Quantification of long-term precipitation use efficiencies of different maize production practices on a semi-arid ecotope in the Free State Province

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Abstract

Precipitation use efficiency (PUE) was estimated for four production practices, i.e. conventional tillage with November planting (CTN), conventional tillage with January planting (CTJ), in-field rainwater harvesting with November planting (WHBN), and in-field rainwater harvesting with January planting (WHBJ), over 80 maize seasons for a semi-arid ecotope in the central Free State Province of South Africa. An empirical yield prediction model was used to obtain maize grain yields. PUE was expressed as the ratio of transpiration: rainfall for each growing season (PUE_T), while transpiration was calculated from total biomass yield, vapour pressure deficit and a transpiration efficiency coefficient for maize. The following equation, based on 10 years of measured data, was developed to estimate daily vapour deficit pressure for the 80 seasons from daily maximum temperature: $Vd = 0.163 \times T_{max} - 2.88$ ($R^2 = 0.73$). Mean PUE_T values over the 80 seasons were: 0.260 for CTN, 0.320 for WHBN, 0.334 for CTJ, and 0.400 for WHBJ. These results confirmed and quantified the advantage of in-field rainwater harvesting over conventional tillage, and the advantage of January planting over November planting. PUE_T results were also expressed as cumulative probability functions. Significance tests showed that PUE_T for in-field rainwater harvesting was significantly better than PUE_T for conventional tillage, and that January planting was significantly better than November planting. It was concluded that the advantage of in-field rainwater harvesting over conventional tillage was mainly due to the absence of runoff and reduced evaporation in the former practice. The use of a short-growing cultivar, which flowers during the month with the most favourable climate, i.e. March, probably resulted in the advantage of January planting over November planting.

Keywords: conventional tillage, in-field rain water harvesting, planting date, transpiration, vapour pressure deficit

Introduction

Water availability is the most important limiting factor for rain-fed crop production in semi-arid areas. Maximising precipitation use efficiency (PUE) is therefore important. This can be achieved by identifying and employing the crop production practice with the highest PUE for that specific ecotope. The ecotope concept is defined by MacVicar et al. (1974).

Water use efficiency (WUE) has been widely used in the past to calculate crop water use efficiency (Hillel, 1972; Tanner and Sinclair, 1983):

$$WUE = \frac{Y}{E+T} \text{ kg·ha}^{-1}\text{·mm}^{-1} \quad (1)$$

where:

- Y = grain yield (kg·ha^{-1})
- E = water lost from the soil surface through evaporation during the growing season (mm)
- T = water used for transpiration during the growing season (mm)

WUE is a measure of the efficiency with which a crop uses water to produce a certain yield. Although valuable in certain cases, WUE does not enable the comparison of different production practices. This is because certain water loss processes, which can be minimised by using suitable water conservation tillage (WCT) practices to improve the efficiency of rainwater use in crop production, are not taken into account. These losses include runoff, evaporation and deep drainage, during the growing and fallow seasons. Precipitation use efficiency (PUE_Y) is considered to be a more appropriate parameter to describe the overall efficiency with which rainwater is used in rain-fed cropping, since the named losses are taken into account (Hensley et al., 1990):

$$PUE_Y = \frac{Y}{P_g + P_f + \left(\theta_{h(n-1)} - \theta_{h(n)}\right)} \text{ kg·ha}^{-1}\text{·mm}^{-1} \quad (2)$$

where:

- PUE_Y = precipitation use efficiency for a particular year, including the fallow season, based on the grain yield (kg·ha^{-1}·mm^{-1})
- Y = grain yield (kg·ha^{-1})
- P_g = precipitation during the growing season (mm)
- P_f = precipitation during the fallow season (mm)
- $\theta_{h(n)}$ = water content of the root zone at harvest in year n (mm)
- $\theta_{h(n-1)}$ = water content of the root zone at harvest in year n-1 (mm)

