Using thermal units for crop coefficient estimation and irrigation scheduling improves yield and water productivity of corn (*Zea mays* L.)

by

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<u>Abstract</u>

Estimates of daily crop coefficient (Kc) for corn and irrigation scheduling were performed during 2009 and 2010 by means of two approaches: treatment I, computation of Kc using the FAO method; treatment II, computation of Kc from relative fraction of thermal units. Corn crop water requirements and irrigation gross depth for treatment I were about 25 to 33 % lower than that for treatment II in 2009 and 2010 respectively. However, the performance of the treatment II was better in terms of grain yield which was 9.2 Mg ha^{-1} (in 2009) and 9.4 Mg ha^{-1} (in 2010), about 37 and 29 % higher than that for treatment I. Water productivity was about 10 % higher for treatment II during 2009 and practically the same than that of treatment I for 2010. Due to the year-to-year variability the water productivity was about 25 % (treatment II) and 11 % (treatment I) for 2010 than for 2009. Finally, economic productivity for treatment II was 2162 $ ha^{-1} for both seasons, much higher than that for treatment I, 1575 (in 2009) and 1679 (in 2010) $ ha^{-1}. These results confirm that the use of fraction of thermal units to estimate corn crop coefficient has improved the yield, and the water management of this crop under the conditions of this study. Because of the limitations of the study (only two years and one experimental plot), further evaluations under other conditions (climatic, cultivar, etc.) should be performed.

Keywords: Daily corn crop coefficients, water use productivity, grain yield, economic productivity.

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Introduction

Total irrigated area in Mexico is 6.46 Mha. Corn crop covers 22% of this surface, with an average yield around 7.33 Mg ha^{-1}; nevertheless, yields in Northern and Central Mexico (semi-arid climate) decrease until 5.37 Mg ha^{-1}.. Factors such as crop genetics, soil characteristics, fertilizer application, and water requirements affect corn production. Tyagi et al. (2003) showed yields and quality of maize declining due to inadequate water supply and inappropriate irrigation scheduling. Kiziloglu et al. (2009) indicated that water stress has an important effect on water consumption and yield of maize and reported a positive, strong linear relationship between yield and water use. Improvement of irrigation water management calls for an accurate knowledge of crop water requirements or crop evapotranspiration (ETc).

ETc is generally calculated as the product of a crop coefficient (K_c) and the reference evapotranspiration (ET_o) (Allen et al. 1998). Kc varies along the crop phenological development, i.e. Kc can be plotted as a function of time during the crop season. Different methodologies have been proposed to plot Kc curves. The Food and Agriculture Organization of the United Nations (FAO) proposed defining four phenological stages (initial, development, mid-season and late or final stages), estimating three Kc values (at the initial, Kc_{ini}, mid-season, Kc_{mid}, and late-season, Kc_{end}), and connecting straight line segments through each of the four growth stages (Allen et al. 1998); horizontal lines are drawn through Kc in the initial and mid-season stages, while diagonal lines are drawn from Kc_{ini} to Kc_{mid} within the course of the development stage and from Kc_{mid} to Kc_{end} within the course of the late-season stage.

Applying the approach proposed by Allen et al. (1998) is quite simple. However, the practical definition of the four crop growth stages is quite cumbersome for a great number of crops because these stages are not based on standard phenological stages as used by farmers or technicians. In addition, the approach proposed by Allen et al. (1998) requires the crop growth stages and the general average meteorological conditions be defined in advance at the beginning of the season. Thus, in practice, this leads to the use of a fixed Kc curve along different years particularly for real time scheduling irrigation. Alternative approaches estimate Kc as a continuous function of other parameters easier to determine along the season allowing the Kc curve be modified as a function of the year-to-year variability. Thus, Kc can be computed as a function of days after sowing (Ojeda-Bustamante et al. 2004; Kang et al. 2003; Sepaskhah and Andam 2001) although this approach show limitations for real-time crop water requirements estimation because they do not take into account the environmental variations that occur year by year and the effect of cultural factors on the rate of canopy development (Martínez-Cob 2008). Other authors have proposed obtaining the K_c curve as a function of several other parameters: leaf area index, percent ground cover and cumulative growing degree days (or thermal units, TU). These approaches use variables that are more closely related to crop development and they respond to the year-to-year variability. Temperature variability prevails as one of the most important environmental factors affecting the growth and yield of crops (Yan and Hunt 1999). That variability has a direct and strong influence on crop development (Ritchie and NeSmith 1991). Several previous studies have developed equations to estimate crop coefficients as a function of that variable, either using the absolute values of cumulative thermal units (TU) or using the fraction of thermal units (FTU, i.e the fraction of cumulative TU at a given period to the total seasonal cumulative

TU) (Martínez-Cob 2008; Kang et al. 2003; Grattan et al. 1998; Steele et al. 1996; Nielsen and Hinkle 1996; Amos et al. 1989; Sammis et al. 1985). The use of thermal units is recommended as it can be easily computed from readily available daily air temperature at on-line weather station networks. The use of FTU is preferred over the use of TU as it allows a general application of the crop coefficient curve across cultivars requiring different TU totals from emergence or budbreak to harvest or physiological maturity (Amos et al. 1989). The generalization of these types of equations would require their validation for conditions different from which they were developed. This validation studies should focus on the consequences on crop water management and crop productivity of using those equations for irrigation scheduling as compared to using the standard, worldwide applied procedure proposed by Allen et al. (1998).

