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5 authors, including:

Cinisani Mfan'fikile Tfwala
University of the Free State

Achamyeleh Mengistu
University of the Free State

Chante Du-preez
University of the Western Cape

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Research article

Seasonal variations of transpiration efficiency coefficient of irrigated wheat

Cinisani M. Tfwala [a,b,*], Achamyeleh G. Mengistu [a], Imoh B. Ukoh Haka [a], Leon D. van Rensburg [a], Chris C. Du Preez [a]

[a] Department of Soil, Crop & Climate Sciences, University of the Free State, P.O. Box 339, 9300 Bloemfontein, South Africa
[b] Department of Agricultural Research and Specialists Services, Ministry of Agriculture, P.O. Box 4, M204 Malkerns, Swaziland

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ABSTRACT

Global diminishing water resources, especially due to climate change have serious impacts on evaporation (E) from the soil surface, transpiration (T) from plants (crops) and grain yield, which relates to water use efficiency of different crops. A study was conducted at Kenilworth over two wheat cropping seasons (2007 and 2008) with the objectives of: (i) evaluating the effect of soils and seasons on T, E and yield, and (ii) relating these parameters to transpiration efficiency coefficient. The treatments included two soil types and two soil surface treatments (bare and mulched), which were all replicated four times. Weekly irrigation was done using a surface drip system while maintaining the water table at a constant depth. Soil water content was monitored using a neutron probe. Neither soils nor seasons were found to significantly influence the partitioning of evapotranspiration (ET), and T varied from 74 to 76% of ET while E varied between 24 and 26%. Surface treatments caused significant differences in grain yield in both seasons. Reducing evaporative loss improves the water productivity of wheat, which has an important implication in dryland farming.

1. Introduction

Wheat (*Triticum aestivum* L.) is the second most important field crop after maize in South Africa and is used for a variety of purposes. The filed production and secondary processing industries of this crop provide a large number of job opportunities. About two decades ago it was revealed that the industry had approximately 3800–4000 commercial wheat growers, providing work to about 28000 people (National Department of Agriculture, 2007). Accordingly, South Africa consumes about 3 million tons of wheat per year of which 2 million are grown locally and the remainder imported. In large parts of the country, water is the most important limiting factor for wheat production, and to achieve higher grain yields, farmers rely in many instances on irrigation to grow wheat (Bennie et al., 1997). It was also reported that approximately 80% of wheat is 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 with high atmospheric evaporative demand. As a result, weather has a huge impact on water loss from soil water evaporation (E) and transpiration (T) (T is a beneficial loss). These losses need to be quantified in order to determine the impact thereof on the 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 Owesis, 1999; Zhang et al., 1999). The use of these relationships, also referred to as crop-water production functions (CWPF), were 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 a linear relationship on farms in the Sandvet, Ramah and Vaalharts Irrigation Schemes. It was also argued that the slope of the line represented WUE or transpiration efficiency (TE) of the crop, while the point where the line crossed the x-axis represented the total E of the season (Hanks, 1976). Further analysis of the CWPF by Bennie et al. (1997) revealed that both the slope and the intercept differed significantly from that of Bennie et al. (1988). 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 weather conditions and agronomical practices. Similar conclusions were made by French and Schultz (1984). The outcome was

* Corresponding author.
E-mail addresses: cinisanitfwala@yahoo.co.uk, 2008004043@ufs4life.ac.za (C.M. Tfwala).

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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 of Doorenbos and Kassam (1979). According to Hanks (1983), there is a linear relationship between transpiration (T) and aboveground biomass (Y_{AGB}) production and the slope of the line represents the so-called crop factor, which gives the TE of the crop. Previously it was also not possible to evaluate the transpiration efficiency coefficient (TEC) value, because of the lack of a lysimeter unit. A field lysimeter unit constructed by Ehlers et al. (2003) is now available for this purpose.

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

2. Materials and methods

2.1. Study area description

The investigation was done at Kenilworth Experimental Farm, Department of Soil, Crop and Climate Sciences, University of the Free State, South Africa, located at lat. -29.02°, long. 26.15°, and elevated 1354 m above sea level. The mean annual precipitation of the study area is 528 mm mostly falling between October and April with an average reference evapotranspiration (ETo) of 1 604 mm, thus classified as semi-arid (Thornthwaite, 1948; UNESCO, 1979). The mean annual minimum air temperature is 11.0 °C and maximum air temperature is 25.5 °C.

