Evapotranspiration and components of corn (Zea mays L.) under microirrigation systems in a semi-arid environment

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Abstract

**Aim of study:** This work summarizes the influence of surface drip irrigation (DI) and subsurface drip irrigation (SDI) systems on corn growth indices and actual evapotranspiration (ET\(_{c-act}\)) and its components of plant transpiration (T\(_p\)) and soil evaporation (E).

**Area of study:** Karaj, Iran

**Material and methods:** The experimental soil was loamy. The corn ET\(_{c-act}\) of each mini-lysimeter was measured based on the water balance method. The E was measured using two mini-lysimeters and T\(_p\) was estimated from the difference between ET\(_{c-act}\) and E.

**Main results:** The resulting data showed that the ET\(_{c-act}\) was lower under SDI (384.8 mm) than under DI (423.4 mm). The K\(_cb-m\) for the corn increased after sowing and peaked during the mid-season stage, with an average value of 0.47, a minimum value of 0.0 and maximum value of 1.52 under DI and 0.53, 0.0 and 1.74 respectively, under SDI. For K\(_e-m\), the average, minimum and maximum values were 0.33, 0.20 and 0.58 under DI and 0.23, 0.15 and 0.46 respectively, under SDI. The biomass yield was much higher under SDI (81.90 ton/ha) than under DI (63.21 ton/ha). Less E and more T\(_p\) occurred under SDI than under DI. SDI achieved superior WUE (8.32 kg/m\(^3\)) compared with DI.

**Research highlights:** SDI was superior to DI based on biomass yield, corn height, stem diameter, and leaf area index which contributed to more favorable soil moisture conditions and low weed incidence; Thus, the SDI system is more productive and would better increase WUE than the DI system.

**Additional keywords:** Zea mays L.; growth indices; lysimeter; LAI; plant transpiration; soil evaporation; water use efficiency

**Abbreviations used:** D (stem diameter); DI (surface drip irrigation); E (soil surface evaporation); ET\(_{c-act}\) (actual crop evapotranspiration); H (plant height); K\(_cb\) (basal crop coefficient); K\(_cb-adj\) (adjusted basal crop coefficient by FAO-56); K\(_cb-m\) (measured basal crop coefficient); K\(_e\) (soil evaporation coefficient); K\(_e-adj\) (adjusted soil evaporation coefficient by FAO-56); K\(_e-m\) (measured evaporation coefficient); LAI (leaf area index); SDI (subsurface drip irrigation); SPAC (soil-plant-atmosphere continuum); T\(_p\) (plant transpiration); WUE (water use efficiency).

**Authors’ contributions:** HD: conceived and designed the experiments, supervised the work, interpreted the data and co-wrote the paper. EK: performed the experiments and drafted the manuscript. SA: substantial contributions to the conception of the work and acquisition, analysis, interpretation of data. All authors approved the final manuscript.

**Citation:** Dehghanisanij, H; Kanani, E; Akhavan, S (2020). Evapotranspiration and components of corn (Zea mays L.) under microirrigation systems in a semi-arid environment. Spanish Journal of Agricultural Research, Volume 18, Issue 2, e1202. https://doi.org/10.5424/sjar/2020182-15647

Received: 25 Aug 2019. Accepted: 09 Jun 2020.

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**Funding agencies/institutions**

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**Introduction**

Corn (Zea mays L.) is a major cereal crop in Iran, ranking third in cultivated area and production after wheat and rice. Since the susceptibility of corn to drought is one of the production challenges in arid and semi-arid regions, providing enough irrigation water for its growth is required. Given the importance of this crop and the decreasing availability of agricultural water resources, increasing water use efficiency (WUE) to produce more crops with the available water is highly important to stable agricultural development. Since water is the most limited resource in arid and semi-arid regions, the agricultural sector should produce more food with less water (Zwart & Bastiaanssen, 2004).
The use of drip irrigation (DI) systems is an effective strategy for increasing water availability in the future (Enciso et al., 2015). The subsurface drip irrigation (SDI) system is the most efficient micro-irrigation methods in arid and semi-arid regions, where the evaporation rate is high during the growing season (Kalfountzos et al., 2007; Sharma et al., 2010). The SDI has greater WUE and saves more water, helping to preserve the nutrients used by crops in comparison to other irrigation methods (Schneider & Howell, 2001; Paul et al., 2013; Panigrahi et al., 2016; Liu et al., 2017; Zhang et al., 2017). The SDI has a larger wetted soil volume than the DI and hence, the volume of available soil for root growth is higher, while the wet radius in the SDI is smaller than that under the DI. In general, under similar irrigation conditions, access to water and nutrients under SDI is increased and root rot and other soil diseases are minimized (Phene & Ruskin, 1995; Kalfountzos et al., 2007).

