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Determination of wheat crop coefficient (Kc) and soil water evaporation (Ke) in Maringa, PR, Brazil

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The objective of the present study was to determine the crop coefficient (Kc) of wheat and soil water evaporation (Ke) in Maringá, PR, Brazil. Wheat crop evapotranspiration (ETc) was determined through the water balance method, using drainage lysimeters integrated with soil moisture measurements. The ETo was calculated using the Penman-Monteith equation with climate data from an automatic weather station, then Kc was calculated. Microlysimeters were built, using PVC pipes with 100 mm diameter and 150 mm length, which were weighted every day to obtain the quantity of water evaporated and then the soil water evaporation coefficient (Ke) was calculated. The calculated values of Kc were compared with values presented by FAO 56. The calculated Kc were 0.67, 0.67, 1.01, 1.03 and 0.42 for tillering, stem extension, heading, flowering and ripening, respectively. The values of Kc presented high correlation and precision as compared to FAO model. The values of evaporation determined through microlysimeters were greater as compared to the ETo during the beginning of the experiment, when soil was uncovered and decreased during the crop development.

Key words: FAO 56, wheat, drainage lysimeters, microlysimeters, evapotranspiration.

INTRODUCTION

Accounting for only twenty percent of the world agriculture, the irrigated agriculture areas are responsible for 40% of world food supply. In contrast, irrigated agriculture consumes 80% of world's freshwater (Shiklomanov, 2000). The knowledge of water requirements by plants helps growers and researchers to improve the management of field activities, such as irrigation events. However, the irrigation water requirement is the total amount of water needed, in addition to precipitation, to satisfy the crop evapotranspiration (ETc) requirement.

The ETc is defined as the plant's transpiration and soil water evaporation systems under standard condition, where there is no stress by water quality constraints, pests or inadequate soil fertility (Allen et al. 2006). Souza and Gomes (2008) mentioned that the ETc can be determined by using water balance in the soil, which consists of monitoring of water storage, water output and

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water input in the soil during the certain period of time.

Different methods existent for determination of evapotranspiration, these methods are direct and indirect methods. The direct methods require the use of lysimeters and soil water balance to calculate the evapotranspiration during a determined period, while the indirect methods calculate the evapotranspiration using the theoretical or empirical equation with meteorological data (Cavalcante Jr et al., 2011). The widely used indirect method to determine the evapotranspiration is proposed by FAO, Food and Agriculture Organization of the United Nations, published in Bulletin No. 56 (Allen et al., 2006) due to the easy applicability and simplicity, in which only crop coefficient (Kc) values and meteorological data are needed.

The Kc is an empirical relation among a crop evapotranspiration (ETc), under ideal conditions, full development, and the evapotranspiration of a hypothetical reference crop (ETo). The Kc is intensely used to estimate crop water use and to schedule irrigation events. The FAO methodology was developed to provide growers with a simple ETc prediction tool for guiding irrigation management decisions. Values of Kc varies over the crop development and increases from a minimum value at planting until a maximum Kc reaches full canopy cover, the Kc tends to decline at a point after a full cover is reached in the crop season (Allen et al., 2006; Ko et al., 2009).

Several studies determine the values of Kc for different locations. Libardi and Costa (1997) studied wheat Kc for Piracicaba, midwest of Brazil, and Kc values ranged from 0.33 at tillering to 1.16 at flowering. In addition, Kc values were 0.79 at stem extension, 1.11 at heading and 0.45 at ripening. In another study developed in the Cerrado region of Brazil, values of Kc were 0.99 at tillering, 1.12 at stem extension, 1.43 at heading and flowering and decreased to 0.45 at ripening, the phenological stages duration were 22, 18, 48 and 12 days, respectively (Guerra and Jacomazzi, 2001).

