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Water Use Efficiency of Maize Varieties under Rain-Fed Conditions in Zambia

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Abstract

This study evaluated water use efficiency (WUE) of selected hybrid maize (*Zea Mays L.*) varieties in Zambia under rain-fed conditions. A randomized complete block field experiment was carried out during the 2014/2015 rainy season at the University of Zambia Agricultural Demonstration Centre. Treatments were 30 maize varieties from the early, medium and late maturity classes. WUE was calculated as the ratio of yield to evapotranspiration (ET) and transpiration (T). Results showed significant differences in WUE dry matter ($_{DM}$) for transpiration ($_{T}$) of early maturing varieties. However, no significant differences were observed in WUE_{DM} for evapotranspiration ($_{ET}$), WUE grain yield ($_{GY}$)$_{, T}$ and $WUE_{GY, ET}$. $WUE_{DM, T}$, $WUE_{DM, ET}$, $WUE_{GY, T}$, and $WUE_{GY, ET}$ were statistically the same among medium maturing varieties. Results further showed that among the late maturing varieties, $WUE_{DM, T}$, $WUE_{DM, ET}$ and $WUE_{GY, T}$ showed significant differences but no significant differences were observed in $WUE_{GY, ET}$. It was concluded that maize varieties from the same maturity classes have different WUEs. The study thus provided options in variety selection based on which varieties performed better, particularly SC 525, SC 513 and PAN 4M 21 from the early maturity class; PHB 30G19, ZMS 606, MRI 634 and SC 637 from the medium maturity class; and PAN ZM 83, SC 709, PAN 8M 93 and SC 719 from the late maturity class. It was recommended however, that repeated experiments over time should be done to validate the findings given that the trial was only conducted in one season.

Keywords: maize varieties, rain-fed, water use efficiency

1. Introduction

Maize (*Zea mays* L.) is a C4 plant, which potentially has more efficient use of carbon dioxide (CO_2), solar radiation, water and nitrogen in photosynthesis than C3 crops, resulting in higher production of dry matter (DM) (Huang, Birch & George, 2006). Even though maize makes efficient use of water, it is considered more susceptible to water stress than other crops because of its unusual floral structure with separate male and female organs and the near-synchronous development of florets on a usually single ear borne of each stem. The production of maize, as is for all other crops is directly related to the capture of resources, such as water and sunlight, and the efficiency with which it converts these physical resources into biological materials. Water Use Efficiency (WUE) is one of the ways to analyze the response of crops to different conditions of water availability as it relates to the production of dry biomass with the amount of water applied or evapotranspired. It is aptly defined as the amount of yield produced per unit of water evapo-transpired or transpired (Doorenbos et al., 1979).

Evapotranspiration (ET) is composed of soil evaporation (E) and plant transpiration (T) and the two are dependent on wetness of the surface soil and canopy size. The actual ET in any field experiment will therefore vary considerably depending on the frequency of the rains and the crop canopy dynamics. Since ET is plant specific, different crops and different varieties from the same crops evapotranspire different amounts of water under similar climatic conditions. These differences provide opportunities to select for appropriate varieties with an efficient use of water. To assess such options, ET estimates of different varieties are required for a specific region. Since allowance is made for differences in atmospheric evaporative demand among varieties, T in general becomes a reasonably stable quantity for most green crops having a closed canopy. This is to be expected because of the close link between CO_2 usage for photosynthesis and plant water use (Gardner, Laryea & Unger, 1999). The advantage of WUE_T over WUE_{ET} is that it avoids the compounding effect of the non-productive soil E and weed T losses (Nyakudya & Stroosnijder, 2014).

Notwithstanding the efforts of breeders to develop high yielding varieties, the yield of maize throughout the production regions in Zambia are generally low, averaging < 1.5 ton ha^{-1} for the majority of small scale farmers (Jayne et al., 2007; Ministry of Agriculture and Livestock [MAL], 2015). Most of the maize that the country produces each year is grown under rain-fed conditions. In areas such as the semi-arid and dry sub-humid environments, the amount of rainfall is not only the limiting factor of rain-fed maize production but also its erratic nature. Therefore, a major focus of rain-fed cropping systems is increasing efficiency of water utilization by crops. One strategy to reduce the effect of water stress on crop yield is to use water efficient species (Stewart & Nielsen, 1991). Bibi, Sadaqat, Akram & Mohammed (2010) also noted that crop plants are usually under stress conditions at one time or another and the plant species able to withstand stresses have great economic potential. Thus rain-fed maize production could be enhanced by adopting varieties that efficiently use soil moisture for biomass and grain production.

Studies on maize WUE have been conducted in some parts of Africa (Frimpong, Amoatey, Ayeh & Asare, 2011; Asare, Frimpong, Ayeh & Amoatey, 2011). However, there is limited information on maize varieties that use water more efficiently under rain-fed agriculture in Zambia with the exception of the work by Phiri, Verplancke, Kwesiga & Mafongonya (2003) who investigated WUE of rain-fed maize in eastern Zambia under different fallow systems with only one variety evaluated. There is need therefore to locally determine WUE of different maize varieties under rain-fed conditions in Zambia under the conventional type of farming. Quantifying WUE of crops is important to identify and subsequently disseminate the best suitable varieties for a specific region. The reason for this is to enhance maize productivity through improved selection of maize varieties which are efficient in water use and to generate evidence not currently existing of the maize varieties for promotion among small scale farmers. This would greatly help in information and decision guides. Given the many varieties readily available on the market, variety selection is a cost effective way of maximizing WUE. It is against this background that the study was initiated. The overall purpose of the current study was to evaluate 30 hybrid maize varieties for their efficiency in use of water for DM and grain yield (GY) production under rain-fed conditions in agro-ecological region IIa of Zambia. Identified maize cultivars, when adopted by farmers could assist in enhancing sustainable maize production in areas where rain-fed maize production is mostly practiced, particularly in areas that experience low and erratic rainfall.

