Maize Yield and Water Use Efficiency Under Different Irrigation Levels and Furrow Irrigation Methods in Semiarid, Tropical Region

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Source: Air, Soil and Water Research, 14(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786221211058177

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Air, Soil and Water Research
Volume 14: 1–7
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DOI: 10.1177/11786221211058177
SAGE

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ABSTRACT: Water scarcity is the major limiting factor of agricultural production and productivity in the central rift valley of Ethiopia. Best use of limited water is necessary through water conservation practices. Field experiments were conducted during the dry cropping seasons of 2016 and 2017 on clay loam soil at experimental farm of Melkassa Agricultural Research Centre to evaluate the impact of irrigated furrow methods and deficit irrigation applications on maize (Zea mays) yield and water use efficiency. The study involved three furrow irrigation methods (conventional, fixed, and alternate furrow irrigation) and three irrigation application levels (100%ETc, 75%ETc, and 50%ETc). Furrow irrigation system as main plot and irrigation levels as sub-plot were arranged in split plot design with three randomized complete blocks each year. Greatest yield was obtained under conventional furrow irrigation supplied with 100%ETc of water. Water use efficiency under the same treatment was lesser and shows no significant difference with fixed furrow irrigation and 50%ETc application. Greatest water use efficiency of maize was obtained from alternate furrow irrigation under 75%ETc application and showed no significant difference with 100%ETc application. However, grain yield reduction under 75%ETc applications was very much higher than 100%ETc application. Water saved as a result of 100ETc and 75%ETc applications were 50% and 62.5%, respectively. Therefore, scheduling irrigation time for maize in the central rift valley of Ethiopia and similar semiarid environments could be 100%ETc or 75%ETc application using alternate furrow irrigation. The 75%ETc application has an advantage over 100%ETc applications in saving more water and hence could be applied when water availability is severely limited.

KEYWORDS: Alternate furrow irrigation, deficit irrigation, furrow irrigation, maize, water use efficiency

RECEIVED: April 14, 2021. **ACCEPTED:** October 19, 2021.

TYPE: Original Research

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Introduction

Maize (Zea mays L.) is one of the most important cereal crops of Ethiopia, ranking first and second in production and area coverage, respectively. It is extensively grown in semi-arid to sub-humid areas for grain and forage. The crop is grown during dry season (January–May) under irrigation and wet season (June–September) under rainfall in the semi-arid part of Awash basin of Ethiopia. In the basin, Awash River is the main source of water for irrigation and a shortage of water resources is becoming a big concern affecting sustainable crop production and productivity.

In areas with limited water resources, the goal is to improve water use efficiency, WUE. The WUE is gaining importance particularly in arid and semi-arid regions to improve water management practice. In these regions, irrigation is required for almost all crop production and furrow irrigation the principal means of applying irrigation water for crop production. Furrow irrigation is characterized by low application efficiency (45%–60%) and causes significant water losses, mainly due to excess application leading to deep percolation from the irrigated area (Raine & Bakker, 1996; Smith et al., 2018). The system of water application in furrow irrigation requires fundamental changes in order to use the limited water resources efficiently.

The greater water losses occurring in conventional furrow irrigation, CFI could be reduced in fixed furrow irrigation, FFI where only one furrow receives irrigation and the adjacent one furrow remain dry throughout the growth period, and alternate furrow irrigation, AFI where two neighboring furrows interchangeably receive irrigation water during successive irrigation periods. Several researchers found that FFI saved water and gave comparable yield as in every furrow irrigation (Rafiee & Shakarami, 2010; Shayannejad & Moharreri, 2009). It was reported that AFI used less irrigation water but can maintain the same grain yield production to that of CFI (Abera et al., 2020). The WUE was greater in AFI than in CFI and FFI for the same irrigation amount (Kang et al., 1998, 2000).

