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Crop Evapotranspiration, Irrigation Water Requirement and Water Productivity of Maize from Meteorological Data under Semiarid Climate

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Abstract: Under the semiarid climate of the Southwest United States, accurate estimation of crop water use is important for water management and planning under conservation agriculture. The objectives of this study were to estimate maize water use and water productivity in the Four Corners region of New Mexico. Maize was grown under full irrigation during the 2011, 2012, 2013, 2014 and 2017 seasons at the Agricultural Science Center at Farmington (NM). Seasonal amounts of applied irrigation varied from 576.6 to 1051.6 mm and averaged 837.7 mm and the total water supply varied from 693.4 to 1140.5 mm. Maize actual evapotranspiration was estimated using locally developed crop coefficient curve and the tabulated United Nations Food and Agriculture Organization (FAO) crop coefficients, and from this maize water productivity was determined. Maize actual daily evapotranspiration (ETa) varied from 0.23 to 10.2 mm and the seasonal ETa varied with year and ranged from 634.2 to 697.7 mm averaging 665.3 mm by the local Kc curve, from 687.3 to 739.3 mm averaging 717.8 mm by the non-adjusted FAO Kc values, and from 715.8 to 779.6 mm averaging 754.9 mm with the FAO adjusted Kc values. Maize irrigation requirements varied from 758.4 to 848.3 mm and averaged 800.2 mm using the local developed Kc and varied from 835.5 to 935.6 mm and averaged 912.2 mm using FAO Kc. The net irrigation requirement varied from 606.8 to 678.6 using local Kc curve, and from 682.78 to 748.5 mm when adopting the FAO Kc values. Average irrigation requirement was 641 mm under the local Kc option and 730 mm under FAO Kc values option. Maize crop water use efficiency (CWUE) ranged from 1.3 to 1.9 kg/m^3 and averaged 1.53 kg/m^3, evapotranspiration water use efficiency (ETWUE) values were higher than CWUE and varied from 2.0 to 2.3 kg/m^3, averaging 2.1 kg/m^3. Maize irrigation water use efficiency (IWUE) was varied with years and averaged 1.74 kg/m^3. There were strong relationships between maize CWUE and maize seasonal irrigation amounts of IWUE and the seasonal irrigation amounts with R^2 of 0.97 and 0.92, respectively. Maize CWUE increased linearly with maize IWUE with a coefficient of determination R^2 of 0.99, while IWUE showed a strong quadratic relationship with ETWUE (R^2 = 0.94). The results of this study can be used as a guideline for maize water management under the semiarid conditions in northwestern New Mexico and other locations with similar climate and management conditions. Irrigation requirements for maize should be adjusted to the local meteorological conditions for optimizing maize irrigation requirement and improving maize water productivity.

Keywords: maize; evapotranspiration; irrigation requirements; water use efficiency

1. Introduction

Crop evapotranspiration (ETa) is an important parameter in hydrological, environmental and agricultural studies and plays a key role in designing and managing irrigation projects and water management under irrigated and rainfed agriculture. While crop ETa is directly measured with lysimeters and Eddy covariance systems, it is also estimated by the indirect method using reference crop evapotranspiration (ETo) and crop coefficients. Jensen [1] was the pioneer relating crop actual evapotranspiration to the reference evapotranspiration using the conversion factor called crop coefficient (Kc). The Kc is crop specific and growth stage specific and results from the combination effects of crop characteristics, soil moisture status and soil type, crop management practices, canopy and aerodynamic resistance, climatic conditions such as the available energy, surrounding air content in vapor, air vapor deficit, etc. [2–4]. The Penman–Monteith reference evapotranspiration method is accepted worldwide and is generally viewed as the most accurate method for estimation of ETo among the numerous ETo equations developed and implemented [5–15]. While different Kc curves are developed for different crops and for different locations, Allen et al. [5] suggested regional crop Kc curves for different crops following the approach suggested by Doorenbos and Pruitt [16]. To account for the local climate and actual crop growing period and crop characteristics, Allen et al. [5] suggested adjustment of mid and late season tabulated Kc to crop height, wind speed and minimum relative humidity to account for the crop resistance and aerodynamic resistance while the initial Kc values mainly depend on soil type and watering status [17]. It is important to identify crop phenology at each location and adjust the tabulated Kc values to the actual crop growth period durations [18]. Crop growth models are also used to simulate crop phenology based on the accumulated thermal units [19–23]. The development of Kc curves as a function of the thermal unit is important and involves consideration of the physiological status of plant organs. Crop ETa estimation by the two-step approach is widely used with generally good agreement between the estimated ETa values and the lysimeter-derived ETa values [24–32].

Water resources are limited under semiarid climates such as that of the Southwestern United States, the hottest and driest region in the United States with diminishing winter and spring precipitation and shifts in precipitation and reference evapotranspiration [33–37]. Cozzetto et al. [38] reported that the Southwest is prone to drought, and its paleoclimate showed severe mega droughts at least 50 years long. This projection is mostly challenging regarding water resources management and planning when the human population is increasing along with the demand for food and an increasing competition among water users such as agricultural producers, industries, mines, communities, environmentalists and others. Across the Southwestern region, 92% of the crop land is irrigated [35]. Prein et al. [39] indicated that the southwestern United States climate may be transitioning to a drier climate state leading to higher drought risk. The USDA [40] reported that irrigation water withdrawals for crop production account for 79% of the total water withdrawal in the Southwestern region. Conservation efforts should target limited irrigation strategies when maintaining or improving crop water productivity across the region under the increasing trend in reference evapotranspiration [37]. Evapotranspiration is one of the largest components of the hydrological cycle and is expected to increase with warming across the Southwestern United States.

To cope with the aforementioned climatic conditions and the future projection, accurate estimation of crop water use may be a priority for water management and planning under conservative agriculture. The objectives of this study were to estimate maize water use and water productivity in the Four Corners region.

2. Materials and Methods

2.1. Station Area

This study was conducted at the New Mexico State University (NMSU) Agricultural Science Center at Farmington (Latitude 36.69′ North, Longitude 108.31′ West) for the 2011, 2012, 2013, 2014

and 2017 growing seasons. Minimum temperature (Tmin), maximum temperature (Tmax), average temperature (Tmean), minimum relative humidity (RHmin), maximum relative humidity (RHmax), average relative humidity (RHmean), wind speed (u_2), and solar radiation (Rs) were collected on a daily basis from an automated weather station installed at the site by the New Mexico Climate Center, located in Las Cruces, New Mexico. Thermal unit (TU) was estimated for maize during maize growing seasons. Annual average weather conditions are summarized in Table 1.