PUE_Y is therefore the grain yield per unit of total rainfall associated with a particular crop, during a particular year. It is necessary to include P_f in Eq. (2) because certain WCT practices result in improved water conservation during the fallow season as well as during the growing season. Such practices generally result in more plant available water at the start of the following growing season than where WCT practices had not been applied

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Received31 May 2006; accepted in revised form 16 November 2006.

during the fallow season. During the growing season unproductive water losses, such as runoff, deep drainage, and excessive evaporation from the soil, will be less on WCT land, resulting in more water being available for growth and therefore increased yield and increased PUE_Y. PUE_Y therefore enables a meaningful and comprehensive comparison to be made between the efficiencies of different production practices.

However, PUE_Y is not strictly an 'efficiency' term. Gregory (1989) stated that 'the two processes (plant growth and water use) are not energetically linked so that a theoretical, maximum value cannot be calculated'. The ratio of transpiration (T, in mm) to the total available rainfall (mm) would therefore provide a better assessment of efficiency (Eq. (3)).

$$PUE_T = \frac{T}{P_g + P_f + \left(\theta_{h(n-1)} - \theta_{h(n)}\right)} \text{ mm·mm}^{-1} \quad (3)$$

Equation (3) can be used for making comparisons between PUE_T values for different seasons for particular, or different, production practices. For long-term comparisons the term ($\theta_{h(n-1)} - \theta_{h(n)}$), however, loses its meaning. Any benefit (positive value) or loss (negative value) which the term may have will be conveyed to the following season. The term ($\theta_{h(n-1)} - \theta_{h(n)}$) is also generally expected to be very small relative to ($P_g + P_f$). Firstly, it describes the water content at the end of the growing season – almost invariably a very low value in semi-arid areas; and secondly, it describes the difference between two such values during consecutive seasons. The influence of the term ($\theta_{h(n-1)} - \theta_{h(n)}$) on PUE_T for different production practices during different seasons is also very variable. Compare, for example, the influence of conventional tillage (CT) and WCT on this term for a particular growing season with a specific rainfall distribution pattern. Where the rainfall is high at the end of the previous growing season (high $\theta_{h(n-1)}$), and low at the end of the current growing season (low ($\theta_{h(n)}$), the term will be positive and larger for a WCT treatment (Fig. 1) than for a CT treatment. This will promote PUE_T (WCT) relative to PUE_T (CT), for that particular season. The yield, and therefore the T value, of the WCT treatment will have benefited by having higher plant-available water at planting than the CT treatment for the particular season for which the calculation is being made. A wide range of different scenarios can be considered in this way, with the WCT treatment benefiting on overall because water losses are minimised. This is confirmed by the results of field experiments reported by Botha (2006). Equation (4) would therefore be acceptable for long-term comparisons of PUE_T for different production practices:

$$PUE_T = \frac{T}{P_g + P_f} \text{ mm·mm}^{-1} \quad (4)$$

PUE_T is dimensionless as both the numerator and denominator are in mm. The theoretical minimum and maximum will therefore be 0 and 1 respectively. The comment of Gregory (1989) regarding the requirements of a true efficiency term is therefore met by Eq. (4).

The purpose of this paper was to quantify and compare the precipitation use efficiencies of four crop production practices on a semi-arid ecotope at Glen.

Material and methods

The Glen/Hutton-Ventersdorp ecotope is located at Glen (28° 55.691' S, 26° 19.599' E), in the central, semi-arid area of the Free State Province of South Africa. The mean annual rainfall is 545 mm and potential evaporation (Class A pan) is 2 243 mm, giving an average aridity index (rainfall/potential evaporation) of 0.23 per year, and 0.32 for the November to April growing season (Botha et al., 2003). The ecotope occurs on a mid-slope terrain morphological unit, with a 3% westerly slope. The soil was classified as a 1 800 mm deep Hutton-Ventersdorp sandy loam (Soil Classification Working Group, 1991). A detailed soil profile description and soil analyses are given by Zere (2003).

