	169	75	25

This demonstrates further that transpiration never stops until the crop is harvested and amounted to between 70 and 80% of the total evapotranspiration. From a management point of view, literature generally suggests that E can be reduced during the plant establishment and the early vegetative stage through an increased plant population (Bennie *et al.*, 1997).

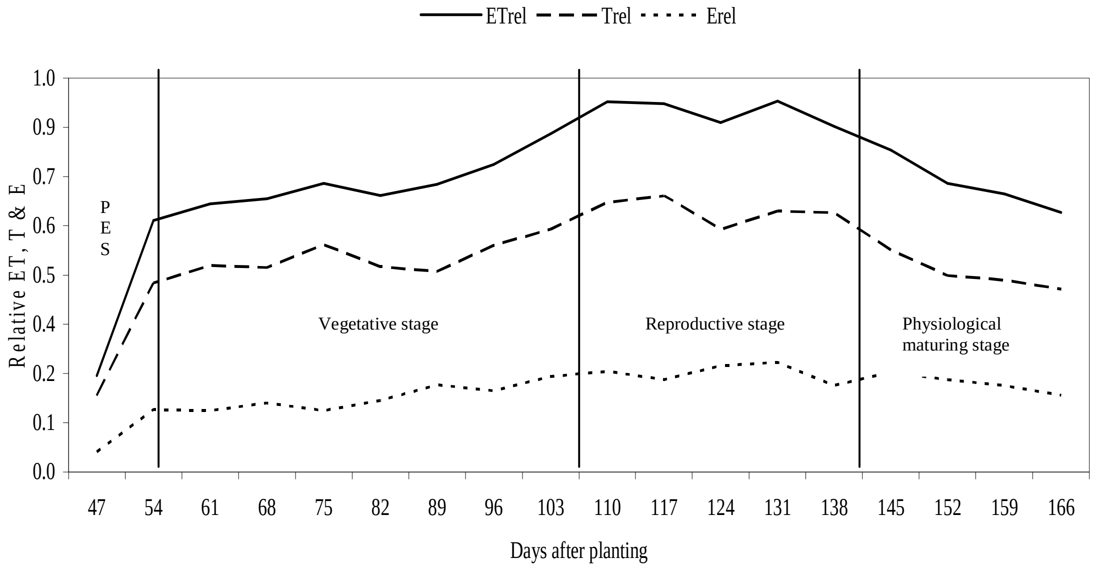

Figure 4.2 Mean relative evapotranspiration, relative transpiration and evaporation for the combined seasons. The values were expressed as a ratio to the maximum ET value (49 mm week^{-1}) obtained during the season. PES is the plant establishment stage.

This is because a higher plant population will ensure covering of the bare soil and therefore reducing direct radiation. Radiation is an important driver of evaporation in semi-arid environments. Despite the shading of the leaves, the results in Figure 4.2 suggested that a significant amount of water still evaporates during the vegetative, reproductive and maturing stages. This is probably due to the wetting of the soil surface during the weekly drip irrigation. Bennie *et al*. (1997) demonstrated the effect of irrigation frequency on ET for maize, wheat, peas and potatoes. They found that ET increased with an increased number of irrigation events. The higher ET values were not always accomplished with higher yields. Therefore they concluded that it was rather an amplification of E and not T.

4.3.4 Grain yield, above-ground biomass yield and harvest index

Analysis of variance on grain yield, above-ground biomass yield and harvest index indicated no significant interaction between soil and surface treatments. Therefore only the means of the main effects are given in Table 4.4. Soils did not affect either grain yield or above-ground biomass yield in both seasons. However, in 2008 the HI of wheat on the Cv soil was significantly lower than on the Bv soil. This can be attributed to frost which lowered the grain yield, but not the above-ground biomass yield. It is not clear why the plants on the Cv soil experienced more frost damage than on the Bv soil. The average grain yield for both seasons was 1443 kg ha^{-1} or 23% higher on the gravel treatment than on the bare surface treatment. A smaller difference (16.6% or 3395 kg ha^{-1}) was observed in the average above-ground biomass of the seasons for the gravel treatment compared to the bare treatment. This is due to the fact that above-ground biomass yield was only in 2008 significantly higher in the gravel surface treatment. As a result of this the HI was also only significantly higher in the 2008 season. It seems thus that the gravel mulch induced generally a higher grain yield which can probably be ascribed to better growing conditions during the reproductive stage. The better growing conditions resulted not necessarily from better water regimes because as explained in Section 4.3.2 the probability for water stress in the bare surface was minimal. However, a more favourable temperature in either the soil or plant canopy could have played a role. Gravel mulch is known to influence temperature regimes within and above the soil (Van Rensburg *et al*., 2003). This aspect warrants research in the future to clarify the higher grain yield under gravel mulching. Analysis of variance revealed that the average grain yield and harvest index in the 2007 season was significantly higher than in the 2008 season.

Table 4.4 Means of grain yield (GY), above-ground biomass (AGB), harvest index (HI) for bare and gravel mulch treatments on Clovelly (Cv) soil and Bainsvlei (Bv) soil for 2007 and 2008 seasons.

Variable	Year	Soil		Surface treatment		Mean
		Cv	Bv	Bare	Gravel	
Grain yield (kg ha^{-1})	2007	8925^{a}	9335^{a}	8316^{b}	9944^{a}	9130^{z}
	2008	4552^{a}	5188^{a}	4241^{b}	5498^{a}	4870^{y}
Above-ground biomass (kg ha^{-1})	2007	20659^{a}	21732^{a}	19873^{a}	22518^{a}	21196^{z}
	2008	22318^{a}	24069^{a}	21122^{b}	25265^{a}	23194^{z}
Harvest Index	2007	0.43^{a}	0.43^{a}	0.42^{a}	0.44^{a}	0.43^{z}
	2008	0.20^{b}	0.22^{a}	0.20^{b}	0.22^{a}	0.21^{y}

Means for soil and surface treatments in any one row followed by the same letter (e.g. a) are not significantly different at P = 0.05. Means for seasons in the last column followed by the same letter (e.g. z) are not significantly different.

The difference in grain yield was 4260 kg ha^{-1} which is a clear indication of the frost damage during the early reproductive stage of the 2008 season. In the 2007 season, an average grain yield of 9130 kg ha^{-1} realized with no environmental stress. This grain yield compares well with the mean grain yield of 9500 kg ha^{-1} measured by Ehlers *et al.* (2003) in the same lysimeter unit during the 1999 season. Similarly, the 2007 season's above-ground biomass yield compared also well with the mean above-ground biomass yield of 25138 kg ha^{-1} of Ehlers *et al.* (2003). Nulsen and Baxter (2004) reported above-ground biomass yield of 28200 kg ha^{-1} for wheat in Western Australia. The HI values obtained in this study especially in the 2007 season are close to the ones reported by Zhang *et al.* (1998) and Solomon and Labuscheagne (2003), namely 0.4 and 0.39 respectively.

4.3.5 Water use and water use efficiencies

The analysis of variance on water related variables (WU, TE and TEC) suggested no significant interaction between soil and surface treatments (Table 4.5). From the results it is clear that the soil treatments did not influenced any of the variables significantly.

Hence, the discussion will focus on the surface treatments which influenced the variables significantly (P = 0.05).