Table 1. Average climatic conditions during the five maize growing seasons, Farmington, New Mexico. u_2: wind speed; Tmax: maximum temperature; Tmin: minimum temperature; RHmax: maximum relative humidity; RHmin: minimum relative humidity; Rs: solar radiation; TU: thermal unit.

Year	u_2	Tmax	Tmin	Tmean	RHmax	RHmin	RHmean	Rs	TU
	(m/s)	(°C)	(°C)	(°C)	(%)	(%)	(%)	(MJ/m²)	(°C)
2011	2.5	27.9	11.4	19.7	68.5	17.1	42.8	23.8	1678
2012	2.3	27.2	9.8	18.5	53.9	15.1	34.5	22.1	1727
2013	2.4	28.8	12.2	20.5	49.5	13.3	31.4	23.0	1717
2014	2.3	28.8	10.7	19.8	63.7	13.1	38.4	22.4	1715
2017	2.1	27.5	10.0	18.8	69.3	15.5	42.4	22.8	1656

2.2. Standardized Penman-Monteith Reference Evapotranspiration Model

Daily grass-reference ET was computed using the standardized ASCE form of the Penman–Monteith (PM-ETo) equation [6]:

$$\text{ETo} = \frac{0.408\Delta(\text{Rn} - \text{G}) + (\gamma \text{Cn } u_2/(\text{T} + 273))(\text{es} - \text{ea})}{\Delta + \gamma(1 + \text{Cd } u_2)} \tag{1}$$

where ETo is the reference evapotranspiration (mm day^{-1}), Δ is the slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}), Rn is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), T is the mean daily air temperature at 1.5–2.5 m height (°C), u_2 is the mean daily wind speed at 2 m height (m s^{-1}), es is the saturation vapor pressure at 1.5–2.5 m height (kPa), ea is the actual vapor pressure at 1.5–2.5 m height (kPa), es − ea is the saturation vapor pressure deficit (kPa), γ is the psychrometric constant (kPa °C^{-1}), Cn and Cd are constants with values of 900 °C mm s^3 Mg^{-1} d^{-1} and 0.34 s m^{-1}. The procedure developed by Allen et al. [5] was used to compute the needed parameters.

2.3. Crop Coefficients (Kc)

Maize was grown under non-limiting water and fertilizer conditions, and the standard crop coefficient curve locally developed by Sammis et al. [41] was used for crop actual evapotranspiration simulation. Maize crop Kc is affected by climate conditions, soil moisture status and crop growth stages. As the crop develops, the ground coverage, crop height and leaf area change. Due to differences in evapotranspiration during various growth stages, the Kc for a given crop varies over the growing period. Maize growing period consists of the initial stage, crop development stage, mid-season stage, and late-season stage. To generate the Kc curve, maize thermal units were estimated for each growing season and the Kc equation by Sammis et al. [41] was applied on a daily basis.

$$\text{Kc} = 0.12 + 0.00168 \times \text{TU} - 2.45 \times 10^{-7} \times \text{TU}^2 - 4.37 \times 10^{-10} \times \text{TU}^3 \tag{2}$$

where Kc is daily crop coefficient and TU is thermal unit (°C).

Maize growing season actual evapotranspiration was also calculated as a cumulative daily ETa. Maize crop coefficients developed under a standard climatic condition by Allen et al. [5], as 0.3, 1.15 and 0.4 for the initial, mid-season and late-season were also used to estimate maize ETa for the study period.

Comparison was made between ETa using the locally developed Kc and the FAO recommended Kc. During crop development and late season stages, crop coefficient Kc was linearly interpolated between two typical values of Kc. The ETa during initial stage mainly consists of evaporation. Therefore, adjustment of Kc for this stage mainly depends on climatic factors. As per the FAO-56 method, the crop coefficient is affected by several factors, among which is the plant height. The typical mid- and late-season stage Kc values were adjusted with climatic condition and maize crop height [5]:

$$\text{Kc Stage} = \text{KcStage} + [0.04(u_2 - 2) - 0.004(\text{RHmin} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{3}$$
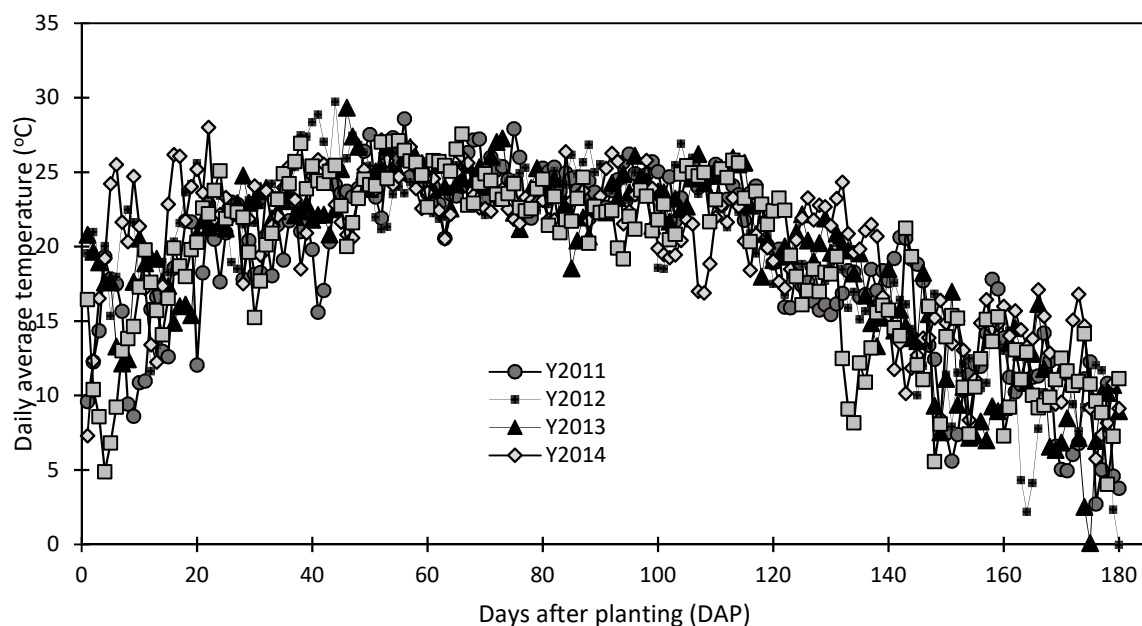
where KcStage is the standard value according to FAO-56 approach [5], u_2 is the value for daily wind speed at 2 m height over grass during the growth stage (m/s), RHmin is the value for daily minimum relative humidity during the growth stage (%), and h is the Plant height for each growth stage (m) (0.1 m–10 m).