Deficit irrigation application has been promoted in areas of where water is the most limiting factor for crop production and several authors emphasized the importance of deficit irrigation as a water saving technique and maximizing WUE in agricultural production (Behboudian & Mills, 1997; Kang et al., 2000; Oweis & Hachum, 2006; Oweis et al., 2000; Zhang et al., 2000). The AFI and deficit irrigation practices have been considered as an important production approach in water scarce areas (Davies et al., 2002; Hsiao et al., 2007; Webber et al., 2006). Both approaches comprise employing the soil water to induce the crop's innate response to water scarce situations, so as to enhance WUE. A study of deficit irrigation application together with CFI, AFI, and FFI showed that AFI and FFI improved water use efficiency over CFI application (Slatni et al., 2011).

Therefore, the aim of this study was to assess the combined effects of different deficit irrigation levels and furrow

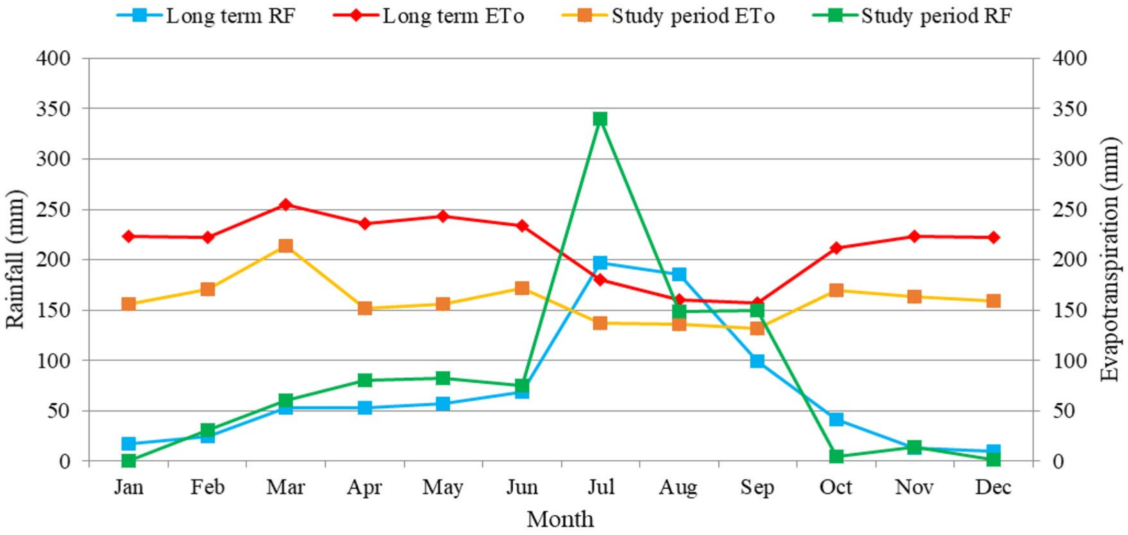

Figure 1. Relationship between reference evaporation (ETo) and rainfall (RF) during the study period and the long-term averages at Melkassa, Ethiopia.

irrigation methods on maize yield and WUE, and identify the optimal irrigation management practices that maximize the WUE under climatic conditions of Melkassa and similar environments.

Materials and Methods

Description of studied area

Field experiments were conducted during the dry cropping seasons of 2016 and 2017 at Melkassa Agricultural Research Center (8°24′N latitude and 39°21′E longitude at altitude of 1,550 masl). The center is located in the semi-arid part of Awash basin of Ethiopia, downstream of Koka dam.

The study area receives about 818 mm rainfall annually. On the other hand, the evapotranspiration demand of the area is about 2,567 mm/year. Greater percentage of the rainfall (67%) occurs from mid-June to mid-September and the maximum is in July (Figure 1). The water balance in the study area indicates the need for irrigation throughout the year except during the months of July and August (Figure 1). The rainfall occurred during the study period was greater than the long-term average rainfall of the area, while the reference evapotranspiration was less than the average of the long-term average.

The mean monthly temperature recorded during the study period was greater than the long-term mean monthly temperature recorded in the study area (Figure 2).

The textural class of the soil of the study area was clay loam. Table 1 shows some of the physiochemical properties of soils of the experimental site.