2.2. Lysimeter facility

The lysimeters used for this experiment were constructed in 1999 as described by Ehlers et al. (2003) for studying the contribution of root accessible water tables towards meeting the water requirements of crops. The lysimeter unit has an experimental area of 70 m × 35 m. At the center of the unit (experimental area of 70 m × 35 m), there are 30 round plastic lysimeters (1.8 m diameter and 2 m deep), which are buried in the soil in two parallel rows. The edges of these lysimeters protrude by 0.05 m above the surrounding soil surface (Figure 1). To enhance drainage, a 0.1 m layer of dolerite gravel (0.001 m in diameter) was laid at the base of each lysimeter. To minimize mixing of the gravel with the overlying repacked soil, the gravel was covered with a plastic mesh. The soil form in one row of lysimeters was the Clovelly (Soil Classification Working Group, 1991) or Quartzipsamment (Soil Survey Staff, 2014), and the other row was filled with Bainsvlei soil form (Hanks and Rasmussen, 1982) or Plinthustalf (Soil Survey Staff, 2014). From the original site, each horizon of both soils was removed separately and repacked in the same order into the lysimeters in order to represent the original soil as closely as possible.

A chamber (1.8 m wide, 2 m deep and 30 m long) was left open underground between the two rows of lysimeters for accessing the lysimeters below the soil surface, as shown in Figure 2. A manometer and a bucket were connected to the lysimeters through openings at the base for recharging and regulating the water table depth. Two neutron probe access tubes with lengths of 1900 mm were installed in each lysimeter. There were reservoirs placed on a 1 m high stand aboveground to enable gravity driven irrigation in the lysimeters. A movable shelter with a transparent roof (30 m long, 10 m wide and 4 m high) was installed to cover the lysimeter unit to avoid interference by rain (Figure 3).

2.3. Experimental setup

For this study, wheat was planted in 16 of the 30 lysimeters, during the 2007 and 2008 seasons. Half of the 16 lysimeters were filled with a sandy Clovelly (Cv) soil and the other half with the sandy loam Bainsvlei (Bv) soil. In each soil type, two soil surface treatments were applied: (i) a bare soil for measuring the actual evaporation 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 3), which was removed just after rain events. Wheat was planted all around the field adjacent to the lysimeters. The details of the physical properties of the soils are given in Table 1.

2.4. Agronomic practices

The lysimeters were leached prior to the commencement of this study in order to remove excess salts, which might have accumulated during previous experiments. Before planting, 4:2:1 (28) NPK fertilizer was manually broadcasted at a rate of 800 kg ha^{-1} and then mixed with the soil to 200 mm depth using a spade. The wheat (var: SST 826) was planted on 30 May 2007 for the first season and 24 April 2008 for the second season using 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}.

After the plants were established, urea was applied at a 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 using the same seed rate (100 kg ha^{-1}). 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 adjacent field plot.

2.5. Soil water balance application

The soil water balance approach states that a change in soil water content (ΔW) during a specified time period is equal the difference of the water added and the water lost in the same time period (Hillel, 1998). The water balance can be mathematically expressed (Marshall et al., 1996; Hillel, 1998; Bennie and Hensley, 2001) as (Equation 1):

$$T = P + I - \Delta W - D - R - E \quad (1)$$

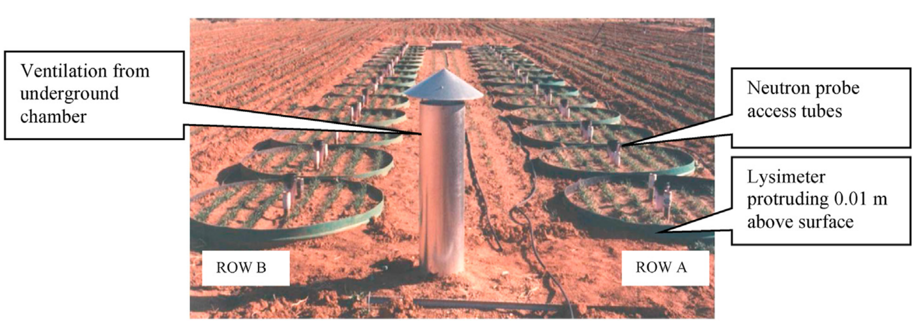

Figure 1. Aboveground view of the lysimeter unit with each lysimeter in row A filled with Clovelly Setlagole soil and in row B with a Bainsvlei Amalia soil. Every lysimeter is equipped with two neutron probe access tubes.

Figure 2. Underground chamber of the lysimeter unit showing that each lysimeter has a manometer through which the height of the water table is regulated by recharging from a bucket.

Transpiration (T) is the central point of focus in the water balance, because it is considered as the only beneficial loss. The drainage (D), runoff (R) and evaporation (E) must be minimized so that most of the water gained as precipitation (P) and/or irrigation (I) can be channeled towards transpiration. The ΔW over profile is an indicator to assess conditions in the soil-plant-atmosphere continuum system, as it shows the relative position between the two soil water management boundaries. Thus, the drained upper limit (DUL) and the drained lower limit (DLL) of plant available water, as explained by Ratliff et al. (1983) and Hensley et al. (2011). Maintaining the soil water content at crop specific thresholds between these boundaries will ensure optimal transpiration and CO_2 assimilation and hence optimal crop growth (van Rensburg, 1988; Bennie et al., 1997).