A number of researches have evaluated yields for various crops under different experimental irrigation doses expressed as percentages of ETc computed using Kc derivedfrom the FAO or other alternative approaches (Bezerra et al. 2012; Dehghanisanij et al. 2009; Dioudis et al. 2009; Ko and Piccinni 2009; López-Urrea et al. 2009; Vories et al. 2009; Kar et al. 2007; Ojeda-Bustamente et al. 2006). Nevertheless, there is a lack of studies comparing several Kc approaches in terms of seasonal crop water requirements, yields and water productivity.

The objectives of this work were: *1)* to estimate daily corn K_c values from FAO methodology as well as using the equation developed by Martínez-Cob (2008) to estimate the corn K_c curve from the fraction of thermal units equation (FTU_{MC}); *2)* to compare the corn crop water requirements and irrigation doses estimated using both approaches; *3)* to

1   evaluate the consequences of both irrigation approaches on the water use productivity and

2   the corn crop production.

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Material and methods

The experimental work was conducted during the 2009 and 2010 growing seasons at a 5 ha commercial farm located at Chupaderos aquifer, 18 km northeast from city of Zacatecas, Mexico (22° 47′ 46.7′′ N latitude, 102° 25′ 21.8′′ W longitude, altitude 2077 m). The soil at the experimental area is sandy clay loam (texture with 64.04 % sand, 21.96 % clay, and 14 % silt) with 3.2 % organic matter content, field capacity of 0.36 m^3 m^{-3} % and permanent wilting point of 0.18 m^3 m^{-3}. The climate is semiarid with minimum and maximum mean monthly temperatures of 6.7 °C (December and January) and 27.3 °C (May), respectively. Average annual precipitation is about 525 mm of which 80% occurs from June through September.

Two treatments were established: a) treatment I: irrigation scheduling using the crop coefficients estimated applying the FAO methodology adapted to the local conditions; b) treatment II: irrigation scheduling using the crop coefficients estimated from the equation developed by Martínez-Cob (2008). An experimental plot of 1 ha (50 m x 200 m) was established within the abovementioned commercial plot. This plot was divided in two subplots (50 m x 100 m), one for each treatment. Each subplot had three replications, 16.5 m x 100 m (about 22 rows within each replicate). At the end of the season, an area of 7.5 m x 7.0 m, at the middle 10 rows of each replication, was sampled for yield determination. The experimental plot was sown with corn (H-311 hybrid) on April 13 (2009) and April 3 (2010); harvesting dates were September 9 (2009) and August 30 (2010). Distance between rows was 0.75 m and average seedling density was about 75,000 plants ha^{-1}. The hybrid H-311 was obtained by the National Research Institute for Forestry, Agriculture and Livestock of Mexico (INIFAP) as a cultivar suited for irrigated land in Mexico. It has been

proved for several years under different experimental and practical conditions showing

yield of grain that ranged between 6 to 10 Mg ha^{-1} (Mojarro et al. 2012). Following INIFAP

recommendations, a fertilizer dose of 200-80-00 (N-P-K) was applied for both years.

An automated weather station (Vantage Pro2 Davis Instruments) located 280 m south of

the experimental field was used to measure daily rainfall, daily average wind speed at 2 m

above ground, daily average relative humidity, daily minimum and maximum air

temperature, and daily total solar radiation. These data were used to estimate ET_o by the

FAO Penman-Monteith method (Allen et al. 1998).

For each replication and treatment, the water productivity was obtained by dividing the

corresponding grain yield by the volume of irrigation water applied (IGD), and the

economic productivity was estimated as the product of grain yield and market price of

corn; according to the Ministry of Agriculture, Livestock, Rural Development, Fisheries

and Food of the Mexican government the annual average price of corn for 2009 and 2010

was 235 $ Mg-1, and 230 $ Mg-1, respectively. An analysis of variance (ANOVA) (single

factor) was conducted using the MSExcel 2007 program, and the significance of the

differences between treatments for grain yield, water productivity and economic

productivity were tested.

Corn crop coefficients

From 2005 to 2008, Mojarro et al. (2008) performed a study to estimate crop coefficients

following the FAO methodology adapted to the local conditions of the Calera aquifer of

the State of Zacatecas (Mexico). This aquifer is placed 45 km from commercial farm used in

this experiment. The Kc curves and length of stages recommended by these authors for

corn crop were used in this work to estimate the Kc values for treatment I (Kc_{FAO},). The Kc

1   values for initial season, mid-season and late season were $Kc_{ini}=0.35$, $Kc_{mid}=1.22$, and

2    $Kc_{end}=0.62$, with lengths of 45 days for initial stage, 30 days for development stage, 45 days

3   for mid-season stage, and 30 days for late stage. The same curve was used for both

4   seasons.

