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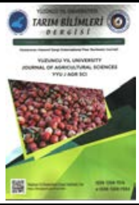

Araştırma Makalesi (Research Article)

Water Use Efficiency and Water Production Function of Corn under Full and Deficit Irrigation in a Cold Semi-arid Environment **

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Abstract: In this study, corn (*Zea mays* L.) yields measured in the fields during eight years from 2005-2006 to 2012-2013 were compared with those simulated by the Agro-ecological Zone method under cold semi-arid environment. The potential yield (Ym) of corn was 10 430 kg ha^{-1} with a net water for irrigation of 6 180 m^3 ha^{-1}. Water-production function for corn was acquired with application efficiency scenarios from 100% to 40%. To produce a potential yield of corn, irrigation water requirement was 6 180, 6 867, 7 725, 8 829, 10 300, 12 360, 15 450 m^3 ha^{-1} under water application efficiency of 100, 90, 80, 70, 60, 50 and 40%, respectively. Results showed that measured yield ranged from 5 784 to 7 026 kg ha^{-1} per ha with an average of 6 404 kg ha^{-1}. Water applied to produce corn averaged 10 567 m^3 ha^{-1}. The water use efficiency (WUE) averaged 0.61 kg m^{-3} during eight years and water application efficiency was 51.2% in corn farms. It is suggested that deficit irrigation could be applied to enhance water use efficiency in corn production under cold semi-arid environment.

Soğuk Yarı Kurak Koşullarda Tam ve Eksik Sulama Altındaki Mısırın Su Kullanım Verimliliği ve Su Üretim Fonksiyonu

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Anahtar kelimeler
Mısır sulama,
Eksik sulama,
Su uygulama etkinliği,
Su verimliliği

Öz: Bu çalışmada, tarla koşullarında 2005-2006‘dan 2012-2013 yılları arasında sekiz yılda ölçülen mısır (Zea mays L.) verimleri soğuk yarı kurak koşullarda Tarımsal Ekolojik Bölge yöntemi tarafından simüle edilen verilerle karşılaştırılmıştır. Mısırın potansiyel verimi (Ym), 618 m^3/da net sulama suyu için 1 043 kg/da olmuştur. Mısır için su üretim fonksiyonu, % 100 ile% 40 arasında uygulama verimliliği senaryolarıyla elde edilmiştir. Potansiyel bir mısır verimi üretmek için, sulama suyu gereksinimi, Sırasıyla % 100, 90, 80, 70, 60, 50 ve 40 su uygulama etkinliği altında 618, 686.7, 772.5, 882.9, 1 030, 1 236, 1 545 m^3/da bulunmuştur. Sonuçlar, ölçülen verimin da başına ortalama 640.4 kg/da olduğu ve 578.4 ila 702.6 kg/da arasında değiştiğini göstermiştir. Mısır üretimi için uygulanan su ortalama 1056.7 m^3/da olmuştur. Mısır çiftliklerinde su kullanım etkinliği (SKE) sekiz yıl boyunca ortalama 0.61 kg/m^3 ve su uygulama verimliliği % 51.2 olarak bulunmuştur. Soğuk yarı kurak ortamda mısır üretiminde su kullanım verimliliğini artırmak için kısıntılı sulamanın uygulanabileceği önerilmektedir.

**This study is a part of extensive research on crop irrigation management at the north-west of Iran.

1. Introduction

Corn (*Zea mays* L.) is one of the valuable and major irrigated crops for human and animal nutrition in the world which has positive response to adequate irrigation water. The corn root system is relatively sparse, it is therefore sensitive to water deficit stress (El-Hendawy et al., 2008). Previous studies showed that in corn production under semi-arid conditions, tasseling and silking stages are extremely sensitive to the water insufficiency. Robins and Domingo (1953) found that in corn production, soil moisture reduction to the wilting point percentage at tassel or pollination stages for one to two days reduced yield as 22%, and for six to eight days by 50%.