2. Materials and Methods

2.1 Area Description

The field experiment was conducted at the University of Zambia Agricultural Demonstration Centre. The site is located at latitude 15° 21′ 25″ South and longitude 28° 27′ 25″ East. The elevation is 1 160 m above sea level. The site is in Chongwe District of Lusaka Province in Zambia. The soil of the study site is of a sandy loam texture, taxonomically belonging to the Chromic Luvisol category (Jones et al., 2013). The pre-planting analysis of the soil of the experimental field indicated generally low total nitrogen and exchangeable potassium contents of 0.06% and 0.231 cmol kg^{-1}, respectively. The amount of available phosphorous was found to be 16.20 mg kg^{-1}, sufficient enough to prevent phosphorous deficiency. Other soil parameters analyzed are shown in Table 1. The study site falls in Agro-Ecological region IIa of Zambia.

2.2 Treatments and Experimental Design

Treatments were 30 hybrid maize varieties consisting of 10 early, 10 medium and 10 late maturity varieties. These varieties were selected based on availability from seed companies during the season (here and hereinafter, mention of brand names of maize varieties is for identification only and does not constitute endorsement of the product(s) by the author(s) or the institution(s) mentioned herein). Maturity of maize hybrids is a genetic characteristic and is generally defined as the period from germination to when the kernel ceases to increase in weight (Brown, Zuber, Darrah & Glover, 1985). The experiment was set up in a Randomized Complete Block Design (RCBD) with three replications. Each subplot measured 5 m x 5 m separated from each other by a border space of 2 m.

2.3 Agronomic Management

The experiment was conducted in the 2014/2015 rainy season and maize varieties were subjected to conventional agricultural practices which included no irrigation. The study site was prepared using a moldboard plough and harrowed to a fine tilth with a tractor before the onset of the rains. Maize varieties were sown on the 17th of December, 2014 at a spacing of 75 cm between rows and 30 cm within rows to give a population of 44, 444 plants ha^{-1}. Compound D (10% N: 20% P_2O_5: 10% K_2O: + 6% S) and Urea (46% N) fertilizers were applied at a rate of 200 kg ha^{-1} to provide 20 kg N ha^{-1}, 17 kg P ha^{-1}, 17 kg K ha^{-1} from Compound D and 92 kg N ha^{-1} from Urea. Glyphosate herbicide was applied before planting at a rate of 125 g ha^{-1} as pre-emergence weed control.

2.4 Biomass and Grain Yield Measurement

Measurements of biomass or DM and GY were done from the net plots and determined at harvest time. A bordered area of 9 m^2 (3 m x 3 m) consisting of 40 plants in each plot was hand-harvested for the measurement of yield. In terms of total biomass, maize plants were cut just above the ground using sickles and weighed. In terms of GY, the harvested ears were counted, weighed, manually shucked and the grain weighed. The grain was then tested for moisture using a grain analysis meter and GY adjusted to 12.5% moisture content. The results of the harvest were expressed in ton ha^{-1}.

Table 1. Soil Characterization of the Study Site

Depth	pH	EC	OC	OM	Sand	Silt	Clay	Texture	ρb	FC	WP	AWC
(cm)	($CaCl_2$)	(mS cm^{-1})			%			(USDA)	g cm^{-3}	% vol		mm m^{-1}
0-10	4.21	0.20	0.25	0.50	73.4	17.5	9.1	SL	1.43	13.8	5.5	83
10-20	4.05	0.23	0.15	0.30	73.5	15.4	11.1	SL	1.45	14.6	6.5	81
20-30	4.04	0.15	0.13	0.26	70.1	13.5	16.4	SL	1.53	17.8	9.6	82
30-40	4.08	0.44	0.14	0.28	70.8	12.1	17.1	SL	1.65	17.3	10.3	70
40-50	4.15	0.23	0.26	0.52	66.8	14.1	19.1	SL	1.70	19.0	11.7	73
50-60	4.10	0.19	0.14	0.28	64.8	12.1	23.1	SCL	1.70	21.6	13.9	77
60-70	4.22	0.11	0.14	0.28	63.5	10.8	25.7	SCL	1.59	24.4	15.7	87
70-80	4.34	0.12	0.10	0.20	60.8	12.8	26.4	SCL	1.57	25.0	15.7	93
80-90	4.53	0.26	0.07	0.14	62.1	11.5	26.4	SCL	1.59	24.6	15.6	90
90-100	4.52	0.26	0.18	0.36	60.1	14.1	25.8	SCL	1.51	25.8	15.8	100

pH = potential of hydrogen (i.e. soil reaction), EC = electrical conductivity, OC = organic carbon, OM = organic matter, USDA = United States Department of Agriculture, ρb = bulk density, FC = field capacity, WP = wilting point and AWC = available water content

2.5 Measurement of Weather Data and Calculation of Water Use Efficiency (WUE)

Weather data during the study was collected from an automated weather station located at latitude 15° 19′ 9″ and longitude 28° 26′ 25″ and altitude 1 149 m above sea level and 4.5 km north of the site. Weather elements recorded included rainfall (mm), minimum and maximum temperatures (℃), wind speed (m s^{-1}), relative humidity (%) and solar irradiance (MJ m^{-2} day^{-1}). This data, together with the soil and crop management and growth data were input into the AquaCrop model (Steduto, Hsiao, Raes & Fereres, 2009; Raes, Steduto, Hsiao & Fereres, 2009 and Hsiao et al., 2009) to help estimate the water balance model for each variety from seed emergence to crop maturity as follows:

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

Where in ΔS = change in root zone soil moisture storage, P = precipitation, in this case, rainfall, I = irrigation, R = runoff, D = downward drainage out of the root zone, E = direct evaporation from the soil surface, and T = transpiration by plants. Irrigation was not considered as the study was conducted under rain-fed conditions. All measurements were in mm.