5   On the other hand, Martínez-Cob (2008) developed a corn crop coefficient curve as a

6   function of fraction of thermal units (FTU) under the semiarid climatic conditions of

7   Aragón (Spain). That equation was validated for the climatic conditions and cultivar used

8   in that study but it should be validated for different conditions and cultivars. Climate

9   conditions in Aragón (Spain) are different than those in Zacatecas (Mexico), with hotter

10   and drier summer when most of the corn development occurs. Thus treatment II used Kc

11   values estimated using the following equation developed by Martínez-Cob (2008):

$$Kc_{FTU\_i} = -3.4245 FTU_i^3 + 1.045 FTU_i^2 + 2.4973 FTU_i + 0.2389 \qquad [1]$$

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13   where Kc_{FTU_i} is the crop coefficient value for day i and FTU_i is the fraction thermal unit

14   for day i calculated as:

$$FTU_i = \frac{TU_i}{TTU} \qquad [2]$$

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16   where TTU is the total cumulative thermal units (°C) and TU_i is the cumulative thermal

17   units for day i (°C); its values were computed as (Ritchie and NeSmith 1991):

$$TU_i = TU_{i-1} + (T_a - T_b)_i \quad if \ T_a > T_b$$

18   $$\qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad [3]$$

$$TU_i = TU_{i-1} \qquad \qquad if \ T_a \leq T_b$$

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1 where TU_{i-1} is the cumulative thermal units for day *i-1* (°C), T_a is the average

2 temperature for day *i* (°C) and T_b is the basal temperature (°C). Basal temperature was

3 assumed as 9 °C (Ruiz-Corral et al. 2002) in this experiment.

4 Application of Eq. (1) requires a priori knowledge of the value of TTU adequate for the

5 cultivar and conditions under study. In this study, that value was not known at the onset

6 of the 2009 season. Thus *TTU* for 2009 corn season was considered as the average of *TTU*

7 computed for 2005-2008, between April 13 and September 9, the season length (150 days)

8 determined by Mojarro et al. (2008) as typical for corn in the area to apply the FAO

9 methodology. The average of these four values was 1661 °C (coefficient of variation, 3%).

10 Temperature data for this period was taken from a weather station monitored by INIFAP

11 located around 15 km (22° 45′ 26.1″ N latitude, 102° 30′ 36.0″ W longitude, altitude 2289

12 m) from the site of the experiment. Because an automatic weather station was available

13 next to the experimental plot during 2009, a TTU value was computed using the

14 temperature data registered at that station. Thus a value of 1768 °C was obtained and used

15 for the 2010 season for treatment II. Considering that the abovementioned coefficient of

16 variation was 3 %, this TTU value of 1768 °C was within the confidence interval (P = 0.05)

17 of the average TTU value of 1661 °C.

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19 **Net corn crop water requirements and irrigation scheduling**

20 During 2009, furrow irrigation was applied. A solid-set sprinkler irrigation system was

21 installed during that season and it became on operation for the 2010 season. Net corn crop

22 water requirements for both treatments were computed as follows:

$$CWR_s = ETc_s - PEF_s \qquad [4]$$

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1 where CWR_s (mm) is the water required by corn crop to compensate the loss of water as

2 evapotranspiration. ETc_s (mm) is the crop evapotranspiration (Eq. 5) and PEF_s (mm) is

3 the effective precipitation (Eq. 6). Due to the different irrigation systems, Eq. (4) during

4 2009 was applied for periods of varying length, ranging from 10 to 25 days, while during

5 2010 was applied on a weekly basis. ETc_s and PEF_s were estimated as follows:

6 $$ETc_s = \sum_{i=t}^{T_s} Kc_i \, ET_{o\_i}$$ [5]

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8 where ET_{o_i} (mm) is the reference evapotranspiration for day i; Kc_i is the crop coefficient

9 for day i (either treatment I or treatment II); t and T_s are the first and last day of the

10 considered period.

$$PEF_s = 0.75 \, P_s \quad if \ P_s > 0.2 \, ET_{o\_s}$$

11 [6]

$$PEF_s = 0.00 \quad if \ P_s \leq 0.2 \, ET_{o\_s}$$

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13 where P_s (mm) and ET_{o_s} (mm) are the precipitation and reference evapotranspiration,

14 respectively, for the considered period.

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16 Irrigation gross depth (mm) was calculated as follows
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$$IGD = \frac{CWR_s}{E_a}$$ [7]

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19 where E_a is the application efficiency.

20 For the 2009 season, an application efficiency of 70 % was assumed for the furrow

21 irrigation system used. This assumption was based on previously experimentation years

22 on the studied commercial field where soil physics and irrigation phases for a chili

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1 (*Capsicum annuum* L.) crop were characterized as well as E_a was estimated using the

2 definition of Howell (2003) for application efficiency as the relation between irrigation

3 needed by the crop and water delivered to the field. Six inches gated pipe was used for the

4 application of irrigation water in furrows. The time consumed in each surface irrigation

5 event was calculated as:

$$T_r = \frac{V_a}{Q_g}$$ [8]

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7 where V_a is the volume applied in each irrigation event (m³), calculated as the product of

8 irrigation gross depth (m), furrow length (in this study, 100 m) and distance between

9 furrows (in this study, 0.75 m). Q_g is the water discharged by the gated pipe in each

10 furrow (m³ h⁻¹); and T_r is the inflow time (h).

11 For the 2010 season, irrigation water was applied by a solid-set sprinkler irrigation system

12 with spacing between sprinklers of 12 m in rectangular arrangement; sprinklers model

13 WR-33 equipped with two nozzles (3.97 mm and 3.18 mm) manufactured by Waderain

14 Inc. (Portland, Oregon, USA) were used in the experiment. The system was operating at

15 200 kPa of hydraulic pressure. For this pressure and the rectangular framework used,

16 three preliminary experimental tests were performed to determine the coefficient of

17 uniformity (CU) (Christiansen, 1942) of the water application under different wind

18 conditions (0.6, 1.2, 2.1 and 3.9 m s⁻¹) following the criteria outlined by Merriam and Keller

19 (1978). Average CU values of 93 %, 91 %, 83 %, and 76 % were obtained for the wind

20 speeds tested (0.6, 1.2, 2.1 and 3.9 m s⁻¹, respectively). An application efficiency of 85% for

21 wind speeds lower than 2.0 m s⁻¹ was claimed by the sprinkler nozzle producer. Recorded

1   average wind speeds during the irrigation events rarely exceeded that threshold value.