Four production practices, based on combinations of the following were used: Conventional tillage (CT), consisting of mouldboard ploughing followed by offset-disc land preparation for planting. Weed control was done by cultivation. The in-field rainwater harvesting with basins (WHB) technique is described in Fig. 1. It results in water being conserved in the following ways during the fallow and growing seasons: ex-field rainwater runoff is prevented; evaporation from the soil surface (Es) is reduced by the presence of mulch in the basins; and Es is suppressed by promoting deep infiltration of the runoff water in the basin area. Weed control was done chemically. November (N) or early planting utilised a long growing season (145 d) maize cultivar, while January (J) planting utilised a short growing season (120 d) maize cultivar. The production practices were categorised as follows:

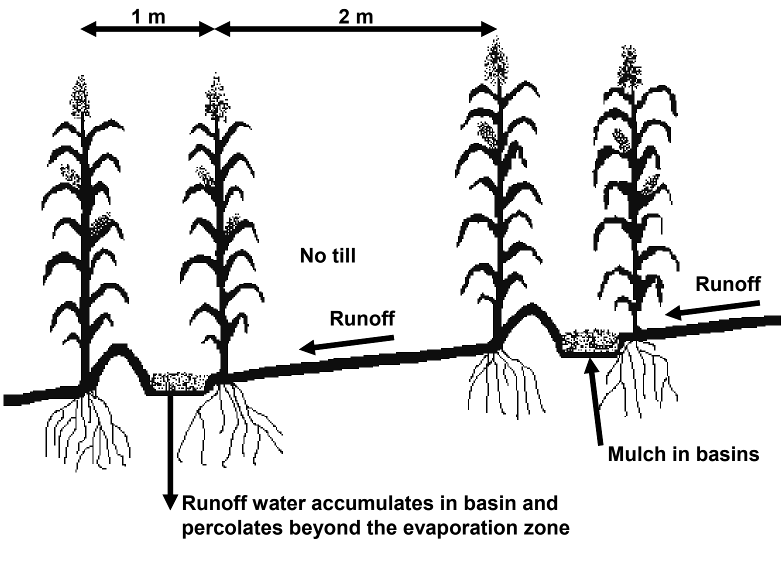

Figure 1
A diagrammatic description of the in-field rain water harvesting production technique (After Hensley et al, 2000)

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ISSN 0378-4738 = Water SA Vol. 33 No. 1 January 2007
ISSN 1816-7950 = Water SA (on-line)

(i) November planting with conventional tillage (CTN)
(ii) November planting with in-field rainwater harvesting (WHBN)
(iii) January planting with conventional tillage (CTJ)
(iv) January planting with in-field rainwater harvesting (WHBJ)

Biomass yields for maize (Y_b) for each of these production practices for the seasons 1922/23 to 2001/02, were estimated using a yield prediction procedure, developed for these ecotopes, based on the evapotranspiration (ET) to potential evaporation (Eo) ratio, and validated against measured maize grain yields for 22 seasons, (Zere et al., 2005a). Total biomass (Y_{bt}) was estimated by multiplying the above ground biomass yields with a factor of 1.2 (Tanner and Sinclair, 1983).

The PUE_T for each growing season was calculated using Eq. (4). Because measured T was not available, it was calculated from the total biomass yield (Y_{bt}), vapour pressure deficit (Vd), and the transpiration efficiency coefficient (k), based on the relationship proposed by Tanner and Sinclair (1983) and Gregory (1989):

$$k = \frac{Y_{bt} \times Vd}{T} \quad kg \cdot ha^{-1} \cdot kPa \cdot mm^{-1} \qquad (5)$$

where:
k = transpiration efficiency coefficient for maize ($kg \cdot ha^{-1} \cdot kPa \cdot mm^{-1}$)
Y_{bt} = total biomass yield ($kg \cdot ha^{-1}$)
Vd = average vapour pressure deficit (kPa) during sunlight hours, over the growing season
T = transpiration (mm)