WUE was calculated as the ratio of yield to ET and T as follows:

$$WUE_{GY,ET} = \frac{GY}{ET} \quad (2)$$

$$WUE_{GY,T} = \frac{GY}{T} \quad (3)$$

$$WUE_{DM,ET} = \frac{DM}{ET} \quad (4)$$

$$WUE_{DM,T} = \frac{DM}{T} \quad (5)$$

Where WUE_{GY} = water use efficiency for grain yield (kg ha^{-1} mm), WUE_{DM} = water use efficiency for dry matter or total biomass (kg ha^{-1} mm^{-1}), ET = evapotranspiration (mm), T = transpiration (mm).

2.6 Data Analysis

Data were analyzed by analysis of variance (ANOVA) using GenStat Statistical Software. The least significant difference test (LSD) was used to compare variety differences. Differences were declared significant at $P < 0.05$.

3. Results

3.1 Weather Conditions

The total amount of rainfall received during the experimental year was 1 031.8 mm (Table 2). The highest monthly total rainfall was recorded in December (326.6 mm), with the lowest rainfall occurring in May (0.4 mm). The highest minimum and maximum temperatures recorded at the experimental site were 19.3 ℃ and 33.4 ℃ respectively, in the month of November. The highest mean relative humidity (RH) at the experimental site was 86.28%, which occurred in January. The mean RH of the entire period was 64.55%. The highest solar radiation and wind speed were 24.77 MJ $m^{-2}day^{-1}$ in November and 2.4 m s^{-1} in September, respectively.

Table 2. Monthly Weather Variables Recorded at the Experimental Site during the Study Period

Year	Month	Rainfall mm	T_{min} ℃	T_{max} ℃	$RH_{average}$ %	$Solar_{radiation}$ MJ m^2 day^{-1}	$Wind_{speed}$ m s^{-1}
2014	June	0.0	9.7	24.8	61.98	17.31	1.9
	July	0.0	8.9	25.0	57.40	18.53	1.9
	August	0.8	8.7	28.0	46.10	20.10	2.2
	September	0.0	14.3	30.2	40.98	22.74	2.4
	October	0.0	17.2	33.4	39.54	24.47	2.2
	November	76.0	19.3	33.4	46.30	24.47	1.9
	December	326.6	18.9	29.4	74.29	18.56	0.9
2015	January	243.6	18.3	27.6	86.28	17.90	1.1
	February	140.0	18.2	28.4	85.80	20.12	1.1
	March	56.4	16.9	28.7	79.23	21.81	1.7
	April	188.0	15.9	25.5	85.74	15.50	1.6
	May	0.4	11.3	26.2	71.01	20.35	1.7
		1 031.8	**14.8**	**28.4**	**64.55**	**20.16**	**1.7**

T_{min} = minimum temperature, T_{max} = maximum temperature and RH = relative humidity

3.2 Yield, Transpiration and Evapotranspiration

3.2.1 Yield, Transpiration and Evapotranspiration of Early Maturing Maize Varieties

Results on total DM, GY, T and ET of early maturing maize varieties are presented in Table 3. DM varied from 4.8 ton ha^{-1} to 13.5 ton ha^{-1}. The average DM was 8.96 ton ha^{-1}. The lowest was with maize variety SC 303 while the highest was with maize variety SC 513. There were no significant differences observed in DM ($P > 0.05$). GY varied from 2.1 ton ha^{-1} to 5.1 ton ha^{-1}. The average grain yield was 3.26 ton ha^{-1}. The lowest GY was found to be with SC 303 while the highest GY was found to be with SC 525. No significant differences were found in GY ($P > 0.05$).

T ranged from 98.7 mm to 232.0 mm with an average of 173.54 mm. The lowest T was observed with SC 303 while the highest was observed with SC 525. There were significant differences observed in T among early maturing maize varieties ($P < 0.05$). ET varied from 288.7 mm to 427.0 mm with an average of 372.20 mm. The lowest ET was observed with SC 303 while the highest was observed with SC 525. Very highly significant differences were observed in ET ($P < .001$).

Table 3. Yield, Transpiration and Evapotranspiration of Early Maturing Maize Varieties

Variety	Biomass ton ha^{-1}	Grain ton ha^{-1}	Transpiration mm	Evapotranspiration mm
SC 303	4.8^{a}	2.1^{a}	98.7^{a}	288.7^{a}
ZMS 402	7.4^{a}	2.4^{a}	160.0^{abc}	344.3^{bc}
GV 409	5.6^{a}	2.5^{a}	131.7^{ab}	336.3^{ab}
P 3253	6.9^{a}	2.6^{a}	178.7^{bcd}	393.3^{cd}
PAN 413	10.7^{a}	2.5^{a}	149.0^{abc}	343.0^{bc}
SC 403	7.7^{a}	3.2^{a}	192.0^{bcd}	403.0^{d}
MRI 514	10.5^{a}	3.5^{a}	183.0^{bcd}	391.7^{cd}
PAN 4M 21	11.1^{a}	3.8^{a}	206.3^{cd}	377.0^{bcd}
SC 513	13.5^{a}	4.9^{a}	204.0^{cd}	417.7^{d}
SC 525	11.6^{a}	5.1^{a}	232.0^{d}	427.0^{d}
Mean	$\mathbf{8.98^{ns}}$	$\mathbf{3.26^{ns}}$	$\mathbf{173.54^{*}}$	$\mathbf{372.20^{***}}$
LSD	5.586	2.249	69.5	50.6
CV (%)	36.3	40.3	23.4	7.9
P-value	0.058	0.116	0.028	<.001

ns = not significant, *= significant, ***= very highly significant, means followed by the same letter(s) are not significantly different

3.2.2 Yield, Transpiration and Evapotranspiration of Medium Maturing Maize Varieties

Results on DM, GY, T and ET of medium maturing maize varieties are presented in Table 4. DM varied from 6.2 ton ha^{-1} to 13.4 ton ha^{-1}. The mean DM was 10.50 ton ha^{-1}. Maize variety SC 647 had the lowest DM while maize variety SC 637 had the highest DM yield. No significant differences were observed in DM ($P > 0.05$). GY varied from 2.3 ton ha^{-1} to 4.8 ton ha^{-1}. The mean GY was 3.52 ton ha^{-1}. Maize variety SC 647 had the lowest GY while maize variety PHB 30G19 had the highest GY. No significant differences were observed in the GY ($P > 0.05$).