Musick and Dusek (1980) reported that water deficit stress during growth stages of tasseling and silking to be the most injurious, while water deficit stress during stage of grain filling was more injurious than water deficit stress during growth stage of vegetative in corn production. According to the findings of Eck (1984) about two and four weeks of water deficit stress during the stage of vegetative of corn reduced its yields up to 23 and 46%, respectively. Also, Johnson et al., (1987) reported that irrigated corn responded as well to midseason irrigation as it did to more frequent irrigations at 50% soil water depletion. Rhoades and Bennett (1990) and Lamm et al., (1995) found that deficit irrigation strategies generally reduce corn yield. Furthermore, based on Darusman et al., (1997) reports, when irrigation and rainfall was totally 75% corn evapotranspiration, drip irrigation method resulted in near-potential corn yield and reduced deep percolation losses beneath the root development zone. Moreover, Norwood (2000) reported that irrigation, plant population, fertilizer and management methods considerably increased yields above those of dryland corn. A single irrigation at the tassel stage along with 112 kg N ha^{-1} increased corn yield with an average of 1.76 Mg ha^{-1} (about 30%). Also, two and three irrigation events in combination with increased N rates and plant populations produced more yields about 11 and 13%, respectively. Two irrigation events were applied at the tassel and dough stage of grain fill and three events were at the 9 to 10 leaf stage; and at tassel and dough stage of grain fill of corn production. Khajeabdollahi and Sepaskhah (1996), reported that furrow irrigation by every other method with an interval of 4 days required less water than 7 days interval with the same yield in corn production. From economic view the first method is profitable, as well. Dawni (1992) showed that 20 days delay in irrigation at corn grain filling stage led to 47% yield decrease. But the same delay period on vegetative period had no effect on yield.

According to the report of Laboski et al., (1998) about 94% of the total corn root length distributed within 60 cm of the soil surface and about 85% of root length was within 30 cm. The Water use efficiency (WUE) is defined the as the ratio of grain produced to the water used in crop production. This index was extensively applied in crop irrigation researches (Nasseri and Fallahi, 2007; Zamani and Nasseri, 2008; Nasseri and Bahramloo, 2009; Abadi et al., 2010; Du et al., 2010; Fang et al., 2010; Guo et al., 2010; Li. 2010; Zhang et al., 2010; Bramley et al., 2013).

According to the reports of Hamdy et al. (2003), increasing WUE by both conditions of irrigated and rainfed productions is an essential priorities in the agricultural production systems. Deficit irrigation method is one of the ordinary strategies for producing crops under water deficit and limitation conditions in an arid and semi-arid environment over of the world. According to the report of Zheng et al. (2019), the highest water productivity under non-full irrigation treatments. Previous studies showed that corn yield is linearly related to the seasonal evapotranspiration (Gilley et al., 1980; Stone, 2003; Klocke et al., 2004; Payero et al., 2006). The water use efficiency of corn under different conditions of irrigation treatments, fertilizers rates and crop populations were investigated by researchers over the world (Howell et al., 1995; Al-Kaisi and Yin, 2003; Karam et al., 2003; Payero et al., 2008; Katerji et al., 2010; El-Wahed and Ali, 2013; Katerji et al., 2013). But Investigation of WUE under different conditions for actual evapotranspiration in semi-arid environment was not accomplished.

Thus, the main aim of present research was to compare corn yields measured from fields during eight years of 2005-2006 to 2013-2014 with those simulated by the Agro-ecological Zone method, to investigate WUE under different conditions for actual evapotranspiration conditions, and to develop water production function for full and deficit irrigation conditions under semi-arid environment.

2. Materials and Methods

2.1. Site description and crop-soil-water parameters

The present study was conducted on the farms with cold semi-arid conditions at the north west (East Azarbaijan, Tabriz) of Iran with latitude 38º 8' N, longitude 46º 17' E and 1364 m above mean sea level. Crop, soil and irrigation parameters and climatic data for evaluation of the corn water use efficiency was shown in Table 1. Corn yields obtained from farms in the region for eight years from 2005-2006 to 2012-2013 (Golizadeh et al., 2014) were compared with the simulated yields by the methods of Rao et al., (1988).