Water use from the gravel mulch treatment (T) was in both seasons lower than on the bare surface (ET) treatment, but it was only significant in the 2007 season. The higher water use from the bare surface treatment is attributed to the evaporation (E) as discussed in Section 4.3.3. Water use efficiency based on grain yield was in both seasons significantly higher on the gravel mulch treatment than on the bare surface treatment. The WUE based on above-ground biomass showed a similar trend. The results demonstrate the importance of reducing evaporation during irrigation practices. Similar results were obtained for the TEC values, where the gravel mulch treatment outperformed the bare surface treatment, irrespective whether it is based on grain yield or above-ground biomass yield.

Table 4.5 Means of water use, water use efficiency (WUE) and transpiration efficiency coefficient (TEC) for the main treatments, *viz.* soils (Clovelly, Cv and Bainsvlei, Bv) (bare and gravel surfaces) for 2007 and 2008 seasons. The subscripts GY and AGB refer to grain and above-ground biomass yields, respectively.

Variable	Year	Soil		Surface treatment		Mean
		Cv	Bv	Bare	Gravel	
Water use (mm)	2007	644^a	578^a	724^a	498^b	611^z
	2008	697^a	635^a	750^a	582^a	666^z
WUE_{GY} (kg ha^{-1} mm^{-1})	2007	13.86^a	16.15^a	11.48^b	19.96^a	15.36^z
	2008	6.53^a	8.17^a	5.65^b	9.44^a	7.45^y
WUE_{AGB} (kg ha^{-1} mm^{-1})	2007	32.08^a	37.60^a	27.45^b	45.22^a	35.59^z
	2008	32.02^a	37.90^a	28.16^b	43.41^a	35.37^z
TEC_{GY} (g kPa mm^{-1})	2007	1.61^a	1.87^a	1.33^b	2.31^a	1.78^z
	2008	0.64^a	0.80^a	0.55^a	0.92^a	0.73^y
TEC_{AGB} (g kPa mm^{-1})	2007	3.72^a	4.36^a	3.18^b	5.24^a	4.13^z
	2008	3.14^a	3.71^a	2.76^b	4.25^a	3.47^z

Means for soil and surface treatments in any one row followed by the same letter (e.g. a) are not significantly different at P = 0.05. Means for seasons in the last column followed by the same letter (e.g. z) are not significantly different.

Comparing the mean TEC values for the two seasons suggest that TEC based on grain yield differed significantly which was probably due to frost damage during the early reproductive stage in the 2008 season. However, it seems that the weather is not of importance when TEC is based on above-ground biomass yield. Only the TEC values from the gravel mulch treatment were of acceptable magnitude. For TEC values from the bare surface treatment to be of acceptable magnitude, the evaporation component must be deducted. Weather had no influence on TEC values based on above-ground biomass yield. The mean TEC_{AGB} of 5.24 g kPa mm^{-1} for 2007 season and 4.25 g kPa mm^{-1} for 2008 season compare well to other C_3 crops cultivated in the semi-arid regions. Clover *et al*. (2001) reported TEC values of 4.12 to 4.56 g kPa mm^{-1} for sugar beet. For groundnuts under varying conditions of vapour pressure deficit, TEC values of 1.50 to 5.20 g kPa mm^{-1} were found by Mathews *et al*. (1988) and Azam-Ali *et al*. (1989).

4.4 Conclusions

Three main conclusions can be drawn from the field lysimeter experiment on wheat conducted over two seasons in a semi-arid environment. Firstly, as expected from a semi-arid zone the weather conditions (aridity index, temperature, occurrence of frost and hail) differed enormously between seasons. Despite this difference, the results illustrates that neither the two soils nor seasons (weather) are important determinants in the partitioning of ET, since E varied between 24 and 26% of ET and T varied between 74 and 76% of ET over the two seasons. A detail analysis showed that large amounts of water evapourates during the different growth stages, probably due to the wetting of the soil surface during irrigations, and transpiration never stops until the crop is harvested. Secondly, the two soils did not influence grain or above-ground biomass yields, water use efficiency and the transpiration efficiency coefficient of wheat. These results confirmed that the method adopted for managing irrigation water ensured that the crop did not experience water or oxygen stress during any part of the season. For this reason the method can be recommended for similar studies. Thirdly, seasons affected the mean grain yield significantly, but not the above-ground biomass yield. Grain yield in the 2008 season was severely hampered by frost that occurred in the early reproductive stage. This effect was transferred to the corresponding water use efficiency and transpiration efficiency coefficient values. The TEC values for the 2007 season (5.24 g kPa mm^{-1}) was significantly higher than that of the 2008 season (4.25 g kPa mm^{-1}). However, both season's TEC values fell within the range of TEC values reported for other C_3 crops in the semi-arid environment despite some frost damage in the 2008 season. Any practice that reduces evaporation, runoff or other water losses to ensure that more water is available for transpiration will greatly increase grain yield in a semi-arid environment.

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Chapter five

Transpiration efficiency of irrigated lucerne under semi-arid conditions

Abstract

Lucerne is regarded as a luxurious water user and this necessitates a water scarce country like South Africa having proper knowledge of the crop's transpiration efficiency. The main aim of this study was to quantify the transpiration efficiency of lucerne for different cutting periods during its first growing season. Field lysimeters filled with Clovelly and Bainsvlei soils were used for the experiment which lasted from 13 March 2008 to 16 March 2009. The experiment was laid out as a split plot design with six cutting periods as treatments. In ensuring that the lucerne experienced no water stress surface drip irrigation was applied weekly and sub irrigation applied daily from a constant water table. Soil water content was measured thrice a week using a neutron water meter. Average transpiration varied between 173 mm for cutting period 3 and 210 for cutting period 2. Likewise, the transpiration rate ranged from 1.1 mm day^{-1} during cutting period 5 and 9.1 mm day^{-1} during cutting period 3. This variation can be attributed to environmental conditions like vapour pressure deficit as well as canopy structure. A mean transpiration efficiency of 2.81 g m^{-2} mm^{-1} and a mean transpiration efficiency coefficient of 2.84 g kPa mm^{-1} were derived for the growing season. Both variables declined however as the growing season progressed. The transpiration efficiency coefficients for lucerne in this study were consistent for that of other C_3 crops such as canola, wheat, common bean and groundnut. Future work should focus on whether physiological changes are responsible for the declining trend in the transpiration efficiency over the growing seasons.