T ranged from 151.3 mm with PAN 53 as the lowest to 217.0 mm with PHB 30G19 as the highest. The average T was 193.06 mm. Yet again, no significant differences were observed ($P > 0.05$). Maize variety PAN 53 had the lowest amount of ET (380.7 mm) while maize variety PHB 30G19 had the highest (424.0 mm). The average ET was 407.96 mm. However, there were no significant differences observed in ET of medium maturing maize varieties ($P > 0.05$).

Table 4. Yield, Transpiration and Evapotranspiration of Medium Maturing Maize Varieties

Variety	Biomass ton ha^{-1}	Grain ton ha^{-1}	Transpiration mm	Evapotranspiration mm
SC 647	6.2^{a}	2.3^{a}	189.3^{a}	408.3^{a}
PAN 53	9.7^{a}	2.7^{a}	151.3^{a}	380.7^{a}
MRI 694	9.3^{a}	2.9^{a}	181.3^{a}	405.0^{a}
P 3812W	10.4^{a}	3.4^{a}	181.0^{a}	403.3^{a}
MRI 624	11.4^{a}	3.5^{a}	198.7^{a}	404.7^{a}
MRI 634	10.9^{a}	3.6^{a}	191.3^{a}	400.3^{a}
ZMS 616	10.1^{a}	3.6^{a}	198.3^{a}	413.0^{a}
SC 637	13.4^{a}	4.2^{a}	211.7^{a}	423.0^{a}
ZMS 606	11.3^{a}	4.2^{a}	210.7^{a}	417.3^{a}
PHB 30G19	12.3^{a}	4.8^{a}	217.0^{a}	424.0^{a}
Mean	**10.50^{ns}**	**3.52^{ns}**	**193.06^{ns}**	**407.96^{ns}**
LSD	3.833	2.722	80.71	44.58
CV (%)	44.8	44.6	24.4	6.4
P-value	0.846	0.702	0.855	0.692

ns = not significant, means followed by the same letter are not significantly different

3.2.3 Yield, Transpiration and Evapotranspiration of Late Maturing Maize Varieties

Results on DM, GY, T and ET of late maturing maize varieties are presented in Table 5. Total DM varied from 5.3 ton ha^{-1} to 22.5 ton ha^{-1}, with a mean of 14.29 ton ha^{-1}. MRI 724 had the lowest DM while SC 709 had the highest. The DM of late maturing maize varieties showed significant differences ($P < 0.05$). On the other hand, late maturing maize varieties exhibited considerable but not statistical differences in GY which varied from 1.5 ton ha^{-1} to 6.0 ton ha^{-1}, with an average of 4.24 ton ha^{-1}. MRI 724 had the lowest GY while PAN ZM-83 had the highest GY.

Table 5. Yield, Transpiration and Evapotranspiration of Late Maturing Maize Varieties

Variety	Biomass ton ha^{-1}	Grain ton ha^{-1}	Transpiration mm	Evapotranspiration mm
MRI 724	5.3^{a}	1.5^{a}	174.3^{a}	402.3^{a}
ZMS 702	10.4^{ab}	2.9^{a}	203.3^{a}	415.0^{a}
PAN ZM 81	12.7^{abc}	3.9^{a}	197.3^{a}	416.0^{a}
GV 635	12.8^{abc}	3.9^{a}	217.3^{a}	424.4^{a}
ZMS 720	13.8^{abcd}	4.1^{a}	236.0^{a}	437.0^{a}
MRI 744	13.4^{abc}	4.4^{a}	237.0^{a}	435.0^{a}
PAN 8M 93	13.9^{abcd}	4.9^{a}	223.7^{a}	425.3^{a}
SC 719	18.5^{bcd}	5.2^{a}	265.7^{a}	459.7^{a}
SC 709	22.5^{d}	5.6^{a}	267.0^{a}	461.3^{a}
PAN ZM 83	19.6^{cd}	6.0^{a}	261.7^{a}	455.3^{a}
Mean	**14.29^{*}**	**4.24^{ns}**	**228.33^{ns}**	**433.13^{ns}**
LSD	8.785	3.452	96.6	59.15
CV (%)	35.8	47.3	24.7	8.0
P-value	0.033	0.294	0.528	0.446

*= significant, ns = not significant, means followed by the same letter(s) are not significantly different

T ranged from 174.3 mm to 267.0 mm with an average of 228.33 mm. The lowest T was with MRI 724 while the highest was with SC 709. However, no significant differences were observed in T ($P > 0.05$). ET ranged between 402.3 mm and 461.3 mm. The average was 433.13 mm. Following the pattern of T, maize varieties MRI 724 and

SC 709 had the lowest and highest ET amounts, respectively but no significant differences were observed among the varieties (P > 0.05).

3.3 Water Use Efficiency

3.3.1 Water Use Efficiency of Early Maturing Maize Varieties

Among early maturing maize varieties, WUE for dry matter yield for evapotranspiration ($WUE_{DM, ET}$) varied from 16.67 kg ha^{-1} mm^{-1} to 32.23 kg ha^{-1} mm^{-1} (Table 6) with a mean of 23.36 kg ha^{-1} mm^{-1}. The lowest and highest $WUE_{DM, ET}$ were found to be with GV 409 and SC 513, respectively. WUE for dry matter for transpiration ($WUE_{DM, T}$) varied from 36.54 kg ha^{-1} mm^{-1} to 68.51 kg ha^{-1} mm^{-1}. The average was 50.52 kg ha^{-1} mm^{-1}. The lowest value was observed to be with P 3253, followed by SC 403 and ZMS 402 while the highest was observed to be with PAN 413, followed by SC 513 and the MRI 514.