Treatment and design

The experiment consisted three furrow irrigation systems (CFI, AFI, and FFI) and three levels of irrigation applications (100%ETc, 75%ETc, and 50%ETc). The 100%ETc application is a control treatment based on allowable soil moisture depletion (p). The experimental treatments had a split plot arrangement in a randomized complete block design with three blocks in which furrow irrigation system was assigned to main plots while irrigation levels were assigned to sub-plots.

Maize agronomy

Maize seed cultivar Melkassa-II, suitable for dry areas, was sown on clay loam soil. Plots were 4.5 m × 5 m. The seed was sown at plant and row spacing of 25 and 75 cm, respectively, with a total plant population of 100 per plot. The spacing between plots of the same block was 1.5 m and the spacing between blocks was 3 m. Planting date was January 14 and January 23 for the 2016 and 2017 experiments, respectively. The treatments received di-ammonium phosphate, DAP, ($(NH_4)_2HPO_4$) at a rate of 100 kg ha^{-1} during planting and two times split application of urea ($CO(NH_2)_2$) at planting and knee height (40 days after planting) at rate of 50 kg ha^{-1}. The experimental treatments received two common irrigations one at planting and the other after germination for better crop establishment. The plant was harvested on May 23 and May 29 for the 2016 and 2017 experiments, respectively. Both years the experiment was conducted at the same site following main season haricot bean harvesting.

Irrigation water management

Irrigation applications to meet treatment levels were based on allowable soil moisture depletion ($p = .50$) of the total available water in the crop root depth (Allen et al., 1998), which for maize in the present study was 90 cm. Daily climatic data (maximum and minimum temperatures, humidity, wind speed and actual sunshine hours) were used in CROPWAT 8.0 for Windows (Food and Agriculture Organization, 1992) to compute reference evapotranspiration, ETo. The crop evapotranspiration, ETc was estimated using "Kc ETo" approach.

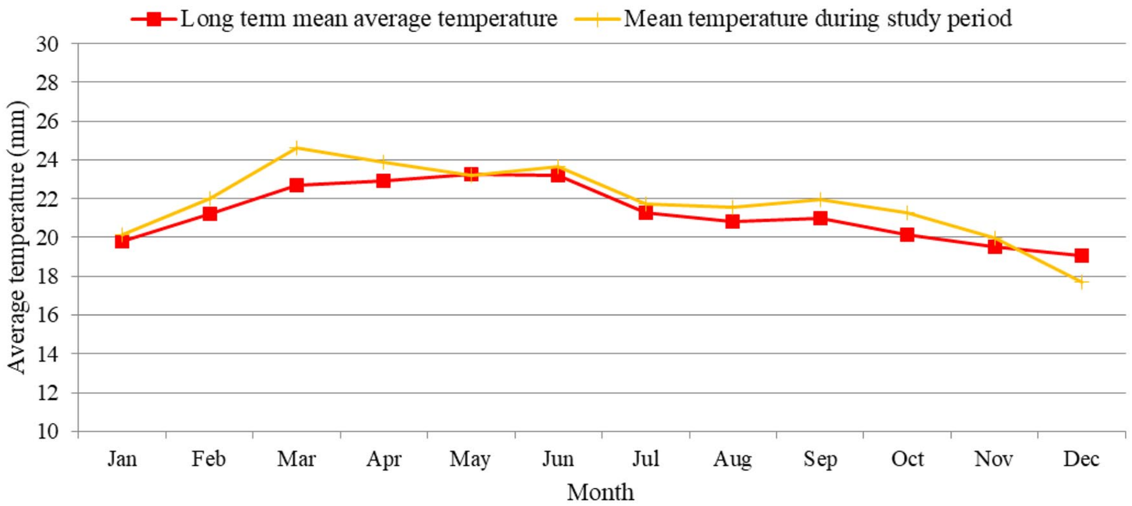

Figure 2. Average long-term and study period mean temperature comparison at Melkassa, Ethiopia.

Table 1. Physical and Chemical Characteristics of the Study Site Soil at Melkassa, Ethiopia.

