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Productivity and soil water use by rainfed maize genotypes in a coastal savannah environment

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A b s t r a c t. Total aboveground biomass, grain yield and actual evapotranspiration data were used to estimate water use efficiency by the maize genotypes in terms of total dry matter and grain yield production. Grain yield and its associated water use efficiency were significantly different ($P \leq 0.05$) among the maize genotypes during the major cropping season, with Mamaba producing the highest grain yield of 7 250 kg ha^{-1} and water use efficiency of 13.2 kg ha^{-1} mm^{-1}. For the minor season, however, no significant difference was observed in grain yield which ranged between 5 800 and 7 200 kg ha^{-1}, with Obatanpa producing the highest grain yield. Similarly, no significant difference was observed in water use efficiency during the minor cropping season which ranged between 14.6 kg ha^{-1} mm^{-1} and 19.1 kg ha^{-1} mm^{-1}, with Obatanpa having the highest water use efficiency. Maize genotypes Mamaba and Obatanpa were identified suitable for the rainfed conditions at the study area because of their comparatively high grain yield and better use of soil moisture for grain yield production.

K e y w o r d s: maize, rainfed, grain yield, water use efficiency

INTRODUCTION

Maize (*Zea mays* L.) is a crop grown over a wide range of climatic conditions. It is fast growing and yields best under moderate temperatures and ample supply of water. As plant reactions are affected by the amount of soil water directly or indirectly (Said-Al Ahl *et al*., 2009), tolerance to drought stress and efficient use of soil water could vary among maize genotypes under rainfed conditions especially in areas that experience erratic rainfall pattern.

Maize is grown extensively under rainfed conditions during the major (April-July) and minor (September-December) rainy seasons in the coastal savannah environment of Ghana, where peri-urban agriculture is extensively practiced in response to readily available market. According to Du-Plessis (2003), the maize crop requires between 350 mm and 450 mm of water per season to carry out its physiological activities, suggesting that between 700 and 900 mm of water are required for the two cropping seasons annually in the coastal savannah environment of Ghana. However, the annual rainfall normally experienced by the area, from records of the local weather station, is less than 800 mm. Besides, seasonal rainfall is erratic and therefore farmers in the area commonly experience poor maize yield or total crop failure in at least one of the cropping seasons. Thus, rainfed maize production in the coastal savannah environment of Ghana could be enhanced by adopting maize genotypes that efficiently use soil moisture for biomass and grain yield production.

The aim of the study was to evaluate three improved maize genotypes for their productivity, seasonal water use and efficiency in soil moisture use for biomass and grain yield production under rainfed condition in the Kwabenya-Atomic area located in the coastal savannah environment of Ghana.

MATERIALS AND METHODS

Field experiments were conducted at the research farm of the Biotechnology and Nuclear Agriculture Research Institute of the Ghana Atomic Energy Commission, Kwabenya-Atomic (Ghana). The site lies on latitude 5° 40’N, 0° 13’W, 76 m a.s.l. The study area is located in the coastal savannah environment of Ghana and receives an annual rainfall less than 1 000 mm according to the Ghana Meteorological Agency. The soil at the site is the Haatso series, a well-drained savannah ochrosol (Ferric Acrisol), derived from quartzite schist. Some of the chemical and physical characteristics of the soil are presented in Table 1. A microelectronic weather station,

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µMETOS® (Pessl Instruments GmbH, Weiz, Austria), located about 100 m from the experimental plots recorded daily weather variables including precipitation.

Maize genotypes used for the experiments were Golden Crystal, Mamaba and Obatanpa which were bred for high grain yield and improved nutritional status (Aflakpui *et al*., 2005). The maize genotype Mamaba is a three-way hybrid quality protein maize (Asiedu *et al*., 2001) while Golden Crystal and Obatanpa are normal open pollinated maize (Aflakpui *et al*., 2005). A three-way maize hybrid is obtained using three parent maize lines in which the female of the crossbred line is crossed with the male of an inbred maize line. Additionally, Obatanpa has been widely adopted by farmers, covering more than 50% of maize acreage in Ghana and some parts in Africa (Dankyi *et al*., 2005).