WUE for grain yield of the water evapo-transpired ($WUE_{GY, ET}$) for the entire growing season was in the range of 6.38 kg ha^{-1} mm^{-1} to 11.86 kg ha^{-1} mm^{-1}. The average was 8.39 kg ha^{-1} mm^{-1}. The lowest value was observed with P 3253 while the highest was observed to be with SC 525. WUE for GY for transpiration ($WUE_{GY, T}$) varied from 13.42 kg ha^{-1} mm^{-1} to 23.83 kg ha^{-1} mm^{-1}. The average was 17.99 kg ha^{-1} mm^{-1}. The lowest value was observed to be with P 3253 while the highest was observed to be with SC 513. The ANOVA of the WUE of early maturing maize varieties (Table 7) indicated that there were no significant differences observed among varieties (P > 0.05) in $WUE_{DM, ET}$, $WUE_{GY, ET}$ and $WUE_{GY, T}$. However, there were significant differences observed in $WUE_{DM, T}$ (P < 0.05).

Table 6. Water Use Efficiency of Early Maturing Maize Varieties

Variety	**$WUE_{DM, ET}$**	**$WUE_{DM, T}$**	**$WUE_{GY, ET}$**	**$WUE_{GY, T}$**
	kg ha^{-1} mm^{-1}			
GV 409	16.67[a]	43.63[ab]	7.26[a]	18.45[a]
SC 303	16.72[a]	50.29[abc]	7.11[a]	20.91[a]
P 3253	17.19[a]	36.54[a]	6.38[a]	13.42[a]
SC 403	18.93[a]	39.58[ab]	7.92[a]	16.46[a]
ZMS 402	20.46[a]	42.79[ab]	6.45[a]	13.84[a]
MRI 514	26.29[a]	55.89[bcd]	8.68[a]	18.41[a]
SC 525	27.22[a]	50.07[ab]	11.86[a]	21.82[a]
PAN 4M 21	28.51[a]	51.39[abc]	9.57[a]	16.81[a]
PAN 413	29.44[a]	68.51[d]	7.01[a]	15.97[a]
SC 513	32.23[a]	66.55[cd]	11.63[a]	23.83[a]
Mean	**23.36[ns]**	**50.52***	**8.39[ns]**	**17.99[ns]**
LSD	11.88	16.39	5.049	7.031
CV%	29.6	18.9	34.9	22.8

ns = not significant, *= significant, means followed by the same letter(s) are not significantly different

Table 7. ANOVA of the WUE of Early Maturing Maize Varieties

Source of variation	df	s.s	m.s	v.r	F pr.
Variate: $WUE_{DM, ET}$					
Replication stratum	2	568.25	284.13	5.93	
Variety	9	961.85	106.87	2.23	0.071
Residual	18	862.74	47.93		
Total	29	2392.84			
Variate: $WUE_{DM, T}$					
Replication stratum	2	790.65	395.32	4.33	
Variety	9	30.97	344.22	3.77	0.008
Residual	18	1642.73	91.62		
Total	29	5531.34			
Variate: $WUE_{GY, ET}$					
Replication stratum	2	69.138	34.569	3.99	
Variety	9	106.821	11.869	1.37	0.271
Residual	18	155.916	8.662		
Total	29	331.875			
Variate: $WUE_{GY, T}$					
Replication stratum	2	120.38	60.19	3.58	
Variety	9	311.05	34.56	2.06	0.092
Residual	18	302.36	16.80		
Total	29	733.79			

df = degrees of freedom, s.s = sum of squares, m.s = mean square, v.r = variance ratio

3.3.2 Water Use Efficiency of Medium Maturing Maize Varieties

$WUE_{DM, ET}$ for medium maturing maize varieties varied from 15.10 kg ha^{-1} mm^{-1} to 30.88 kg ha^{-1} mm^{-1} (Table 8). The mean was 25.25 kg ha^{-1} mm^{-1}. The lowest and highest values were observed with SC 647 and SC 637, respectively. $WUE_{DM, T}$ was in the range 32.30 kg ha^{-1} mm^{-1} to 63.52 kg ha^{-1} mm^{-1}. The mean was 52.85 kg ha^{-1} mm^{-1} with maize variety PAN 53 having the highest and SC 647 having the lowest values.

$WUE_{GY, ET}$ varied from 5.62 kg ha^{-1} mm^{-1} to 11.29 kg ha^{-1} mm^{-1} with average of 8.56 kg ha^{-1} mm^{-1}. The lowest among the medium maturing varieties was found to be with SC 647. The highest was found to be with PHB 30G19. In terms of $WUE_{GY, T}$ values varied from 12.03 kg ha^{-1} mm^{-1} to 22.07 kg ha^{-1} mm^{-1} with average of 17.79 kg ha^{-1} mm^{-1}. The lowest was observed with SC 647 and the highest was observed with PHB 30G19. Results of the ANOVA showed that statistically no significant differences were observed (P > 0.05) among medium maturing varieties in $WUE_{DM, ET}$, $WUE_{DM, T}$, $WUE_{GY, ET}$ and $WUE_{GY, T}$ (Table 9).