2.4. Thermal Unit (TU)

Thermal unit is the accumulation of the growing degree days (GDD), which is a cumulative temperature that contributes to plant growth during the growing season and is expressed as follows:

$$\text{TU} = \sum_{i=1}^{n} \frac{\text{Tmax} + \text{Tmin}}{2} - \text{Tbase} \tag{4}$$

where TU = thermal unit (°C), Tmax = maximum air temperature (°C), Tmin = minimum air temperature (°C), Tbase = base temperature threshold for maize (10 °C), and n = number of days. The base temperature for calculating growing degree days is the minimum threshold temperature at which plant growth starts. The maximum and minimum temperature thresholds of 30 °C and 10 °C, respectively, were used. All temperature values exceeding the threshold were reduced to 30 °C, and values below 10 °C were taken as 10 °C because no growth occurs above or below the threshold (base) temperature values. If the average daily temperature was below the base temperature, the TU value was assumed to be zero. Trends in average daily temperature for the fine growing seasons are summarized in Figure 1.

Figure 1. Trends in the daily average temperature for maize growing seasons 2011, 2012, 2013, 2014 and 2017, Agricultural Science Center at Farmington, NM.

2.5. Crop Management

Maize was planted on May 11, 15, 14, 14, 15 and harvested on 28 November, 5 November, 25 September, 13 November and 16 November during the 2011, 2012, 2013, 2014 and 2017 growing seasons, respectively. Nitrogen, phosphorus and potassium fertilizer applied rates were based on the NMSU recommendation and were 252, 285, 303, 303 and 269 kg/ha for nitrogen, 84, 58, 87, 123 and 60 kg/ha for P_2O_5, and 101, 67, 101, 185 and 76 kg/ha for K_2O during maize 2011, 2012, 2013, 2014 and 2017 growing seasons. Herbicides and hand weeding were used as needed to maximize grain yield. The field was fully irrigated through a center pivot irrigation system to avoid any impact of water stress on crop growth, development and grain yield. Irrigation scheduling was based on evapotranspiration and the depletion criterion of 40% to 45% total available water (TAW) was practiced to prevent the plants from experiencing any water stress, as the center pivot requires two or three days to complete a full revolution. The field was kept weed free by herbicide application or hand weeding as needed. Insecticide was also applied in case any insect damage was noticed. At harvest, maize was combine harvested for grain yield. Plot grain mass and moisture content were determined and the grain yield was estimated in kg/ha and was adjusted to 15.5% moisture content.

2.6. Actual Evapotranspiration Estimation (ETa)

Maize actual crop evapotranspiration was estimated according to the equation proposed by Jenson [1] and Allen et al. [5].

$$ETa = Kc \times ETo \tag{5}$$

where ETa = daily actual evapotranspiration (mm), Kc = daily crop coefficient, ETo = grass reference evapotranspiration (mm)

2.7. Irrigation Water Requirement (IWR)

At the study site, there is not usually enough rainfall before the growing season starts. Pre-irrigation is practiced to facilitate crop germination and emergence. The irrigation water requirement was calculated following Equation (5):

$$IWR = \frac{PR + ETa + DP + Ro - Pe}{Eff} \tag{6}$$

where PR = pre-irrigation (mm), equal to the soil water holding capacity, ETa = actual evapotranspiration (mm), DP = deep percolation (mm), Ro = runoff (mm), and Pe = effective precipitation (mm), Eff = efficiency of the center pivot installed within the field. Under a semiarid climate similar to the New Mexico Four Corners Regions, irrigation water is well managed and it is assumed no runoff occurred. Deep percolation was estimated by soil water balance approach using a program written in Microsoft Visual Basic [42] and the effective precipitation was estimated according to Chen et al. [43].

2.8. Crop Water Use Efficiency

Crop water use efficiency related to crop evapotranspiration (CWUE), evapotranspiration water use efficiency (ETWUE), and seasonal irrigation water use efficiency (IWUE) were estimated by the following equations [44–47]:

$$CWUE = \frac{Yield}{Seasonal\ water\ supply} \tag{7}$$

$$ETWUE = \frac{Yield}{Maize\ seasonal\ ETa} \tag{8}$$

$$IWUE = \frac{Yield}{Seasonal\ irrigation\ amount} \tag{9}$$

where CWUE, ETWUE and IWUE are in kg/m^3, yield in kg/ha, maize seasonal ETa is the seasonal cumulative ETa (mm), the seasonal irrigation amount is the sum of the irrigation amounts throughout the season (mm), and seasonal water supply is the sum of seasonal precipitation and seasonal irrigation amount (mm).

2.9. Evaluation Criteria

Comparisons were made using the t-test, graphics and simple linear regression. A paired sample t-test (two-samples for means) was performed for any significant difference between maize ETa estimated with the two Kc sets at 5% significance level. The null hypothesis was that the seasonal maize ETa estimates using the locally developed Kc and the seasonal maize ETa estimates using the FAO recommended Kc came from the same population and that mean difference between maize ETa estimates was zero. The linear regressions were forced through the origin because ideally all equations should produce zero ETo when there is no evapotranspiration. The seasonal irrigation requirements estimated and the actual irrigation amounts were compared with the same criteria as for the seasonal ETa.

3. Results and Discussion

3.1. Maize Actual Evapotranspiration

Maize actual daily ETa varied between 0.2 and 9.4 mm in 2011, 0.0 to 8.7 mm in 2012, 0.10 to 10.2 mm in 2013, 0.1 to 10.1 mm in 2014, and 0.4 and 7.8 in 2017 (Figure 2). The maximum daily actual ETa was observed 80, 70, 73, 61 and 65 days after planting in 2011, 2012, 2013, 2014 and 2017, respectively (Figure 2). Maize daily ETa showed a second order polynomial relationship with the accumulated growing degree days, with high coefficients of determination that ranged from 0.90 to 0.94 (Figure 2). Maximum maize daily ETa occurred on average at thermal unit of 796 °C and the seasonal total thermal units accumulated by maize were 1678, 1719, 1716, 1715 and 1656 °C during the 2011, 2012, 2013, 2014 and 2017 growing seasons, respectively (Table 1; Figure 3). In all five years combined, maize daily ETa showed a good relationship with the accumulated thermal units (R^2 = 0.92) demonstrating the applicability of maize daily water use through the accumulated thermal units. Maximum daily ETa was obtained at the thermal unit values of 804, 842, 855, 737 and 744 °C in 2011, 2012, 2013, 2014 and 2017, respectively (Figure 4). These results are in agreement with Djaman and Irmak [3] who reported maize thermal unit values at maturity of 1726 and 1701 °C in south-central Nebraska. At the study site, the length of the growing season is dependent on the occurrence and the intensity of the late spring and first fall freeze. Thus, Table 2 shows the duration of frost-free periods during the 2011, 2012, 2013, 2014 and 2017 seasons. The 2017 growing season was the shortest because of the very early fall freeze. Maize seasonal ETa showed poor correlation with the seasonal irrigation amount with coefficient of determination of 0.37 when considering all five growing seasons (Figure 5a). When considering the 2011–2014 period, maize seasonal ETa had good relationship with the seasonal irrigation amount with R^2 value of 0.67 (Figure 5b). The early fall freeze that occurred on 25 September 2017, changed crop physiology and there was early irrigation cutoff and this might have impacted the relationship between seasonal ETa and seasonal irrigation amount. The intensity of the first fall freeze might affect the duration and the physiology of the maize plants and impact late season crop evapotranspiration.