The units of Y_{bt} can be simplified by dividing by 10 to give $g \cdot m^{-2}$. To further simplify the units of k, Gregory (1989) proposed 'normalising' Vd by dividing by Vd_o (1 kPa). Following this procedure the units of k become $g \cdot m^{-2} \cdot mm^{-1}$. Tanner and Sinclair (1983) reported a k value of 9.5 $g \cdot m^{-2} \cdot mm^{-1}$ for maize. Similar values for maize were reported by Walker (1986) working in Canada and Hattingh (1993) working at Glen, when the appropriate conversion for the above-ground biomass to total biomass had been made (Hensley et al., 2000). The value of 9.5 $g \cdot m^{-2} \cdot mm^{-1}$ has therefore been considered acceptable for this study. Changing the subject in Eq. (5) enables the calculation of T:

$$T = \frac{Y_{bt} \times Vd}{k} \quad mm \qquad (6)$$

where:
Vd = as in Eq. (5), but considered to be unit-less due to division by 1 kPa

A problem which arose was that measured Vd values were not available for each of the 80 growing seasons (1922/23 to 2001/02) for which Y_{bt} values could be estimated. The following procedure was followed to obtain acceptable estimates of Vd values for the study period. There is a fixed relationship between the saturated vapour pressure of the atmosphere (Vs) and the temperature (Allen et al., 1998):

$$Vs = 0.6108 \times e^{\left(\frac{17.27 \times T_{av}}{T_{av} + 273.2}\right)} \qquad (7)$$

where:
Vs = average hourly saturation vapour pressure of the atmosphere (kPa)
T_{av} = average hourly temperature (°C)

and:

$$Vd = Vs - Va \qquad (8)$$

and:

$$Va = \frac{Vs \times RH}{100} \qquad (9)$$

where:
Va = actual vapour pressure (kPa)
RH = relative humidity (%)

therefore:

$$Vd = Vs - \left(Vs \times \frac{RH}{100}\right) \qquad (10)$$

Since Vs is directly related to T_{av} (Eq. (7)), and RH is also related to temperature, it is logical to expect some degree of correlation between Vd and temperature. The following procedure was adopted to identify the best relationship between temperature and Vd.

Hourly Vd values were available for the nearby Bloemfontein airport meteorological station (29° 10' S; 26° 30' E) for the period 01/01/1992 to 31/04/2002 (SAWS, 2005). Hourly Vd data were averaged over the sunshine hours to obtain Vd values for each day over the growing season (December to April) for 10 years, giving 1 635 data points. The sunshine hours at Bloemfontein for each day over the growing season (Table 1) are available from Allen et al. (1998) and from SAWS (2005). Day length in full hours was used in calculations, because only hourly data were available.

TABLE 1
Sunshine periods for Bloemfontein used in the calculation of mean daily vapour pressure deficit (Vd), for all growing seasons

Month	Sunshine period [1]			Sunshine hours [2]
	Sunrise	Sunset	Day length (hours)	
Dec	05:00	19:00	14:00	13.9
Jan	05:00	19:00	14:00	13.7
Feb	06:00	19:00	13:00	13.0
Mar	06:00	18:00	12:00	12.2
Apr	07:00	18:00	11:00	11.3