Keywords: Soil water balance; transpiration efficiency; transpiration efficiency coefficient

5.1 Introduction

Lucerne *(Medicago sativa* L.) is one of the most widely used perennial legumes for grazing or hay and seed production in South Africa. Production statistics on the crop is generally lacking, especially for grazing. Estimations by Gronum *et al.* (2000) revealed that between 200 000 - 240 000 ha was used for hay production in the nineties, giving a mean yield of 3.8 million ton per annum. Over the period 2002 - 2009, the South African National Seed Organization (2010) estimated that more than 3 million ton of lucerne seeds was sold locally while about 200 000 ton was exported. The total market value based on retail selling price was ZAR160 million during the period under review. Comparing the statistics with that of the nineties indicated that there was not much expansion in the last decade. Thus, the seed was basically used to replant old fields because lucerne is grown for 4 to 5 years under irrigation and 6 to 9 years under dryland before it is replaced with other crops in the cropping system. Despite lucerne's high adaptability to drought and hence suitability for dryland farming (Carter and Sheaffer, 1983; Peterson *et al.*, 1992; Koukoura *et al.*, 1997), most of the hay (about 90%) is produced under irrigation in South Africa (Gronum *et al.*, 2000). The crop is generally perceived as a luxurious water user, *viz.* 800 - 1600 mm per growing season (Doorenbos and Kassam, 1979). This pressurized the already scarce water sources of South Africa. Backeberg *et al.* (1996) stated that the country had reached a point where there is no further water available for irrigation expansion, despite ample suitable soils. Situations like this motivate research to ensure efficient use of irrigation water in especially semi-arid areas. Unfortunately, water-related research on lucerne was severely neglected during the past two decades in South Africa. International literature indicates that lucerne has a high water requirement compared to other crops (Krogman and Hobbs, 1965; Daigger *et al.*, 1970; Blad and Rosenberg, 1976).

According to Sinclair *et al.* (1984), biomass accumulation is "inextricably linked to transpiration", and Cowan (1977) proposed that plants dynamically adjust their stomata to maintain an optimal balance between photosynthesis and transpiration. The point is that although transpired water is not incorporated into carbohydrates, consumption of water inevitably accompanies photosynthesis. Hanks *et al.* (1969) argue that there exists a close relationship between dry matter yield and transpiration. This is especially true in water-limiting conditions found in the arid and semi-arid environments.

A number of reports showed linear relationships between cumulative dry matter production and cumulative water use for lucerne (Bauder *et al*., 1987; Bolger and Matches, 1990; Grimes and El-zik, 1992). These relationships may vary from one climatic region to another (Hill *et al*., 1983), from one season to another, and from one harvest to another during the growing season (Myer *et al*., 1991). Water use efficiency based on ET ranges between 11 and 23 kg ha^{-1} mm^{-1} with greater values in the cooler climates (Kisselbach *et al*., 1929; Stanhill, 1986; Bolger and Matches, 1990; Grimes and El-zik, 1992). Earlier studies of numerous species grown under screen shelters in large containers (Briggs and Shantz, 1914; de Wit, 1958 as cited by Hanks 1983) showed that relative to crops such as small grains, lucerne produces less shoot biomass per unit of water transpired. In other words, transpiration efficiency (TE) for shoot biomass production is low. This conclusion is supported by TE comparisons using data from reports where lucerne and other crops were grown as communities in the field (Teare *et al*., 1973; Hanks, 1983; Tanner and Sinclair, 1983; Nulsen and Baxter, 2004). Tanner and Sinclair (1983) suggested that transpiration is a function of total biomass (roots plus shoots) and integrated vapour pressure deficit to normalize the effect of weather.

Lucerne plays a significant role in the agronomic sustainability of irrigation schemes in South Africa and probably in most other irrigations schemes in the world. Firstly, it provides an economically viable opportunity to farmers in breaching the undesirable wheat-maize crop rotation system often used. Secondly, as shown in a recent study at Vaalharts and Riet River Irrigations Schemes (Van Rensburg *et al*., 2010), through its well developed rooting system and apparently high water use it helps to control the level of shallow water tables in these schemes and hence prevent waterlogging. It is impossible to sort out the water balance components under shallow water table conditions, especially transpiration when there is constant recharge of the water table from other water sources than irrigation. A reliable transpiration efficiency coefficient (TEC) value is required so that transpiration could be estimated from the measured biomass. Such a coefficient will enable the SWAMP and other models (Bennie *et al*., 1998) to simulate the contribution of lateral inflow towards transpiration under water table conditions. The aim of this study was to quantify the transpiration efficiency and transpiration efficiency coefficient of lucerne for different cutting periods during its first growing season.

5.2 Materials and methods

The experiment was conducted at the lysimeter unit described in Section 2.2.1. This unit consists of 30 lysimeters whereof 15 of them are filled with a sandy soil (Clovelly, Cv) and the other 15 with a sandy loam soil (Bainsvlei, Bv). Only 12 of the lysimeters, namely six from the Cv soil and six from the Bv soil were used for this experiment.

Figure 5.1 Lucerne under the movable shelter (30 m long, 10 m wide and 4 m high), covering the lysimeter unit to prevent the influence of rain.

The surfaces of all 12 lysimeters were covered with a 50 mm thick dolerite gravel mulch to restrict evaporation to the minimum during transpiration. The experimental layout was based on a split plot design with two soils (Bv and Cv) and six cutting periods (CP) for lucerne, (CP1 = 188 -216 DAP, CP2 = 217 – 249 DAP, CP3 = 250 – 277 DAP, CP4 = 278 – 307 DAP, CP5 = 308 – 340 DAP and CP6 = 341 – 368 DAP). These cutting periods represent the intervals between biomass samplings (15 September, 15 October, 17 November, 15 December, 15 January, 16 February and 16 March) during the first production season of 2008/2009.

Prior to planting a fertilizer mixture with a composition of 4:2:1 (28) was manually broadcast at a rate of 600 kg ha^{-1} together with 2000 kg ha^{-1} superphosphate, resulting in an application of 96 kg N ha^{-1}, 258 kg P ha^{-1} and 24 kg K ha^{-1}. The fertilizer was mixed with the soil to 200 mm depth using a spade. Lucerne (var: SA Standard) was planted manually at a rate of 20 kg ha^{-1} on 13 March 2008 in a row width of 300 mm. After the plants established, the soil surface of all the lysimeters were covered with 50 mm thick gravel mulch. This variety was also planted in a similar manner adjacent to the lysimeter unit on a 20 m x 20 m area for root sampling. Weeds were manually controlled with hand-hoes and there were no pests or diseases during the experiment period in both the lysimeter unit and field plot. Lucerne was irrigated once a week with a sprinkler irrigation system and was used specifically for root measurements.

Measurements and calculations for obtaining the soil water balance components were the same as described in Section 2.2.4.1 and therefore not repeated here. In this study however the lysimeters were covered with gravel mulch and hence evaporation was assumed negligible as shown in Section 3.3.1. Thus transpiration (T) was calculated as follows:

$$T = (-\Delta W) + I - D \qquad (5.1)$$

Where ΔW is change in soil water content, I, irrigation and D, drainage.

The allowable depletion level, drained upper limit (DUL) and the lower limit (LL) of plant-available water were obtained in a similar way as described in Section 2.2.4.2.

Root samples for mass determination were manually collected from the area adjacent to the lysimeter unit at the same time when lucerne was cut. The procedure applied was exactly as described in Section 2.2.4.3.

Above-ground biomass was determined when the lucerne was 50% in flowering. Plants on an area of 2.5 m^{-2} per lysimeter were cut at their base, oven dried at 65^{o}C for 72 hours and then weighed.

Weather data was extracted from the records of the automatic weather station located at Kenilworth research station. Calculations were done using the relationship described in Section 2.2.4.4.

For every cutting period the transpiration efficiency (TE, g m^{-2}) and transpiration efficiency coefficient (TEC, g kPa mm^{-1}) of lucerne were calculated respectively with Equation 2.7 and Equation 2.10 as described in Section 2.2.4.5. A calculation of both variables was based only on above-ground biomass for reasons given earlier. The vapour pressure deficit values used in the calculation of TEC were 1.10, 1.18, 0.86, 0.96, 0.99 and 0.96 kPa for cutting periods 1 to 6, respectively.