For the above reason, the SDI has been recommended as a high-efficiency method, reducing water losses through soil surface evaporation and creating more suitable conditions for plant transpiration (Tiwari et al., 2014, Parthasarathi et al., 2017; Reddy et al., 2018). A large number of experiments have been conducted to define the main advantages of SDI for several crops, and its superior performance was confirmed in all of them (Seyfi & Rashidi, 2007; Van Donk et al., 2013; Albasha et al., 2015; Biswas et al., 2015; Lamm, 2016). Thus, the SDI can be an alternative to other irrigation methods and could be used to increase the growth of fruits, vegetables and row crops due to the precise application of water and provision of adequate moisture in the root zone (Intiyaz et al., 2000). Unfortunately, knowledge of irrigation water management at the farm level is poorly developed in Iran and most of the farmers act based on their own experience. Therefore, detailed on-farm information on water and crop could support the design and management of sustainable and beneficial irrigation systems.

The aim of this work was to evaluate the corn growth indices and actual evapotranspiration (ET\textsubscript{act}), i.e., plant transpiration (T\textsubscript{p}) and soil evaporation (E) under DI and SDI systems to understand how the advanced irrigation systems could benefit growers from the point of view of yield and water use.

**Material and methods**

**Experimental site**

The experiments were carried out at the Agricultural Engineering Research Institute (35°46′ N, 50°55′ E, 1260 m a.s.l.) during the 2014 and 2015 growing seasons. The area is semi-arid with an average annual precipitation of approximately 279.3 mm. Daily meteorological data (air temperature, relative humidity, wind speed, rainfall, and solar radiation data) were collected from a synoptic meteorology station, 5 km from the field site. Average daily values of meteorological characteristics are shown in Fig. 1. The minimum air temperature during the 2014 and 2015 corn growing seasons ranged from 5.7 to 23.6°C and 9.5 to 25.5°C, respectively. Also, the average maximum air temperature ranged from 20.8 to 41.4°C and 23.2 to 39.7°C, respectively. The daily relative humidity was 11 to 90% and 15 to 87%, respectively. On average, wind speed and solar radiation were higher in 2014 by about 6.4 and 2.7%, respectively (Fig 1).

The experimental soil was loamy with mean volumetric field capacity and permanent wilting point of 22.3 and 9.63%, respectively; the mean soil bulk density was 1.42 g/cm\(^3\) (Table 1).

To monitor water consumption by corn under DI and SDI, eight mini-lysimeters (Dugas & Bland, 1989; Kong et al., 2012) were placed within a corn farm of 18-ha considering having adequate fetch and filled with soil excavated from the study site to resemble the original soil profile conditions. The mini-lysimeters had a diameter of 40 cm and a depth of 70 cm. Every 6 mini-lysimeters were used as three replicates for DI and SDI, respectively. The DI and SDI were equipped with 40 cm emitter apart and discharge of 4 L/h. For the subsurface drip irrigation, the drip-line was buried 30 cm below the soil surface. Inside each mini-lysimeters, three forage corn (Single Cross 704) seeds were planted with 13 cm spacing on 6th August 2014 and 2015. Water and nutrients were optimally provided for the mini-lysimeters. Each of the treatments received the same amount of water and nutrients through DI or SDI during each growing season. The depth of water applied for each of the two experimental seasons is shown in Fig. 2. Additionally, two unplanted mini-lysimeters were used to measure evaporation from the soil surface under DI and SDI, and were placed near the other mini-lysimeters.

**Irrigation management**

The required irrigation water depth was estimated daily using the FAO-Penman-Monteith model (Allen et al., 1998; Eqs. (1) and (2)) confirmed for the Karaj region by Dehghanisanj et al. (2004) and corn crop coefficient (K\textsubscript{c}) recommended for Karaj by Farshi et al. (1997) according to the following equations:

\[
ET_c = ET_0 \times K_c
\]

\[
ET_0 = \frac{0.408 \Delta (R_n-G) + \gamma [890 (T+273)]U_2 (e_s - e_a)}{\Delta + \gamma (1+0.34U_2)}
\]

where ET\textsubscript{c} is the crop evapotranspiration; ET\textsubscript{0} is the reference evapotranspiration (mm/day); R\textsubscript{n} is the net radiation and \(\Delta = C_P \cdot c_P \cdot (t_2 - t_1)\) is the change in sensible heat capacity.

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Figure 1. Climate variables: daily maximum and minimum temperature, daily relative humidity, daily wind speed and daily solar radiation during 2014 and 2015 corn growing seasons.