2.2. Relation between corn yield and evapotranspiration

Doorenbos and Kassam (1979) developed the linear function between relative crop yield (Ya/Ym) and relative evapotranspiration (ETa/ETm) as the following relation:

$$(1-\frac{\mathrm{Ya}}{\mathrm{Ym}}) = \mathrm{Ky}\,(1-\frac{\mathrm{ETa}}{\mathrm{ETm}}) \quad (1)$$

where Ya and Ym are respectively actual and potential corn yields; Eta and ETm are respectively actual and potential corn evapotranspiration. Crop yield response factor (Ky) depends on crop, irrigation management and crop growth stage (Turhan and Kuscu, 2019).

Rao et al. (1988) developed a multiplicative form of relation proposed by Doorenbos and Kassam (1979) which comprising crop growth stages response to water deficit and can be described as:

$$\frac{Ya}{Ym} = \prod_{i=1}^{m}\left[1 - Ky_i\left(1-\frac{\sum_{j=1}^{m} ETa_{ji}}{\sum_{j=1}^{m} ETm_{ji}}\right)\right] \quad (2)$$

where Ya is the actual corn yield (kg ha^{-1}) from Eta (m^{3}) and Ym is the potential corn yield (kg ha^{-1}) from ETm (m^{3}), Ky is crop yield response factor which was 0.40, 1.50, 0.50, 0.2 and 1.25 for the vegetative, flowering, yield formation, ripening and total growing stages in corn production (Doorenbos and Kassam, 1979); and m is the number of days of the corn growing season and n the number of months of the corn growing season. The agro-ecological zone method was applied to simulate corn yield potential for a cold semi-arid environment at the north- west of Iran.

2.3. Estimation of potential yield of corn

By the following relation potential yield (Ymp) of corn was estimated as (Doorenbos and Kassam, 1979):

$$\mathrm{Ymp} = \mathrm{CL}\times\mathrm{CN}\times\mathrm{CH}\times\mathrm{G}\times\mathrm{Yo} \quad (3)$$

where CL= correction factor for corn development and leaf area; CN= correction factor for dry matter production; CH= correction factor for harvested index, 0.35 for corn; G= total growing period (days); Yo = the gross dry matter production of standard crop was calculated as:

$$\mathrm{Yo} = \mathrm{F}\times\mathrm{Yo} \times (0.8 + 0.01\times\mathrm{Ym}) + (1-\mathrm{F}) \times \mathrm{Yc} \times (0.5 + 0.025 \times\mathrm{Ym}) \quad (4)$$

where Yo = the gross dry matter production of standard crop (kg ha^{-1} day^{-1}); F = fraction of the daytime that sky is clouded, fraction; or can be obtained from:

$$\mathrm{F} = (\mathrm{Rse}-0.5\times \mathrm{Rs}) / (0.8 \times\mathrm{Rse}) \quad (5)$$

in which Rse = the highest active in coming shortwave radiation on clear days in cal cm^{-2} day^{-1} and Rs = the actual measured incoming shortwave radiation in cal cm^{-2} day^{-1} and Yo = the gross dry matter production rate of standard crop for a given location on a completely overcast day (kg ha^{-1} day^{-1}); and Yc = the gross dry matter production rate of standard crop for a given location on a clear (cloudless) in kg ha^{-1} day^{-1} and Ym = the highest leaf gross dry matter production rate of a crop for a given climate (kg ha^{-1} day^{-1}).

2.4. Estimating reference evapotranspiration (ETo)

The reference evapotranspiration was estimated by Penman Monteith method as follows (Doorenbos and Kassam, 1979):

$$ETo= C\times(W\times Rn+ (1-W)\times F(u)\times(ea-ed)) \quad (6)$$

where ETo= the reference evapotranspiration in mm day^{-1}; (ea-ed) = the difference between saturation vapor pressure (ea) at mean air temperature (in mbar) and actual vapor pressure (ed) in mbar i.e. vapor pressure deficit where can be estimated by ed= ea× RH/100; F(u) = wind function; Rn=the total net radiation in mm day^{-1}; C= an adjustment factor

2.5. Estimation of potential evapotranspiration for corn (ETm)

The potential evapotranspiration (ETm in mm) for corn was estimated based on the reference evapotranspiration (ETo in mm) and crop coefficient (Kc) by the following relation (Doorenbos and Kassam, 1979; Karaca et al., 2018):

$$ETm=Kc\times ETo \quad (7)$$

Crop coefficient (Kc) for corn development stages was 0.50-0.79 (day 0-40), 0.98-1.02 (day 41-110), 0.84-0.65 (day 111-130) at studied region.