Seeds of the maize genotypes were sown on April 28 and September 1, 2008 for the major and minor cropping season, respectively. Seeding was done at a distance of 0.4 m within rows and 0.8 m between rows. Seedlings were thinned to 2 plants per hill one week after germination to obtain 78,750 plants ha^{-1}. A total of 275.0 kg ha^{-1} of 15:15:15 NPK fertilizer were split-applied by broadcasting two weeks and four weeks after germination (Aflakpui *et al*., 2005). Weeds were controlled mechanically by hoeing whenever necessary. A 100 ml broad spectrum insecticide, Pyrinex 48 EC (O, O-Diethyl 0-3, 5, 6-trichloro-2-pyridylphosphorothionate) in 100 l of water was applied five and seven weeks after crop establishment during the major and minor cropping seasons. The experimental design used was the randomized complete block design in four replicates with the three maize genotypes as treatments. Each sub-plot measured 8 m by 4 m.

Polyvinyl chloride pipes were installed as access tubes in each of the sub-plots to 120 cm soil depth before 50% seed germination. The tubes were installed in between 2 central rows within each sub-plot to facilitate in situ moisture monitoring at 20 cm stepwise in a 120 cm soil profile with Campbell Pacific Nuclear 503DR Hydroprobe (neutron probe) at 14 days interval for the entire maize growing seasons.

Eight maize plants were sampled on 14, 28, 42, 56, 70, 84 and 98 days after emergence (DAE) from an area of 1.28 m^2 in each sub-plot. Plant samples were separated into leaves, stem, ear, cob, husk and grain components. Sub-samples of fresh plant components were oven-dried at 70°C for three days for total dry matter determination. Additionally, grain yield at crop maturity was taken from a 5.12 m^2 area on August 8 and December 10, 2008 for the major and minor cropping seasons, respectively. Grain yield (GY) was determined at grain moisture content that ranged between 13 and 15%.

Actual evapotranspiation (AET) for the maize genotypes was estimated from seed emergence to crop maturity using the water balance model of the root zone:

$$\Delta S = P + I - R - D - AET, \tag{1}$$

where: P is precipitation (mm), I is irrigation (mm), AET is actual evapotranspiration (mm), R is run-off (mm), D is drainage or capillary rise (mm) and ΔS is the change in stored soil moisture in the root zone (mm). Irrigation (I) was set to zero as the experiments were conducted under rainfed conditions. Run-off was also set to zero because the slope of the land is less than 1%.

The estimation of drainage or capillary rise requires knowledge of the soil water retention curve, which is one of the most important soil hydraulic properties for monitoring water flow and solute transport in variably saturated soils (Ghanbarian-Alavijeh and Millán, 2010), as well as the soil hydraulic conductivity. Drainage or capillary rise (D) below the root zone (100 cm below the soil surface) was estimated based on the Darcy's water flux density model integrated over the measuring time interval:

$$D = -\left[K(\theta)\frac{\Delta H}{\Delta z}\right]\Delta t, \tag{2}$$

where: $K(\theta)$ is the hydraulic conductivity (mm d^{-1}) corresponding to the soil moisture content (θ), ΔH is the change in hydraulic head (mm), which is made up of the change in matric potential (Ψ_m) and change in gravimetric potential

T a b l e 1. Some of the chemical and physical properties of the soil at the experimental site

Soil layer (cm)	pH_{H_2O} (1:2)	$C_{org.}$	Total N	$P_{av.}$ (mg kg^{-1})	K (cmol +kg^{-1})	Sand	Sil	Clay	Bulk density (kg m^{-3})
		(%)					(%)		
0-20	7.33	1.06	0.36	11.07	0.41	41.4	43.2	15.4	1.34
20-40	7.39	0.50	0.34	6.79	0.30	40.4	44.7	14.9	1.22
40-60	7.83	0.50	0.31	4.28	0.25	45.3	43.8	10.9	1.41
60-80	7.99	0.39	1.26	3.89	0.19	48.0	41.1	11.1	1.33
80-100	7.79	0.36	0.42	2.40	0.21	46.3	43.0	10.7	1.47
100-120	7.85	0.23	1.13	2.10	0.22	55.8	36.4	7.8	1.38

(Ψ_g), Δ_z (mm) is the difference between the two soil depths at which Ψ_m and Ψ_g were estimated for ΔH computation and Δt (d) is the measuring time interval.