[1] *SAWS (2005)*
[2] *Allen et al. (1998)*

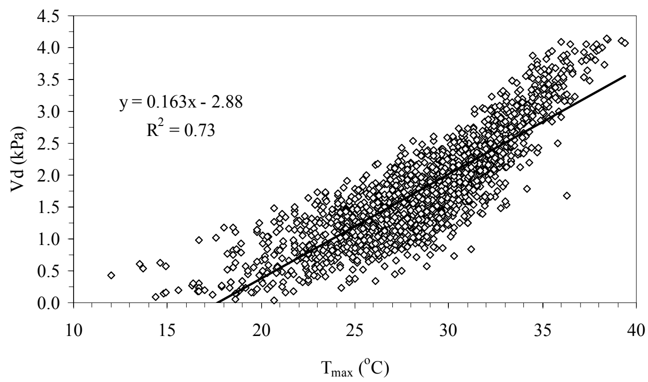

Figure 2
Regression of daily vapour pressure deficit (Vd) against daily maximum temperature (T_{max}), during the growing season, for the Bloemfontein meteorological station over ten years (n = 1 635)

TABLE 2
Correlation equations of daily vapour pressure deficit (Vd) against daily temperature (T) for the Bloemfontein meteorological station (n = 1 635)

	Equation	R^2
maximum temperature (T_{max})	$Vd = 0.163 \times T_{max} - 2.88$	0.73
average daily temperature (T_{av})	$Vd = 0.153 \times T_{av} - 1.27$	0.49
minimum temperature (T_{min})	$Vd = 0.029 \times T_{min} + 1.42$	0.02

TABLE 3
Long-term precipitation use efficiency (PUE_T) for the Glen/Hutton-Ventersdorp ecotope using November planting with conventional tillage (CTN), November planting with in-field rainwater harvesting (WHBN), January planting with conventional tillage (CTJ), and January planting with in-field rainwater harvesting (WHBJ)

Growing season	Production technique				Growing Season	Production technique			
	CTN	WHBN	CTJ	WHBJ		CTN	WHBN	CTJ	WHBJ
1922/23	0.284	0.414	0.205	0.262	62/63	0.157	0.227	0.257	0.305
23/24	0.309	0.410	0.308	0.371	63/64	0.186	0.278	0.537	0.624
24/25	0.159	0.205	0.322	0.415	64/65	0.362	0.419	0.343	0.383
25/26	0.324	0.408	0.358	0.434	65/66	0.319	0.415	0.111	0.256
26/27	0.339	0.424	0.317	0.471	66/67	0.190	0.217	0.202	0.253
27/28	0.210	0.259	0.238	0.283	67/68	0.363	0.323	0.325	0.401
28/29	0.247	0.290	0.357	0.432	68/69	0.267	0.357	0.468	0.581
29/30	0.191	0.243	0.299	0.386	69/70	0.498	0.521	0.329	0.526
30/31	0.169	0.215	0.208	0.274	70/71	0.230	0.241	0.274	0.466
31/32	0.227	0.276	0.410	0.474	71/72	0.234	0.301	0.246	0.320
32/33	0.299	0.351	0.527	0.626	72/73	0.447	0.548	0.322	0.386
33/34	0.181	0.232	0.256	0.281	73/74	0.223	0.231	0.191	0.214
34/35	0.208	0.262	0.310	0.374	74/75	0.237	0.343	0.267	0.286
35/36	0.213	0.270	0.351	0.404	75/76	0.179	0.232	0.221	0.260
36/37	0.213	0.285	0.292	0.358	76/77	0.232	0.320	0.332	0.409
37/38	0.278	0.307	0.297	0.337	77/78	0.269	0.343	0.259	0.310
38/39	0.228	0.263	0.251	0.279	78/79	0.358	0.420	0.516	0.577
39/40	0.195	0.235	0.344	0.429	79/80	0.347	0.393	0.417	0.442
40/41	0.281	0.362	0.236	0.275	80/81	0.240	0.302	0.180	0.197
41/42	0.300	0.331	0.321	0.391	81/82	0.184	0.237	0.320	0.422
42/43	0.188	0.233	0.274	0.316	82/83	0.328	0.385	0.450	0.497
43/44	0.180	0.222	0.394	0.425	83/84	0.204	0.417	0.521	0.589
44/45	0.276	0.343	0.328	0.408	84/85	0.314	0.344	0.297	0.365
45/46	0.257	0.347	0.241	0.304	85/86	0.271	0.340	0.312	0.388
46/47	0.257	0.320	0.350	0.421	86/87	0.493	0.574	0.380	0.457
47/48	0.173	0.232	0.263	0.327	87/88	0.187	0.196	0.211	0.245
48/49	0.446	0.453	0.423	0.449	88/89	0.170	0.260	0.247	0.287
49/50	0.198	0.236	0.427	0.513	89/90	0.287	0.293	0.303	0.366
50/51	0.164	0.205	0.413	0.470	90/91	0.254	0.289	0.346	0.413
51/52	0.398	0.478	0.237	0.277	91/92	0.616	0.640	0.892	0.926
52/53	0.183	0.230	0.225	0.353	92/93	0.217	0.257	0.389	0.463
53/54	0.199	0.258	0.280	0.331	93/94	0.292	0.385	0.242	0.268
54/55	0.342	0.369	0.458	0.506	94/95	0.292	0.377	0.351	0.420
55/56	0.126	0.199	0.265	0.287	95/96	0.271	0.343	0.382	0.486
56/57	0.300	0.273	0.378	0.406	96/97	0.194	0.272	0.348	0.428
57/58	0.316	0.246	0.405	0.499	97/98	0.253	0.394	0.274	0.376
58/59	0.151	0.326	0.298	0.350	98/99	0.274	0.322	0.547	0.592
59/60	0.158	0.251	0.310	0.441	99/00	0.239	0.269	0.359	0.390
60/61	0.162	0.306	0.341	0.366	00/01	0.239	0.291	0.386	0.458
61/62	0.220	0.318	0.339	0.413	01/02	0.305	0.381	0.501	0.556
					Mean	**0.260**	**0.320**	**0.334**	**0.400**