Maize seasonal ETa varied with year and ranged from 634.2 to 697.7 mm averaging 665.3 mm by the local Kc curve and, from 687 to 739 mm averaging 718 mm by the non-adjusted FAO Kc values (Table 3). Maize actual evapotranspiration estimation from the adjusted FAO Kc resulted in maize seasonal ETa that varied from 716 to 780 mm and averaged 755 mm (Table 3). ETa estimation using the non-adjusted FAO Kc value showed on average 8% ETa overestimation while the adjusted FAO Kc value contributed to 13% ETa overestimation. These results are in agreement with Barnes [48] who found maize seasonal ETa average of 684 mm with non-adjusted FAO Kc values and 751 mm with adjusted FAO Kc values for Farmington, NM, for the period of 2000–2010. Pablo et al. [49] reported maize seasonal ETa of 685 mm for

subsurface drip-irrigated maize at the same experimental site. Djaman et al. [50] reported maize actual evapotranspiration that varied from 481 to 634 mm for rainfed, different limited irrigation and full irrigation treatment, with the lowest ETa obtained by the rainfed maize. Araya et al. [51] reported maize seasonal ETa as a function of planting date and it varied from 675 to 703 mm for early, from 664 to 702 mm for normal, and from 623 to 675 mm for late planting, respectively, in sandy clay loam soils and from 679 to 709 mm, from 662 to 714 mm, and from 625 to 687 mm in silt loam soils for the respective planting dates. Maize ETa estimation based on crop coefficients as a function of maize thermal unit showed good agreement with the measured crop ETa in northeastern Colorado [50]. Nielsen and Heinkle [52] reported that Kc based on observed growth stage or thermal unit simplifies evapotranspiration prediction and irrigation scheduling