The water use efficiency (kg ha^{-1} mm^{-1}) of the maize genotypes was estimated in terms of total above ground biomass (WUE_{TDM}):

$$WUE_{TDM} = \frac{CTDM}{CAET}, \quad (3)$$

and also in terms of grain yield (WUE_{GY}):

$$WUE_{GY} = \frac{GY}{CAET}, \quad (4)$$

where: CTDM is cumulative total dry biomass (kg ha^{-1}) and GY is grain yield (kg ha^{-1}), respectively and CAET is the cumulative actual evapotranspiration (mm).

Data for total dry biomass, grain yield, cumulative actual evapotranspiration and water use efficiencies at various sampling periods were subjected to the analysis of variance based on the experimental design used and means separated for the appropriate probability level when the F-ratio test proved significant.

RESULTS AND DISCUSSION

Generally, a lower precipitation was received during the minor season compared to that of the major cropping season. Specifically, a total of 502.4 cm of precipitation was received during the major cropping season (April-July) of which 325.0 mm occurred in May during the vegetative stage of the maize crops. For the minor cropping season (September-December), however, the total precipitation was 290.7 mm, with the lowest and the highest precipitation occurring in September and October, respectively (Fig. 1).

Air temperatures recorded were generally higher during the minor cropping season compared to values recorded for the major cropping season. On the average, the maximum and minimum air temperatures were 30.5 and 23.5°C for the major cropping season, respectively, as against corresponding values of 31.9 and 23.6°C for the minor cropping season. The mean solar radiation for the major and minor cropping seasons was 212.1 and 229.7 W m^{-2}, respectively. Additionally, the mean relative humidity for the major cropping season was 81.4% and 78.2% for the minor cropping season.

The maize genotypes accumulated statistically similar total dry biomass (TDM) levels at each of the growth stages during the major cropping season with TDM peaking on 84 DAE at an average value of 7 000 kg ha^{-1} before declining to the mean value of 3 800 kg ha^{-1} on 98 DAE (Fig. 2, Table 2). For the minor cropping season, however, TDM for all the maize genotypes peaked on 70 DAE, averaging 7 500 kg ha^{-1}, before declining to a mean value of 4 000 kg ha^{-1}. Generally, TDM accumulated by the maize genotypes was higher at all growth stages during the minor cropping season compared to values for the major cropping season.

The maize genotypes Obatanpa, Mamaba and Golden Crystal produced grain yield of 5 880, 7 250, and 5 550 kg ha^{-1}, respectively, during the major cropping season, with Mamaba significantly ($P \leq 0.05$) out-yielding Obatanpa and Golden Crystal. During the minor cropping season, however, the maize genotypes produced statistically similar grain yield with Obatanpa producing the highest grain yield of 7 130 kg ha^{-1} followed by Mamaba with 5 770 kg ha^{-1} and then Golden Crystal with 5 410 kg ha^{-1}.

The maize genotypes used statistically similar levels of soil water during the major cropping season except on 28 DAE for which significantly different levels ($P \leq 0.05$) of soil water were used (Fig. 3). Though seasonal AET of the maize genotypes for the major cropping season were not significantly different, Golden Crystal had the highest seasonal AET value of 553.5 mm followed by Obatanpa (549.6 mm) and then Mamaba (548.3 mm). Similarly, for the minor cropping season, no significant differences were observed in AET at each growth stage of the maize genotypes (Fig. 3). However, seasonal AET values during the minor cropping season were 375.3, 372.8, and 369.6 mm for Obatanpa, Mamaba and Golden Crystal, respectively.

The efficiency with which soil water was used for biomass production (WUE_{TDM}) during the major cropping season increased from a mean value of 1.0 kg ha^{-1} mm^{-1} for the maize genotypes on 14 DAE, peaked at 18.0 kg ha^{-1} mm^{-1} on 84 DAE and declined to 6.0 kg ha^{-1} mm^{-1} on 98 DAE. Additionally, the maize genotypes had similar WUE_{TDM} at each crop growth stage, with Golden Crystal generally having the highest WUE_{TDM} values during the major cropping season (Fig. 4, Table 3). A similar trend was observed in WUE_{TDM} for the maize genotypes during the minor cropping season except that WUE_{TDM} values during this period were generally higher than values for the major cropping season. Though no significant differences were observed in WUE_{TDM}, Obatanpa generally had the highest WUE_{TDM} during the minor cropping season.