The soil water content was measured three times a week at 0.3 m depth intervals down to 1.8 m using a Campbell Pacific Neutron Water Meter (Model 503DR). The soil water content was increased to near DUL using a surface drip irrigation system whenever the available water (AW) approached 50% to ensure that the crop was not water stressed throughout the experiment. As the rain shelter was used to cover the unit during rainfall events, there was no contribution of P in the soil water content. Drainage (D) was also zero, as the lysimeters did not allow any deep percolation. Runoff (R) was also zero, because the protruding lysimeter edges prevented water flow in and out of the lysimeters and the surface. There was no E from mulched lysimeters while E occurred concurrently with T in the bare soil surface treatments as evapotranspiration (ET). The only remaining parameter responsible for ΔW was T in the gravel mulch treatments, while on the bare soil surface lysimeter water was lost through ET. The E component was estimated as the difference between ET and T.

2.6. Weather components

Weather data were recorded at an automatic weather station located at the study site. Computations of the required parameters were done following FAO 56 (Allen et al., 1998) and summarized as follows (Equation 2):

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \quad (2)$$

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

Eq. (3) was used to determine the saturation vapor pressure.

$$e_s = \frac{e^\circ(T_{\max}) + e^\circ(T_{\min})}{2} \quad (3)$$

where e_s is the saturation vapor pressure; $e^\circ(T_{max})$, saturation vapor pressure at maximum temperature; $e^\circ(T_{min})$, the saturation vapor pressure at minimum temperature.

Ambient vapor pressure (e_a) was calculated using Eq. (4).

$$e_a = \frac{e^\circ(T_{\min})\frac{RH_{\max}}{100} + e^\circ(T_{\max})\frac{RH_{\min}}{100}}{2} \quad (4)$$

where $e^\circ(T_{min})$ is the saturation vapor pressure at minimum temperature (kPa); RH_{max}, the maximum relative humidity (%); $e^\circ(T_{max})$, the saturation vapor pressure at maximum temperature (kPa); RH_{min}, the minimum relative humidity (%).

The slope of vapor pressure curve (Δ) for different temperatures (T) was determined using Eq. (5).

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \quad (5)$$

The mean vapor pressure deficit (VPD) expressed in kPa is calculated as the difference between the period during which the crop is actively transpiring (07:00–17:00, South African standard time (GMT+2)) as shown in Eq. (6).

$$\text{VPD} = e_s - e_a \quad (6)$$

2.7. Yield and water productivity components

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 h. The dried heads were counted and threshed whereafter the grain and head residues were weighed separately. Other plant residues, comprising leaves and stems were also dried at 65 °C for 72 h before being weighed. Grain yield (GY) and above-ground biomass (AGB) yield (grain plus all remains) were then summed to calculate the total biomass production. The harvest index (HI) was expressed as the ratio of the grain yield to above-ground biomass yield.

The water use efficiency (WUE, kg ha^{-1} mm^{-1}) of wheat in the lysimeters was calculated with Eq. (7).

$$\text{WUE} = \text{Y/ET} \quad (7)$$

where Y is either grain or above-ground biomass yield. By substituting ET with T, this equation was used to calculate WUE of wheat in the lysimeters with gravel mulch. The transpiration efficiency coefficient (TEC, g kPa mm^{-1}) was calculated with Eq. (8) (Tanner and Sinclair, 1983).

$$\text{TEC} = (\text{Y/ET})\text{VPD} \quad (8)$$

By substituting ET with T, the equation was also used 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.

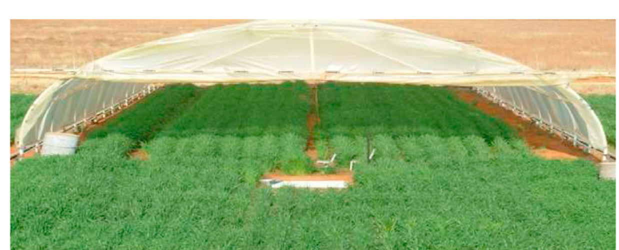

Figure 3. Wheat under the movable shelter (30 m long, 10 m wide and 4 m high), covering the lysimeter unit to prevent the influence of rain.

Table 1. Particle size distribution of both soils for the different depths at which it was packed in the lysimeters.

Soil type	Family	Soil depth (mm)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
Clovelly	Setlagole	0–300	1.3	10.7	79	4	5
		300–600	1.4	25.6	65	3	5
		600–900	1.4	25.6	65	3	5
		900–1,200	1.4	25.6	65	3	5
		1,200–1,500	1.4	25.6	65	3	5
		1,500–1,800	1.4	25.6	65	3	5
Bainsvlei	Amalia	0–300	0.3	6.4	83.3	2	8
		300–600	0.2	4.1	77.8	4	14
		600–900	0.1	3.5	78.4	4	14
		900–1,200	0.1	5.7	76.2	4	14
		1,200–1,500	0.1	5.1	70.8	4	20
		1,500–1,800	0.2	5.2	70.7	4	20

(Adapted from: Barnard et al., 2010).