because there is no need for adjustment for abnormal weather conditions or planting dates. Allen et al. [17] indicated the usefulness of the dual Kc procedure for ETa estimation for irrigation scheduling at field level and estimation of total water use when impacted by wetting frequency. As much as is practical, crop producers should use crop actual evapotranspiration in place of the reference evapotranspiration for irrigation scheduling in the arid and semiarid regions similar to New Mexico environment [53]. Beutler and Keller [54] had successfully implemented the FAO-56 Penman–Monteith evapotranspiration method to schedule irrigation for a 28,000 ha irrigation project in northern New Mexico after applying local crop growth stages to the Kc data, a user-defined wind limit, incorporating aridity code, adding the FAO-56 suggested climatic correction, and the adjustment of tabulated FAO-56 Kcb coefficients. They reported reduction of error on ETa after these corrections and adjustment from 75 mm (23% ETa) to 10 mm (3% ETa) for the first 80 days. Several studies showed strong relationships between crop yield and crop seasonal ETa [50,51,55,56]. Maize ETa values ranged from 667 to 984 mm under furrow irrigation [57], from 750–973 under sprinkler irrigation [58–60] while it largely varied from 750 to 1200 mm in farmer's fields [61]. Colaizzi et al. [62] reported a subsurface drip-irrigated maize ETa range of 711–818 mm at Bushland, TX and Hao et al. [63] reported maize ETa that varied from 634 to 796 mm. From field studies across Nebraska, fully irrigated maize ETa ranged from 526 mm to 655 mm [50,64–67].
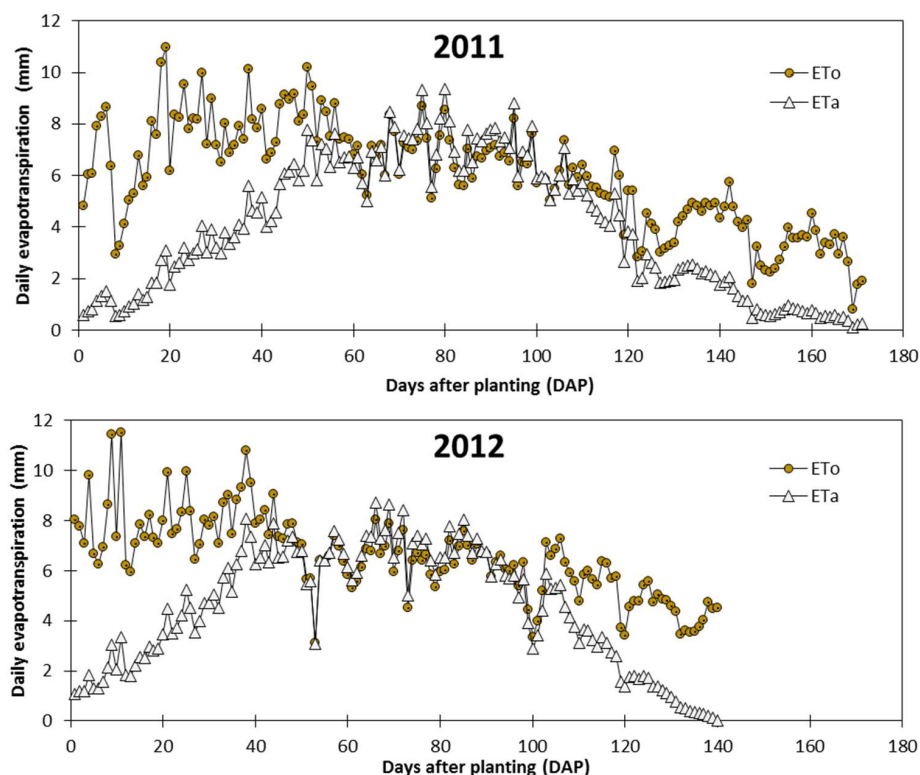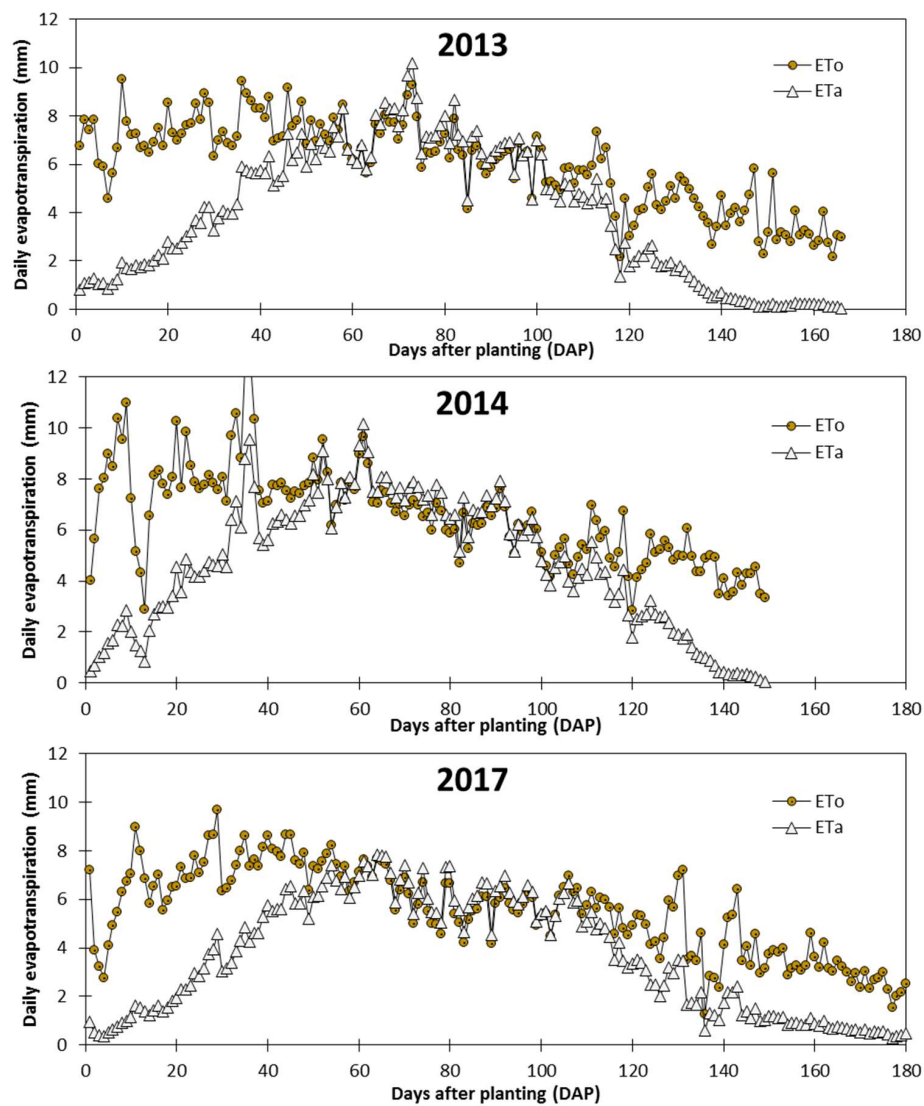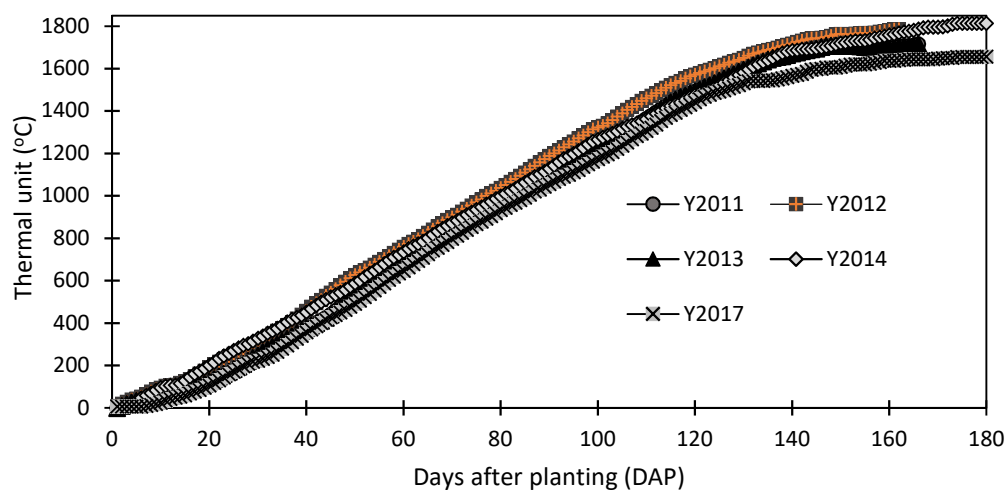