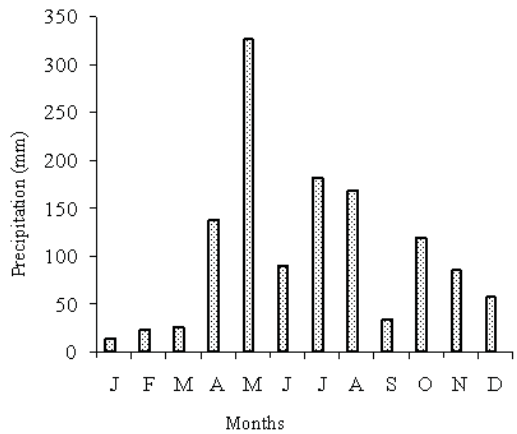

Fig. 1. Monthly precipitation for the year 2008.

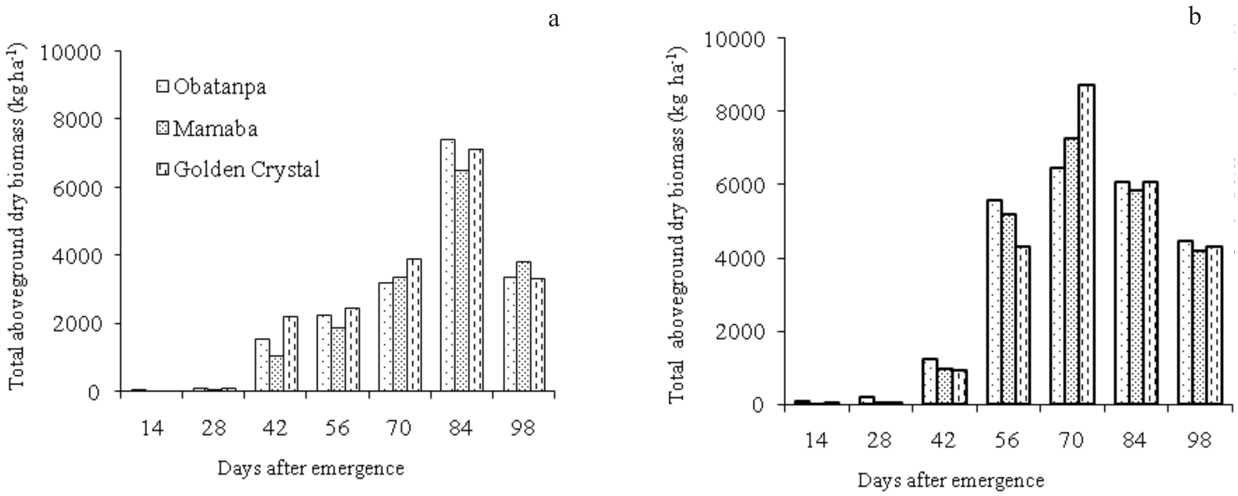

Fig. 2. Time course of total dry matter of three maize genotypes during: a – major, and b – minor cropping seasons.

T a b l e 2. Relationship between total aboveground dry biomass (TDM) and evapotranspiration (ET) for three maize genotypes during the major and minor cropping seasons

Cropping season	Maize genotype	Regression model	r^2	p-value
Major	Golden Crystal	TDM = 12.30 ET - 1183.0	0.609	0.038*
	Mamaba	TDM = 11.34 ET - 615.5	0.463	0.092
	Obatanpa	TDM = 11.92 ET - 994.4	0.455	0.096
Minor	Golden Crystal	TDM = 16.58 ET + 517.2	0.540	0.060
	Mamaba	TDM = 17.96 ET - 440.2	0.492	0.079
	Obatanpa	TDM = 11.92 ET - 994.4	0.596	0.042*

*Significant.