2.8. Statistical analysis

Analysis of variance determined 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).

3. Results and discussion

3.1. Meteorological conditions

Two weather parameters (air temperature and reference evapotranspiration), which were perceived to have a great influence on the growth of the crop, are presented in Figure 4. The precipitation was not presented here, as there was always shelter to prevent it in the present study. The two seasons were representative of the weather patterns in this site with both parameters at their peaks around December and January, while the minimums were around June and July.

The two seasons were generally the same in as far as the weather was concerned. The mean air temperature was 13.4 °C in the 2007 season versus 14.4 °C in the 2008 season. However, there were occasional incidences of one or a few days that occurred especially in the 2008 season, which caused differences in the crop growth between the two seasons. Hail and strong winds occurred on the 1st of May 2008 and the shelter could not effectively cover the unit. The plants quickly recovered fully, because this occurred in the plant establishment phase of crop development. There was also a severe frost on the 6th August 2008 that occurred during the reproductive phase, which damaged some of the leaves of the crop.

3.2. Partitioning of evapotranspiration

The mean evapotranspiration (from bare soil surface treatment), transpiration (from gravel mulch treatment) and evaporation (obtained by subtracting T from ET) for the 2007 and 2008 seasons are summarized per soil type in Table 2. 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 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 were important determinants in the partitioning of ET, since T varied between 74 and 76% and E varied between 24 and 26%,

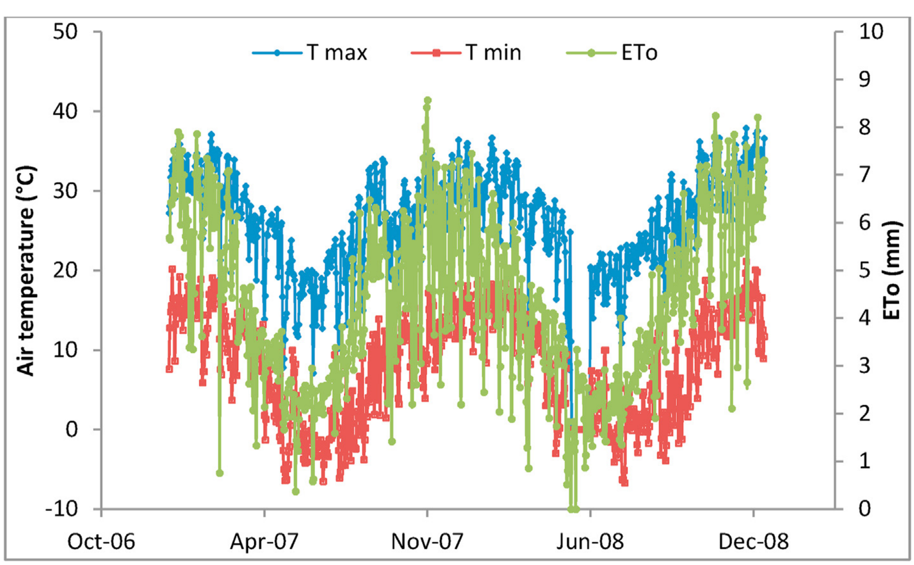

Figure 4. Maximum and minimum air temperatures (T_{max} and T_{min}), and reference evapotranspiration at Keneliworth Experimental Farm during 2007 and 2008 seasons.

Table 2. Partitioning of seasonal evapotranspiration (ET, mm) into its component of transpiration (T) and evaporation (E) for wheat grown on Clovelly (Cv) and Bainsvlei (Bv) soils for the 2007 and 2008 seasons.

Season	Soil type	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*	*25*
2008	Cv	691	523	168	76	24
	Bv	635	470	165	74	26
	Mean	*663*	*497*	*167*	*75*	*25*
Overall mean		**671**	**502**	**169**	**75**	**25**

irrespective of soils and seasons. This result seems inconsistent with previous research that reported the importance of soils (by influencing the hydraulic properties) and seasonal weather parameters (temperature, relative humidity and wind speed) affecting ET partitioning significantly (e.g., Zhang et al., 2013; Wei et al., 2018; Ma et al., 2018). However, the small influence of soils to the partitioning of ET could be ascribed to the similar textural class of the two soils. The Cv horizons vary between loam-sand to sandy soils whereas the Bv horizons vary between loamy-sand to sandy-loam (Mengistu et al., 2019). As stated in Section 3.1, the two seasons (2007 and 2008 seasons) had similar weather records that could have accounted for the low impact of seasons to ET partitioning. A study by Klocke et al. (1985) reported E losses ranging between 20 and 30% of ET for sprinkler irrigated maize in Kansas, USA. In another study conducted in Spain, Fereres and Villabos (1990) recorded E to range between 15 and 17% of ET for tomatoes. A model and lysimeter study by Wei et al. (2018), showed that T varied between 84 and 93% of ET for different development stages of winter wheat. Zhang et al. (2013) found up to 80% E in the crop establishment stage that decreased to 5–6% of ET during the mid-season period for winter wheat.