The comparison between local Kc and the existent FAO values is always performed to ensure the quality of the new values (Araujo et al., 2011; Cavalcante Jr et al., 2011; Rácz et al., 2013; Filho et al., 2015; Kisi, 2016). A study developed in Texas (USA) found coefficient of Pearson of 0.87 for the new values of Kc for wheat as compared to the FAO value (Ko et al., 2009). Cavalcante Jr. et al. (2011) determined the coefficient of sunflower crop and obtained values of 0.87 and 0.76 for coefficiency of Pearson, and Willmott index respectively, when compared with the values proposed by Allen et al. (2006). Furthermore, there are few other data analysis methods available as statistical comparison index, such as root mean square error (RMSE) and coefficient of determination (R^2).

The soil water evaporation coefficient (Ke) has high influence in determining the Kc during the initial phase of crop development when the soil is most exposed and the crop transpiration capacity is reduced. The evaporation component varies daily according to surface soil moisture. The transpiration component has more stable behavior, being tabulated in ranges of variation for each phase of crop development (Allen et al., 2006).

The rate of soil water evaporation can be grouped into different stages. The first stage can comprise from one to three days, depending on the magnitude of the evaporation rate of this stage, which depends on the atmospheric conditions and is approximately 90% of the evaporative requirement. The length of this stage is influenced by the rate of evaporation, soil depth and soil hydraulic properties (Freitas et al., 2006). The second stage occurs when soil surface becomes drier and evaporation occur beneath the surface. The water vapor reaches the surface by molecular diffusion and mass flow, caused by fluctuating of air pressure.

Studies using direct measurement methods to determine evapotranspiration have been performing to determine the soil water evaporation. The use of lysimeter properly installed performs precise evaporation measurements for the different layers set up (Carvalho et al., 2007). Furthermore, microlysimeters is an option to measure evaporation of discovered and cultivated soil (Burt et al., 2005). The microlysimeter is PVC pipe filled up with soil, installed between crop rows and weighted periodically to calculate the mass difference by evaporation during the period desired. Flumignam et al. (2012) compared the water evaporation from the soil lysimeters and microlysimeters, and concluded that the use of microlysimeters is valid. Dalmago et al. (2010) validated the use of microlysimeters for absolute measurements and relative values of water evaporation from the soil to compare the planting methods.

Although, the FAO methodology is a great tool to determine the crop water requirement, there are weather variabilities over different locations, as well as values of Ke and Kc for all crop development stages. Standard values should be used only in the absence of local values; therefore, the objective of the study was to determine the crop coefficient (Kc) of wheat and soil water evaporation (Ke) and to compare the values with the methodology proposed by the FAO No. 56 bulletin.

MATERIALS AND METHODS

The study was conducted at the experimental field at the Irrigation Training Center of State University of Maringá, located in Maringá, PR, Brazil (Latitude 53°25', Longitude 51°56' and Altitude 542 m). The soil at the research area is classified as Eutroferric Red Latosol, according to EMBRAPA (2006), typically found in Maringa. The soil has 8% of the slope with a clay texture, the proportion of particle fractions are 6% sand, 13% silt and 81% clay. The climate of Maringá is Cfa - Humid Subtropical Climate, according to the classification of Koppen. The rainy period occurs from December to February, characterized as summer, while from July to August are the dryer months, winter.

Three drainage lysimeters were installed in the experimental area, with a volume of 2 m^3, the soil was set inside each lysimeter

Table 1. Performance of the comparison coefficient (indicator "c") developed by Camargo and Sentelhas (1997).

"c" Indicator values	Performance
>0.85	Great
0.76 a 0.85	Very good
0.66 a 0.75	Good
0.61 a 0.65	Medium
0.51 a 0.60	Poorly
0.41 a 0.50	Very poorly
≤ 0.40	Extremelly poorly

Source: Camargo and Sentelhas (1997).

to mimic soil layers from the soil profile around the lysimeters. In addition, in the bottom of each lysimeter, a layer of stone gravel and sandy covered by a grid were set up to avoid soil leaching. Soil moisture was controlled using time domain reflectometry (TDR) sensors (TRASE 6050X1, Soil Moisture Equipment Corp). TDR sensors were installed in each lysimeter at 5, 15, 25, 35 and 45 cm of soil depth and data was collected every day.