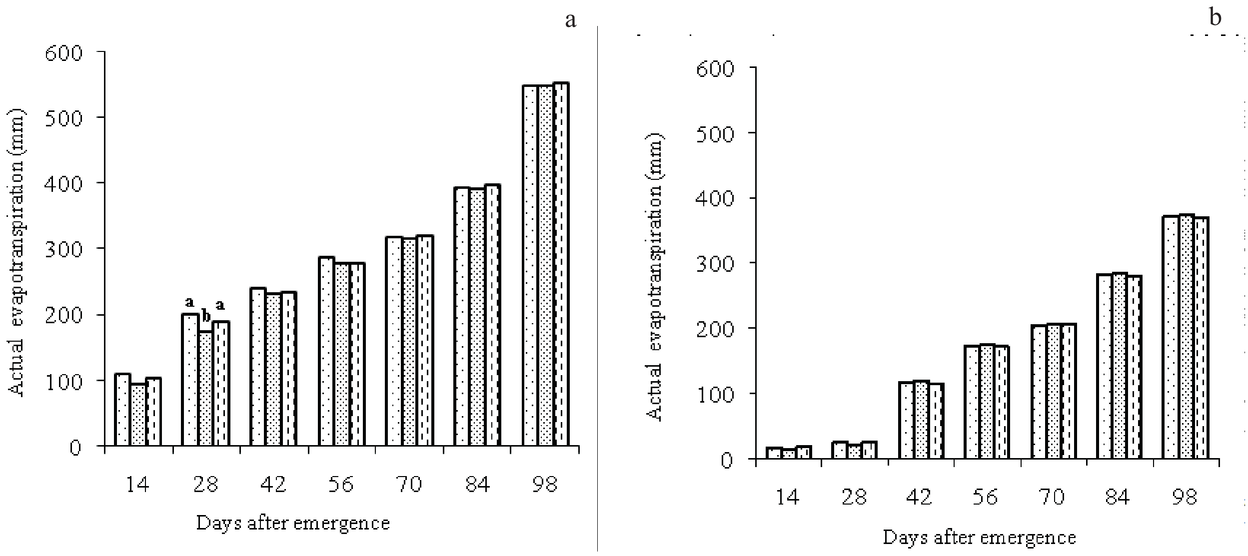

Fig. 3. Time course of cumulative actual evapotranspiration of three maize genotypes during: a – major, and b – minor cropping seasons. Bars with the same letters and those without letters are not significantly different at p=0.05. Explanations as in Fig. 2.

T a b l e 3. Relationship between water use efficiency (WUE_{TDM}) and total aboveground dry biomass (TDM) for three maize genotypes during the major and minor cropping seasons and for the combined seasons

Cropping season	Maize genotype	Regression model	r^2	p-value
Major	Golden Crystal	WUE_{TDM} = 0.002 TDM + 1.26	0.890	≤0.001*
	Mamaba	WUE_{TDM} = 0.002 TDM + 1.02	0.918	≤0.001*
	Obatanpa	WUE_{TDM} = 0.002 TDM + 1.09	0.928	≤0.001*
Minor	Golden Crystal	WUE_{TDM} = 0.003 TDM + 3.19	0.864	≤0.002*
	Mamaba	WUE_{TDM} = 0.002 TDM + 1.02	0.845	≤0.001*
	Obatanpa	WUE_{TDM} = 0.003 TDM + 5.86	0.756	≤0.001*
Major + Minor	Golden Crystal	WUE_{TDM} = 0.003 TDM + 1.70	0.822	≤0.001*
	Mamaba	WUE_{TDM} = 0.003 TDM +1.22	0.792	≤0.001*
	Obatanpa	WUE_{TDM} = 0.003 TDM +2.71	0.697	≤0.001*
	All combined	WUE_{TDM} = 0.003 TDM + 1.89	0.765	≤0.001*

*Highly significant.