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ISSN 0378-4738 = Water SA Vol. 33 No. 1 January 2007
ISSN 1816-7950 = Water SA (on-line)

Available temperature data for the 80 seasons comprised T_{max} and T_{min}, from which T_{av} could be calculated. Because T_{max} will almost invariably occur during sunshine hours, it was expected that the best correlation will be between Vd and T_{max}. Correlations with T_{av} and T_{min} were nevertheless also tested against the 1 635 data points. Results are presented in Table 2. As predicted, T_{max} had the best correlation ($R^2 = 0.73$) with Vd (Fig. 2). Equation (11) could therefore be used to estimate Vd from long-term T_{max} data.

$$Vd = 0.163 \times T_{max} - 2.88 \quad R^2 = 0.73 \qquad (11)$$

PUE_T for each production practice could therefore be calculated using Eqs. (4), (6) and (11). The resulting PUE_T data were expressed as cumulative probability functions, and average values. This gave 'treatments' (conventional tillage vs. in-field rainwater harvesting and November vs. January planting) that could be evaluated against each other, using the Kolmogorov-Smirnov test (Steel et al., 1997).

Results and discussion

PUE_T was calculated, using Eqs. (4), (6) and (11), for each of the four production practices over 80 seasons (1922/23 to 2001/02) on the Glen Hutton-Ventersdorp ecotope (Table 3).

November planting with conventional tillage (CTN) had the lowest mean $PUE_T = 0.260$, followed by November planting with in-field rainwater harvesting (WHBN), with mean $PUE_T = 0.320$, January planting with conventional tillage (CTJ), mean $PUE_T = 0.334$ and January planting with in-field rainwater harvesting (WHBJ), mean $PUE_T = 0.400$ (Table 3). The PUE_T values for WHBJ are higher than those for CTJ for all the years, and values for WHBN are higher than CTN for 77 out of the 80 years (Table 3).