SOIL PROPERTY	PARTICLES PROPORTION (%)			TEXTURAL CLASS	BULK DENSITY (G/CM3)	FC (%V)	PWP (%V)	TAW (MM/M)	PH	ECE (DS/M)	ECW (DS/M)	OM (%)
	SAND	SILT	CLAY									
Average	34.5	29.7W	35.8	Clay loam	1.1	34.6	18.7	175.0	7.5	0.20	0.38	2.3

Note. FC, PWP, TAW, ECe, ECw, and OM represent field capacity, permanent wilting point, total available water, electrical conductivity of the soil saturated paste, electrical conductivity of water, and organic matter content, respectively.

The sum of daily ETc was added between two irrigation events following the water balance equation (1).

$$ETc = P + I - D - \Delta S \tag{1}$$

Where, ETc is crop evapotranspiration (mm), P is precipitation (mm), I is irrigation (mm), D is deep percolation (mm), and ΔS is change in soil water storage (mm).

Irrigation was provided for the control treatment when 50% of the total available water within the root depth was depleted. The remaining treatments received the allocated percentage of control treatment in the same date. The gross irrigation application was estimated by using average application efficiency of 60% for furrow irrigation (Raine & Bakker, 1996). The required depth of irrigation water was applied using 3-inch Parshall flume.

Data collection

The crop was harvested after physiological maturity, when relatively low grain moisture content was attained (18%–25%) (SESI Technologies, 2020). Data on aboveground biomass and grain yield were collected from each plot. Stover weight was measured after oven drying at 70°C temperature for 48 hours. Maize cobs were harvested and shelled. The grain was weighed, grain moisture measured using digital moisture meter and eventually corrected for moisture content at 12.5%. Yield was extrapolated and then reported on a hectare basis. To avoid border effects, both stover and cobs were collected from the three central rows, and two plants were left from both ends of the furrow length, with a net plot size of 9 m^2.

Crop WUE was computed as a ratio of grain yield (kg/ha) to seasonal crop evapotranspiration (mm ha/ha). Harvest index based on maize grain yield and biomass yield was calculated using equation (2) (Du et al., 2010):

$$HI = \frac{Y_g}{Y_b} \tag{2}$$

Where, HI is the harvest index, Y_g (kg ha^{-1}) is the grain yield, and Y_b (kg ha^{-1}) is the biomass yield.

The yield response factor, Ky, was estimated following equation (3) (Doorenbos & Kassam, 1979).

$$\{1 - Ya/Ym\} = Ky\{ETa/ETm\} \tag{3}$$

where, Ya and ETa are, respectively, the actual yield and actual ET for the deficit treatments, Ym and ETm are the maximum yield and maximum ET, respectively; obtained from the fully irrigated treatment, and (1–Ya/Ym) is the relative yield decrease to the corresponding relative ET deficit (1–ETa/ETm).

Data analysis

The obtained data were subjected to analysis of variance suitable for split plot design and year considered to be random

Table 2. Significance of Furrow Method, Irrigation Level, Furrow Method × Irrigation Level, Replication, Replication × Furrow Method, Year, Year × Furrow Method, and Year × Furrow Method × Irrigation Level on Maize Parameters Over Two Years and Three Randomized Complete Blocks at Melkassa, Ethiopia..

FACTORS	*F*-VALUE			
	GRAIN YIELD (KG HA^{-1})	WUE (KG HA-MM^{-1})	BIOMASS (KG HA^{-1})	HARVEST INDEX
Furrow method	333.54*	75*	43.51**	46.86*
Irrigation level	295.78***	14.67**	309.43***	61.48***
Furrow method × irrigation level	16.03**	22.84***	4.62*	11.33**
Replication	4.98^{NS}	9.1^{NS}	15.43*	16.59*
Replication × furrow method	0.38^{NS}	0.23^{NS}	9.09***	1.39^{NS}
Year	1.49^{NS}	0.35^{NS}	13.36^{NS}	0.05^{NS}
Year × furrow method	2.37^{NS}	2.01^{NS}	0.49^{NS}	1.29^{NS}
Year × furrow method × irrigation level	0.49^{NS}	0.81^{NS}	1.12^{NS}	0.82^{NS}