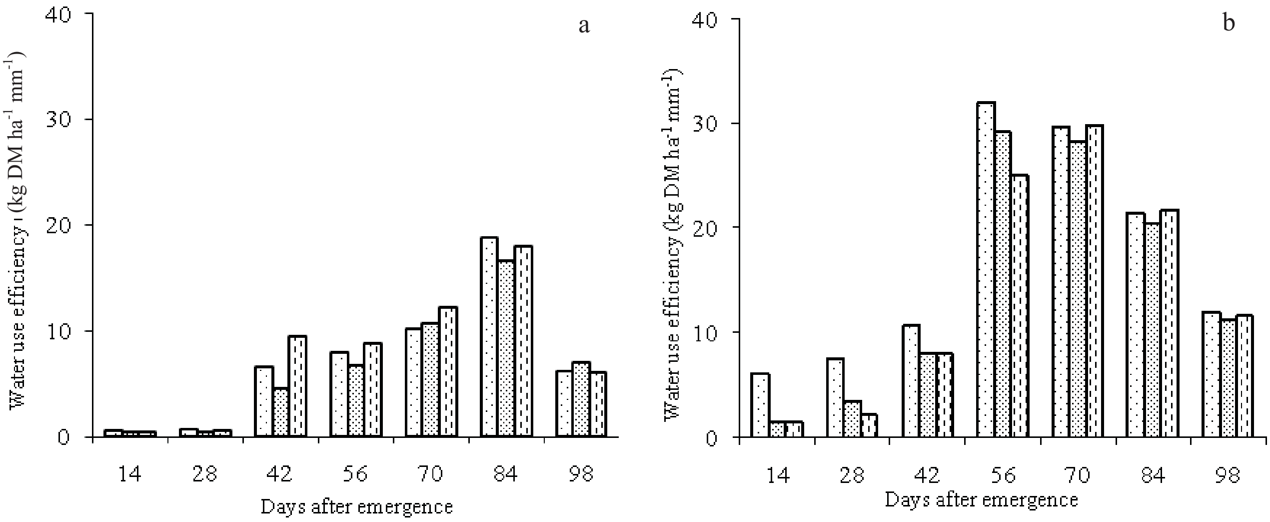

Fig. 4. Time course of water use efficiency, based on total dry matter for three maize genotypes during: a – major, and b – minor cropping seasons. Explanations as in Fig. 2.

T a b l e 4. Relationship between total water use efficiency (WUE_{GY}) and grain yield (GY) for the combined maize genotypes during the major and minor cropping seasons and for the combined seasons

Cropping season	Maize genotype	Regression model	r^2	p-value
Major	All combined	WUE_{GY} = 0.001 GY – 0.067	0.996	≤0.0001*
Minor		WUE_{GY} = 0.002 GY + 0.289	0.992	≤0.0001*
Major+Minor		WUE_{GY} = 0.002 GY + 0.476	0.548	≤0.0001*

*Extremely significant.

Water use efficiency in terms of grain yield (WUE_{GY}) during the major cropping season was 13.2 kg ha^{-1} mm^{-1} for Mamaba, 10.7 kg ha^{-1} mm^{-1} for Obatanpa and 10.0 kg ha^{-1} mm^{-1} for Golden Crystal. Besides WUE_{GY} for Mamaba being significantly the highest ($P \leq 0.05$), comparatively, Obantapa and Golden Crystal had statistically similar WUE_{GY} values during the major cropping season. During the minor cropping season, however, WUE_{GY} was not significantly different among the maize genotypes but it was 19.1 kg ha^{-1} mm^{-1} for Obatanpa, 15.4 – for Mamaba and 14.6 – for Golden Crystal, respectively (Table 4).

The mean seasonal TDM of 3 520.1 and 4 318.2 kg ha^{-1} for the maize genotypes observed during the major and minor cropping season, respectively, were in agreement with TDM values of 3 726.0 and 4 845.0 kg ha^{-1} reported by Gwenzi *et al.* (2008) for maize grown under rainfed semi-arid environment in Zimbabwe during the 2002/2003 and 2003/2004 cropping season, respectively. However, seasonal TDM for Obatanpa, Mamaba and Golden Crystal for both the major and minor cropping seasons were less than the TDM value of 10 000 kg ha^{-1} reported by Morgado and Willey (2008) and Li *et al.* (2002) for maize grown under irrigation. This reinforces the significance of adequate soil water, particularly at critical crop growth stages, in enhancing the productivity of crops. Though the seasonal precipitation for the minor cropping season was 58% of that of the major cropping season, the mean seasonal TDM levels accumulated by the maize genotypes were significantly ($P \leq 0.05$) higher. Higher mean air temperature and solar radiation coupled with better distribution of precipitation likely accounted for the higher seasonal TDM for the minor season compared to that of the major season.

Highly significant ($P \leq 0.003$) harvest index of 57.5% accounted for the significantly highest grain yield of Mamaba during the major cropping season compared to statistically similar grain yield levels produced by Obatanpa and Golden Crystal. Furthermore, statistically similar harvest indices and seasonal TDM accounted for similar grain yield levels by the maize genotypes during the minor cropping season.