Table 1. Soil physical characteristics at the experimental site.

| Soil depth (cm) | BD (g/cm³) | FC (%) | WP (%w) | pH  | EC (dS/m) | Soil texture |
|----------------|------------|--------|---------|-----|-----------|--------------|
| 0-20           | 1.42       | 22.5   | 9.8     | 7.8 | 1.41      | Loam         |
| 20-40          | 1.42       | 22.4   | 9.6     | 7.9 | 1.21      | Loam         |
| 40-60          | 1.42       | 22.1   | 9.5     | 8.14| 2.46      | Loam         |

BD: bulk density. FC: field capacity. WP: permanent wilting. EC: electrical conductivity.

(MJ/m²/day); G is the soil heat flux density (MJ/m²/day); T is the mean temperature (°C); \(U_2\) is the wind speed at 2-m height (m/s); \(\gamma\) is the psychrometric constant (kPa/°C); \(\Delta\) is the slope vapor pressure curve (kPa/°C); \(e_a\) is the actual vapor pressure (kPa); \(e_s\) is the saturation vapor pressure (kPa).

Fertilizers were applied through the irrigation water from the 3 and 4 leafed stage of corn growth to 45 days before harvesting. The corn received 250 kg/ha ammonium phosphate and 200 kg/ha urea.

Measurements

**Actual evapotranspiration (**\(ET_{c-act}\)**)

Daily corn water consumption or actual evapotranspiration (**\(ET_{c-act}\)**) of each mini-lysimeter was measured based on the water balance method using Eq. (3) (Allen *et al.*, 1998):

\[
ET_{c-act} = P + I - D_p - R - \Delta S
\]
where P is the rainfall (mm); I is the irrigation depth (mm); Dp is the water loss through drainage from the mini-lysimeter (mm); R is the runoff (mm) which here was zero and Δs is the change in soil water storage in the mini-lysimeter (mm). The change in soil water storage (Δs) was determined using Eq. (4) (Allen et al., 1998):

\[ \Delta S = S_t - S_{t-1} \]  

where \( S_t \) and \( S_{t-1} \) are the available water in the root zone at the beginning and end of the selected period (mm), respectively.

**Soil surface evaporation (E) and plant transpiration (\( T_p \))**

Evaporation from the soil surface (E) was measured using two mini-lysimeters. When these mini-lysimeters were placed inside the soil, their edges were about one cm above the soil surface, and the soil inside the mini-lysimeter was about 1 to 1.5 cm below the edge. The E was estimated from the difference between the amount of intake and drainage water in the mini-lysimeter at each irrigation interval. Plant transpiration (\( T_p \)) was estimated from the difference between \( \text{ET}_{c-\text{act}} \) and E, by the following equation (Moran et al., 2009):

\[ T_p = \text{ET}_{c-\text{act}} - E \]  

**Basal crop coefficient (\( K_{cb} \)) and soil evaporation coefficient (\( K_e \))**

Crop coefficient can be applied as a single crop coefficient which is influenced by evaporation and transpiration together and dual crop coefficient that is expressed by soil evaporation coefficient (\( K_e \)) and basal crop coefficient (\( K_{cb} \)), separately (Allen et al., 1998). The measured \( K_e \) and \( K_{cb} \) (\( K_{cb-m} \) and \( K_{e-m} \)) are defined using Eqs. (6) and (7) (Majnooni-Heris et al., 2012):

\[ K_{cb-m} = \frac{\text{ET}_{c-\text{act}} - E}{\text{ET}_o} = \frac{T_p}{\text{ET}_o} \]  

\[ K_{e-m} = \frac{E}{\text{ET}_o} \]  

\( K_{cb-m} \) and \( K_{e-m} \) were also compared with estimated values based on FAO-56 (Allen et al., 1998). In this study, the \( K_{cb} \) and \( K_e \) suggested by FAO-56 were adjusted (\( K_{cb-adj} \) and \( K_{e-adj} \)) based on the climatic conditions of the study area.