Note. NS = Not significant.
*Significant at $p < .05$. **significant at $p < .01$. ***significant $p < .001$.

effect while furrow method and irrigation level were considered to be fixed effects. Analysis of variance tests were performed for the model using the Mixed procedure (SAS version 9.00, SAS Institute) with block considered to be a random effect (KLI, 2007). Mean separations were conducted using the SAS macro pdmix800 (Saxton, 1998) with Fisher's LSD at an error rate of 5% ($p = .05$).

Results and Discussion

Depth of irrigation water applied

Irrigation water depth of 594.10 mm was given to the maize for its entire growing period under conventional furrow irrigation with full irrigation (CFI 100%ETc). For CFI 75%ETc, 75% of full irrigation (445.58 mm) was applied, while for CFI 50%ETc irrigation depth of 297.05 mm was applied in CFI. In both AFI 100%ETc and FFI 100%ETc treatments, total irrigation depth of 297.05 mm was given under full irrigation treatment, because water was applied to half of the plot area through alternate and specific furrows, respectively. For AFI 75%ETc, AFI 50%ETc, FFI 75%ETc, and FFI 50%ETc irrigation depth of 222.79 mm and 148.53 mm of water was applied respectively.

Maize grain yield and water use efficiency

Maize grain yield and WUE were not significantly different between years (Table 2). No significant interaction between years and furrow method, and year × furrow method × irrigation level was observed for grain yield and WUE (Table 2). The analysis of variance showed significant variation on maize grain yield and WUE among the different furrow irrigation methods and deficit irrigation levels (Table 2). Grain yield obtained under the main plot factor was significantly greater for CFI than AFI, while the lesser was from FFI (Table 3). However, no significance difference in WUE was observed due to furrow method. The difference in grain yield recorded due to difference in subplot factor, irrigation level, was significant. Greater grain yield was obtained for 100%ETc followed by 75%ETc, and lesser value was obtained from 50%ETc. WUE was statistically similar for 75 and 100%ETc, but lesser for 50%ETc (Table 3). Among the furrow methods, FFI had the least performance in grain yield and WUE compared to CFI and AFI (Table 3).

Significance differences were observed on maize grain yield and WUE by the interaction effect of furrow methods and irrigation levels (Table 2). The greatest grain yields were measured for CFI 100%ETc and CFI 75%ETc, which were not significantly different from each other (Table 4). Application of CFI 75%ETc gave the highest maize yield from the other deficit irrigation levels and showed no difference with AFI 100%ETc application. The lowest maize grain yield in CFI was obtained from 50%ETc irrigation application, which is also statistically similar with result of AFI at 75%ETc irrigation (Table 4). A similar study by Kang et al. (2000) confirmed that reduction in yield due to AFI application was statistically similar to FFI.

The WUE of AFI 75%ETc and AFI 100%ETc was greater than the other treatments, however the difference between them was not significant. Kang et al. (1998) and Mehari et al. (2020) showed that AFI is most effective to improve WUE. The lowest WUE was obtained from FFI 50%ETc irrigation and it was statistically similar result with CFI 100%ETc application (Table 4). Better WUE was also observed from deficit application of CFI 50%ETc and CFI 75%ETc. However, in terms of crop yield, the CFI 75%ETc had comparable yield with AFI 100%ETc. This could be because of

Table 3. Grain Yield, WUE, Biomass and Harvest Index for Furrow Method and Irrigation Level on Maize at Melkassa, Ethiopia. Values are the Means of Two Years and Three Replicates.