The mean grain yield ranged between 5 550 and 7 250 kg ha^{-1} for the major and minor cropping seasons, respectively. A similar grain yield range of 5 380 to 7420 kg ha^{-1} for maize grown under farmers conditions in Ethiopia had been reported by Negassa *et al.* (2001) while Soler *et al.* (2007) also reported grain yield of 4 09 kg ha^{-1} for maize hybrids grown under rainfed condition in the sub-tropical environment of Brazil. Additionally, grain yield of Mamaba for the major cropping season (7 250 kg ha^{-1}) and that of Obatanpa for the minor cropping season (7 130 kg ha^{-1}) were close to the potential grain yield of 7 000 kg ha^{-1} reported by Prabhu and Shivaji (2000) for sub-tropical regions of the sub-Saharan Africa.

Higher level of precipitation accounted for the higher seasonal AET of the maize genotypes during the major cropping season, which was on average 550.5 mm and close to 600.0 mm reported by Cai and Rosegrant (2003) and Liu *et al*. (2005) for maize grown under irrigated conditions in China, contrasting the range of AET values 140.0-350.0 mm obtained by Meena *et al*. (2009) and Mox *et al*. (2005) for maize under rainfed conditions in semi-arid environments. Thus, the seasonal precipitation of 502.4 mm during the major cropping season was adequate for maize production. Comparatively, the seasonal AET for the minor cropping season was about 68% of the mean value of 550.5 mm observed for the major cropping season.

Water use efficiency is an important crop index which can be used to assess how soil water has been used for total biomass and economic yield production. It is particularly important for rainfed agriculture and in environments such as savannahs, semi-arid and arid zones where seasonal rainfall is often inadequate for optimal crop production and its distribution unpredictable.

Similar seasonal AET and TDM accounted for similar WUE_{TDM} produced by the maize genotypes for both the major and minor cropping seasons. The mean seasonal WUE_{TDM} of 6.40 kg ha^{-1} mm^{-1} for the major cropping season was close to 5.25 kg ha^{-1} mm^{-1} reported by Phiri *et al*. (2003) and 8.00 kg ha^{-1} mm^{-1} reported by Mox *et al*. (2005) for rainfed maize grown in eastern Zambia and North China Plains, respectively, but fell below the range 16.50 to 21.50 kg ha^{-1} mm^{-1} reported by Dagdelen *et al*. (2006) for maize grown in Turkey. However, the mean seasonal WUE_{TDM} of 11.60 kg ha^{-1} mm^{-1} for the minor cropping season was greater than 5.25 kg ha^{-1} mm^{-1} reported by Phiri *et al*. (2003) in Zambia. The higher mean WUE_{TDM} observed for the minor cropping season was due to higher TDM but lower seasonal AET and reduced loss of available water by soil evaporation, which led to a more efficient use of soil water for TDM production.

Highly significant difference ($P \leq 0.007$) in WUE_{GY} for the major cropping season was the result of higher harvest index of 57.5% for Mamaba. The higher WUE_{GY} (which ranged from 14 to 20 kg ha^{-1} mm^{-1}) for the minor cropping season compared to that of the major cropping season was due to higher grain yield. Similar WUE_{GY} values ranging from 11.0 to 18.0 kg ha^{-1} mm^{-1} and from 9.3 to 13.8 kg ha^{-1} mm^{-1} have been reported by Tijani *et al*. (2008) and El-Tantawy *et al*. (2007), respectively, for maize grown under rainfed conditions. Though WUE_{GY} for the minor cropping season was higher than that of the major cropping season, all the three maize genotypes had similar WUE_{GY} in response to similar grain yield and seasonal AET. Thus, biomass accumulation and partitioning by the maize genotypes were similarly affected by reduced seasonal precipitation during the minor cropping season.

CONCLUSIONS

1. The maize genotypes generally produced similar total aboveground biomass, actual evapotranspiration and consequently were similarly efficient in the use of soil moisture for total biomass production during each of the cropping seasons (major and minor).

2. The maize genotype Mamaba produced significantly the highest grain yield during the major cropping season as a result of its significantly high biomass partitioning (harvest index) and was consequently the best maize genotype in terms of efficient use of soil moisture for grain yield production for the cropping season.

3. The maize genotype Golden Crystal is not suitable for the experimental site because of its poor biomass partitioning, low grain yield under low rainfall regime and, comparatively, its low efficiency in the use of soil moisture for grain yield production.

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