The water balance from irrigation, precipitation, drainage and soil moisture variation was used to calculate the crop evapotranspiration (ETc). The non-uniform water movement into the soil resulted in a greater water drainage close to the water supply than farther areas; however, water drainage reduced over time. The soil water balance was calculated in timing intervals between rainfall events or irrigation events, using the following equation 1:

$$\mathrm{ETc} = \frac{\Delta A\ (\Sigma P + \Sigma I + \Sigma D)}{N_p} \tag{1}$$

Where: ETc- crop evapotranspiration, calculated by data collected from lysimeters (mm d^{-1}); ΔA- storage variation in a specific time, data from TDR (mm); P- precipitation between events (mm); I- irrigation, total of water applied between events (mm); D- total of water drainage between events (mm); Np- days between events.

To calculate the reference evapotranspiration, data were collected from the automatic weather station installed in the field experiment, and used in the Equation 2. The Equation 2 was estimated by Penman-Montheith method, as recommended by FAO No. 56 bulletin (Allen et al., 2006).

$$\mathrm{ETo} = \frac{0.408\Delta.\ R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0{,}34\, u_2)} \tag{2}$$

Where: ETo- daily evapotranspiration reference (mm d^{-1}); Δ- slope the vapor pressure curve at the point T (kPa $ºC^{-1}$); γ- psychrometric constant (kPa $ºC^{-1}$); Rn- daily solar radiation balance (MJ m^{-2} d^{-1}); G- daily flow of soil heat (MJ m^{-2} d^{-1}); λ- latent heat of vaporization (MJ kg^{-1}); T- average daily air temperature (ºC); U_2- average daily wind speed from 2 m height; e_s- average daily saturation pressure of water vapor (kPa); e_a- average daily pressure of water vapor (kPa).

The Kc (Equation 3) was determined by the ratio of the ETc average values, which was obtained during events between two points, or the ETc average in this same period, the result represents the Kc in number of days, which were placed within each phase of the culture seeking to obtain the medium value of Kc of each phenological stage proposed by Allen et al. (2006).

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETo}} \tag{3}$$

To determine Ke, four PVC microlysimeters, 100 mm diameter and 150 mm height with the bottom sealed by a lid, were installed between the wheat rows. During all the seasons, the micro-lysimeters were daily weighted and the difference in mass between days determined to evaluate the daily evaporated water.

To quantify the amount of water in the mycrolysimeter, a baker was used, which allowed supplying the same quantity of water to lysimeters. The mean values from microlysimeter were used to quantify the evaporation values or Ke, according to the Equation 4.

$$\mathrm{Ke} = \frac{\mathrm{Evaporation}}{\mathrm{ETo}} \tag{4}$$

Where: Evaporation- evaporation from microlysimeters (mm).

The methodology for calculating the Kc and Ke from FAO-56 is described in Allen et al. (2006), where the tabulated values are corrected by the local climatological data, and the Kc and Ke for each region were estimated.

The comparative analysis between the estimated and determined ETc was performed by a statistical comparison index, suggested by Camargo & Sentelhas (1997). The degree of accuracy was obtained by the correlation coefficient of Pearson "r" (Equation 5), the accuracy was evaluated by Willmott index "d" (Equation 6) and the performance by the indicator "c". Where "c" obtained by the product of the ratio "d" and coefficient "r". The values of indicator "c" classified according to Table 1.

$$r = \frac{\sum_{i=1}^{N}(O_i - O)*(P_i - P)}{\sqrt{\sum_{i=1}^{N}(O_i - O)^2} * \sqrt{\sum_{i=1}^{N}(P_i - P)^2}} \tag{5}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}\left(\left|P_i - O\right| + \left|O_i - O\right|\right)^2}\right] \tag{6}$$

Where: Pi- estimated value; P- average of the estimated value; Oi- determined value; O- average of the determined values. Considering that for the coefficient "r"- 0.70 up or down indicates a strong correlation; 0.30 to 0.70 positive or negative indicates a moderate correlation; 0 to 0.30 indicates a weak correlation. For the index "d"- values range from zero (for no concordance) to 1 (for total concordance).