2   The duration of each solid-set sprinkler irrigation event was estimated as:

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$$T_s = \frac{10\,A\,IGD}{Q}$$

[9]

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5   where T_s is the total operating hours of the sprinkler system (h), A is the irrigated area

6   (0.5 ha for each experimental plot), 10 is a constant for units transformation, IGD is the

7   irrigation gross depth between two irrigation events (mm), and Q is the discharge by the

8   sprinkler (m³ h⁻¹). According to the Waderain Product Catalog, the discharge for WR-33

9   sprinkler is around 1.20 m³ h⁻¹ for double nozzle operating at 200 kPa. Solid-set sprinkler

10   irrigation events were set for night time periods.

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Results and discussion

The meteorological conditions for the 2009 and 2010 corn seasons (13 April to 9 September in 2009, and 3 April to 30 August in 2010) are presented in Figure 1. Air temperature averages were 19.6 °C for 2009 and 19.2 °C for 2010 respectively; minimum and maximum air temperature values were 17.6 °C and 22.9 °C for 2009, and 17.2 °C and 22.9 °C for 2010. Vapor pressure deficit (VPD) ranged between 0.38 to 1.98 kPa for 2009, and 0.33 to 1.80 kPa for 2010; averages values were 1.11 kPa and 1.05 kPa, respectively. Wind speed was higher for 2010 than 2009; mean daily values were rarely above 2 m s^{-1} although maximum gusts of 4.9 m s^{-1} (in 2009) and 6.1 m s^{-1} (in 2010) were reached; seasonal average wind speed was 0.8 m s^{-1} for 2009, and 1.1 m s^{-1} for 2010. In accordance with these differences in the meteorological conditions, there also were some differences between the corresponding estimates of ET_o (Figure 1). The ET_o ranged between 3.6 to 7.3 mm day^{-1} for 2009, and 2.6 to 7.2 mm day^{-1} for 2010; the average ET_o values were 4.8 mm day^{-1} for 2009 and 4.7 mm day^{-1} for 2010. The main difference in ET_o between both seasons was observed during July and August when ET_o rates for 2010 were much lower. This difference was mainly due to the lower VPD values observed for 2010 (Figure 1). The decrease in ETo and VPD observed for the summer period for both years was due to higher precipitation amounts recorded during this period. Precipitation in summer is relatively high at the study area, leading to slightly lower temperatures and a reduction of the dryness of the air.

The crop coefficient curves used to estimate crop water requirements for both treatments are plotted in Figure 2. The Kc_{FTU} values estimated from Equation 1 led to different curves for both corn seasons due to the different values of total cumulative thermal units (TTU). The value of TTU used for 2009 was 6.1 % lower than that for 2010 resulting in smaller

1   values of crop coefficients at the end of the 2009 season. In addition, the 2010 season was

2   slightly cooler than the 2009 season, particularly in the second-half of the season (Fig. 1).

3   This situation led to a Kc_{TTU} curve for 2010 slightly longer than that for 2009. Seasonal

4   average Kc_{FTU} was about 7.1 % greater for 2010 (0.91 for 2009, and 0.98 for 2010), while

5   seasonal Kc_{FAO} was 0.81 for both seasons. Figure 2 shows that the Kc_{FTU} values were

6   greater for 2009 than those for 2010 when the Kc curve was rising (from beginning of crop

7   season to maximum Kc); the opposite occurred when the Kc curve was declining (from

8   maximum Kc to end of crop season). The equation (1) implies that a maximum value of

9   Kc_{FTU} = 1.37 will be reached when FTU = 0.625. In this work this occurred 84 and 88 days

10 after sowing for 2009 and 2010, respectively. Differences between Kc_{FTU} (2009 and 2010)

11 and Kc_{FAO} occurred mainly during the initial and development stages. This difference also

12 shows the importance of using local, real-time meteorological data for scheduling

13 irrigation. Thus the Kc_{FAO} values used in this study were obtained at a location (Calera

14 Aquifer) with an average air temperature (18.2 °C for the period 2005 to 2008) lower than

15 that in the commercial plot where this study was performed (19.6 °C and 19.2 °C in 2009

16 and 2010). This lower temperature at the Calera Aquifer led to a longer initial and

17 development stages when using the Kc_{FAO} curve as compared to the Kc_{FTU} curve.

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19 **Corn crop water requirements and irrigation scheduling**

20 Figure 3 shows 10-day values of estimated effective precipitation. The total effective

21 precipitation during 2009 (148 mm) was about 35% higher than that for 2010 (96 mm). A

22 great proportion of the effective precipitation occurred during the period June 21 to June

23 30 for both years: 34 % for 2009, and 26 % for 2010. Most of the remaining seasonal

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1   effective precipitation occurred during the last third of the corn season: 45 % for 2009 and

2   68 % for 2010.