Analysis of variance was conducted to establish significant differences between soils and cutting periods using the GLM Procedure of SAS System (Local, XP_PRO) (SAS Institute Inc., 1999).Variables such as above-ground biomass, transpiration, transpiration efficiency and transpiration efficiency coefficient were statistically tested and Fisher's least significant difference (LSD) procedure for means comparison was applied (Fisher, 1935).

5.3 Results and discussion

5.3.1 Impact of irrigation strategy on soil water regimes

Results on irrigation application (a) and soil water content (b) are presented in Figure 5.2 for the Cv soil and in Figure 5.3 for the Bv soil. Irrigation through surface drip (IRsd) amounted to a total of 79 mm per cutting period in both soils, i.e. one application per week over four weeks. These fixed or main irrigation events were supported by smaller sub irrigations (IRs) to ensure that daily water demand of the crop is met. The daily amounts irrigated this way varied between 1.7 and 9.8 mm over the season. This approach resulted in a variable total irrigation (IRsd + IRs) for cutting periods that ranged from 168 mm in CP4 to 201 mm in CP2.

Another feature of the adopted irrigation approach is that it resulted in very low fluctuation of soil water contents (SWCs) over the cutting treatments for both soils, *viz*. between 374 and 407 mm for the Cv soil and between 426 and 460 mm for Bv soil. Further analysis showed that the variation of the SWCs of the unsaturated and saturated zones irrespective of soil type were both very low, *viz*. <4% in the unsaturated zone and <2% in the saturated zone. This phenomenon can be attributed to the irrigation methods followed. The sub irrigation method influenced the SWCs of the saturated zone directly, as it was recharged on a daily basis. This daily recharging of the saturated zone indirectly stabilized the SWCs of the unsaturated zone through capillary supply. Ehlers *et al*. (2003) estimated that the capillary rise above the water table is 659 mm in the Cv soil and 822 mm in the Bv soil. Hence, the observed variation in the SWCs of the unsaturated zone can be attributed towards the surface drip irrigation method, which allowed the topsoil to dry between the weekly irrigations. Overall, it can be concluded that the combined effect of irrigation method and irrigation frequency in the experiment had led to very stable SWC of the profiles.

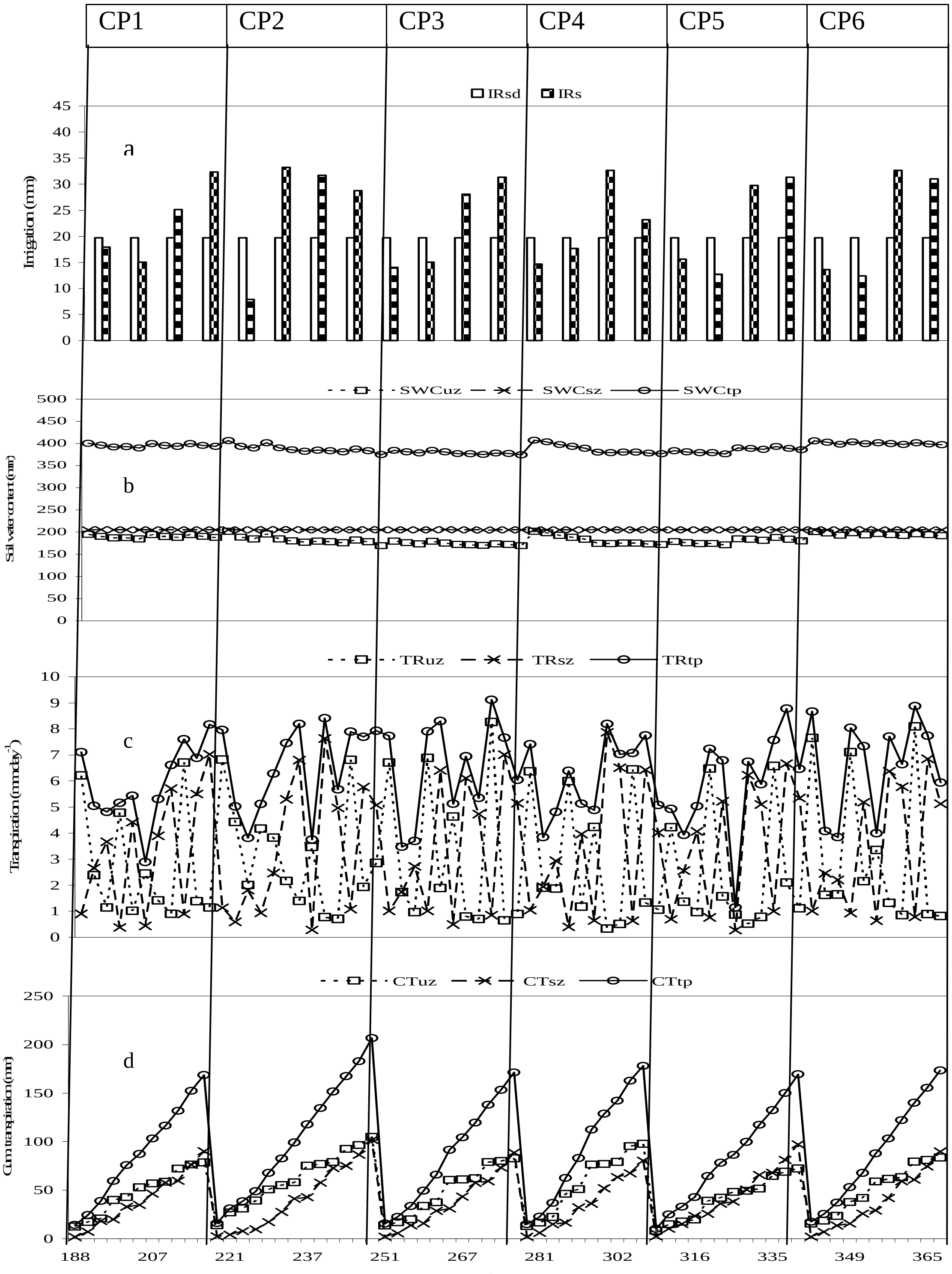

Figure 5.2 Soil water balance components during six cutting periods of lucerne on the Clovelly soil: (a) irrigation (IR), (b) soil water content (SWC), (c) transpiration rate (TR) and (d) cumulative transpiration (CT). sd = surface drip; s = sub irrigation; uz = unsaturated zone; sz = saturated zone; tp = total profile.