**Corn growth indices and water use efficiency (WUE)**

Leaf area index (LAI), plant height (H), stem diameter (D) and yield (biomass) were measured during the growing season. LAI was measured with the electronic leaf area-meter, CI–202, seven times during the growing season. WUE (kg/m³) was calculated using Eq. (8) (Sakthivadivel et al., 1999) where yield represents the biomass of corn:

\[ \text{WUE} = \frac{\text{Yield (kg)}}{\text{ET}_{c-\text{act}}(\text{m}^3)} \]  

**Statistical analysis**

Statistical analysis was done to evaluate the influence of different point source irrigation systems on actual evapotranspiration (\( \text{ET}_{c-\text{act}} \)) and growth indices of corn by using the SAS package. LSD (least significant difference)
Results and discussion

Variations in actual evapotranspiration (ET<sub>c-act</sub>), plant transpiration (T<sub>p</sub>) and soil evaporation (E)

The values for ET<sub>c-act</sub> and T<sub>p</sub> of corn and E under DI and SDI during the corn growing season are shown in Fig. 3. The ET<sub>c-act</sub> varied from 2.1 to 9.7 mm/day, depending on the crop growth stage and climatic condition. The daily ET<sub>c-act</sub> and T<sub>p</sub> increased rapidly and peaked 48 days after planting at the mid-season stage with average values of 9.7 and 7.6 mm/day under DI and 9.5 and 8.7 mm/day under SDI. The minimum ET<sub>c-act</sub> values occurred at the initial stage with an average of 2.5 and 2.1 mm/day under DI and SDI. During the first week after planting, the most share of ET<sub>c-act</sub> was E, because the soil was kept wet for corn seed germination. Transpiration increased faster under the SDI than the DI (Fig. 3) because of moisture distribution close to the root mass and better root development under the SDI at the initial stage.

Significantly lower corn ET<sub>c-act</sub> and E values were obtained under the SDI than under DI but for both seasons, the T<sub>p</sub> was higher under SDI than DI (Table 2). The average annual ET<sub>c-act</sub> was 423.49 mm under DI and 384.84 mm under SDI. Similar results have been reported by Chuan-yan & Zhongren (2007), Liu et al. (2017) and Zhang et al. (2017). Evaporation accounted for a small proportion of ET<sub>c-act</sub> and decreased with time and increasing LAI. Transpiration was smaller than E at the initial growth stage (Fig. 3), and the total contribution to ET<sub>c-act</sub> at that stage was from E because more water was lost through soil surface evaporation and the crop canopy was not fully developed yet as reported in Allen et al. (1998) and Valentín et al. (2020). The T<sub>p</sub> increased to a peak at the mid-season stage (Liu et al., 2002; Kang et al., 2003; Majnooni-Heris et al., 2012). During this stage, E was reduced and the reduction was compensated with higher amounts of water for T<sub>p</sub>, coinciding with increasing LAI until the crop achieved near or full ground cover (Table 2).

The average annual T<sub>p</sub> during the two growing seasons was 221.9 and 250.2 mm, and that for E was 198.0 and 157.6 mm under DI and SDI, respectively. Under SDI, the soil surface usually remained drier than under DI. Accordingly, the total T<sub>p</sub> was 53.0 and 64.2% of corn ET<sub>c-act</sub> under DI and SDI. Also, the average annual E was 46.9 and 35.9% of corn ET<sub>c-act</sub> under DI and SDI during two growing seasons (Table 2). At the initial stage during which the portion of the bare or low covered soil surface was high and considering that under DI, moisture accumulation occurred on the soil surface, the DI showed 27.70% more evaporation (82.9 mm) than SDI (64.9 mm).

Relationship between the ratio of plant transpiration (T<sub>p</sub>) and soil evaporation (E) to actual corn evapotranspiration (ET<sub>c-act</sub>) and leaf area index (LAI)

Based on the soil-plant-atmosphere continuum (SPAC), the variations in T<sub>p</sub> and ET<sub>c-act</sub> are affected by meteorological data, soil moisture and plant factors (Zhou et al., 2017). The variations in T<sub>p</sub>/ET<sub>c-act</sub> and LAI for each growing season are presented in Fig. 4. The data indicated that the ratio was controlled by soil surface cover and LAI. The average T<sub>p</sub>/ET<sub>c-act</sub> varied from 0.0 at sowing to 82 and 87% at full growth under DI and SDI. The value of T<sub>p</sub>/ET<sub>c-act</sub> increased faster when LAI was smaller than 3.0. Thus, two polynomial functions were computed to show the relation between the ratio of T<sub>p</sub>/ET<sub>c-act</sub> and E/ET<sub>c-act</sub> with LAI under SDI and DI (Eqs. 8 and 9; Fig. 4), as reported by other authors (e.g., Kang et al., 2003; Majnooni-Heris et al., 2012).

\[
\begin{align*}
\frac{T_p}{ET_{c-act}} & = -10.27 \text{ LAI}^2 + 58.716 \text{ LAI} - 636.58 \quad R^2=0.93 \quad \text{(DI)} \quad (9) \\
\frac{T_p}{ET_{c-act}} & = -5.791 \text{ LAI}^2 + 40.697 \text{ LAI} + 21.087 \quad R^2=0.92 \quad \text{(SDI)} \quad (10)
\end{align*}
\]