3   The values of the net crop water requirements (CWR_s, Eq. 4) estimated for each irrigation

4   event during each year of experimentation are presented on Figure 4. The number of

5   irrigation events was 8 for 2009 and 16 for 2010 because of the different irrigation system

6   used during those two seasons, furrow irrigation and solid-set sprinkler irrigation,

7   respectively. Subsequently, the average values of CWR_s per irrigation event were higher

8   for 2009, 53 mm (ranging from 25 to 79 mm) for treatment I (Kc_{FAO}), and 76 mm (ranging

9   from 40 to 131 mm) for treatment II (Kc_{FTU}). The corresponding average values of CWR_s

10   for 2010 were 28 mm (ranging from 12 to 59 mm) for treatment I, and 37 mm (ranging

11   from 13 to 69 mm) for treatment II.

12   Figure 4 shows that the values of CWR_s for both treatments were relatively similar for the

13   second half of the crop season, while CWR_s for treatment II was much higher during the

14   first half of the crop season. This was the consequence of the different crop coefficient

15   curves for both treatments (Fig. 3). The Kc curve for treatment I (Kc_{FAO}) was shifted with

16   respect to the curve for treatment II (Kc_{FTU}) and the peak values for treatment I were

17   delayed with respect to those for treatment II. The Kc_{FAO} curve was applied using

18   information from previous works (Mojarro et al., 2008) and it may not completely

19   correspond to the current phenological development for the particular cultivar and

20   climatic conditions of this study. Martínez-Cob (2008) used the current phenological

21   development and climatic conditions of the particular cultivar used in his study, obtaining

22   a better similarity between the Kc_{FAO} and the Kc_{FTU} curves and a moderately higher

23   estimated CWR_s values for the FAO approach. In accordance with the abovementioned

24   results, the total irrigation gross depth (IGD, Eq. 7) applied was also higher for 2009 than

1   for 2010: 610 mm (treatment I) and 762 mm (treatment II) for 2009, and 527 mm (treatment

2   I) and 701 mm (treatment II) for 2010 (Table 1). Thus, IGD for 2009 was about 16 % higher

3   than that for 2010 for treatment I, and about 8 % higher for treatment II.

4   Table 2 shows the grain corn yield, the water productivity and the economic productivity

5   for the two treatments for both seasons. The grain yield was significantly ($P < 0.05$) higher

6   for treatment II than for treatment I for both years, about 37.5 % for 2009 and 28.8 % for

7   2010; agreeing with results obtained by previous researches (Ko and Piccinni 2009; Voires

8   et al. 2009; Payero et al. 2006) about yield increase with irrigation to the extent that crop

9   evapotranspiration is satisfied. For all cases, these grain yields exceeded the average yield

10   for the semi-arid climatic conditions of the state of Zacatecas (5.37 Mg ha^{-1}). The higher

11   yields obtained for treatment II indicate that actual crop evapotranspiration (consumptive

12   water use) was higher for that treatment as there is a strong positive relationship between

13   grain yield and evapotranspiration (Howell, 1990). In other words, treatment I led to an

14   underestimation of actual crop water requirements (and gross irrigation needs). Thus

15   these were not adequately met and the crop suffered water stress leading to lower grain

16   yields. Treatment II was able to meet more adequately those crop water requirements and

17   therefore grain yield was higher. This study used a Kc_{FAO} curve described in the literature

18   (Mojarro et al., 2008) and therefore may not be adequately adjusted according to the

19   particular conditions (climatic and cultivar) of the experimental seasons. Martínez-Cob

20   (2008) used current phenological development and climatic conditions when estimating

21   the Kc_{FAO} curve (after the end of the season) to be compared to the Kc_{FTU} curve. For this

22   reason, the computed ET values with these two approaches by Martínez-Cob (2008)

23   showed a much lower difference (about 8 %) among them. This reflects the importance of

24   using crop coefficient curves that match more closely the particular conditions of each

season. For irrigation scheduling, the need for a previous knowledge of phenological development implicit in the FAO approach as described by Allen et al. (1998) imposes an important limitation for an accurate estimation of current crop water requirements. Use of variables such as the FTU, which can be easily obtained as the season progresses, can improve those estimations leading to higher grain yields.

On the other hand, during 2009, the average water productivity for treatment I was lower, 1.10 kg m^{-3} than that for treatment II, 1.21 kg m^{-3}; nevertheless, in 2010, this indicator for treatment I was slightly higher, 1.38 kg m^{-3} than that for treatment II, 1.34 kg m^{-3} (Table 2). These differences were not significant (P>0.05). Kiziloglu et al. (2009) reported water productivity for corn crop of 1.48 kg m^{-3} and 1.53 kg m^{-3} using irrigation doses of 352.8 mm (the water needed to satisfy 100 % of actual crop evapotranspiration), and 282.2 mm (irrigation water applied just to satisfy the 80 % of full irrigation) respectively. In addition, the economic productivity was also significantly higher (P<0.05) for treatment II, 2162 $ ha^{-1} (during 2009 and 2010), than that for treatment I, 1575 $ ha^{-1} (during 2009) and 1679 $ ha^{-1} (during 2010). Table 2 also shows that the differences between years for treatment I, in terms of water and economic productivity, were about 25 % and 7 % respectively while for treatment II water productivity increased by about 11 % from 2009 to 2010; nevertheless economic productivity remains equal. Comparing these same indicators but between treatments results that water productivity was about 10 % higher for treatment II during 2009 and 3% lower during 2010 than that of treatment I while economic productivity in both years was higher for treatment II than that of treatment I (37 % and 29 % respectively). Therefore, the use of the FTU to estimate crop water requirements have led to higher corn yields and lower year-to-year variability in terms of water and economic

1   productivity. Of course, two years of study is not too much and a longer and more

2   detailed analysis should be performed.