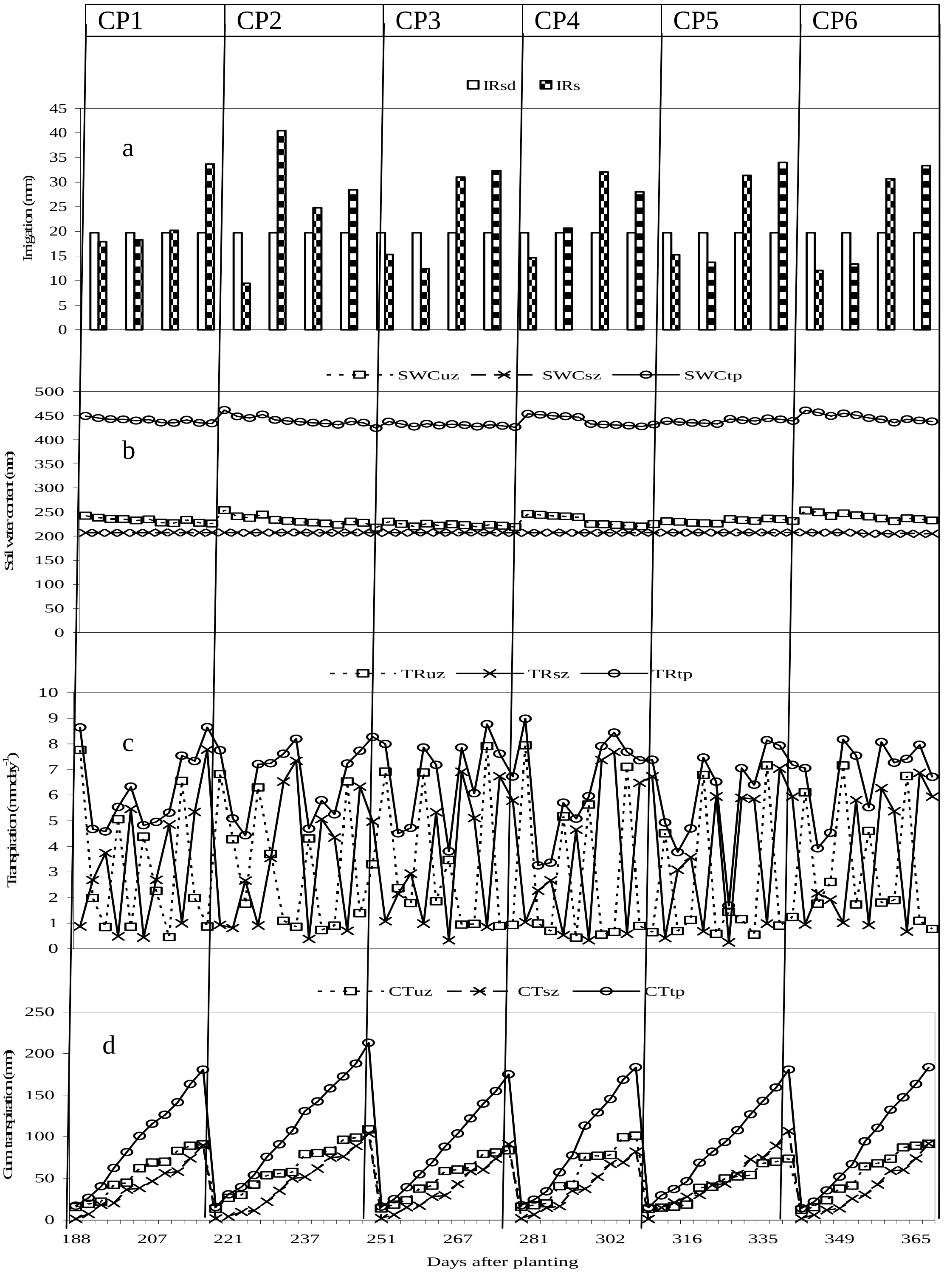

Figure 5.3 Soil water balance components during six cutting periods of lucerne on the Bainsvlei soil: (a) irrigation (IR), (b) soil water content (SWC), (c) transpiration rate (TR) and (d) cumulative transpiration (CT). sd = surface drip; s = sub irrigation; uz = unsaturated zone; sz = saturated zone; tp = total profile.

Taken into account that the total soil water contents were never near the pre-selected allowable depletion values of 233 mm per 1800 mm for the Cv soil and 313 mm per 1800 mm for the Bv soil, reveals that there was no risk of plant water stress during the season. The risk of oxygen stress caused by poor management of the water table levels can be excluded in the experiment. Lal and Shukla (2004) and Surya *et al*. (2006) demonstrated that water tables shallower than 500 mm result in waterlogging that is restrictive to root respirations. The stable water contents of the saturated zone over the season in both soils, confirm the effort made to control the water table levels in the lysimeters.

5.3.2 Contribution of unsaturated and saturated zones to transpiration

The daily (c) and cumulative (d) transpiration during each of the six cutting periods are plotted in Figure 5.2 for the Cv soil and in Figure 5.3 for Bv soil. Within the entire soil profile (0 - 1800 mm), transpiration over the cutting periods ranged from 1.2 to 9.1 mm day^{-1} for Cv soil and from 3.4 to 9 mm day^{-1} for the Bv soil. Cumulative transpiration was from the unsaturated zone 56% and from the saturated zone 44% of the total transpiration in the Cv profile and Bv profile. This phenomenon can be attributed to the irrigation management strategy used which exploited both the rooting characteristics of the crop and capillary forces of the soils.

Lucerne is renowned for its deep taproot system that proliferates well over depth (Metochis, 1979; Gherardi and Rengel, 2003) as confirmed by the root length density and mass results of the six cuttings (Figure 5.4). It should be kept in mind that the rooting pattern reflects on the plot adjacent to the lysimeter. Therefore, root distribution in the lysimeters was probably restricted to the unsaturated zone (0 – 1200 mm), as it is documented that roots do not grow within saturated zones under field conditions (Ehlers *et al*., 2003). Converting the rooting density (mm mm^{-3}x10^{-3}) data into total root length per unit area (mm mm^{-2}) indicates that the roots below 1200 mm depth contributed only 28% towards the total root length (11 mm mm^{-2}) or 6% of the total root mass. Thus, emphasizing the role of roots in the unsaturated zone in supplying water to the canopy.

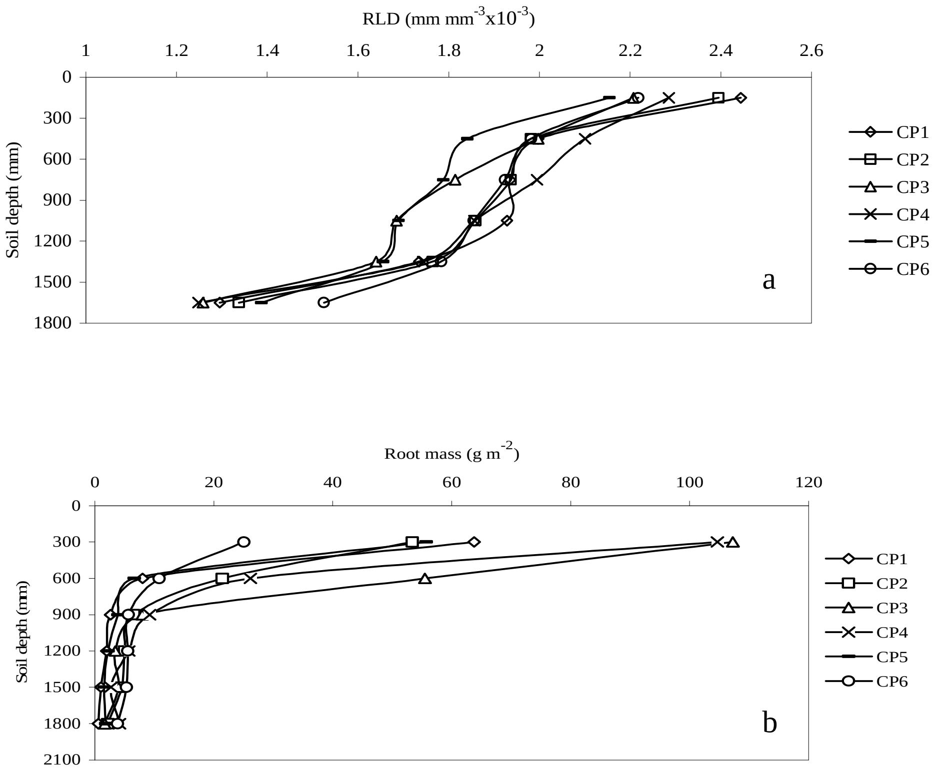

Figure 5.4 Root distributions expressed in (a) mm $mm^{-3}x10^{-3}$) or root length density (RLD) and (b) in g m^{-2}, measured in a field plot adjacent to the lysimeter unit. CP = cutting period.