RESULTS

The wheat development stages were classified in tillering, stem extension, heading, flowering and ripening (Large, 1954). The growth stage duration was 25, 22, 17, 15 and 20 days for tillering, heading, flowering and ripening, respectively. The life cycle of wheat was 99 days.

The cumulative rainfall during all crop development was 316.6 mm, and the total irrigation applied was 292.9 mm. The total water drainage during all field trial was 254 mm and the drainage was directly related to rainfall events. In particular, at 20 and 21/06, the water drainage had its

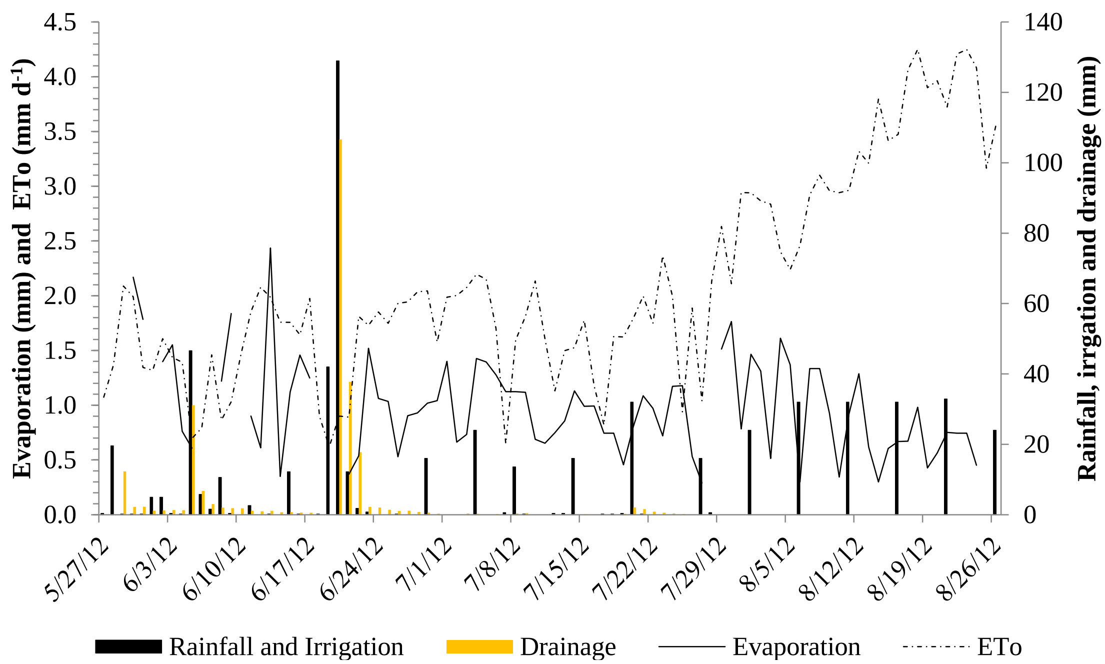

Figure 1. Cumulative rainfall and irrigated water, water drainage, ETo and soil water evaporation determined through microlysimeters during the experimental field.