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Conclusions

Two irrigation scheduling treatments were evaluated during two corn crop seasons, 2009 and 2010: treatment I, using Kc values computed using the FAO methodology; and treatment II, using Kc values computed using an equation developed by Martínez-Cob (2008) to estimate them from fraction of thermal units. Corn crop water requirements and irrigation doses were estimated for the two treatments as well as water use productivity and corn crop production. Total net crop water requirements estimated for each irrigation event were 427 mm (2009), and 448 mm (2010) for treatment I; and 533 mm (2009), and 596 mm (2010) for treatment II. Nevertheless, the use of fraction of thermal units to estimate corn crop coefficients provided better results against FAO methodology in terms of corn production. Thus, grain yield was higher for treatment II than for treatment I for both years, about 37.5 % for 2009 and 28.8 % for 2010. In addition, the economic productivity was higher for treatment II, 2162 $ ha^{-1} (during 2009 and 2010), than that for treatment I, 1575 $ ha^{-1} (during 2009) and 1679 $ ha^{-1} (during 2010). On the other hand, water productivity was 10 % lower for treatment I than for treatment II for 2009, but in 2010 was 3 % higher for treatment I than for treatment II.

These results confirm that the use of fraction of thermal units to estimate corn crop coefficient has improved the yield, and the water management of this crop under the conditions of this study. This improvement seemed to be somewhat higher when using furrow irrigation system as compared to sprinkler irrigation. Because of the limitations of the study (only two years and one experimental plot), further evaluations under other conditions should be performed.

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11   plants using only the cardinal temperatures". Annals of Botany, 84:607-614.

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List of Tables

Table 1. *Crop water requirements (CWR), irrigation gross depth applied (IGD), and effective precipitation (PEF) values for 2009 and 2010 corn seasons. Treatment I, scheduling irrigation using a crop coefficient computed following Allen et al. (1998); treatment II, scheduling irrigation using a crop coefficient computed following Martínez-Cob (2008).*

Table 2. *Performance indicators for 2009 and 2010 corn seasons. Treatment I, scheduling irrigation using a crop coefficient computed following Allen et al. (1998); treatment II, scheduling irrigation using a crop coefficient computed following Martínez-Cob (2008).*

List of Figures

Figure 1. *10-day averages of the daily mean meteorological conditions recorded at the nearby station during the 2009 and 2010 corn seasons. Daily vapor pressure deficit (VPD) and reference evapotranspiration computed following Allen et al. (1998).*

Figure 2. *Crop coefficient curves used to estimate crop water requirements for: treatment I, using a crop coefficient (Kc) curve computed following Allen et al. (1998) (FAO); and treatment II, using a Kc curve computed following Martínez-Cob (2008) (FTU).*

Figure 3. *Cumulative effective precipitation for 10-day periods occurred during the 2009 and 2010 corn seasons.*

Figure 4. *Net corn crop water requirements for: treatment I, crop coefficient computed following Allen et al. (1998) (FAO); and treatment II, crop coefficient computed following Martínez-Cob (2008) (FTU), during two seasons: 2009 and 2010.*

Table 1

1 Table 1. *Crop water requirements (CWR), irrigation gross depth applied (IGD), and effective precipitation (PEF) values for 2009 and 2010 corn*

2 *seasons. Treatment I, scheduling irrigation using a crop coefficient computed following Allen et al. (1998); treatment II, scheduling irrigation*

3 *using a crop coefficient computed following Martínez-Cob (2008)*

4

5

Year	CWRs (mm)		IGD (mm)		PEFs (mm)
	I	II	I	II	
2009	427.1	533.3	610.1	761.8	148.1
2010	448.1	596.0	527.1	701.2	96.0

6

Table 2

1   Table 2. *Performance indicators for 2009 and 2010 corn seasons. Treatment I, scheduling irrigation using a crop coefficient computed following*

2   *Allen et al. (1998); treatment II, scheduling irrigation using a crop coefficient computed following Martínez-Cob (2008)*

3

Year	Grain yield‡ (Mg ha^{-1})		Water productivity‡ (Kg m^{-3})		Economic productivity‡ ($ ha^{-1})	
	I	II	I	II	I	II
2009	6.70[a]	9.20[b]	1.10[a]	1.21[a]	1575[a]	2162[b]
2010	7.30[a]	9.40[b]	1.38[a]	1.34[a]	1679[a]	2162[b]

4
5   ‡ Different letters indicate that the treatments were significantly different and same letters indicate that the treatments were not

6   significantly different (P<0.05).