2.6. Research scenarios

In the present study, different scenarios comprising actual yield to potential yield (Ya/Ym) under different water application efficiencies of 40%, 50%, 60%, 70%, 80% and 100% were considered and the water use efficiency (WUE in kg m^{-3}) of each scenario was estimated by the following relation.

$$WUE = \text{Corn yield (kg ha}^{-1}\text{) / Water applied (m}^{3}\text{ ha}^{-1}\text{)} \quad (8)$$

3. Results and Discussion

The potential evapotranspiration for corn was obtained by reference evapotranspiration and crop coefficient. Reference evapotranspiration was estimated with Penman`s method based on long-term meteorological data. In Fig. 1 crop coefficient and monthly and cumulative evapotranspiration of corn during different growing months were presented. Results showed that crop coefficient for corn varied from 0.3 (in May) to 1.14 (in July). The highest monthly evapotranspiration was obtained 202 mm (in July) and cumulative potential evapotranspiration during the growing season under cold semi-arid conditions was 618 mm. Also, application of Agro-ecological Zone method produced the potential yield (Ym) of corn as 10430 kg ha^{-1} with net water for irrigation of 6180 m^3 ha^{-1}.

Table 1. Crop, soil and irrigation parameters and climatic data for evaluation of corn water use efficiency

Parameters	Value(s)
Crop parameters	
Corn variety	Single cross 704
Rooting depth (cm)	20 (week 0-4), 80 (week 9-20)
Seed planting and end dates	21 April to 31 August
Crop coefficient	0.50-0.79 (day 0-40), 0.98-1.02 (day 41-110), 0.84-0.65 (day 111-130)
Seed moisture at harvest time	12-13%
Climatic data	
Corn evapotranspiration	618 mm
Effective rainfall (average)	50±7 mm
Annual rainfall	225 mm, more than 45% occurs from October to July and about 40% from April to July
Air temperature (averages)	12 ˚C
Annual sunshine duration	2919 h
Irrigation parameters	
Irrigation method	Furrow irrigation
Water application efficiency	51.2%
Irrigation intervals	7 days
Soil parameters	
Soil texture	loamy sand (5% clay, 8% silt and 87% sand)
Bulk density (g cm^{-3})	1.54
Field capacity (%)	10
Permanent wilting point (%)	4
pH	7.6

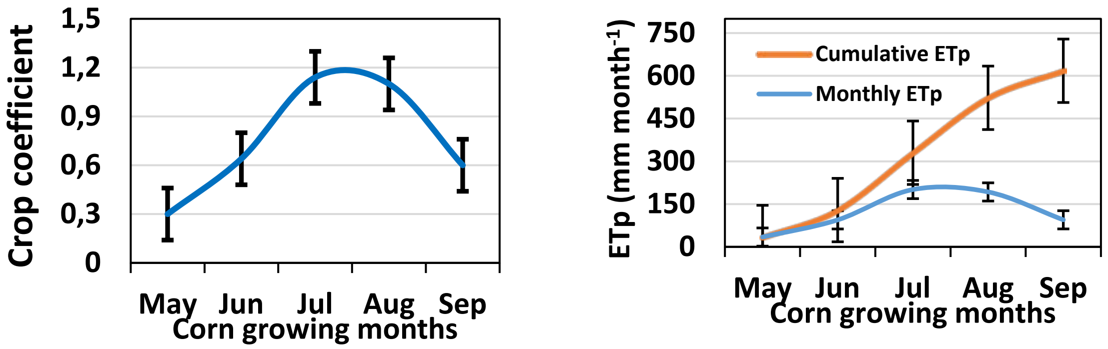

Figure 1. Crop coefficient, monthly and cumulative evapotranspiration of corn during growing months under cold semi-arid conditions