The cumulative probability functions for conventional tillage and in-field rainwater harvesting are plotted in Fig. 3. The clear separation between the two lines in Fig. 3, and the high significant difference (Table 4) confirmed and quantified the advantage of the in-field rainwater harvesting production practice over the conventional tillage production practice for almost all 80 seasons studied. The main advantage was probably due to the absence of runoff, and reduced evaporation in the in-field rainwater harvesting production practice, compared to the conventional tillage production practice with more evaporation and considerable runoff (Zere et al., 2005b). These PUE_T results are similar to values obtained in field experiments on another ecotope at the Glen experiment station, where average PUE_T values over four consecutive growing seasons for CT and WHB treatments on a Glen/Bonheim-Onrus ecotope were 0.145 and 0.250 respectively (Botha, 2006).

November and January planting could also be evaluated, using the available dataset (Fig. 4). January planting was significantly more efficient in terms of rainfall use than November planting (Table 4). Maize is very sensitive to drought conditions during flowering. Maize planted in November will flower in January which has a long-term average aridity index (AI) of 0.30, whereas maize planted early in January will flower in March with an equivalent AI value of 0.46 (Botha et al., 2003). The advantage of January planting is therefore clearly due to a more favourable climate during flowering. January planting is only possible with a short-season cultivar as the heat units available become marginal in April and later.

Figure 5 shows the cumulative probability functions for the CTN, CTJ, WHBN and WHBJ production practices. WHBJ had

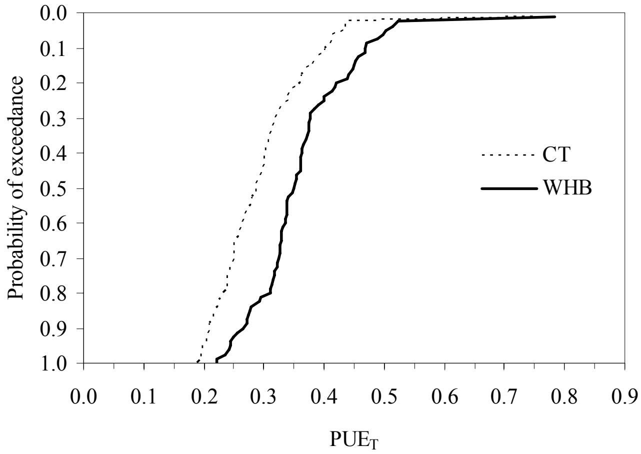

Figure 3
Cumulative probability functions of precipitation use efficiency (PUE_T) over 80 seasons, for the conventional tillage (CT) and in-field rainwater harvesting (WHB) production techniques

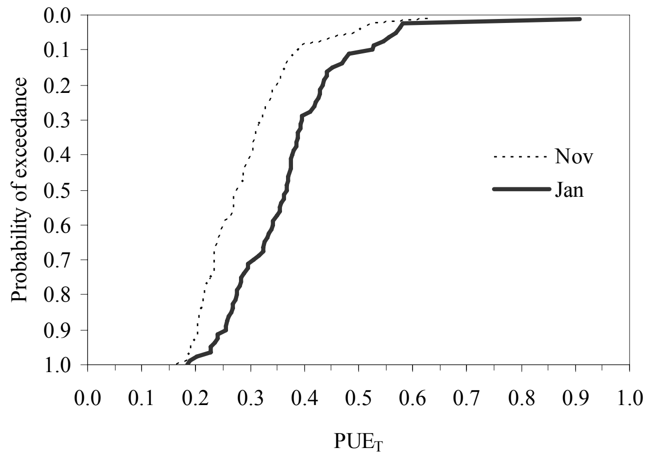

Figure 4
Cumulative probability functions of precipitation use efficiency (PUE_T) over 80 seasons, for the November (Nov) and January (Jan) planting production techniques