Table 8. Water Use Efficiency of Medium Maturing Maize Varieties

Variety	**$WUE_{DM, ET}$**	**$WUE_{DM, T}$**	**$WUE_{GY, ET}$**	**$WUE_{GY, T}$**
	kg ha^{-1} mm^{-1}			
SC 647	15.10[a]	32.30[a]	5.62[a]	12.03[a]
MRI 694	22.65[a]	49.91[a]	7.28[a]	15.89[a]
ZMS 616	24.07[a]	48.42[a]	8.67[a]	17.27[a]
PAN 53	24.47[a]	63.52[a]	6.92[a]	17.17[a]
P 3812W	25.52[a]	57.08[a]	8.25[a]	18.20[a]
ZMS 606	26.91[a]	52.82[a]	10.44[a]	20.65[a]
MRI 634	27.08[a]	56.94[a]	9.03[a]	18.95[a]
MRI 624	27.37[a]	52.24[a]	8.44[a]	16.49[a]
PHB 30G19	28.50[a]	54.42[a]	11.29[a]	22.07[a]
SC 637	30.88[a]	60.88[a]	9.69[a]	19.22[a]
Mean	**25.25[ns]**	**52.85[ns]**	**8.56[ns]**	**17.79[ns]**
LSD	16.82	22.37	5.791	7.929
CV%	38.8	24.6	39.4	26.0

ns = not significant, means followed by the same letter are not significantly different

Table 9. ANOVA of the WUE of Medium Maturing Maize Varieties

Source of variation	df	s.s	m.s	v.r	F pr.
Variate: $WUE_{DM, ET}$					
Replication stratum	2	410.29	205.14	2.13	
Variety	9	429.94	54.77	0.57	0.805
Residual	18	1731.56	96.20		
Total	29	2634.79			
Variate: $WUE_{DM, T}$					
Replication stratum	2	693.0	346.5	2.04	
Variety	9	2001.9	222.4	1.31	0.299
Residual	18	3062.0	170.1		
Total	29	5757.0			
Variate: $WUE_{GY, ET}$					
Replication stratum	2	17.70	8.85	0.78	
Variety	9	76.77	8.53	0.75	0.662
Residual	18	205.12	11.40		
Total	29	299.58			
Variate: $WUE_{GY, T}$					
Replication stratum	2	11.72	5.86	0.27	
Variety	9	207.58	23.06	1.08	0.423
Residual	18	384.60	21.37		
Total	29	603.90			

df = degrees of freedom, s.s = sum of squares, m.s = mean square, v.r = variance ratio

3.3.3 Water Use Efficiency of Late Maturing Maize Varieties

The range of $WUE_{DM, ET}$ of late maturing maize varieties varied from 13.11 kg ha^{-1} mm^{-1} to 47.91 kg ha^{-1} mm^{-1} with a mean of 32.20 kg ha^{-1} mm^{-1}. The lowest value was observed with MRI 724 while the highest value was observed with SC 709 (Table 10). In terms of $WUE_{DM, T}$ values varied from 30.26 kg ha^{-1} mm^{-1} to 84.44 kg ha^{-1} mm^{-1}. The mean was 60.43 kg ha^{-1} mm^{-1} and MRI 724 had the lowest while the highest was found to be with SC 709.

The efficiency with which soil water was used for GY production varied from 3.69 kg ha^{-1} mm^{-1} to 12.85 kg ha^{-1}

mm^{-1}. The mean $WUE_{GY, ET}$ was 9.56 kg ha^{-1} mm^{-1}. The lowest value was found to be with MRI 724 while the highest was found to be with PAN ZM-83. $WUE_{GY, T}$ was in the range 8.36 kg ha^{-1} mm^{-1} to 22.54 kg ha^{-1} mm^{-1}. The mean was 17.77 kg ha^{-1} mm^{-1}. Maize varieties MRI 724 and PAN ZM 83 had the lowest and highest values, respectively. The ANOVA of late maturing maize varieties (Table 11) showed that $WUE_{DM, ET}$ and $WUE_{GY, T}$ were significantly different ($P < 0.05$) among the varieties while $WUE_{DM, T}$ revealed very highly significant differences ($P < .001$) among varieties. However, $WUE_{GY, ET}$ was not significantly different among the varieties ($P > 0.05$).

Table 10. Water Use Efficiency of Late Maturing Maize Varieties

Variety	$WUE_{DM, ET}$	$WUE_{DM, T}$	$WUE_{GY, ET}$	$WUE_{GY, T}$
	kg ha^{-1} mm^{-1}			
MRI 724	13.11^{a}	30.26^{a}	3.69^{a}	8.36^{a}
ZMS 702	24.79^{ab}	49.82^{b}	6.90^{a}	13.56^{ab}
GV 635	29.74^{bc}	56.63^{bc}	9.29^{a}	17.79^{bc}
PAN ZM 81	30.30^{bc}	63.69^{bcd}	9.26^{a}	19.17^{bc}
MRI 744	30.76^{bc}	56.63^{bc}	10.16^{a}	18.56^{bc}
ZMS 720	31.23^{bc}	57.03^{bc}	9.19^{a}	16.68^{bc}
PAN 8M 93	32.24^{bc}	62.33^{bcd}	11.38^{a}	21.74^{c}
SC 719	39.98^{bcd}	69.11^{cde}	11.24^{a}	19.40^{bc}
PAN ZM 83	41.92^{cd}	74.31^{de}	12.85^{a}	22.54^{c}
SC 709	47.91^{d}	84.44^{e}	11.70^{a}	19.90^{bc}
Mean	**32.20***	**60.43*****	**9.56^{ns}**	**17.77***
LSD	15.46	16.59	6.360	7.692
CV%	28.0	16.0	38.8	25.2

*= significant, ***= very highly significant, ns= not significant, means followed with the same letter(s) are not significantly different