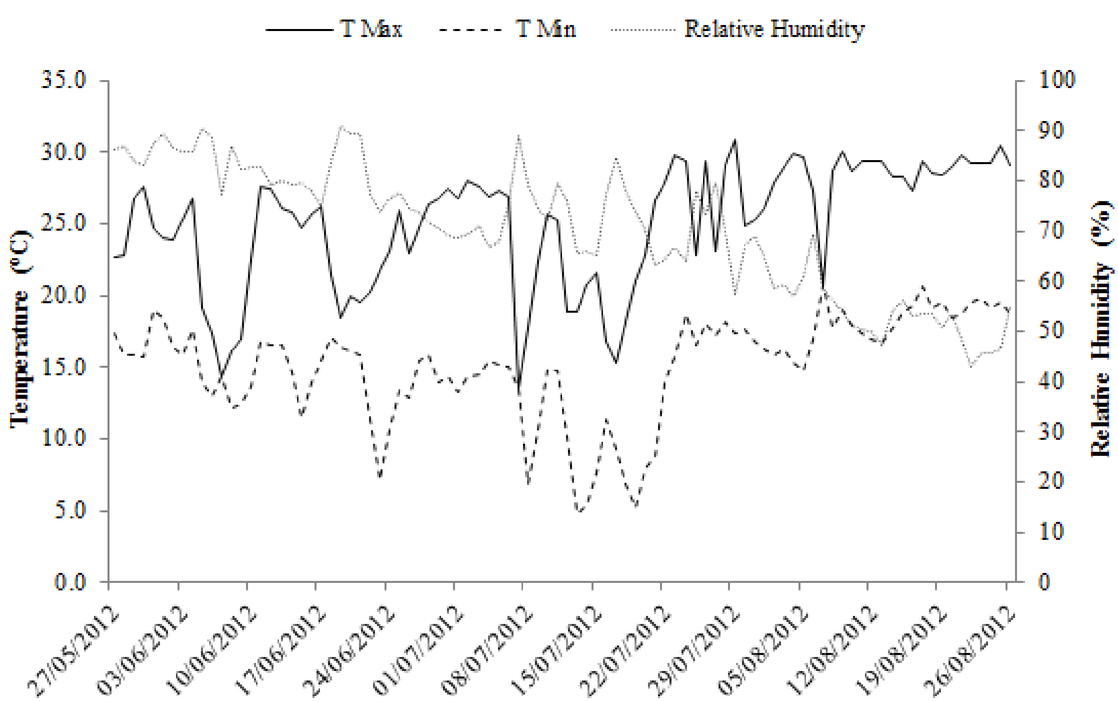

Figure 2. Maximum and minimum temperature and relative humidity during the field experiment.

maximum value (144 mm), in response to a rainfall event of 183 mm at 19, 20 and 21/06 (Figure 1).

The average temperature for the crop season was 19.5°C, with maximum and minimum temperature of 24.6 and 11.8°C, respectively. The relative humidity average was 70.8% (Figure 2). The daily solar radiation and wind speed presented in Figure 3 were used to calculate the ETc. Weather variables were directly affected by rainfall

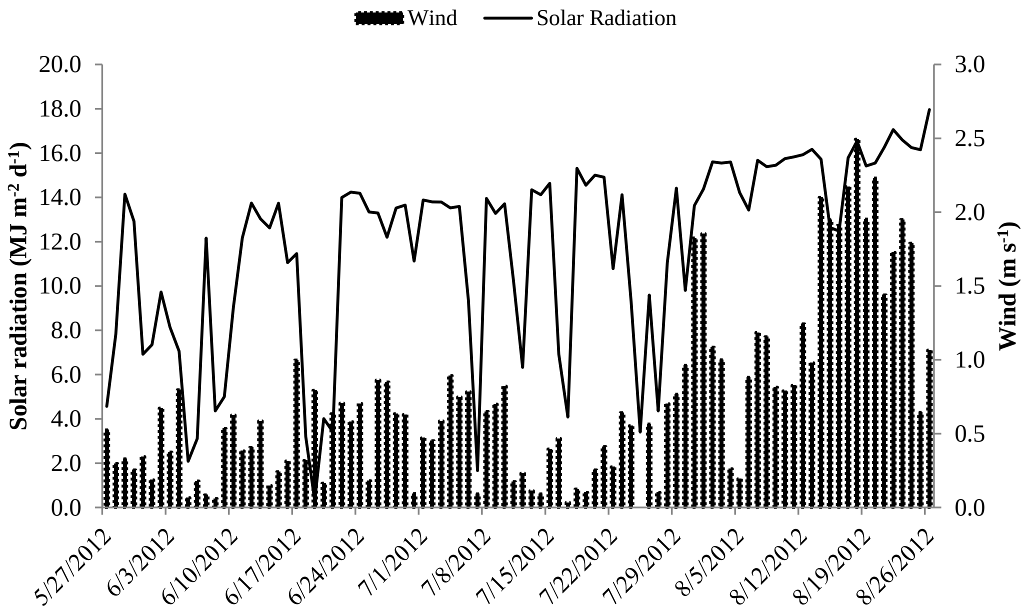

Figure 3. Solar radiation and wind speed during the field experiment.