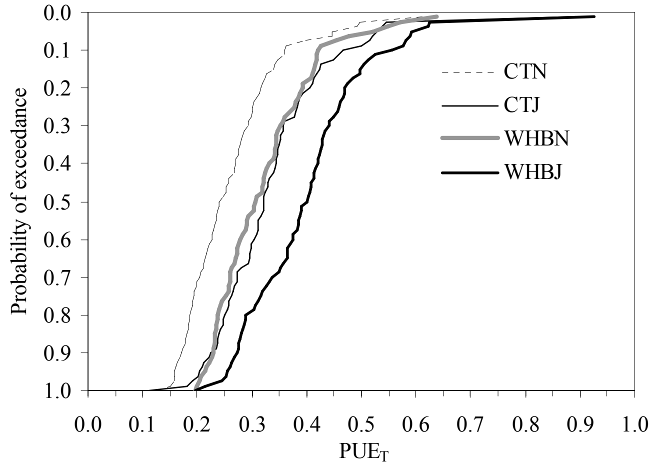

Figure 5
Cumulative probability functions of precipitation use efficiency (PUE_T) over 80 seasons, for the November planting with conventional tillage (CTN), November planting with in-field rainwater harvesting (WHBN), January planting with conventional tillage (CTJ), and January planting with the in-field rainwater harvesting (WHBJ) production technique

TABLE 4
Results of the Kolmogorov-Smirnov comparison (Steel et al., 1997) of the grouped cumulative probability functions (CPF) in Figures 2 and 3

CPF pair	D-statistic	Probability level
CT *vs*. WHB	0.4625*	0.000
Jan *vs*. Nov	0.4000*	0.000

** High significant difference*

TABLE 5
Results of Kolmogorov-Smirnov comparison (Steel et al., 1997) of the cumulative probability functions (CPF) in Figure 4

CPF pair	D-statistic	Probability level
CTN *vs*. WHBN	0.3250*	0.000
CTN *vs*. CTJ	0.3750*	0.000
CTN *vs*. WHBJ	0.5750*	0.000
WHBN *vs*. CTJ	0.1250^{ns}	0.532
WHBN *vs*. WHBJ	0.3875*	0.000
CTJ *vs*. WHBJ	0.3750*	0.000

** High significant difference*
^{ns} No significant difference

the highest yield probability of all the production practices considered, and therefore had the best PUE_T. Similarly, CTN was shown to have the worst PUE_T. Although WHBN always had a higher yield probability than CTJ (Fig. 4), and was therefore considered to have a consistently better PUE_T, the probability lines were very close together and were therefore not significantly different (Table 5). It was concluded that the advantages associated with January planting using conventional tillage were matched by the disadvantages of November planting using in-field rainwater harvesting.

Conclusions

Mean precipitation use efficiency (PUE_T) was 0.260 for CTN, 0.320 for WHBN, 0.334 for CTJ, and 0.400 for WHBJ, over the 80 seasons under consideration. The results demonstrated and quantified the advantage of in-field rainwater harvesting relative to conventional tillage, and January planting relative to November planting. Cumulative probability functions, based on estimated long-term yields, tested statistically using the Kolmogorov-Smirnov test, showed that PUE_T for in-field rainwater harvesting was significantly better than PUE_T for conventional tillage. It was similarly shown that PUE_T for January planting was significantly better than PUE_T for November planting.

It was concluded that the higher PUE_T of the in-field rainwater harvesting production practice compared to the conventional tillage production practice was probably due to very little runoff and reduced evaporation in the former. It was concluded that the higher PUE_T for January planting relative to November planting was mainly due to the short growing season cultivar that flowered in March, the month with the most favourable climate.

Results presented here reflect the unique environmental conditions for the semi-arid Glen/Hutton-Ventersdorp ecotope, located at Glen and should therefore only be extrapolated to other study areas with caution.

Acknowledgements

Our sincere thanks to Ms. Linda De Wet for aiding in the computation of the vapour pressure deficit and Mr. Mike Fair for helping with the statistical analyses. Both are affiliated with the University of the Free State.

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