Data sets for seasons and soils were pooled, because none affected 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}. Figure 5 shows the relationship between E, T and ET within the four growth stages *viz*. the plant establishment stage, vegetative stage, reproductive stage and physiological maturing stage. The parameters all increased gradually in the vegetative stage and reached a peak during the reproductive stage, where after gradually declining in the maturity stage. Therefore, the partitioning of ET is highly influenced by crop developmental stages. This effect is supported by Zhang et al. (2013) and Wei et al. (2018). Other factors that are important in the partitioning of ET are canopy cover and leaf area index (Wei et al., 2018). Soil through its impact on the hydraulic properties (Lawrence et al., 2007; Ma et al., 2018) can also be mentioned here, although its effect was minimal in this study.

This demonstrated further that transpiration never stops until the crop is harvested. 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). This is because a higher plant population will ensure covering of the bare soil and therefore reducing direct radiation, as radiation is an important driver of evaporation in semi-arid environments. Despite the shading of the leaves, the results in Figure 5 suggested that a significant amount of water still evaporated during the vegetative, reproductive and maturing stages. The study by Bennie et al. (1997) demonstrated that ET increased with an increased number of irrigation events. The higher ET values were not always associated with higher yields. Therefore the authors concluded that it was rather an amplification of E and not T in some of the ET measurements.

3.3. 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 3. Soils did not affect either grain yield or above-ground biomass yield in both seasons. This could be due to the similar textural

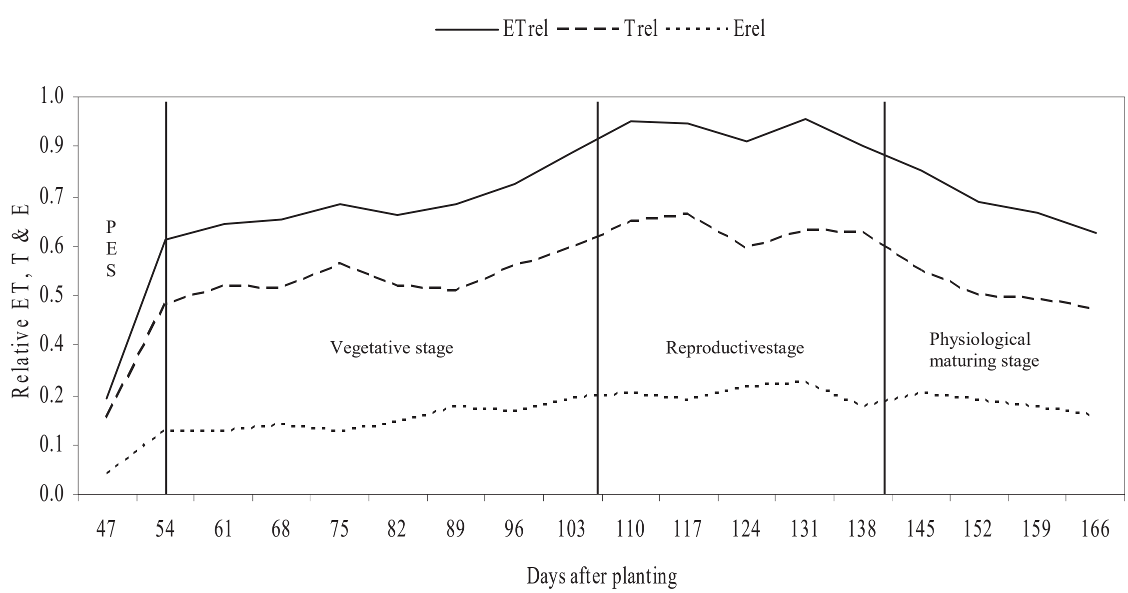

Figure 5. Mean relative evapotranspiration (ET), relative transpiration (T) and evaporation (E) for the combined seasons. The values were expressed as a ratio to the maximum ET value (49 mm week^{-1}). PES is the plant establishment period.

Table 3. 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 type		Soil surface treatment		Mean
		Cv	Bv	Bare	Gravel	
Grain yield (kg/ha)	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)	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) is 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.

Table 4. 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 type		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/mm)	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/mm)	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}	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_{ABG} (g kPa/mm)	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) is 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.

composition of the two soil types as explained in Section 3.2. However, in 2008 the HI of wheat on the Cv soil was significantly lower than that of the Bv soil. This can be attributed to the impact of frost that 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}, which was 23% higher on the gravel mulch treatment than the bare soil surface treatment. A smaller difference was observed in the average above-ground biomass of the two seasons (3395 kg ha^{-1}) where the gravel treatment was 16.6% higher compared to the bare soil surface treatment. The above-ground biomass yield between the mulched and un-mulched treatments was only significantly different in 2008 in favor of the gravel mulched soil surface treatment. Subsequently, the HI was also only significantly higher for the mulched treatment in the 2008 season. Besides its influence on water use, mulch is known to influence temperature regimes within and above the soil (van Rensburg et al., 2003). This aspect warrants research 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.