7

Figure 1

Figure 1. *10-day averages of the daily mean meteorological conditions recorded at the nearby station during the 2009 and 2010 corn seasons. Daily vapor pressure deficit (VPD) and reference evapotranspiration computed following Allen et al. (1998).*
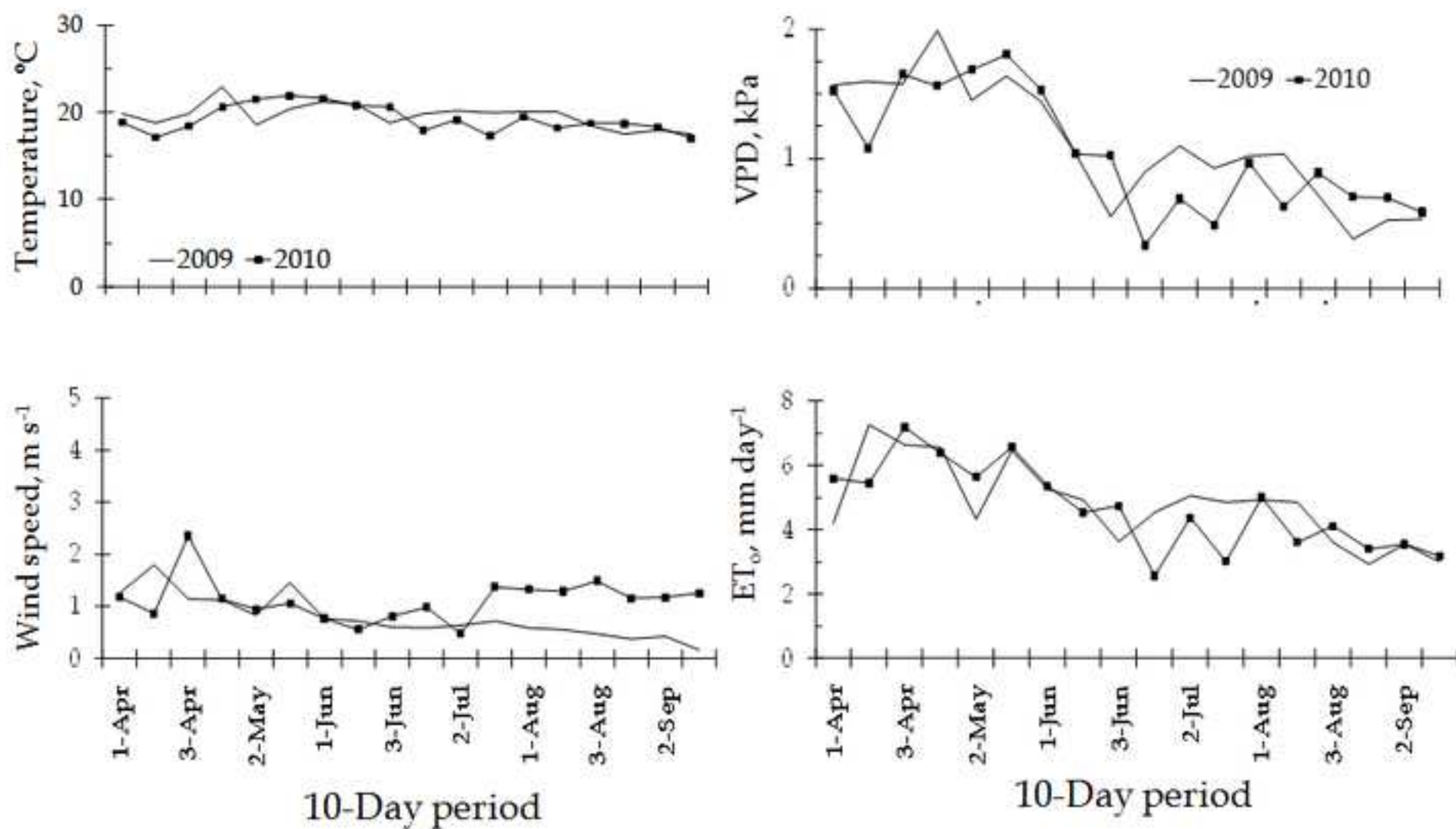
Figure 2

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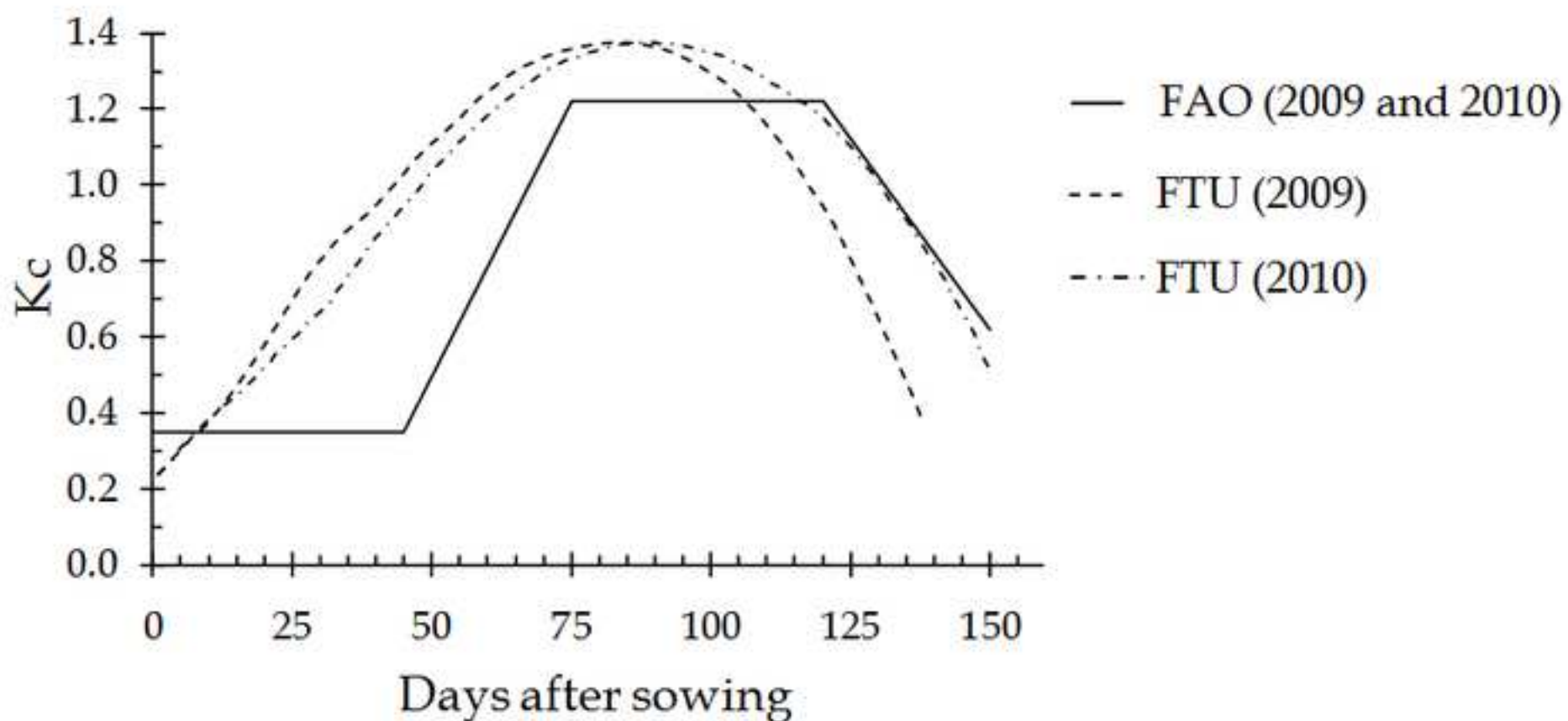Figure 3