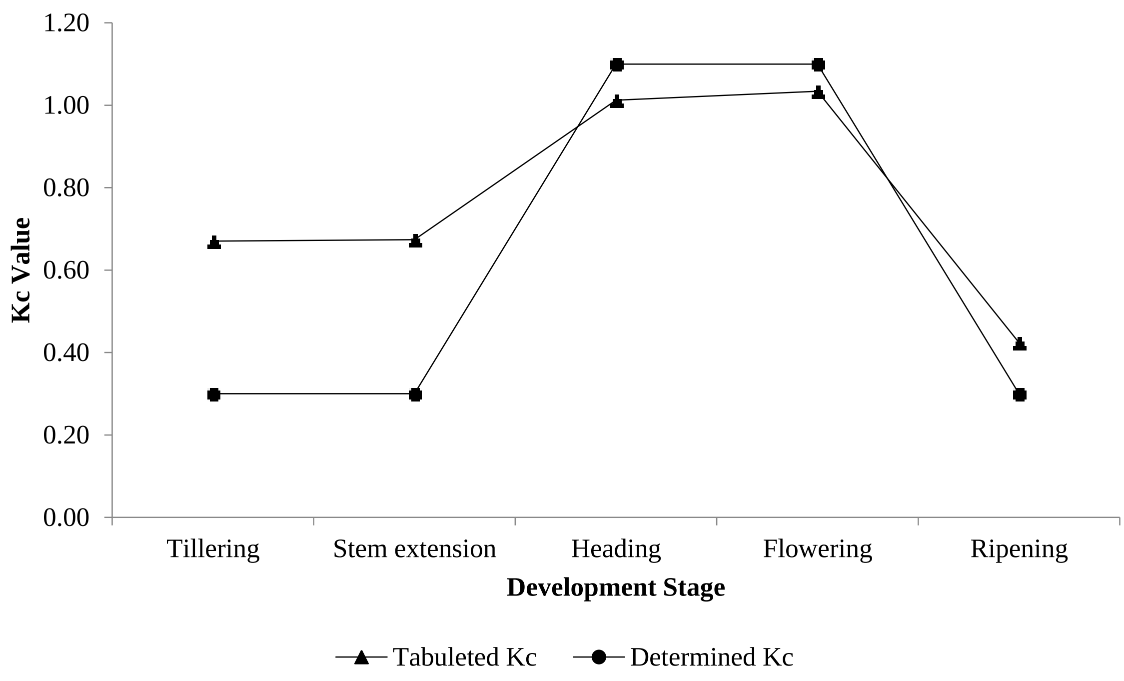

Figure 4. Comparison between the study determined values of Kc and the FAO-56 tabuleted Kc values for each wheat development stages (tillering, stem extension, heading, flowering and ripening).

events, in the presence of rain there is a decrease in daily solar radiation, which can be observed at the end of the crop season. The average solar radiation was 11.8 MJ m^{-2} d^{-1} and average wind speed was 0.7 m s^{-1}.

The calculated Kc values were 0.67, 0.67, 1.01, 1.03 and 0.42 for tillering, stem extension, heading, flowering and ripening growth stages (Figure 4), respectively. The Kc values were compared with values from FAO-56 and the coefficients were 0.952 for Pearson, 0.946 for Willmott index and 0.9 for the indicator 'c' from Camargo