The difference in grain yield was 4260 kg ha^{-1}, which was mainly attributed to frost damage during the early reproductive stage of the 2008 season. In the 2007 season, an average grain yield of 9130 kg ha^{-1} was obtained and there was no environmental stress during this cropping season. 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 also compared well with the mean above-ground biomass yield of 25138 kg ha^{-1} (Ehlers et al., 2003). In the following year, 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, were close to those reported by Zhang et al. (1998) and Solomon and Labuschagne (2003), namely 0.4 and 0.39 respectively.

The study by Ehlers et al. (2003) showed that irrigated wheat on similar soils do not experience water stress if the soil water level remains between a set allowable depletion level (ADL) and the DUL. According to Ehlers et al. (2003), the optimum water table level for these soils is 1200 mm for most field crops. Water logging is mostly likely to occur with water table levels shallower than 750 mm (Lal and Shukla, 2004; Surya et al., 2006). Thus, it is highly unlikely that the plants could have experienced water or oxygen stress during any of the seasons in the present study.

3.4. Water use and water use efficiencies

The analysis of variance of water related variables (WU, TE and TEC) suggested no significant interaction between soil and surface treatments (Table 4). The analysis also indicated that the soil treatments did not influence any of the variables significantly, but the soil surface treatments did. Hence, the discussion will focus on the surface treatments that influenced the variables significantly (P = 0.05).

Water use from the gravel mulch treatment (T) was lower in both seasons than that of the bare soil surface (ET) treatment, but was only significant in the 2007 season. The higher water use from the bare soil surface treatment was attributed to evaporation. In both seasons the water use efficiency based on grain yield was significantly higher on the gravel mulch treatment than on the bare soil surface treatment. The WUE based on above-ground biomass showed a similar trend. The results demonstrated the importance of minimizing evaporation for improved water productivity in crop production. Similar results were obtained for the TEC values, where the gravel mulch treatment outperformed the bare soil surface treatment, irrespective of whether it was based on grain yield or above-ground biomass yield. The increase of yield by mulching is supported by many reports (e.g., Peng et al., 2015; Minhua et al., 2018; Hu et al., 2018). Peng et al. (2015) found a WUE increase of 15–18% when using mulch compared to bare surface treatment. Minhua et al. (2018) found a 27% increase of WUE using mulch compared to the bare surface treatment of winter wheat. This efficient use of water was due to the significant decrease of E by the surface mulch. The impact of mulch in decreasing the rate of evaporation (unproductive loss) has an important implication in dryland agriculture where soil moisture is scarce. The use of mulching with conservation tillage and other dryland agricultural practices will improve productivity through increasing water use efficiencies (Peng et al., 2015; Minhua et al., 2018).

Comparing the mean TEC values for the two seasons suggested that TEC based on grain yield differed significantly and was lower in the 2008 season, probably due to the frost damage during the early reproductive stage. The mean TEC_{AGB} of 5.24 g kPa mm^{-1} for 2007 season and 4.25 g kPa mm^{-1} for 2008 season compared well to other C_3 crops cultivated in semi-arid regions. An investigation by Clover et al. (2001) reported TEC values of 4.12–4.56 g kPa mm^{-1} for sugar beet. For groundnuts under varying conditions of vapor pressure deficit, TEC values of 1.50–5.20 g kPa mm^{-1} were found by Mathews et al. (1988) and Azam-Ali et al. (1989) respectively.

4. Conclusions

Several conclusions were drawn from the field lysimeter experiment on wheat conducted over two seasons in a semi-arid environment. The results illustrated that neither the two soils nor seasons (weather) were important determinants in the partitioning of ET into its components of T and E. The two soils did not influence grain or above ground biomass yields, water use efficiency and the transpiration efficiency coefficient of wheat. The seasons affected the mean grain yield significantly, but not the above-ground biomass yield. The water use of the crops gradually increased until reproductive stage and then started to decline during maturity. The crop did not provide effective canopy cover to eliminate the evaporation component, as such mulching practices minimized the evaporation losses during production. Grain yield in the 2008 season was hampered by frost, which occurred in the early reproductive stage. This effect was transferred to the corresponding water use efficiency and transpiration efficiency coefficient values. The harvest index was higher on the gravel mulch treatments than the bare soil surface treatment. The total water use was significantly higher on the bare soil surface treatment than the gravel mulch treatment, which translated to high water use efficiency in the mulched treatments. This was attributed to the elimination of evaporation in the mulched treatments. Both season's TEC values fell within the range of those reported for other C_3 crops in semi-arid environments despite some frost damage in the 2008 season. Any practice that reduces evaporation, runoff or other water losses ensures that more water is available for transpiration, which in turn will greatly increase water productivity in crop production.

Declarations

Author contribution statement

Cinisani M. Tfwala; Achamyeleh G. Mengistu: Analyzed and interpreted the data; Wrote the paper.