Table 11. ANOVA of the WUE of Late Maturing Maize Varieties

Source of variation	df	s.s	m.s	v.r	F pr.
Variate: $WUE_{DM, ET}$					
Replication stratum	2	117.00	58.50	0.72	
Variety	9	2502.23	278.03	3.42	0.013
Residual	18	1462.90	81.27		
Total	29	4082.12			
Variate: $WUE_{DM, T}$					
Replication stratum	2	353.09	176.55	1.89	
Variety	9	5773.26	641.47	6.85	< .001
Residual	18	1684.57	93.59		
Total	29	7810.92			
Variate: $WUE_{GY, ET}$					
Replication stratum	2	10.30	5.15	0.37	
Variety	9	191.30	21.26	1.55	0.206
Residual	18	247.41	13.75		
Total	29	449.02			
Variate: $WUE_{GY, T}$					
Replication stratum	2	13.62	6.81	0.34	
Variety	9	467.24	51.92	2.58	0.041
Residual	18	361.90	20.11		
Total	29	842.77			

df = degrees of freedom, s.s = sum of squares, m.s = mean square, v.r = variance ratio

4. Discussion

During the crop growing season, there was a continuous 23 days-dry spell that occurred in the month of March. As a result, plants experienced water stress and this was evidently visible on the plants especially through wilting of leaves to near permanent point; therefore, optimum crop growth was not achieved. Limitation of transpiration, which is the process that ensures use of water for plant growth as well as for cooling purposes, as was observed with the early maturing maize variety SC 303, caused plants to pay, sooner or later, in terms of reduced growth since the same stomates that transpired water also served to absorb CO_2 that was needed in photosynthesis. Additionally, reduced transpiration often results in warming of the plants and hence in increased respiration and further reduction of net photosynthesis (Hillel, 2004), and this was evidenced by the low GY (see also Ludlow, 1975). Whereas no variety tested in this experiment gave a yield of < 1.5 ton ha^{-1}, the Zambian Central Statistical Office (CSO) reported that unit yields stood at 1.5 - 2.0 ton ha^{-1} each year in most provinces of Zambia (CSO, 2014). Factors that accounted for the yield expansion in this study could have included changing hybrid seed use and also the influence of the ever changing weather pattern. In this study, it was not possible to detect significant varietal differences in GY, especially of late maturing maize varieties. Although significant differences in GY could not be detected, it cannot be concluded that varietal differences did not exist, since C.Vs were very high. One of the effects of drought on maize is delay in silking. The trial was planted in mid-December, 2014. Tasselling and silking coincided with the drought in March, 2015. This caused poor synchrony between silking and tasselling. This is because the anthesis-silking interval is a prediction of seed set in many maize varieties when under stress at flowering (Edmeades, Bolanos, Elingo, Banziger & Westgate, 2000). Slatyer (1969) explains that water reduction especially at anthesis can markedly reduce fertilization and grain set in most cereals, especially maize; with reductions of over 50% in yield being caused by relatively brief periods of wilting.

Water extracted from the soil by the roots of plants has been shown to depend on the plant characteristics such as leaf surface area and rooting density; and soil physical properties such as the water holding capacity and hydraulic conductivity (Kamara, Kling, Ajala & Menkir, 2004). Many authors are of the consensus view that often, over 98% of water taken up by the plant is lost as vapor in the process of T (Hillel, 2004). However, the results of this study showed that contrary to that view, of the total 433.1 mm of seasonal water use by late maturing maize varieties, only 53% was lost as T. Although maize is susceptible to water deficit, research has shown that there is a marked genotypic variation in root density, morphological and physiological characteristics in the crop thereby causing differences in ET under identical environmental conditions (Farhad, Cheema, Saleem & Saqib, 2011; Kamara et al., 2004). These characteristics include resistance to transpiration, plant height, plant leaf roughness and reflection and ground cover. Maize varieties PAN 53 and P 3812w had lower ET (380.0 and 403.0 mm, respectively) yet produced greater GY (2.7 and 3.4 ton ha^{-1}) and had higher $WUE_{GY, ET}$ (6.92 and 8.25 kg ha^{-1} mm^{-1}, respectively) compared to that of hybrid SC 647 and MRI 694 (5.62 and 7.28 kg ha^{-1} mm^{-1}) with GY of 2.3 and 2.9 ton ha^{-1}, respectively yet had higher ET (408.0 and 405.0 mm, respectively). Thus it seems that increases in yield and WUE by PAN 53 and P 3812w hybrids were not due to a better ability to take up water from the soil, but a better ability to create yield per unit of water.

DM and GY depend on photosynthesis; and photosynthesis involves the uptake of carbon dioxide through stomata. However, open stomata required for carbon dioxide uptake are an open gate for water loss. Thus, there is a tight trade-off between uptake of carbon dioxide and water loss, and this explains the close link between crop production and water use. The comparatively higher seasonal $WUE_{DM, T}$ for maize variety PAN 413 (68.51 kg ha^{-1} mm^{-1}) to that of ZMS 402 (42.79 kg ha^{-1} mm^{-1}) and P 3253 (36.54 kg ha^{-1} mm^{-1}) was due to higher biomass accumulated (10.7 ton ha^{-1} for PAN 413 compared to 7.4 and 6.9 ton ha^{-1} for ZMS 402 and P 3253, respectively) at relatively low T (149.0 mm for PAN 413) as opposed to the T of ZMS 402 and P 3253 of 160.0 mm and 178.7 mm which was higher. Maize varieties SC 525 and SC 513 resulted in higher GY compared to SC 303 and ZMS 402. This may have been due to their longer growth cycle (about 30 days difference), allowing the crops to obtain more water resources for plant growth and grain production. It means that yield increase in this case was not dependent on greater WUE but on the more rain water received from the longer growing season. The mean seasonal $WUE_{GY, ET}$ of 8.42 kg ha^{-1} mm^{-1} of early maturing maize varieties was close to 8.80 kg ha^{-1} mm^{-1} reported by Phiri et al. (2003) for rain-fed continuous maize with fertilizer kind of farming in eastern Zambia and also fell within the range that Sadras, Grassini & Steduto (2011) reported for maximum yield per unit seasonal ET for maize as 6 - 23 kg ha^{-1} mm^{-1}. The relationship between WUE and yield was direct, meaning that the higher the yield, the higher the WUE. Even though no significant differences were observed in WUE_{GY}, however, it turns out that high producing varieties were more efficient water users. Several previous studies have indicated that relationships between resource capture and use efficiency are affected by the temporal distribution of captured resources in different development stages (Mwale, Azam-Ali & Massawe, 2007 a,b). Notably, crop biomass production and grain yield appear to be most strongly correlated to resource capture during the reproductive stage since grain yield especially is directly associated with the current rates of assimilation and translocation. Since inadequate water will produce no grain, WUE expressed on the basis of grain rises rapidly as water availability increases.