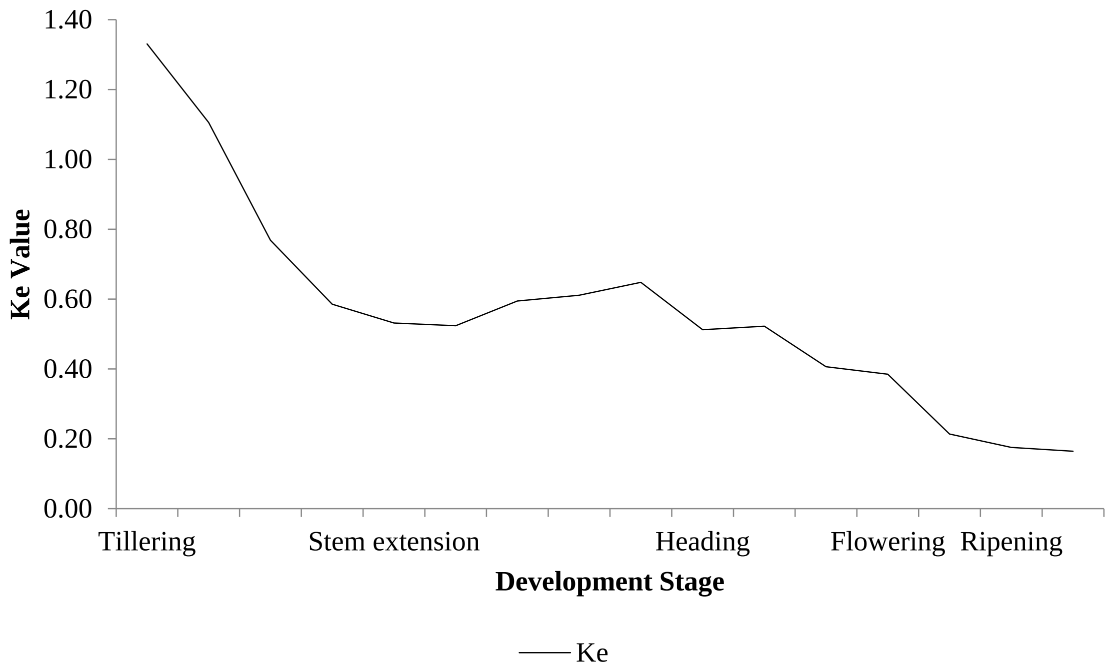

Figure 5. Controlled values of Ke during the wheat experimental development stages (tillering, stem extension, heading, flowering and ripening).

Table 2. Values of field determined Ke and estimated Ke values using the FAO-56 methodology for each wheat growth stages (tillering, stem extension, heading, flowering and ripening).

Development stages	Ke	
	Determined	Estimated FAO
Tillering	1.090	0.900
	1.092	0.869
	0.945	0.900
	0.589	0.900
Stem extension	0.499	0.500
	0.530	0.500
	0.600	0.500
	0.741	0.500
Heading	0.680	0.192
	0.568	0.179
	0.493	0.172
Flowering	0.415	0.130
	0.406	0.138
	0.117	0.105
Ripening	0.177	0.900
	0.142	0.900

and Sentelhas (1997).

The Ke was calculated over the season according to the FAO-56 methodology and expressed in Figure 5. Despite the ripening growth stage, the determined Ke values for all wheat growth stages were similar to those estimated by FAO-56 (Table 2). All Ke values were analyzed with those estimated by FAO-56 and the comparison coefficients were 0.348 for Pearson, 0.628

Table 3. Comparision coefficient for the study determining Ke values and estimated by FAO 56 methodology.

Coefficient of Pearson "r"	Willmott Index "d"	Indicator "c" from Camargo and Sentelhas
0.348	0.628	0.219

Table 4. Comparision coefficient for the study determining Ke values and estimated by FAO 56 methodology, excluding the ripening stage.

Coefficient of Pearson "r"	Willmott Index "d"	Indicator "c" from Camargo & Sentelhas
0.779	0.790	0.615

for Willmott index and 0.219 for the indicator ‘c’ from Camargo and Sentelhas (1997) (Table 3). However, when ripening Ke values are not included in the analysis with the Ke values of other wheat growth stages, there is an increase in comparison coefficients. The Pearson coefficient was 0.779, Willmott index was 0.790 and 0.615 for the indicator ‘c’ from Camargo and Sentelhas (1997) (Table 4).