Doorenbos and Kassam (1979) also stated that lucerne has a deep rooting system extending up to 3000 mm in deep soils and that the maximum root depth is reached after the first year. They are of the opinion that the crop can draw water from a great soil depth and little responses to irrigation have been shown with groundwater tables at 2000 mm or shallower. Estimations made with the capillary height predictive equation of Ehlers *et al.* (2003) suggested that the capillary fringe reaches vertical distances of 659 mm above the water table in the Cv soil and 822 mm in the Bv soil. Thus, a large section of the unsaturated zone (0 – 1200 mm), especially in the Bv soil could be supplied by recharging of the water table. The effect was that the surface drip irrigation supplied on average 78 mm and the sub irrigation 106 mm of the crop water demand per cutting cycle.

5.3.3 Effect of cutting periods

Analysis of variance revealed that the two soils influenced neither biomass yields nor any transpiration efficiency variables. Therefore, the two soils were regarded as replications for the purpose of comparing the six cutting periods (Table 5.1).

5.3.3.1 Biomass production

Above-ground biomass yield decreased significantly ($P = 0.05$) from 615 g m^{-2} in CP1 to 413 g m^{-2} in CP6. Thus CP1 produced 20% and CP6 13% of the total above-ground biomass that amounted to 3064 g m^{-2}. A similar trend was described by Andueza *et al.* (1999) who reported cumulative above-ground biomass yields of between 231 and 314 g m^{-2} in Zaragoza, Spain. Contreras-Govea *et al.* (2008) observed in the Southern High Plains, USA mean above-ground biomass yields of 403 and 406 g m^{-2} per cutting for 2007 and 2008 seasons, respectively. Martiniello *et al.* (1996) reported in Italy above-ground biomass yields of 260 to 289 g m^{-2} per cutting. Doorenbos and Kassam (1979) obtained 200 to 250 g m^{-2} per cutting period of 25 to 30 days in Davis, California, USA.

The differences in above-ground biomass yields in this study and other studies can be attributed *inter alia* to environmental and experimental conditions that differed. Another contributing factor could be the kind of cultivar used. In general, annual yields of lucerne decline with age of stand. This decline is accelerated by factors such as winter and summer damage, pests and diseases, and mismanagement (Corletto *et al.*, l994).

Root mass over the profile varied from 0.6 to 104 g m^{-2} between samplings (Figure 5.3b). No particular trend was observed as for above-ground biomass. However, the role and function of lucerne roots have been explained by Gramshaw (1994) who stated that the periods of storage and utilization of the carbohydrate root reserves follow a cyclic pattern. The percentage of total nonstructural carbohydrate in the roots declines with the initiation of growth after each cutting and increases as the re-growth approaches flowering. The build up to the total root mass signify the trend of non structural carbohydrates reserves in the roots of lucerne, which is used to produce new vegetative growth and energy for many of the processes that occur within the plant.

Table 5.1 Means of irrigation applications, above-ground biomass and transpiration efficiencies per cutting periods.

Variable	Cutting period						LSD
	CP1	CP2	CP3	CP4	CP5	CP6	
Surface drip (mm)	78.8	78.8	78.8	78.8	78.8	78.8	nd
Sub irrigation (mm)	100.3	121.9	103.0	89.6	114.7	104.6	nd
Total irrigation (mm)	179.1	200.7	181.8	168.4	193.5	183.4	nd
Above ground biomass (g m^{-2})	615^{a}	568^{a}	550^{ab}	479^{bc}	439^{c}	413^{c}	76.70
Transpiration (mm)	175^{c}	210^{a}	173^{c}	182^{b}	175^{bc}	178^{bc}	9.20
TE_{AGB} (g m^{-2} mm^{-1})**	3.51^{a}	2.71^{bc}	3.18^{ab}	2.63^{c}	2.51^{c}	2.32^{c}	0.53
TEC_{AGB} (g kPa mm^{-1})**	3.86^{a}	3.20^{b}	2.73^{bc}	2.52^{c}	2.50^{c}	2.22^{c}	0.51

Means in any one column followed by the same letters are not significant at $P = 0.05$.
LSD = least significant difference
** TE & TEC based on above-ground biomass.
nd = not determined

The current experimental set up where lysimeters are used for determining above-ground biomass and a field plot for studying roots are not ideal to capture the delicate exchange of carbohydrates between roots and shoots during cutting periods. Therefore because of the high coefficient of variation of total root mass amongst samplings (22.8%) it was decided not to calculate total biomass. Additionally, root growth and development are influenced by many factors such as climatic conditions soil environment, plant species, etc. (Gramshaw, 1994; Asseng *et al.*, 1998; Xue *et al.*, 2003).

5.3.3.2 Transpiration efficiency

The TE values for above-ground biomass decreased from 3.51 g m^{-2} mm^{-1} in CP1 to 2.32 g m^{-2} mm^{-1} in CP6 (Table 5.1). This phenomenon is probably because of better growing conditions in the beginning of the season and the potential to use stored carbohydrates in the roots (Gramshaw, 1994). The average TE value over the six cutting periods was 2.81 g m^{-2} mm^{-1}. This value is found to be within the range of values reported by other authors. For example Tow (1993) found that the TE of lucerne ranged in New South Wales, Australia from 1.7 to 3.1 g m^{-2} mm^{-1}. (Singh *et al.*, 2007) observed in Central India TE values of 0.9 to 2.5 g m^{-2} mm^{-1} for lucerne. Thus, TE values of lucerne can vary considerably during the season like in this study and also between growing cycles and years as in other studies due to variation in vapour pressure deficit and canopy structure. Analysis of Tanner and Sinclair (1983) indicates that the upper limit of transpiration efficiency is genetically and environmentally determined with the environmental limit being a function of the integrated vapour pressure deficits over the growing season.

5.3.3.3 Transpiration efficiency coefficient

As suggested by Tanner and Sinclair (1983), vapour pressure deficit (VPD) values were used in normalizing the weather and the resulting TEC values for different cutting periods are summarized in Table 5.1. TEC values based on above-ground biomass revealed significance differences (P = 0.05) between cutting periods. As in the case of TE, TEC decreased from 3.86 g kPa mm^{-1} in CP1 to 2.22 g kPa mm^{-1} in CP6.