Water-production function for corn was acquired by plotting corn yield (kg ha^{-1}) on the Y-axis and irrigation water (mm) on the X-axis which is plotted in Figs. 2 to 3 for furrow irrigation with application efficiency from 100% to 40%. Effective rainfall during the corn growing season based on long term meteorological data was 50 mm. Results showed that corn yield is a function of irrigation water application as a quadratic function. The best fitting function for water-yield relations were as follows:

Ea=100%	Yield = 0.040 W^2 - 8.52 W	R^2=0.99	(9)
Ea=90%	Yield = 0.033 W^2 - 7.88 W	R^2=0.99	(10)
Ea=80%	Yield = 0.026 W^2 - 7.00 W	R^2=0.99	(11)
Ea=70%	Yield = 0.019 W^2 - 6.13 W	R^2=0.99	(12)
Ea=60%	Yield = 0.015 W^2 - 5.25 W	R^2=0.99	(13)
Ea=50%	Yield = 0.010 W^2 - 4.38 W	R^2=0.99	(14)
Ea=40%	Yield = 0.006 W^2 - 3.50 W	R^2=0.99	(15)

To produce potential yield (10 430 kg ha^{-1}) of corn, irrigation water requirement was 6 180, 6 867, 7 725, 8 829, 10 300, 12 360, 15 450 m^3 ha^{-1} under water application efficiency of 100, 90, 80, 70, 60, 50 and 40%, respectively. Therefore, with increasing water application efficiency, irrigation water requirement to produce potential yield was obviously decreased. Consequently, to achieve potentila yield, the water use efficiencies were respectively 1.69, 1.52, 1.35, 1.18, 1.01, 0.84, 0.68 kg m^{-3} under water application efficiency of 100, 90, 80, 70, 60, 50 and 40%.

To produce 70% of potential yield (Ya/Ym=0.70 and Ya=7 453 kg ha^{-1}) of corn, irrigation water requirement (and water use efficiency) is 5 562 (1.34 kg m^{-3}), 6 180 (1.21 kg m^{-3}), 6 953 (1.07 kg m^{-3}), 7 946 (0.94 kg m^{-3}), 9 270 (0.80 kg m^{-3}), 11 124 (0.67 kg m^{-3}), 13 905(0.54 kg m^{-3}) m^3 ha^{-1} under water application efficiency of 100, 90, 80, 70, 60, 50 and 40%, respectively. To produce 50% of potential yield (Ya/Ym=0.50 and Ya=5 126 kg ha^{-1}) of corn, irrigation water requirement (and the water use efficiency) is 12 360 (0.41 kg m^{-3}), 9 888 (0.52 kg m^{-3}), 8 240 (0.62 kg m^{-3}), 7 063 (0.73 kg m^{-3}), 6 180 (0.83 kg m^{-3}), 5 493 (0.93 kg m^{-3}), 4 944 (1.04 kg m^{-3}) m^3 ha^{-1} under water application efficiency of 40, 50, 60, 70, 80, 90 and 100%, respectively. To produce 30% of potential yield (Ya/Ym=0.30 and Ya=3 352 kg ha^{-1}) of corn, irrigation water requirement (and the water use efficiency) is 4 326 (0.77 kg m^{-3}), 4 807 (0.70 kg m^{-3}), 5 408 (0.62 kg m^{-3}), 6 180 (0.54 kg m^{-3}), 7 210 (0.46 kg m^{-3}), 8 652 (0.39 kg m^{-3}), 10 815 (0.31 kg m^{-3}) m^3 ha^{-1} under water application efficiency of 100, 90, 80, 70, 60, 50 and 40%, respectively.