Figure 2. *Cont.*

Figure 2. Trends in the daily reference evapotranspiration and maize actual evapotranspiration during the growing season 2011, 2012, 2013, 2014 and 2017.
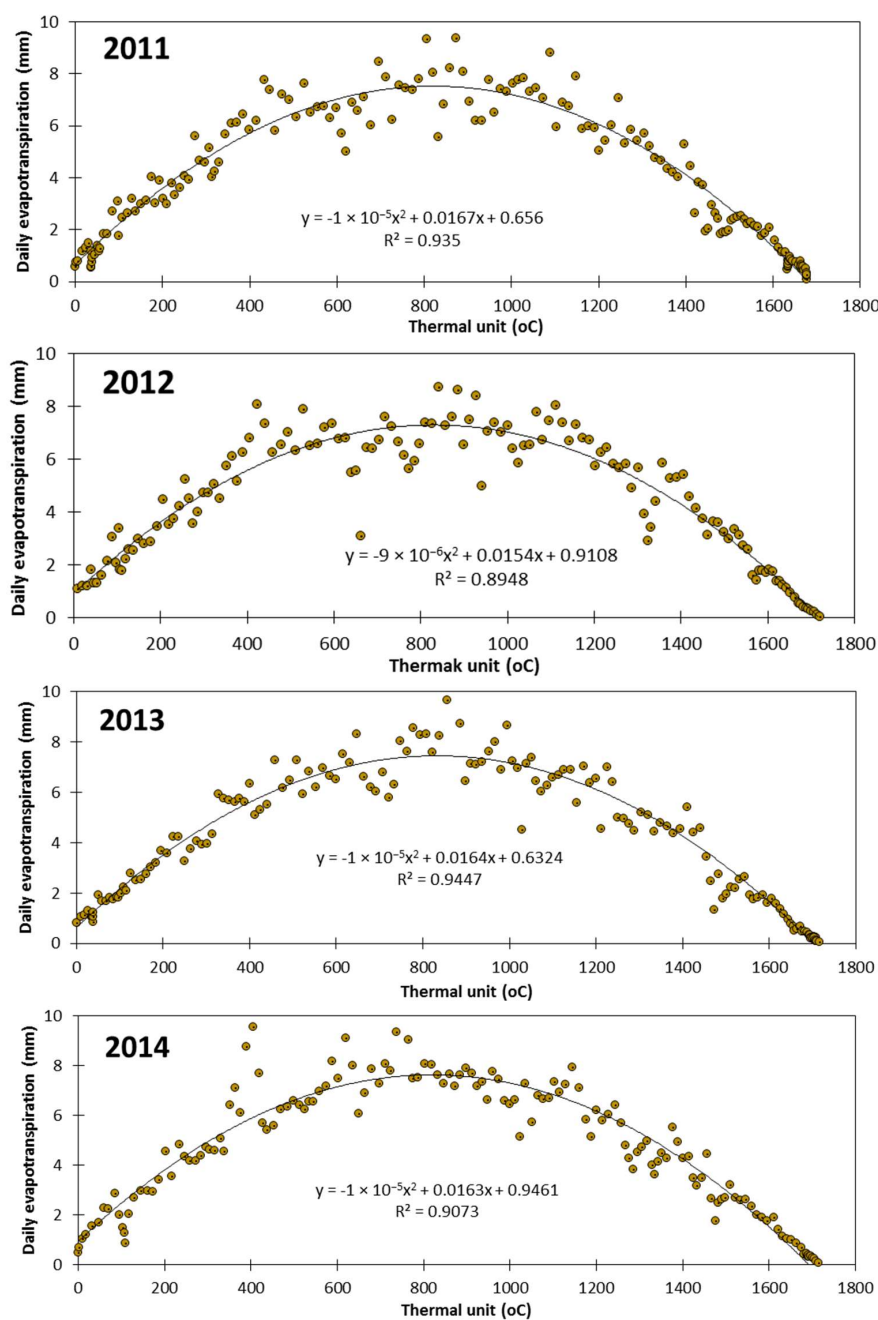

Figure 3. Cumulative thermal units in the 2011, 2012, 2013, 2014 and 2017 growing seasons at the experimental site.
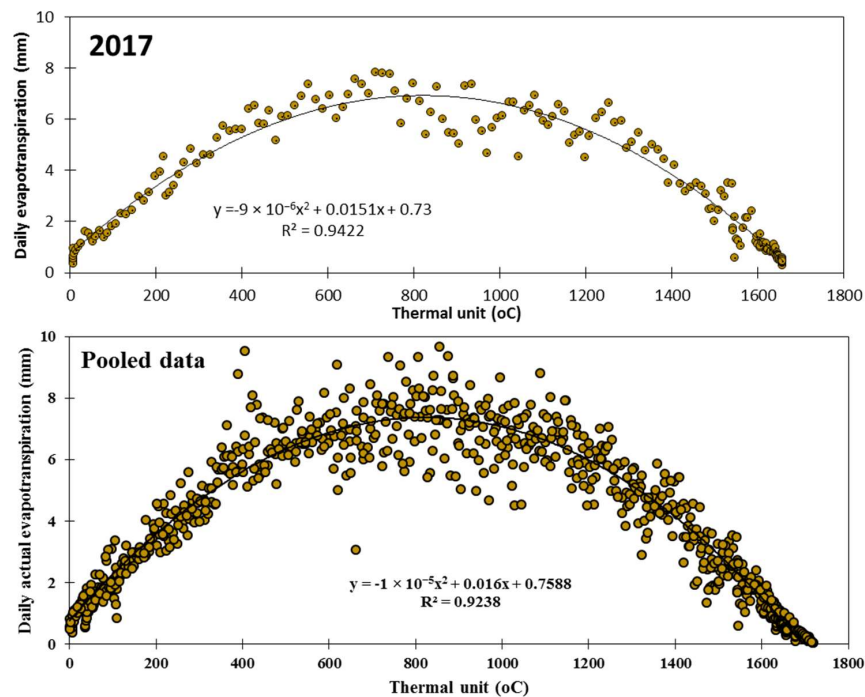
Table 2. Last spring and first fall freeze dates and the frost-free period during the five maize growing seasons, ASC Farmington, NM.

Year	Last Spring	First Fall	Frost Free
	Freeze	Freeze	Period (days)
2011	3-May	3-October	152
2012	16-April	25-October	191
2013	3-May	5-October	154
2014	13-May	3-November	173
2017	19-May	25-September	129

$y = -1 \times 10^{-5}x^2 + 0.0167x + 0.656$
$R^2 = 0.935$

$y = -9 \times 10^{-6}x^2 + 0.0154x + 0.9108$
$R^2 = 0.8948$

$y = -1 \times 10^{-5}x^2 + 0.0164x + 0.6324$
$R^2 = 0.9447$

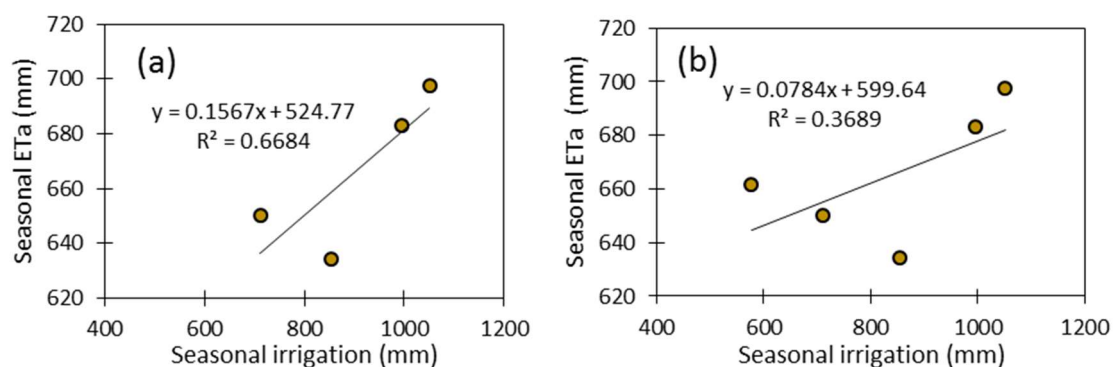$y = -1 \times 10^{-5}x^2 + 0.0163x + 0.9461$
$R^2 = 0.9073$

Figure 4. *Cont.*

Figure 4. Relationship between maize actual evapotranspiration and thermal units during the growing seasons 2011, 2012, 2013, 2014 and 2017 and the five seasons pooled data.