DISCUSSION

The wheat has a lot of development under temperatures of 18 and 24°C; however, each growth stage has an optimum temperature of 11.7, 23.0 and 21.3°C for stem extension, flowering and ripening, respectively (Farooq et al., 2011). The maximum and minimum temperatures increased over the crop development, which matches with the beginning of winter. The higher temperatures at plants senescence reduced the relative humidity, and both were influenced by the low precipitation presented during the growth stage, as compared to early season. The wind was used to calculate the ETo and had no direct effect on crop development, under moderated wind conditions; the crop canopy has the above ground moist air layer replaced by a typically drier air, which provides a high vapor pressure gradient that increases the evapotranspiration. The study determined Kc and FAO-56 values had similar trend over the wheat crop development (Figure 4), and the comparison coefficients had acceptable values, which were similar to those measured by Liu and Luo (2010), Cavalcante Jr et al. (2011), Neto et al. (2011) and Cavalcante Jr et al. (2013).

The differences between calculated and FAO-56 Kc values indicates the necessity of FAO-56 values adjustments for each wheat growing location. During initial growth stages, the determined Kc was different from the FAO-56 of 0.37 for tillering and stem extension, respectively. However, this difference was reduced with the crop development. At tillering and stem extension, most of the soil is bared, which increase soil water evaporation and explain such difference of both growth stages. Once the crop canopy is completely covering the soil, the influence of water evaporation on determining the evapotranspiration is reduced because of a reduction in soil water evaporation (Allen et al., 2006) and the determined values were closer to FAO-56.

The microlysimeters were a useful tool to estimate the soil water evaporation, although the equipment must be careful managed during the data collection and data analysis. The same was stated by Dalmago et al. (2010) and Flumignam et al. (2012). The Ke values had high comparison coefficients when ripening growth stage data were not included in the analysis.

The ripening Kc value was removed from the data analysis because at the end of the crop development when plants maturation process is ending, water was no longer required and irrigation was cut off. Microlysimeters received no water anymore and even with a reduction in leaf area due to crop maturation, which usually increases Ke values, the amount of available water for evaporation within microlysimeters was very small.

Ke responses to canopy closing are inversely proportional to Kc, when soil is bared, which usually occurs in the initial stages of crop development, the values of Ke is extremely high. The high Ke is explained by the high soil water evaporation; however, as leaf area increases the soil was covered and water evaporation reduced, consequently Ke was also reduced. The Ke plateau occurred when the soil was completely covered by crop canopy.

During the crop development, the soil water evaporation was quietly similar to ETo at initial crop growth stages, when transpiration was low or zero. The crop transpiration increased as crop advanced for next growth stages, there was an increasing in soil water uptake and decreasing in soil available water for evaporation. In addition, the proportion of covered soil by plant leaf area was increased as plants were under development, making difficult the incidence of solar radiation on the soil and reducing soil water evaporation. At plant senescence, the leaf area and transpiration rate were reduced and soil evaporation should increase; however, rainfall events decreased and irrigation ceased in the late season;

consequently, soil water evaporation reduced.

Conclusion

The study concluded that the FAO-56 values of Kc for each crop development stage of wheat have to be determined for the desired growing region, to fix local weather conditions. The wheat crop coefficients for the studied region were 0.67 for the tillering stage; 0.67 for the booting stage; 1.01 during the flowering stage; 1.03 during grain filling; and 0.42 for the maturation stage to Maringá, PR, Brazil. These values can be used for similar weather conditions and will help researchers and growers to determine the wheat water requirements over the season.

The soil water evaporation during wheat development induced high initial values of ETo when the crop canopy had not fully covered the soil. The well developed crop reduced soil water evaporation. At the end of the cycle, another decrease was observed, because there was no water supply and increased evaporative demand is required by ETo.

When grain filling data were used and the system water supply was constant, the Ke values obtained by using the microlysimeters showed high correlation but low accuracy with the methodology proposed by the 56 FAO bulletin.

Conflict of Interests

The authors have not declared any conflict of interests.

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