High C.Vs were observed in the statistical analysis of all maturity classes. The C.V expresses the standard deviation per experimental unit as a percentage of the general mean of the experiment. The high C.Vs were attributed to crop failure in some plots due to the severe rain reduction (drought) observed during flowering and yield formation stages of growth. Drought effects make plot to plot error differences high. Although the total rainfall received during the experimental year (1 031.8 mm) should have satisfied the crop water requirements, plant water deficits originated due to the erratic rainfall distribution during the crop growing period. The 23-days dry spell that occurred during the critical phase of crop growth (flowering and grain formation) affected efficiency of water utilization by the crop varieties. Yield production was thus critically affected and consequently WUE too. Maize generally requires well rainfall distribution during the growing period. Any inconsistent or irregular rainfall distribution affects the efficiency of water utilization by the crop.

Generally, the mean seasonal $WUE_{DM, ET}$ for medium maturing maize varieties were comparable to the value of 20.7 kg $ha^{-1}mm^{-1}$ reported by Phiri et al. (2003) for rain-fed maize in eastern Zambia. Efficient use of water in the production of dry matter depends on many factors. ET is essentially dependent on the energy available from net radiation and advection. DM production or net photosynthesis is largely determined by crop and soil characteristics that maximize use of net radiation. When a grain crop like maize, runs out of water at the critical period, yields and WUE are drastically reduced without lowering much of the total seasonal ET which then explains why WUE of medium maturing maize varieties at the end of the season would not be significantly different among varieties. In fact, maize was shown to prioritize radiation interception by maintaining leaf area expansion at the cost of nitrogen concentration per unit leaf area which causes photosynthetic rates to be reduced (Lamaire, van Oosterom, Jeuffroy, Gastal & Massignam, 2008). Similar $WUE_{GY, ET}$ values ranging from 11.0 – 18.0, 9.3 – 13.8, and 11.4 – 14.4 kg ha^{-1} mm^{-1} have been reported by Tijani, Oyedele and Aina (2008), El-Tantawy, Ouda and Khalil (2007) and Meena, Meena and Bhimavat (2009) respectively, for maize grown under rain-fed conditions in Africa.

With regard to late maturing maize varieties, the significant differences observed in WUE were a direct result of differences in total aboveground dry matter produced. The higher the dry matter produced, the higher the WUE. The lower total dry matter production was generally due to the less soil water extraction by the varieties. The prolonged crop growing period of long maturity maize varieties may have led to greater vapor flow and ET, which in theory would be harmful to the sustainable use of dry land agricultural production. Considering that hybrids were compared under the same environment and had the same length to maturity, yet their yields were different, the difference was simply due to superior hybrid(s) resulting in higher WUE (Ritchie & Basso, 2007). Thus, whenever water becomes limited during development or maturation, then yield differences may be partly or wholly due to plants WUE. When water supply is limited, the assimilation rate, plant growth and consequently crop yield are all related quantitatively to the water supply. Additionally, although photosynthate accumulated prior to anthesis contribute to grain filling, and in some cases may provide a significant portion of grain yield, the greatest contribution is usually from photosynthate after anthesis by the ear, leaves and stem (Eastin, Haskins, Sullivan & van Bavel,1969). In another study, Liu et al. (2009) found that under water limited conditions, crop yields appear to be strongly related to water resource use; thus GY can be dramatically reduced by water resource deficits. Blum (2009) also noted that effective use of water implies maximum capture for T and minimal loss through E. Seasonal rainfall therefore has an impact on biomass partitioning for GY in maize and consequently has effects on WUE_{GY}. Sadras et al. (2011) reported a maximum yield per unit seasonal T for maize of 30 – 37 kg ha^{-1} mm^{-1}. Arguably, the $WUE_{GY, T}$ for all the varieties tested in the current study irrespective of the maturity class fell far below the reported values (13.42 – 23.83, 12.03 – 22.07 and 8.36 – 22.54 kg ha^{-1} mm^{-1} for early, medium and late maturing maize varieties, respectively). This clearly indicated that WUE is variety and location specific and thus justified the need to have locally determined WUE with regional varieties under local climate conditions.

5. Conclusion

The sustainability of agriculture depends on the improvement of WUE, which is more production with less water. This study evaluated the WUE of 30 maize varieties within the early, medium and late maturity classes under rain-fed conditions in Zambia's agro-ecological region IIa. As plant reactions were affected by the amount of water directly or indirectly, efficient use of soil water varied among maize varieties. It was concluded that maize varieties from the same maturity classes have different WUEs. Therefore, breeding for maximal water capture and use for increased transpiration would be important targets for yield improvement under unfavorable water conditions. However, because of the dry spell that occurred during the flowering and grain formation stages of plant growth and the trial only having been evaluated in one season, these results are not conclusive. Nevertheless, the results provided an indication that some varieties tested used water more efficiently than others. The study thus provided options in variety selection for high WUE based on which varieties performed better, particularly SC 525, SC 513 and PAN 4M 21 from the early maturity class; PHB 30G19, ZMS 606, MRI 634 and SC 637 from the medium maturity class; and PAN ZM 83, SC 709, PAN 8M 93 and SC 719 from the late maturity class. It was recommended that repeated experiments over time should be done to validate the findings given that the trial was only conducted in one season.

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