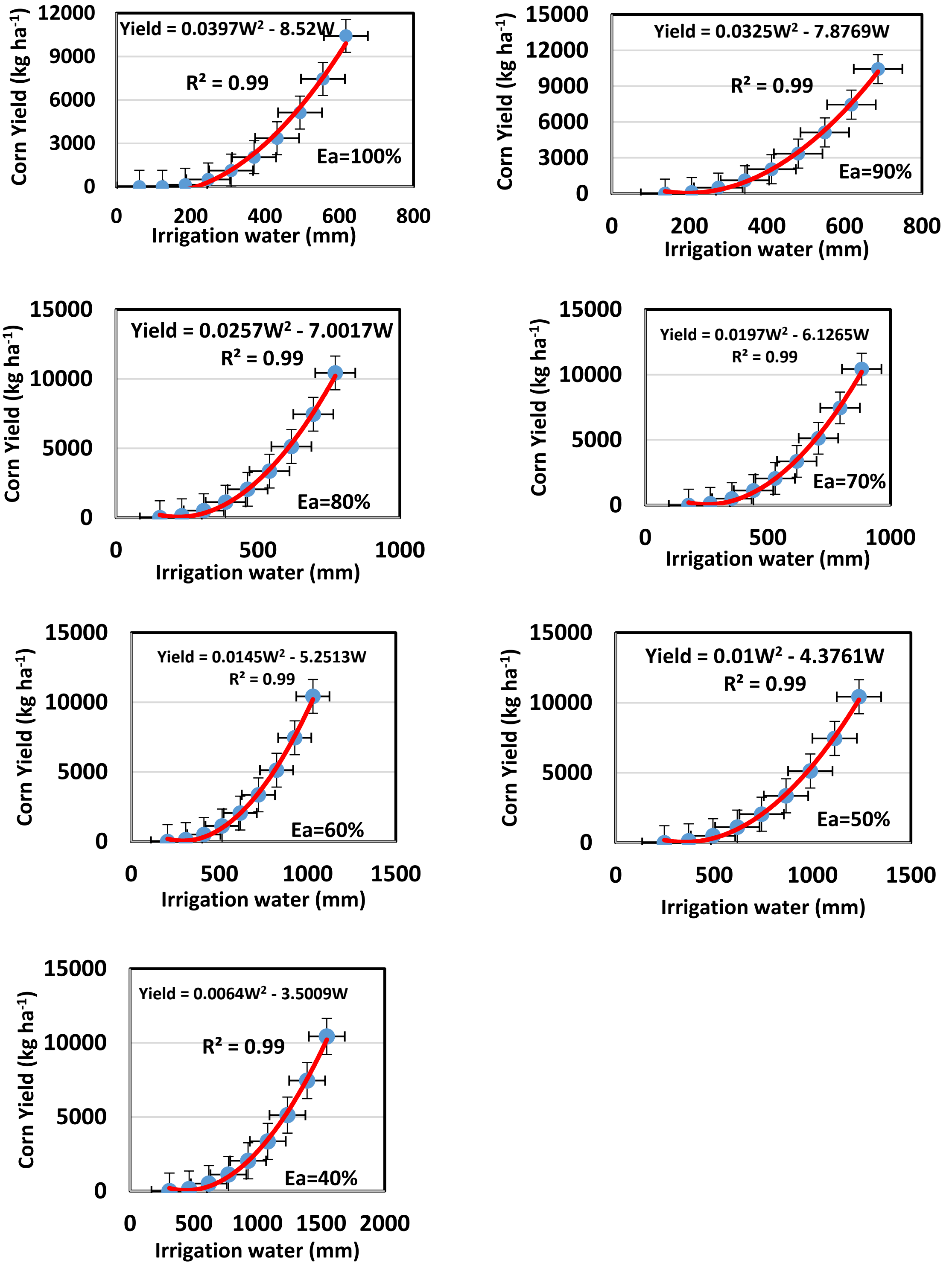

Figure 2. Crop yield versus irrigation water under cold semi-arid conditions

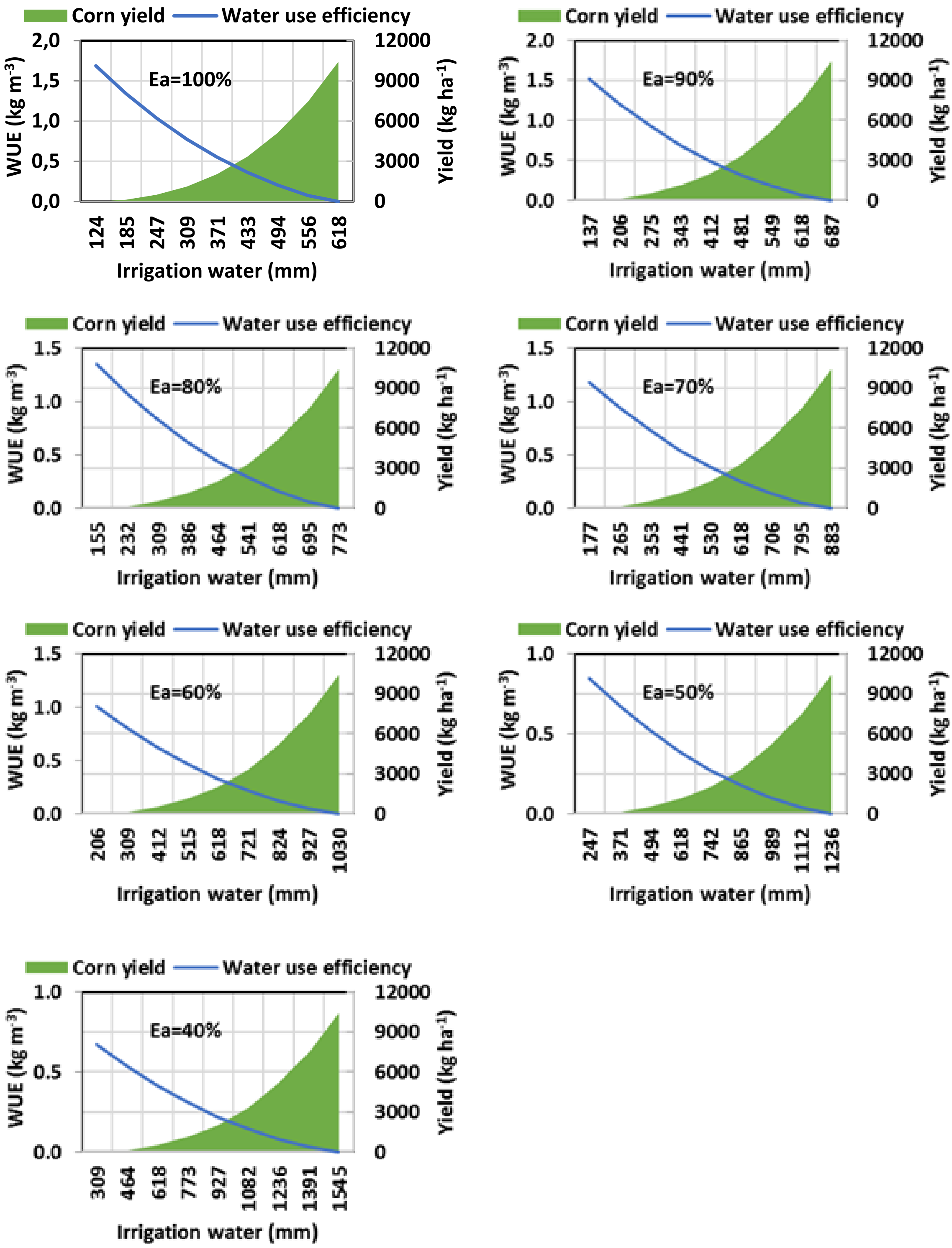

Figure 3. Corn yield and water use efficiency versus irrigation water under cold semi-arid conditions

Measured yield, water applied and the water use efficiency of corn during eight years from 2005-2006 to 2012-2013 under actual and conventional conditions were presented in Fig.s 4 and 5. Results showed that measured yield ranged from 5 784 to 7 026 kg ha^{-1} with an averge of 6 404 kg ha^{-1}. Water applied to produced corn was from 10 238 to 10 897 m^{3} ha^{-1} and averaged 10 567 m^{3} ha^{-1} (Fig. 4). Simliar to researchers (Bramley et al., 2013; Abadi et al., 2010; Du et al., 2010; Fang et al., 2010; Guo et al., 2010; Li. 2010; Zhang et al., 2010; Nasseri and Bahramloo, 2009; Zamani and Nasseri, 2008; Nasseri and Fallahi, 2007). Index of the water use efficiency was applied to evaluate corn productivity by irrigation water. The water use efficiency were from 0.56 to 0.64 kg m^{-3} with an average of 0.61 kg m^{-3} (Fig.5) during eight years. Water aplication efficiency was 51.2% in corn farms (Abbasi et al., 2016). It is sugested that deficit irrigation could be applied to enhence the water use efficiency in corn production under cold semi-arid environment. Further studies are necessary to evaluate interaction effect of deficit irrigation and fertilizers applications on corn yield under cold semi-arid environment.