Table 3. Seasonal water supply and crop evapotranspiration during the five growing seasons. [ETa-LKc is ETa estimated using locally developed Kc curve (Equation (2)); ETa-FAO is ETa estimated using adjusted tabulated FAO crop coefficients, irrigation LKc is estimated using ETa-LKc, irrigation FAO is estimated using ETa-FAO].

Year	Irrigation Applied (mm)	Rainfall (mm)	Total Water Supply (mm)	ETa-LKc (mm)	ETa-FAO (mm)	Irrigation LKc Require. (mm)	Irrigation FAO Require. (mm)
2011	996	113	1109	683	780	815	936
2012	853	50	903	634	747	794	934
2013	711	137	848	650	769	758	908
2014	1052	89	1141	698	763	848	930
2017	577	117	693	662	716	786	854
Average	838	101	939	665	755	800	912

Figure 5. Relationship between seasonal maize evapotranspiration and season irrigation amount (**a**) for the 2011, 2012, 2013, 2014 and (**b**) for the 2011, 2012, 2013, 2014 and 2017 seasons.

3.2. Maize Seasonal Irrigation Requirements

The seasonal amount of applied irrigation varied from 576.6 to 1051.6 mm and averaged 837.7 mm (Table 3). Seasonal precipitation varied from 49.5 to 137.2 mm and the total water supply varied from 693.4 to 1140.5 mm. The lowest irrigation amount was applied in 2017 due to the early freeze on September 25. The 2017 had the shorted frost-free period (Table 2). Maize irrigation requirements were estimated to have varied from 758.4 to 848.3 mm and averaged 800.2 mm using the locally developed Kc and varied from 835.5 to 935.6 mm and averaged 912.2 mm using FAO Kc. The net irrigation requirement was 652.1, 634.8, 606.8, 678.6 and 628.6 mm (using local Kc curve) in 2011, 2012, 2013, 2014 and 2017, respectively, and 748.5, 747.5, 726.1, 744.0 and 682.78 mm when adopting the FAO Kc values. Mean net irrigation requirement was 641 mm under the local Kc option and 730 mm under FAO Kc values option. While the net irrigation requirement may not vary from one field to another, the brute irrigation requirement may deeply vary as a function of the irrigation system, water application efficiency of the irrigation system and the management practices of each producer. Fields equipped with surface irrigation system might have high irrigation requirement and the production under subsurface drip irrigation with higher efficiency might have lower brute irrigation requirement for maize production at the study region and other regions with similar climate and management practices [68–70]. Net irrigation water requirement ranged from 671 to 945 mm across the state of Nevada from the Diamond Valley to Lovelock Valley [71]. Long-term net irrigation requirement was 391 mm for irrigated corn in Kansas [72]. Lamm and Trooien [73] indicated that careful management of subsurface drip irrigation (SDI) systems reduced net irrigation needs by nearly 25% while still maintaining top yields. The 25% reduction in net irrigation needs was associated primarily with the reduction of in-season deep percolation, a non-beneficial component of the water balance [74].
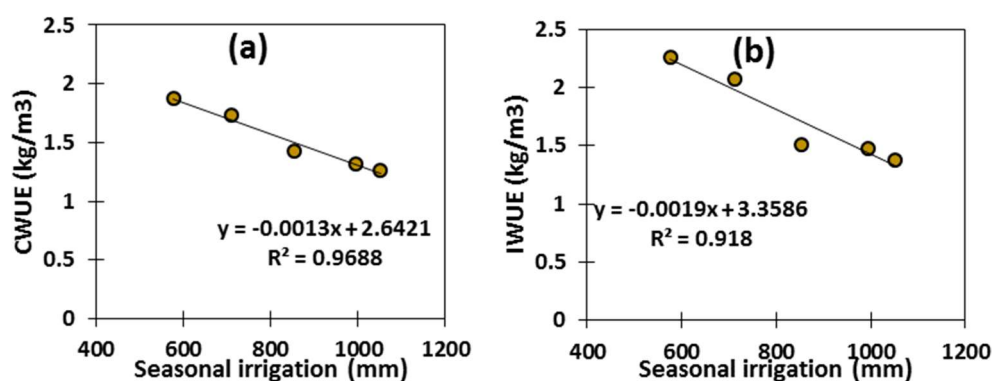
3.3. Maize CWUE, ETWUE, and IWUE