It was presumed, as occurred for the T<sub>p</sub>/ET<sub>c-act</sub> ratio, that the E/ET<sub>c-act</sub> was also affected by LAI and surface soil moisture (Liu et al., 2002). Fig. 5 shows the trends in the ratio of E/ET<sub>c-act</sub> with LAI under DI and SDI during the growing seasons. The E/ET<sub>c-act</sub> decreased significantly with increases in LAI. The relationship between LAI and E/ET<sub>c-act</sub> based on the experimental data was calculated as follows:

\[
\begin{align*}
\frac{E}{ET_{c-act}} & = 11.716 \text{ LAI}^2 - 65.137 \text{ LAI} + 105.18 \quad R^2=0.97 \quad \text{(DI)} \quad (11) \\
\frac{E}{ET_{c-act}} & = 5.636 \text{ LAI}^2 - 40.175 \text{ LAI} + 79.887 \quad R^2=0.93 \quad \text{(SDI)} \quad (12)
\end{align*}
\]

From these relationships, the E/ET<sub>c-act</sub> decreased sharply when LAI was at about 3, which was attributed to lower evaporation due to the development of crop canopy (Fig. 5). Under SDI, the soil surface between crops usually remains dry, so that evaporation loss from the soil surface is low but moisture distribution at the root zone is suitable for crop growth. Thus, the SDI can improve water uptake by reducing soil evaporation (Liu et al., 2002).

Variations in basal crop coefficient (K<sub>cb</sub>), soil evaporation (K<sub>e</sub>) and LAI

The mean variations for the two years for K<sub>cb-m</sub> and K<sub>e-adj</sub> compared to K<sub>cb-adj</sub> and K<sub>e-adj</sub> are presented in Fig. 6. The values of K<sub>cb-m</sub> increased from 0.0 to its peak value in the mid-season stage. The average, minimum
and maximum values of $K_{cb-m}$ were 0.47, 0.0 and 1.52 under DI and 0.53, 0.0 and 1.74 under SDI; for $K_{e-m}$ the values were 0.33, 0.20 and 0.58 under DI and 0.23, 0.15 and 0.46 under SDI, respectively. The peak value of $K_{cb-m}$ was observed in the mid-season stage when LAI was maximum.

For the whole growing season, the values of $K_{cb-m}$ were smaller than the adjusted values based on FAO-56.

Figure 3. Variations in actual corn evapotranspiration ($ET_{c-act}$), plant transpiration ($T_p$) and soil evaporation ($E$) during the 2014 and 2015 corn growing seasons.
Evapotranspiration and components of corn (<i>Zea mays</i> L.) under micro irrigation systems

Table 2. The ratio of soil evaporation (E) and plant transpiration (T<sub>p</sub>) to actual corn evapotranspiration (ET<sub>c-act</sub>) under surface drip irrigation (DI) and subsurface drip irrigation (SDI) systems during 2014 and 2015 corn growing seasons.

| Treatment | Stage     | 2014     | 2015     | Mean    |
|-----------|-----------|----------|----------|---------|
|           |           | DI       | SDI      | DI      | SDI      |
| ∑ET<sub>c-act</sub> (mm) | Initial   | 85.6a    | 75.6b    | 95.0a   | 70.7b    | 90.3a   | 73.1b |
|           | Development | 141.2a  | 137.7b  | 164.0a  | 137.1b  | 152.6a  | 137.4b |
|           | Middle    | 153.7a  | 151.5a  | 207.3a  | 196.9b  | 180.5a  | 174.2b |
|           | Sum       | 380.5a  | 364.8b  | 466.3a  | 404.7b  | 423.4a  | 384.7b |
| ∑E (mm)   | Initial   | 79.7a   | 62.8b   | 86.1a   | 67.0b   | 82.9a   | 64.9b |
|           | Development | 64.4a  | 56.4b   | 80.2a   | 60.6b   | 72.3a   | 58.5b |
|           | Middle    | 35.5a   | 32.5a   | 50.0a   | 35.9b   | 42.7a   | 34.2b |
|           | Sum       | 179.6a  | 151.7b  | 216.3a  | 163.5b  | 197.9a  | 157.6b |
| ∑T<sub>p</sub> (mm) | Initial   | 5.8b    | 12.7a   | 7.7b    | 15.3a   | 6.8b    | 14.0a |
|           | Development | 76.8b  | 81.3a   | 81.4b   | 95.9a   | 79.1b   | 88.6a |
|           | Middle    | 118.2a  | 118.9a  | 153.7b  | 176.0a  | 135.9b  | 147.5a |
|           | Sum       | 200.8b  | 212.9a  | 242.8b  | 287.2a  | 221.8b  | 250.1a |
| ∑T<sub>p</sub>/ET<sub>c-act</sub> (%) | Initial   | 6.7b    | 16.7a   | 8.1b    | 21.6a   | 7.5b    | 19.1a |
|           | Development | 54.3b  | 59.0a   | 49.6b   | 69.9a   | 51.8b   | 64.4a |
|           | Middle    | 76.9a   | 78.4a   | 74.1b   | 89.3a   | 75.2b   | 84.6a |
|           | Sum       | 52.7b   | 58.4a   | 52.0b   | 70.9a   | 52.3b   | 65.0a |
| ∑E/ET<sub>c-act</sub> (%) | Initial   | 93.1a   | 83.0b   | 90.6a   | 94.7a   | 91.9a   | 88.7b |
|           | Development | 45.6a  | 40.9b   | 48.9a   | 44.2b   | 47.2a   | 42.5b |
|           | Middle    | 23.0a   | 21.4a   | 24.1a   | 18.2b   | 23.6a   | 19.6b |
|           | Sum       | 47.2a   | 41.5b   | 46.3a   | 40.4b   | 46.7a   | 40.9b |