	GRAIN YIELD (KG HA^{-1})	WUE (KG HA-MM^{-1})	BIOMASS (KG HA^{-1})	HARVEST INDEX
Main plot factor	Furrow method			
AFI	4403^{b}	17.35^{a}	7608^{b}	0.56^{b}
FFI	2790^{b}	11.13^{a}	6505^{c}	0.42^{c}
CFI	6150^{a}	13.13^{a}	9085^{a}	0.68^{a}
LSD$_{0.05}$	1653	6.59	807	0.07
p-Value	.039	.081	.003	.022
Subplot factor	Irrigation level			
100%ETc	5788^{a}	14.28^{a}	8847^{a}	0.66^{a}
75%ETc	4750^{b}	14.98^{a}	7963^{b}	0.57^{b}
50%ETc	2805^{c}	12.34^{b}	6389^{c}	0.43^{c}
LSD$_{0.05}$	305	1.67	245	0.04
p-Value	<.0001	.005	<.0001	<.0001

Note. AFI, FFI, and CFI represent alternate, fixed and conventional furrow irrigation, respectively, ETc represents crop evapotranspiration. Means within a column and treatment effect followed by the same letters are not significantly different.

Table 4. The Furrow Irrigation Method × Irrigation Level Interaction on Grain Yield, WUE, Biomass, and Harvest Index (HI) of Maize in 2016 and 2017 at Melkassa, Ethiopia. Values are the Means of Two Years and Three Replicates.

TREATMENTS	GRAIN YIELD (KG HA^{-1})	WUE (KG HA-MM^{-1})	BIOMASS (KG HA^{-1})	HI
AFI 100%ETc	6330^{a}	19.57^{a}	8980^{b}	0.70^{a}
AFI 75%ETc	4816^{b}	19.80^{a}	7709^{c}	0.62^{b}
AFI 50%ETc	2062^{d}	12.68^{bcd}	6135de	0.35^{cd}
FFI 100%ETc	4053^{b}	12.47^{bcd}	7319^{c}	0.57^{b}
FFI 75%ETc	2783^{c}	11.43^{cde}	6784^{cd}	0.40^{c}
FFI 50%ETc	1535^{d}	9.48^{e}	5412^{e}	0.28^{d}
CFI 100%ETc	6981^{a}	10.80^{de}	10241^{a}	0.70^{a}
CFI 75%ETc	6651^{a}	13.72^{bc}	9395^{b}	0.70^{a}
CFI 50%ETc	4816^{b}	14.87^{b}	7619^{c}	0.65^{ab}
Mean	4448	13.87	7733	0.55
CV (%)	12	12.16	6.56	16.08
LSD$_{0.05}$	534	2.15	677.87	0.08
p-Value	.002	.0009	.048	.005

Note. AFI, FFI, CFI, WUE, and HI represent alternate, fixed and conventional furrow irrigation, water use efficiency and harvest index, respectively. Means with the same column followed by the same letters are not significantly different.

better application efficiency and less evapotranspiration related to AFI and deficit irrigation (Hassene & Seid, 2017; Subhan et al., 2021). On the other hand, the obtained WUE values agreed with the globally measured average WUE for maize which ranged from 11 kg ha-mm^{-1} to 27 kg ha-mm^{-1} (Yazar et al., 2009).

The values estimated for WUE have some very important implications. Under a limited water supply situation where the goal may be to achieve the highest possible WUE, using AFI 100%ETc and AFI 75%ETc offers opportunities for water savings. Otherwise, if the objective is to maximize yield, the use of CFI with 100 or 75%ETc would be better.

Biomass and harvest index

No significant difference was observed over years, by interaction of year and furrow method, and year × furrow method × irrigation level for biomass and HI (Table 2). Biomass and harvest index were reduced significantly from CFI to AFI and FFI in furrow method treatments and from 100%ETc to 75%ETc and 50%ETc (Table 3). The result was in agreement with those reported by Bryant et al. (1992) and Farré and Faci (2009). Bryant et al. (1992) reported that water stress reduced yield by reducing both accumulated biomass and the harvest index. Farré and Faci (2009) also reported a significant effect of limited irrigation on HI.