Maize CWUE ranged from 1.3 to 1.9 kg/m^3 and averaged 1.53 kg/m^3. ETWUE values were higher than CWUE and varied from 2.0 to 2.3 kg/m^3, averaging 2.1 kg/m^3. Maize IWUE was varied with years and averaged 1.74 kg/m^3 (Table 4). There were strong relationships between maize CWUE and maize seasonal irrigation amounts IWUE and the seasonal irrigation amounts with R^2 of 0.97 and 0.92, respectively. CWUE and IWUE linearly decreased with increasing irrigation amounts (Figure 6). Maize CWUE increased linearly with maize IWUE with a coefficient of determination R^2 of 0.99 while IWUE showed strong quadratic relationship with ETWUE (R^2 = 0.94) (Figure 7). Inter-annual variability in climatic variables and vapor pressure deficit might have impacted the magnitude of grass reference evapotranspiration and, in turn, maize actual evapotranspiration. Inter-annual variation in the seasonal precipitation and its distribution impacted the seasonal irrigation amount [45,50,64,65]. Variation in seasonal ETa and seasonal irrigation amount and total water supply impacted CWUE, ETWUE, and IWUE. Producing more grain yield with less water should result in improving water productivity under sustainable agriculture. The CWUE values reported in this study are in agreement with the values reported by Pablo et al. [49] who found maize CWUE of 1.24, 1.75 and 2.03 kg/m^3 under drip irrigation at the same site. Subsurface drip-irrigated maize similar findings were reported by Irmak and Djaman [45] who found maize IWUE that varied with planting date and plant density in Nebraska and ranged from 1.20 kg m^{-3} to 5.22 kg/m^3 and the ETWUE varied from 2.27 kg/m^3 to 2.81 kg/m^3 during the 2011 and 2012 growing seasons. Hybrid maize CWUE range of 1.65–1.70 kg/m^3 was reported by Howell et al. [75]. Djaman et al. [50] reported irrigated maize CWUE from 1.89 to 2.50 kg/m^3, IWUE from 1.89 to 5.9 kg/m^3 and ETWUE from 4.65 to 6.73 kg/m^3 in south-central Nebraska. Pejić et al. [76] reported maize ETWUE values that varied from 0.67 to 2.34 kg m/^{3} and Howell et al. [77] reported ETWUE values ranging from 1.79 to 2.38 kg/m^3. Mishra et al. [78] reported maize ETWUE of 1.58 kg/m^3 in India where yield was lower compared to maize yield in the US. Pejić et al. [79] indicated that maize ETWUE is dependent on seasonal precipitation amount and distribution. Howell [44] indicated that the greatest ETWUE values are obtained when less irrigation is applied as complementary to rainfall, implying full use of the applied water and perhaps a tendency
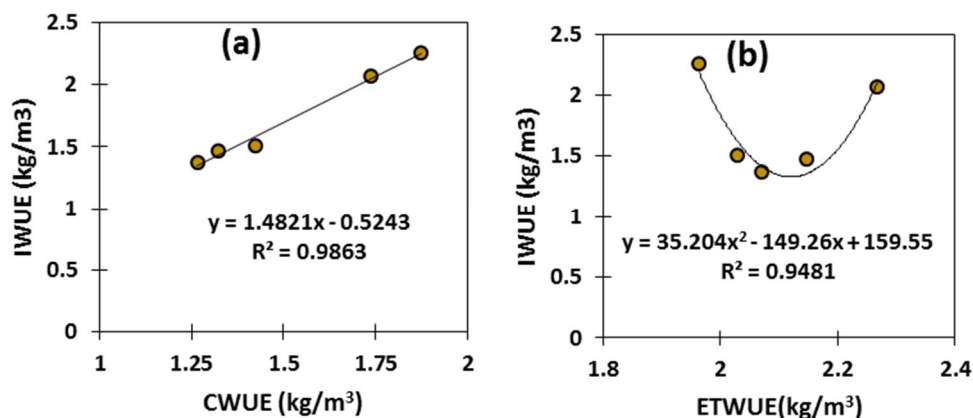
to promote deeper soil water extraction to make better use of both stored soil water and growing season rainfall, which is not the case in northwestern New Mexico where rainfed maize production is not feasible. Irmak [64,65] reported long-term maize ETa values that ranged from 517 to 655 mm, and CWUE ranging from 1.73 to 2.34 kg/m^3 under different irrigation settings in Nebraska. Similarly, Klocke et al. [80] reported CWUE range of 1.35—1.95 kg/m^3 under fully irrigated and limited irrigation treatments in Kansas State. Araya et al. [51] also reported maize CWUE varying from 0.6 to 1.7 kg/m^3 in Kansas. Maize CWUE varied from 1.80 to 2.17 kg/m^3 at Bushland [62], from 1.66 to 2.69 kg/m^3 at Clay Center, Nebraska [81], from 1.58 to 1.75 kg/m^3 at Bushland, Texas [82]. Howell et al. [82] reported greatest CWUE of 1.45 kg/m^3 and the greatest IWUE of 2.36 kg/m^3 obtained under limited irrigation settings. Under water scarcity, crop water productivity could be improved by adopting new irrigation and crop management strategies with limited deficit irrigation while maintaining grain yield. Variability in CWUE, ETWUE, and IWUE is related in the variation in crop ETa, seasonal irrigation, water supply, meteorological conditions and the management practices as they differ in the aforementioned studies. Djaman et al. [50] and Irmak et al. [70] demonstrated 25% of irrigation savings with 75% of the fully irrigation treatment with no yield penalty under subsurface drip and sprinkler irrigation. Also, in northwest New Mexico, where there is not enough precipitation and preplant irrigation is practiced, there is a need to investigate the optimum preplant irrigation for optimizing maize yield and maximizing maize water use efficiency. The decision to apply preplant irrigation should be evaluated and implemented carefully in combination with other agricultural water management technologies and strategies to minimize nonproductive water losses [83–85].

Table 4. Maize average grain yield and crop, evapotranspiration and irrigation water use efficiencies during five growing seasons. CWUE: crop water use efficiency; ETWUE: evapotranspiration water use efficiency; IWUE: irrigation water use efficiency.

Year	Yield	CWUE	ETWUE	IWUE
	(kg/ha)	kg/m^3	kg/m^3	kg/m^3
2011	14,662.11	1.3	2.1	1.5
2012	12,872.41	1.4	2.0	1.5
2013	14,742.07	1.7	2.3	2.1
2014	14,446.58	1.3	2.1	1.4
2017	12,994.00	1.9	1.7	2.3
Average	13,943.43	1.53	2.04	1.74

Figure 6. Relationship between maize seasonal irrigation amount and (**a**) crop water use efficiency and (**b**) irrigation water use efficiency.

Figure 7. Relationship between (**a**) maize crop water use efficiency and irrigation water use efficiency, and (**b**) maize evapotranspiration and maize irrigation water use efficiency.

4. Conclusions

Fully-irrigated maize water use and water productivity were estimated during the 2011, 2012, 2013, 2014 and 2017 growing seasons for Farmington, NM. Seasonal applied irrigation varied from 576.6 to 1051.6 mm and the total water supply varied from 693.4 to 1140.5 mm. Maize seasonal actual evapotranspiration (ETa) varied with year and averaged 665.3 mm by the local Kc curve and 717.8 mm by the non-adjusted FAO Kc values, and 754.9 mm with the adjusted FAO Kc values. Maize irrigation requirements averaged 800.2 mm and 912.2 mm using the locally developed Kc and the FAO Kc, respectively. The net irrigation requirement averaged 641 mm under the local Kc option and 730 mm under FAO Kc values option. There was inter-annual variation in maize CWUE, ETWUE and IWUE. Maize CWUE and IWUE were strongly related to the applied seasonal irrigation amounts with $R^2 \geq 92$. Maize CWUE increased linearly with maize IWUE with a coefficient of determination R^2 of 0.99 while IWUE showed a strong quadratic relationship with ETWUE ($R^2 = 0.94$). The results of this study can be used as a guideline by irrigation designers, agricultural project managers, consultants, university scientists, producers, and other stakeholders for maize water management and for maximizing either CWUE, IWUE or ETWUE under the semiarid conditions in northwestern New Mexico and other locations with similar climate and management conditions. Irrigation requirements for maize in the Four Corners Regions, and particularly on the New Mexico side, should be adjusted to the actual water requirements by using actual and local meteorological data. This approach could optimize maize irrigation requirement under sustainable agriculture in the semiarid climate where water resources are limited. Additional research should be conducted for optimizing maize pre-season irrigation amount and timing to cope with late spring freeze and early fall freeze to maximize maize water productivity.

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