For each year, means within a column bearing the same letter do not differ significantly at the 0.05 level of probability.

This was attributed to the overestimation of ET<sub>s</sub> by FAO-Penman-Monteith model for this region (Dehghani-sanij et al., 2004).

For the different irrigation systems, the peak values of K<sub>e-m</sub> were obtained under SDI at the mid-season stage, and the K<sub>e-m</sub> under the DI peaked at the initial stage. The K<sub>e-m</sub> decreased with crop development during the growing season due to the increase in the percentage of the shaded area by the plant canopy. Again, Fig. 6 emphasizes that the evaporation from soil surface was higher than the transpiration from the crop at the initial stage and with an increase in plant shading, evaporation was lower than transpiration during crop development and mid-season stages. Moreover, the K<sub>e-m</sub> varied temporally during the
Figure 4. Relationship between the variation in the ratio of plant transpiration (Tp) to actual corn evapotranspiration (ETc-act) and leaf area index (LAI) under surface (DI) and subsurface drip irrigation (SDI) during the 2014 and 2015 corn growing seasons.

corn growing season. Thus, the average Ke-m peaked at the initial stage, and decreased gradually during the growing season, reaching a minimum value at the mid-season stage (Table 3).

The amounts of Kcb-FAO during the initial stage, crop development and mid-season stage of corn growth (Kcb-init, Kcb-dev, and Kcb-mid) were 0.15, 0.15-1.15 and 1.15, respectively (Allen et al., 1998). The values of Kcb-dev and Kcb-mid changed on the basis of plant height, wind speed and relative humidity in different regions. Therefore, the recommended Kcb values were adjusted to 0.15, 0.70, and 1.20 under DI and 0.15, 0.76, and 1.29 under SDI during the initial stage, crop development, and mid-season stages, respectively (Table 3). The maximum value of Kcb-adj was 1.30 under SDI at the mid-season stage, which was attributed to the higher Tp. The Kc-adj varied temporally during the corn growing season. Also, the Kc-adj value was higher at the initial stage and gradually decreased, reaching a minimum value of only 0.14 under SDI at the mid-season stage (Fig. 6).

The Kcb-adj and Kc-adj were higher than Kcb-m and Kc-m during the initial stage and crop development. Whether for DI or SDI, the Kcb-adj values were overestimated when compared to Kcb-m for the whole growing season. Comparisons of Kcb-m and Kc-m vs Kcb-adj, and Kc-adj values are shown in Fig. 7. For both DI and SDI, the relationships between Kcb-m and Kc-m as well as Kcb-adj and Kc-adj were linear linear. The Kcb-adj under DI performed better than that under SDI. The slopes of the linear regression were 0.93 and 0.85 with a coefficients of determination of 0.75 and 0.71 for Kcb-adj under DI and SDI, respectively.

The Kcb-m and Kc-m values were overestimated as compared to Kcb-m and Kc-m during the initial and crop development stages and underestimated during the mid-season stage. Also, Kc-adj under DI provided a better performance than that under SDI. The slopes of the linear regression were 0.67 and 0.67 with a coefficients of determination of 0.25 and 0.19 for Kc-adj under DI and SDI, respectively.

The difference between Kcb-m and Kc-m and adjusted values by FAO-56 clearly emphasizes the difficulty of applying Kcb and Kc values across locations due to varying climatic and agricultural management factors like irrigation method and frequency (Katerji & Rana, 2014).
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Figure 5. Relationship between the variation in the ratio of soil evaporation (E) to actual corn evapotranspiration (ETc-act) and leaf area index (LAI) under surface (DI) and subsurface drip irrigation (SDI) during the 2014 and 2015 corn growing seasons.