Imoh B. Ukoh Haka: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Leon D. van Rensburg; Chris C. Du Preez: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome 300 (9), D05109.

Azam-Ali, S.N., Simmonds, L.P., Nageswara Rao, R.C., Williams, J.H., 1989. Population, growth and water use of groundnut (*Arachis hypogea*) maintained on stored water. III. Dry matter, water use and light interception. Exp. Agric. 25, 77–86.

Barnard, J.H., van Rensburg, L.D., Bennie, A.T.P., 2010. Leaching irrigated saline sandy to sandy loam apedal soils with water of a constant salinity. Irrigat. Sci. 28 (2), 191–201.

Bennie, A.T.P., Hensley, M., 2001. Maximizing precipitation utilization in dryland agriculture in South Africa – a review. J. Hydrol. 241, 124–139.

Bennie, A.T.P., Coetzee, M.J., vav Antwerpen, R., van Rensburg, L.D., Burger, R., Du, T.A., 1988. Water Balance Model for Irrigation Based on the Profile Water Supply Rate and Crop Water Demand [Afrikaans]. Water Research Commission. Report No. 144/1/88, Pretoria, South Africa.

Bennie, A.T.P., Van Rensburg, L.D., Strydom, M.G., Du Preez, C.C., 1997. Response of Crops on Pre-programmed Deficit Irrigation [Afrikaans]. Water Research Commission Report no 423/1/97, Pretoria, South Africa.

Clover, G.R.G., Jaggard, K.W., Smith, H.G., Azam-Ali, S.N., 2001. The use of radiation interception and transpiration to predict the yield of healthy, droughted and virus-infected sugar beet. J. Agric. Sci. 136, 169–178.

Doorenbos, J., Kassam, A.H., 1979. Yield Response to Water. U.N. Food and Agriculture Organization Irrigation and Drainage Paper No. 33, Rome.

Ehlers, L., Bennie, A.T.P., Du Preez, C.C., 2003. The Contribution of Root Accessible Water Tables towards the Irrigation Requirements of Crops. Water Research Commission, Report No. 1089/1/03, Pretoria, South Africa.

Fereres, E., Villabos, F.J., 1990. The partitioning of evapotranspiration into evaporation and transpiration for the irrigation scheduling of vegetable crops. Acta Hortic. 278.

Fisher, R.A., 1935. The Design of Experiments. Oliver and Boyd, Edinburgh and London.

French, R.J., Schultz, J.E., 1984. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. Aust. J. Agric. Res. 35, 743–764.

Hanks, R.J., 1976. Model for predicting plant yield as influenced by water use. Agron. J. 66, 660–665.

Hanks, R.J., 1983. Yield and water use relationships: an overview. In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to Efficient Water Use in Crop Production. ASA, CSSA, SSSA., Madison, WI, USA, pp. 393–411.

Hanks, R.J., Rasmussen, V.P., 1982. Predicting crop production as related to plant water stress. Adv. Agron. 35, 193–215.

Hensley, M., Bennie, A.T.P., van Rensburg, L.D., Botha, J.J., 2011. Review of 'plant available water' aspects of water use efficiency under irrigated and dryland conditions. Water SA 37 (5), 771–779.

Hillel, D., 1998. Environmental Soil Physics. Academic Press, San Diego, USA.

Hu, C., Zheng, C., Sadras, V.O., Ding, M., Yang, X., Zhang, S., 2018. Effect of straw mulch and seeding rate on the harvest index, yield and water use efficiency of winter wheat. Sci. Rep. 8 (1), 1–8.

Klocke, N.L., Heermann, D.F., Duke, H.R., 1985. Measurement of evaporation and transpiration with lysimeters. Trans. ASAE 28, 183–192.

Lal, R., Shukla, M., 2004. Principles of Soil Physics. CRC Press.

Lawrence, D.M., Thornton, P.E., Oleson, K.W., Bonan, G.B., 2007. The partitioning of evapotranspiration into transpiration, soil evaporation, and canopy evaporation in a GCM: impacts on land–atmosphere interaction. J. Hydrometeorol. 8 (4), 862–880.

Ma, Y., Kumar, P., Song, X., 2018. Seasonal variability in evapotranspiration partitioning and its relationship with crop development and water use efficiency of winter wheat. Hydrol. Earth Syst. Sci. Discuss. 1–46.