Barnard *et al*. (1998) working on legumes (lucerne, soybean, sorghum and cowpea) determined TEC values ranging from 2 to 2.5 g kPa mm^{-1}. Although the mean TEC value of the six cutting periods (2.84 g kPa mm^{-1}) is in the same category as that reported by Barnard *et al*. (1998), the study showed clearly that TEC declined gradually as the growing season progressed. The reason for this probably lies in the roots which can either be a sink or source of carbohydrates. This aspect could not be determined in the current experiment due to facility constraints, but warrants further research.

5.4 Conclusions

This study on lucerne in lysimeters filled with a sandy Clovelly soil and a sandy loam Bainsvlei soil entailed detailed measurements of the soil water balance to quantify the efficiency of transpiration of the crop. It can be concluded that irrigation scheduling played a significant role in creating optimum conditions for the crop to thrive well throughout the season. Lucerne grown in the lysimeters although individually irrigated could transpire optimally without any water or oxygen stress which attests to the effectiveness of irrigation scheduling. The unsaturated and saturated zones contributed 56% and 44% respectively of the total transpiration irrespective of soil. During the first growing season lucerne's transpiration efficiency and transpiration efficiency coefficient decreased over time. This is due to progressively lower above-ground biomass production. No explanation could be given for why there is disparity in terms of biomass production as all cutting periods were treated equally. The mean transpiration efficiency (2.81 g m^{-2} mm^{-1} and transpiration efficiency coefficient (2.84 g kPa mm^{-1}) for the six cutting periods compares well with values reported by researchers elsewhere. Lucerne grown under semi-arid conditions should be irrigated more frequently with smaller amounts of water to attain high transpiration efficiencies that coincide with high yields. The transpiration efficiency coefficient obtained in this study is consistent with values reported for other C_3 crops and can therefore be used in separating evapotranspiration into its components. Further research is suggested to clarify the decline of above-ground biomass production as the growing season progressed.

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Chapter six

Summary, recommendations and further studies

6.1 Summary

As can be derived from the title of the thesis, the theme or broader application of the study is centered on the soil water balance with the aim of improving water management of field crops. The focus of this study, however, was on the determination of transpiration efficiencies, specifically the transpiration efficiency coefficient (TEC). TEC is a very important variable that relates to the efficiency of water management to crop production. It is defined as the ratio of seed or biomass yield to the product of transpiration and vapour pressure deficit. That's why it is of utmost importance to measure these variables, of which transpiration is the most difficult to obtain under field conditions. Transpiration is often given as an integrated component of evapotransporation (ET), the sum of evaporation from the soil (E) and transpiration from the plant (T) in soil water balance studies: $\Delta S = I + P - R - D - ET$, where ΔS is the change in soil water content, I is irrigation, P is precipitation and D is drainage. Hence, the main aim of the experiments conducted for this study was to partition ET into its components of E and T.

There are indirect and direct methods available for partitioning ET. Most researchers resorted to the use of micro-lysimeters for measuring the E component of ET. The disadvantage of the method is its sensitivity to spatial variability, especially when the soil is wet. Another method is the use of weighing lysimeters where the crop is planted in a large volume of soil (more than 1 m^3) and water losses can be controlled and measured on a mass basis using load cells. However, the main disadvantage is the high cost associated with the equipment, installation and maintenance of such systems.

In this study, the well established non-weighing lysimeter unit of the University of the Free State at Kenilworth near Bloemfontein was used for conducting experiments with canola, wheat and lucerne (Table 6.1). It covers an experimental area of 70 m x 35 m. In the center of the area, 30 round plastic lysimeters (1.8 m diameter and 2 m deep) are buried in the soil in two parallel rows of 15 each, with their rims 50 mm above the bordering soil surface. One row of lysimeters was filled with a sandy Clovelly Setlagole

(Cv) soil and the other row with a sandy loam Bainsvlei Amalia (Bv) soil. An underground chamber (1.8 m wide, 2 m deep and 30 m long) allows access to the inner walls of the lysimeters with an opening at the bottom of each lysimeter connected to a manometer and a bucket used for recharging the water tables on a pre-selected level. Each lysimeter is equipped with two neutron probe access tubes. A movable shelter (30 m long, 10 m wide and 4 m high) is available to cover the lysimeter unit to prevent any interference by rain. In this unit, changes in soil water contents were measured with the renowned Campbell Pacific Neutron Water Meter instead of load cells.

Irrespective of the use of weighing or non-weighing lysimeters, the problem of separating E from ET requires the minimizing or ultimately the prevention of E during the evapotranspiration process. In most ET partitioning field experiments, evaporation from the soil is minimized by covering the exposed soil surface with plastic sheets. The use of plastic cover has a risk of interfering with gas exchange between the soil-root system and the atmosphere. Therefore, an alternative way of restricting E without impeding gas exchange was introduced. The method involved the placement of a 50 mm thick dolerite gravel mulch (mesh size of 10 mm) on the surface of the lysimeter with the aim of evaluating the effectiveness of gravel mulch to plastic mulch in reducing evaporation. The experiment reported in Chapter 3 revealed that evaporation from the gravel mulch was only 3% higher than from the plastic mulch irrespective of soils. It was concluded that the gravel mulch can replace the plastic sheets on the soil surface of the lysimeters for studying the TEC of crops. Crop water use on gravel mulched lysimeters, therefore, represents transpiration.

Based on above findings, two experiments were done with the aim of partitioning ET of canola (Chapter 3) and wheat (Chapter 4) into its components using the soil water balance. These experiments were based on a split plot, with two soils (Cv and Bv) and two surface treatments which comprised of (i) a bare soil for measuring evapotranspiration and (ii) a 50 mm thick gravel mulch for measuring transpiration. Gravel mulch was applied after establishing the two crops. The soil water balance components measured were ET from the bare surface treatment, T from the gravel mulch treatment and E was derived by subtracting T from ET. The main results on ET, E and T of the experiments (canola 2007 and wheat 2007 and 2008) are summarized in Table 6.1.

From these results it was clear that soils had no effect on these variables, mainly because of the careful management of irrigation. The percentage of evaporation in relation to total evapotranspiration differed markedly amongst canola (12% of total ET which was 809 mm) and wheat (27% of total ET which was 639 mm). It was similar for transpiration, where canola transpired 718 mm or 88% of total ET and wheat 489 mm or 63% of total ET. Thus, it is clear that the two crops should be managed differently with respect to their individual irrigation water demands.

The remaining part of the study centered on water use efficiency and specifically the determination of the TEC of selected C_3 crops (plants that form a pair of three carbon-atom molecules during the first steps in CO_2 assimilation), namely canola, wheat and lucerne. The experiments can be grouped, *viz*. where the TEC values were determined for growth periods (canola 2006, Chapter 2), as an integrated value for the season (wheat 2007 and 2008, Chapter 4) and for individual cuttings (lucerne 2008/09, Chapter 5). Due to the different aims, the experimental designs differed somewhat. However, in all of them the soil water balance was measured in lysimeters, where T was obtained from gravel mulched ones. Details of the experimental layouts and treatments are summarized in Chapters 2, 4 and 5 for canola, wheat and lucerne, respectively. TEC can be expressed either as grain (G) or seed (S) yield, above-ground biomass yield (AGB, which includes grain or seed plus all the remaining aerial parts) and total biomass (TB, which includes all above-ground parts plus roots). The results on TEC for wheat, canola and lucerne are summarized in Table 6.1. TEC values for canola differed significantly amongst growth periods but not between soils. Both TEC_{ABG} and TEC_{TB} increased from GP1 (84 – 98 DAP) to GP2 (98 – 112 DAP) and then decreased to GP4 (126 – 140 DAP). The lower values of TEC at GP4 were attributed to lower efficiencies associated with leaf senescence and transpiration by either green pods or stems. For growth periods, TEC_{ABG} varied between 3.82 and 4.95 g kPa mm^{-1}, while TEC_{TB} fluctuated between 3.94 and 5.04 g kPa mm^{-1}. These values compared well with that of other C_3 crops reported in literature.