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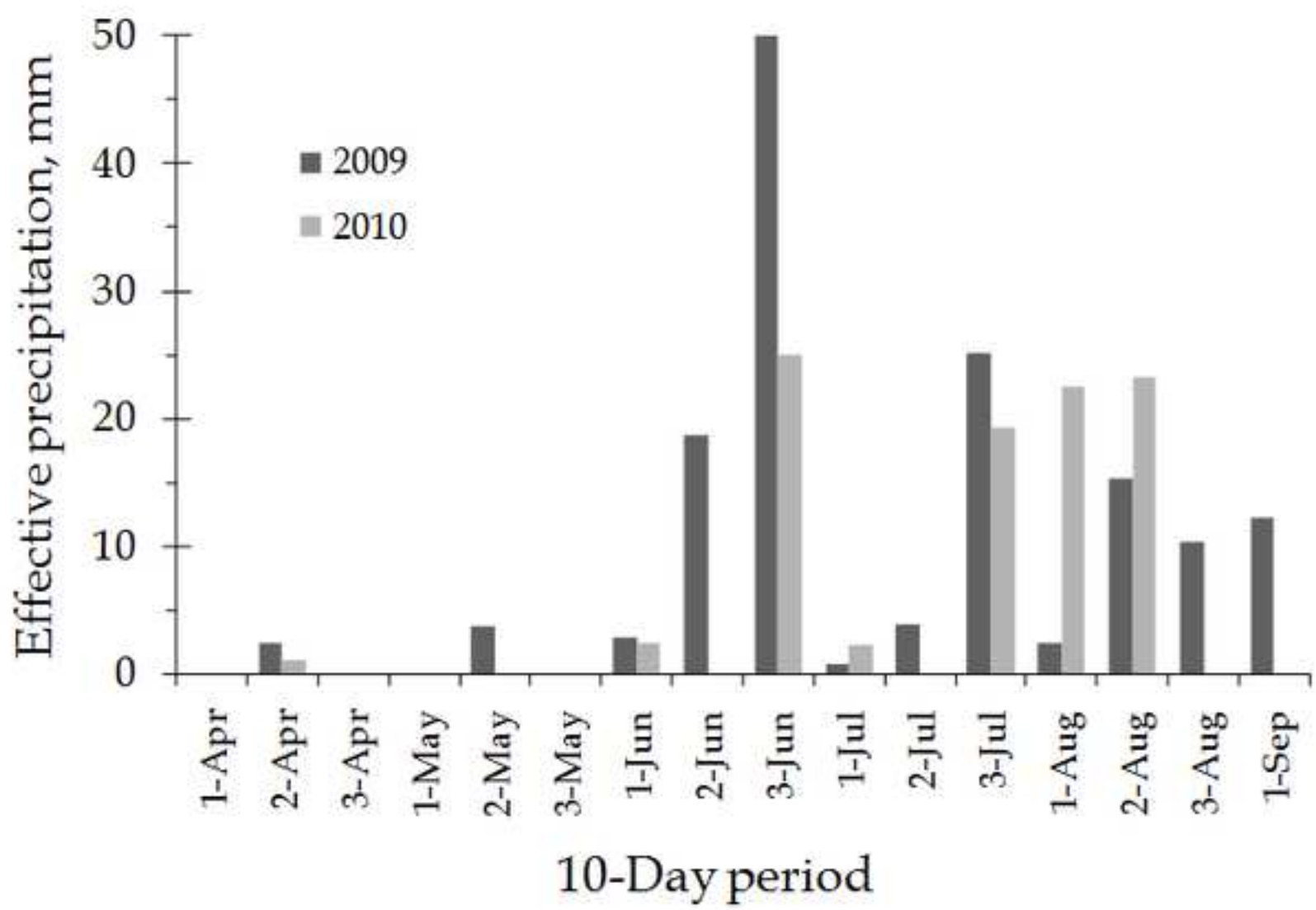
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