Marshall, T.J., Holmes, J.W., Rose, C.W., 1996. Soil Physics. Cambridge University Press.
Mathews, R.B., Harries, D., Nageswara Rao, R.C., Williams, J.H., Adia, K.D.R., 1988. The physiological basis for yield differences between four genotypes of groundnut (*Arachis hypogea*) in response to drought. I. Dry matter production and water use. Exp. Agric. 24, 191–202.
Mengistu, A.G., Mavimbela, S.S., van Rensburg, L.D., 2019. Characterisation of the soil pore system in relation to its hydraulic functions in two South African aeolian soil groups. S. Afr. J. Plant Soil 36 (2), 107–116.
Minhua, Y., Yuannong, L., Yuanbo, X., Changming, Z., 2018. Effects of mulches on water use in a winter wheat/summer maize rotation system in Loess Plateau, China. J. Arid Land 10 (2), 277–291.
Mogenson, V.O., Jeensen, H.E., Rab, M.A., 1985. Grain yield, yield components, drought sensitive, and water use efficiency of spring wheat subjected to water stress at various growth stages. Irrig. Sci. 6, 131–140.
Musick, J.T., Jones, O.R., Stewart, B.A., Dusek, D.A., 1994. Water–yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. 86, 980–986.
National Department of Agriculture, 2007. Agricultural Statistics. Directorate of Agricultural Statistics, Pretoria, South Africa.
Nulsen, R.A., Baxter, I.N., 2004. Water Use by Some Crops and Pastures in the Southern Agricultural Areas of Western Australia. Resource Management Technical Report No.32. Division of Resources Management, Western Australia Dept Agric, South Perth, Australia.
Peng, Z., Ting, W., Haixia, W., Min, W., Xiangping, M., Siwei, M., Rui, Z., Zhikuan, J., Qingfang, H., 2015. Effects of straw mulch on soil water and winter wheat production in dryland farming. Sci. Rep. 5, 10725.
Ratliff, L.F., Ritchie, J.T., Cassel, D.K., 1983. Field-measured limits of soil water availability as related to laboratory-measured properties 1. Soil Sci. Soc. Am. J. 47 (4), 770–775.
SAS INSTITUTE INC, 1999. SAS/STAT User's Guide, Version 8, Cary, NC. USA.
Singh, S.D., 1981. Moisture-sensitive growth stages of dwarf wheat and optimal sequencing of evapotranspiration deficits. Agron. J. 73, 387–391.
Soil Classification Working Group, 1991. Soil Classification: a Taxonomic System for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No 15. Department of Agricultural Development, Pretoria, South Africa.
Soil Survey Staff, 2014. Keys to Soil Taxonomy. United States Department of Agriculture, Natural Resource Conservation Service.
Solomon, K.F., Labuschagne, M.T., 2003. Variation in water use and transpiration efficiency among durum wheat genotypes grown under moisture stress and non-stress conditions. J. Agric. Sci. 141 (1), 31–41.
Steiner, J.L., Smith, R.C.G., Meyer, W.S., Adeney, J.A., 1985. Water, foliage temperature, and yield of irrigated wheat in southeastern Australia. Aust. J. Agric. Res. 36, 1–11.
Surya, P., Bhattarai, P., Pendergast, L., Midmore, D.J., 2006. Root aeration improves yield and water use efficiency of tomato in heavy and saline soils. Scientia Hort 108, 278–288.
Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or re-research. In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to Efficient Water Use in Crop Production. American Society of Agronomy, Madison, WI.
Thornthwaite, C.W., 1948. An approach toward rational classification of climate. Geogr. Rev. 38 (1), 55–94.
UNESCO, 1979. Map of the World Distribution of Arid Regions. Accompanied by Explanatory Notes. UNESCO, Paris, France. MAB Technical Note No. 17.
van Rensburg, L.D., 1988. The Prediction of Soil Induced Plant Water Stress for Selected Soil-Plant-Atmospheric Systems [Afrikaans]. M.Sc. dissertation. University of the Free State, Bloemfontein, South Africa.
van Rensburg, L.D., Zerizghy, M.G., 2008. Upgrading of the BEWAB Model to BEWAB+. Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa.
van Rensburg, L.D., Nhlabatsi, N.N., Anderson, J.J., Botha, J.J., Kuschke, R., 2003. Predicting Evaporation from the Soil Surface as Affected by Mulching and Soil Factors. Report to OSWU. ARC- Institute for Soil, Climate and Water, Private Bag X79, Pretoria, South Africa.
Wei, Z., Lee, X., Wen, X., Xiao, W., 2018. Evapotranspiration partitioning for three agro-ecosystems with contrasting moisture conditions: a comparison of an isotope method and a two-source model calculation. Agric. For. Meteorol. 252, 296–310.
Zhang, H., Owesis, T., 1999. Water yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agric. Water Manag. 38, 195–311.
Zhang, J., Sui, X., Li, B., Su, B., Li, J., Zhou, D., 1998. An improved water-use efficiency for winter wheat grown under reduced irrigation. Field Crops Res. 59, 91–98.
Zhang, H., Wang, X., You, M.Z., Liu, C.M., 1999. Water yield relations and water use efficiency of winter wheat in the North China Plain. Irrig. Sci. 19, 37–45.
Zhang, B., Liu, Y., Xu, D., Zhao, N., Lei, B., Rosa, R.D., Paredes, P., Paço, T.A., Pereira, L.S., 2013. The dual crop coefficient approach to estimate and partitioning evapotranspiration of the winter wheat–summer maize crop sequence in North China Plain. Irrigat. Sci. 31 (6), 1303–1316.