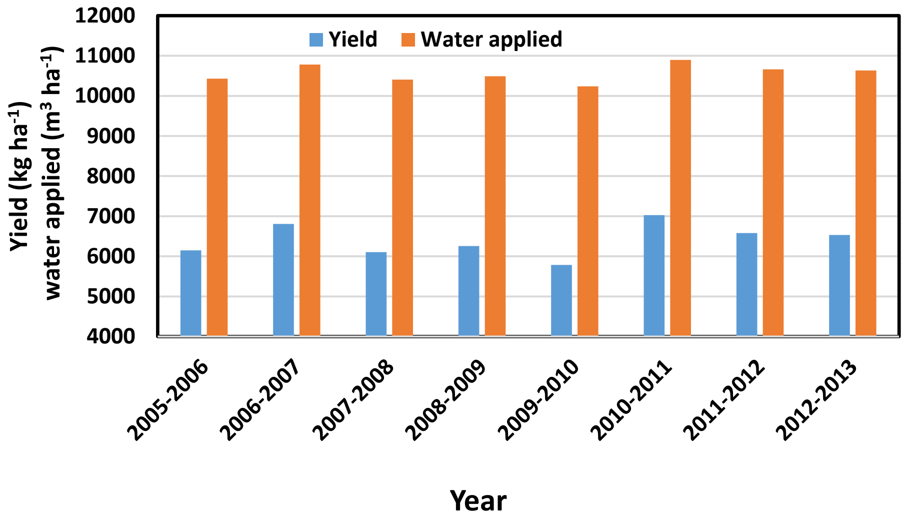

Figure 4. Measured corn yield and irrigation water during eight years from 2005-2006 to 2012-2013

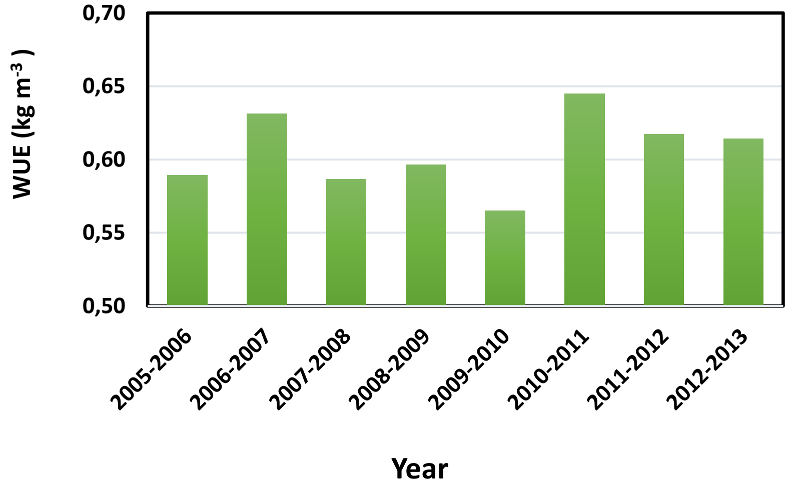

Figure 5. Water use efficiency of corn during eight years from 2005-2006 to 2012-2013

4. Conclusion

Under cold semi-arid environment, corn (*Zea mays* L.) yields measured from fields during eight years from 2005-2006 to 2012-2013 were compared with those simulated by the Agro-ecological Zone method. Under different scenarios of application efficiency from 100% to 40%, water-production function for corn was acquired which can be applied to estimate or forecast corn yield with available water for irrigation. It is suggested that deficit irrigation could be applied to enhence the water use efficiency in corn production under cold semi-arid environment. Further studies is necessary to evaluate interaction effect of deficit irrigation and fertilizers applications on corn production under cold semi-arid environment.

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