As a response to the crop development, the $K_e$ was higher than the $K_{cb}$ at the initial stage, and with an increase in LAI and plant shading, the resulting decreases in soil surface evaporation could be used to estimate the variations in $K_{cb}$ and $K_e$ as functions of LAI (Fig. 8).

Overall, the relationship between LAI and $K_{cb}$ and $K_e$ based on the experimental data was calculated using second-order polynomial equations with high coefficients of determination ($R^2$) as follows:

$$K_{cb-m} = -0.0645LAI^2 + 0.56LAI - 0.1005 \quad R^2=0.93 \text{ (DI)} \quad (13)$$

$$K_{cb-m} = -0.0761LAI^2 + 0.5962LAI + 0.04 \quad R^2=0.94 \text{ (SDI)} \quad (14)$$

$$K_{cb-m} = 0.0494LAI^2 - 0.2661LAI + 0.5308 \quad R^2=0.92 \text{ (DI)} \quad (15)$$

$$K_{cb-m} = 0.0242LAI^2 - 0.1687LAI + 0.3996 \quad R^2=0.91 \text{ (SDI)} \quad (16)$$

The $K_e$ of corn at the mid-season stage was larger because of the large LAI at this stage and consequently, the smaller soil evaporation, compared to plant transpiration. Similar relationships have been reported for bean and canola (De Medeiros et al., 2001; Majnooni-Heris et al., 2012).

Variations in leaf area index (LAI), plant height (H), stem diameter (D), wet and dry mass yield and water use efficiency (WUE)

The variations in mean LAI, H, D, biomass yield and WUE under DI and SDI are presented in Table 4 and Fig. 9. The LAI increased slowly in the initial stages and more rapidly reached its peak at about 3.4 m$^2$/m$^2$ under DI and 4.6 m$^2$/m$^2$ under SDI. Also, the H increased slowly at the initial stages and more rapidly at the mid-season stage, with the tallest plants (229.2 cm) under SDI at the mid-season stage. Moreover, the D also increased during the growing season and peaked during mid-season with values of 3.2 cm under DI and 3.6 cm under SDI. Between the irrigation systems, the lowest values of LAI, H and D occurred under DI (Table 4 and Fig. 9) as reported in Chuanyan & Zhongren (2007).
Table 3. Mean values of measured (m) and adjusted (adj) soil evaporation coefficient ($K_e$) and basal crop coefficient ($K_{cb}$) under surface drip irrigation (DI) and subsurface drip irrigation (SDI) systems during 2014 and 2015 corn growing seasons.

| Treatment | Stage   | 2014         | 2015         | Mean         |
|-----------|---------|--------------|--------------|--------------|
|           |         | DI | SDI | DI | SDI | DI | SDI |
| $K_{cb-m}$ | Initial | 0.03b | 0.07a | 0.04b | 0.09a | 0.04b | 0.08a |
|           | Development | 0.35a | 0.37a | 0.36b | 0.45a | 0.35b | 0.41a |
|           | Middle | 0.82a | 0.83a | 1.08b | 1.25a | 0.95b | 1.04a |
| $K_e-m$   | Initial | 0.37a | 0.29b | 0.43a | 0.31b | 0.40a | 0.30b |
|           | Development | 0.28a | 0.20b | 0.32a | 0.22b | 0.32a | 0.22b |
|           | Middle | 0.23a | 0.15b | 0.028a | 0.18b | 0.028a | 0.18b |
| $K_{cb-adj}$ | Initial | 0.15a | 0.15a | 0.15a | 0.15a | 0.15a | 0.15a |
|           | Development | 0.68a | 0.72b | 0.72b | 0.80a | 0.70b | 0.76a |
|           | Middle | 1.19b | 1.22a | 1.21b | 1.36a | 1.20b | 1.29a |
| $K_{e-adj}$ | Initial | 0.46a | 0.38b | 0.50a | 0.42b | 0.48a | 0.40b |
|           | Development | 0.36a | 0.32b | 0.42a | 0.40b | 0.39a | 0.36b |
|           | Middle | 0.16a | 0.13b | 0.18a | 0.15b | 0.17a | 0.14b |

For each year, means within a column bearing the same letter do not differ significantly at the 0.05 level of probability.