Comparing the mean TEC values for the two wheat seasons suggested that TEC based on grain yield was significantly affected by seasons, probably due to the impact of frost during the early reproductive stage in 2008. However, it seems that weather is not of importance when TEC is based on above-ground biomass since it was quite similar for the two seasons. The mean TEC_G (1.62 g kPa mm^{-1}) and TEC_{AGB} (4.75 g kPa mm^{-1}) for the two seasons compare well to TEC's of other C_3 crops cultivated in semi-arid areas.

TEC values based on above-ground yield of lucerne revealed significance differences ($P = 0.05$) between cutting periods. TEC decreased from 3.86 g kPa mm^{-1} in CP1 (188 – 216 DAP) to 2.22 g kPa mm^{-1} in CP6 (341 – 368 DAP). Although the mean TEC value of the six cutting periods (2.84 g kPa mm^{-1}) is in the same category as that reported by other authors, the study showed clearly that TEC declined gradually as the growing season progressed.

The experiments also provided additional information with respect to water management in lysimeters and the contribution of water tables towards total transpiration.

Water management in lysimeters: An important factor that can affect TEC determinations is undesired plant water stress induced by poor irrigation management. Water stress in plants can influence the TEC's of crops and for this reason it is of utmost importance that the soil water contents are managed in such a way that plants do not experience water stress during any part of the growing season. Hence, two irrigation methods were introduced to ensure that soil water content never drops below 50% of the plant-available water level, also called the allowable depletion level. During the growing seasons, the top-soil was irrigated with a surface drip system and the water table was recharged with a sub irrigation system. Both systems were manually controlled and irrigation timing (not amounts) was fixed, *viz*. weekly for surface drip and daily for sub irrigation. Sub irrigations were aimed at keeping the water table at a constant level of 1200 mm from the surface. Managing of irrigations according to these principles resulted in very stable soil water contents in both soils. Water contents were measured with a neutron soil water meter in 300 mm depth intervals over the total profile, three times a week. Evidence of the stable water contents can be seen in the coefficient of variation (CV) of these measurements for the total profile (PRO, mm/1800 mm), unsaturated zone (UZ, mm/1200 mm) and saturated zone (SZ, mm/600 mm) in Table 6.1 for all experiments.

The results indicated that the soil water content never dropped below the allowable depletion levels in any of the experiments (results not shown here), neither did the water table height induce any oxygen stress to crops at any stage. From these results it can be concluded that the irrigation approach was effective in preventing water stress and is therefore recommendable for experiments using non-weighing lysimeters.

Table 6.1 Means of soil water content (SWC), water use (WU), water table contribution (WTC), yields and transpiration efficiency coefficients (TEC) for canola, wheat and lucerne for 2006 to 2009 respective seasons.

Variable		Canola							Wheat				Lucerne							
		2006						2007					2008/2009							
		Growth period											Cutting period							
		1	2	3	4	Mean	CV		2007	2008	Mean	CV	1	2	3	4	5	6	Mean	CV
SWC (mm)	PRO	367	379	381	373	375	3	440	411	411	411	0.0	395	386	379	389	385	400	389	2.0
	UZ	176	187	187	182	183	3	200	204	205	205	0.3	205	205	205	205	205	205	205	0.0
	SZ	191	193	194	191	192	2	240	209	203	206	2.2	190	181	174	184	180	195	184	4.2
WU (mm)	ET							809	644	633	639	0.0								
	E							91	172	167	170	0.0								
	T	53	136	236	342	192	65	718	507	470	489	0.1	88	103	88	94	84	89	89	8
WTC (%)	ET							45	46	42	44	6								
	T	42	53	55	54	51	12	40	33	28	31	12	46	41	43	39	51	43	44	10
Yield (g m^2, kg ha^{-1})	G / S							2593	9130	4870	7000	43								
	AGB	251	281	297	231	265	30						615	568	550	479	439	413	511	16
	TB	260	286	302	236	271	29	8285	21196	23193	22195	7								
TEC (g kPa mm^{-1})	G / S								2.3	0.9	1.6	57								
	AGB	3.8	5.0	4.2	3.8	4.2	13						4.0	3.3	2.9	2.7	2.6	2.3	2.9	21
	TB	3.9	5.0	4.3	4.0	4.3	12		5.2	4.3	4.8	14								

Contribution of water tables: The results showed that shallow water tables contributed significantly to total transpiration but the amounts varied between crops. In the 2006 canola experiment, the water table contributed 51% of total transpiration during the reproductive stage with a CV of 12% over the four growth periods. For the 2007 canola experiment, the contribution was 40% of total transpiration and 45% of total evapotranspiration. In the case of the two wheat experiments (2007 and 2008), the mean contribution from the water tables to total transpiration amounted to 31% and to total evapotranspiration 44%. For lucerne, the water table contributed 44% of total transpiration with a CV of 10% for six cutting periods, irrespective of soils.

6.2 Recommendations

- Non-weighing field lysimeters are useful tools for studying crop water relations, provided that the soil water content can be accurately measured with instruments such as the Campbell Pacific Neutron Water Meter. The combination of the two methods of irrigation; surface drip and sub irrigation, and the frequency of application as used in this study are recommended for the determination of TEC of crops in field lysimeters. The irrigation scheduling approach ensured that the crops had a water and oxygen stress free environment.
- The partitioning of a soil profile into unsaturated and saturated zones is also recommended to ascertain the contributions of individual zones towards T or ET.
- The results showed that plastic mulch can be replaced with gravel mulch (50 mm thick and 10 mm mesh size) in TEC experiments where it is of utmost importance to obtain transpiration. Gravel mulch is therefore recommended for studies of this nature.
- Effective mulching is crucial towards restricting evaporation in a crop field to improve water use efficiency. More research on mulching is recommended for achieving effective water management in semi-arid areas.
- It is also recommended that for TEC values to be of greater value that they are quantified for the different growth stages of crops.
- The TEC values estimated for canola, wheat and lucerne in this study are consistent with reported values for other C_3 crops in the semi-arid environment and are therefore recommended for use in models.

6.3 Further studies

Further studies should be undertaken in quantifying the transpiration efficiency and transpiration efficiency coefficient of other C_3 crops like peas, oats, barley and some C_4 crops such as maize, sorghum and millets to proffer comparative analysis for C_3 and C_4 crops.

Physiological proof must also be found for the phenomenon that morphological changes caused variations in TEC values during the reproductive stage of canola.

Effective, affordable and sustainable mulching materials are important in semi-arid environments and therefore warrant proper investigation. It will be of scientific and global importance to study the effect of climate change on C_3 and C_4 species in semi-arid areas.