Higher biomass yield was observed from the 100%ETc application in CFI and shows no significant difference with deficit irrigation application of 75%ETc and 100%ETc under CFI and AFI, respectively (Table 4). The FFI performed low in biomass (BM) yield and shows no significant differences with CFI at 50%ETc and AFI at 75%ETc and 50%ETc applications. Low harvest index, HI for maize was recorded from FFI and similar response was obtained from AFI with 50%ETc application. Highest HI of 0.71 was recorded from CFI with 75%ETc application and showed no difference with 100%ETc application under AFI. The AFI with 100%ETc application saved 50% water compared to the CFI furrow irrigation with 100%ETc application and could be considered best water saving technology in water limited area (Table 4).

Yield response to water deficit

Maize grain yield response to water deficit was obtained from the relationship between seasonal yield reduction and the corresponding seasonal ET deficit (Table 5). The relative yield reduction corresponding to relative water deficit was noticed to increase with increase in irrigation deficit in all the three furrow methods. For the same amount of water deficit, the yield reduction incurred was greater for FFI than AFI (Table 5). The greatest yield response factor was obtained from FFI 50%ETc, while it was less than 1 for all the other treatment combinations (Table 5). As Ky represents a measure of the relative sensitivity of a crop to drought in a particular environment (Ferreira & Gonçalves, 2007), the obtained result indicates that using combined furrow method and irrigation level as a management strategy could be employed in semi-arid regions as effective scarce water utilization practices. As noted by Araya et al. (2011), values for Ky above 1 indicate that the crop is sensitive to moisture stress, whereas values below 1 indicate that the crop can tolerate some levels of moisture stress in its growing environment.

Table 5. Relative Yield Reduction, Relative ETc Deficit and Yield Response Factor of Maize Using Different Irrigation Methods and Deficit Irrigation at Melkassa, Ethiopia. Values are the Means of Two Years and Three Replicates.

TREATMENTS	1–(YA/YM)	1–(ETA/ETM)	KY
AFI 100%ETc	0.09	0.50	0.19
AFI 75%ETc	0.31	0.62	0.50
AFI 50%ETc	0.70	0.75	0.94
FFI 100%ETc	0.42	0.50	0.84
FFI 75%ETc	0.60	0.62	0.96
FFI 50%ETc	0.78	0.75	1.04
CFI 100%ETc	0.00	0.00	*
CFI 75%ETc	0.05	0.25	0.19
CFI 50%ETc	0.31	0.50	0.62

Note. Ky is yield response factor, expressed as the ratio of relative yield reduction to relative irrigation deficit, Ya is the actual yield of each treatment (kg/ha), Ym is the maximum yield for CFI 100%ETc that is, $6980.7\,kg\,ha^{-1}$, ETa is actual evapotranspiration and it is the irrigation amount applied throughout the entire growth period for each treatment (mm), ETm is the maximum evapotranspiration estimated from CFI 100%ETc (594.1 mm), (1–Ya/Ym) is the relative yield reduction, and (1–ETa/ETm) is the relative ET deficit.
*There was no water deficit and yield reduction, thus no yield response value for CFI 100%ETc.

Conclusion

Limited water resources availability is becoming the main challenge for sustainable crop production in semiarid regions such as the Central Rift Valley of Ethiopia. Alternate furrow irrigation and deficit irrigation practices have been considered as a valuable and sustainable production strategy to improve maize yield and WUE in these regions. The FFI with 50%ETc application and CFI with 100%ETc application resulted in significantly lesser WUE. The AFI with 100 and 75%ETc treatment combinations resulted in significantly greater WUE. In terms of crop yield the CFI 75%ETc and AFI 100%ETc were not different. Hence, the AFI with 100%ETc was superior to 75%ETc application considering crop yield. Nonetheless, the 75%ETc application in AFI could be applicable in areas with severely limited water resources.

Author Contributions

All the authors conducted field experiment and data collection, analyzed the data, performed result interpretation, and prepared draft manuscripts for publication. Finally, all authors read and approved the final manuscript. The author(s) received financial support for the research from Ethiopian Institute of Agricultural Research (EIAR), but received no financial support for authorship, and/or publication of this article.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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