The highest yield (biomass) was 81.90 ton/ha under SDI compared to only 63.21 ton/ha under DI. Also, the WUE (kg/m³) of corn was 8.32 under SDI and 6.67 under DI (Table 4). This better performance under SDI could be explained by the conservation of optimal moisture status in the root zone, which favoured water and nutrient uptake by the crop (Zotarelli et al., 2008; Badr et al., 2010).

In summary, the results of this study showed that the lowest ET$_c$-act for corn occurred under SDI, mainly because of reduced evaporation (E) from the soil surface in comparison to the DI system. Consequently, higher T$_p$ and lower E rates were observed under the SDI system. The T$_p$/ET$_c$-act started from 0 at sowing and peaked at the mid-season stage when the LAI was also at peak levels. The DI and SDI systems had different influences on the LAI of corn during the growing season. A better understanding of these components (T$_p$, E, ET$_c$-act and T$_p$/ET$_c$-act) can provide important insights to water saving under
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\[ y = 0.6706x + 0.1661 \quad R^2 = 0.1936 \]

\[ y = 0.6719x + 0.1032 \quad R^2 = 0.2594 \]

**Figure 7.** Comparison of measured basal crop coefficient \((K_{cb-m})\) vs adjusted basal crop coefficient based on FAO-56 \((K_{cb-adj})\) and measured soil evaporation coefficient \((K_e-m)\) and soil evaporation coefficient by FAO-56 \((K_e-adj)\) (mean of 2014 and 2015).

\[ y = 0.0484x^2 - 0.2661x + 0.5308 \quad R^2 = 0.9202 \]

\[ y = 0.0242x^2 - 0.1687x + 0.3996 \quad R^2 = 0.9187 \]

\[ y = -0.0761x^2 + 0.5962x + 0.04 \quad R^2 = 0.9456 \]

\[ y = -0.0645x^2 + 0.56x - 0.1005 \quad R^2 = 0.9393 \]

**Figure 8.** Relationship between the variation in the measured basal crop coefficient \((K_{cb-m})\), measured soil evaporation \((K_e-m)\) and leaf area index \((LAI)\) (mean of 2014 and 2015).

**Figure 9.** Variations in plant height \((H)\) and stem diameter \((D)\) during the growing seasons (mean of 2014 and 2015).
irrigated corn production. The highest LAI occurred under the SDI system. Overall, the SDI system reduced soil evaporation loss and increased the efficiency of water consumption; it also produced superior biomass yield. Thus, the SDI system is more productive and would better increase WUE than the DI system.

Acknowledgments

The authors wish to render heartfelt gratitude to Egrinya Eneji, Professor of Agronomy & Honourable Commissioner, Ministry of Training and Doctrine, Cross River State, Nigeria, for carefully editing the manuscript linguistically and technically.

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Table 4. Corn yield and growth attributes under surface drip irrigation (DI) and subsurface drip irrigation (SDI) during 2014 and 2015 corn growing seasons.

| Treatment | Stage     | 2014 DI | 2014 SDI | 2015 DI | 2015 SDI | Mean DI | Mean SDI |
|-----------|-----------|---------|---------|---------|---------|---------|---------|
| H (cm)    | Initial   | 26.5b   | 29.8a   | 29.1b   | 33.9a   | 27.8b   | 31.8a   |
|           | Development| 101.6b  | 111.2a  | 108.7b  | 124.7a  | 105.1b  | 117.9a  |
|           | Middle    | 191.3b  | 215.3a  | 199.6b  | 229.2a  | 195.4b  | 222.2a  |
| D (cm)    | Initial   | 1.13a   | 1.10a   | 1.27a   | 1.30a   | 1.20a   | 1.20a   |
|           | Development| 2.33b   | 2.41a   | 2.47b   | 2.99a   | 2.40b   | 2.70a   |
|           | Middle    | 2.83b   | 2.95a   | 3.57b   | 4.25a   | 3.20b   | 3.60a   |
| LAI (m²/m²) | Initial   | 0.17a   | 0.18a   | 0.22a   | 0.23a   | 0.20a   | 0.20a   |
|           | Development| 1.42b   | 1.82a   | 1.58b   | 1.98a   | 1.50b   | 1.90a   |
|           | Middle    | 3.08b   | 4.31a   | 3.72b   | 4.89a   | 3.40b   | 4.60a   |
| Yield (ton/ha) | Total  | 60.18b  | 77.36a  | 66.24b  | 86.44a  | 63.21b  | 81.90a  |
| WUE (kg/m³) | Total    | 6.14b   | 7.96a   | 7.20b   | 8.68a   | 6.67b   | 8.32a   |

H: plant height. D: stem diameter. LAI: leaf area index. Yield (biomass). WUE: water use efficiency. For each year, means within a column bearing the same letter do not differ significantly at the 0.05 level of probability.
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