Crop coefficient for coffee as a function of leaf area index

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This study was conducted in an experimental site at the Federal University of Lavras, Brazil, to estimate the single crop coefficient (K_c) for drip-irrigated coffee (*Coffea arabica*) and provide a mathematical description based on leaf area index (LAI). The cultivar used was Catiguá MG-3 planted in May 2007 with a spacing of 2.5 × 0.6 m. The LAI were obtained from the average of plant height and canopy diameter with data derived from bimonthly measurements between 2007 and 2013. K_c values were determined from crop evapotranspiration (ET_c) and reference evapotranspiration (ET_o). ET_c was estimated from the water balance between the periods of successive irrigations in which there was no precipitation, while ET_o was obtained using the Penman–Monteith equation parameterized by FAO. To describe the relationship between K_c and LAI, linear and nonlinear models were used. The logistic model was best for describing the K_c values as a function of LAI. The determined minimum, mean and maximum K_c values were 0.21, 0.57 and 0.80 respectively.

Keywords: Crop height, coffee, drip irrigation, evapotranspiration, leaf area index.

GLOBAL water scarcity has led to the search for alternatives to improve and minimize water use in irrigation. However, the adoption of irrigation in coffee plantations has increased substantially in recent years, as the coffee plant responds positively to irrigation and shows significant increase in productivity[1–8].

According to Silva *et al.*[9], part of the success in irrigated agriculture is related to adequate management of soil–water natural resources which, interacting with the atmosphere and the plants, determine the potential conditions of maximum productivity of a crop in good health with proper nutrition.

According to Souza *et al.*[10], just being aware of the total water requirements of a plant does not lead to efficient irrigation management; knowledge of the water demand in different development stages is essential.

The study of variables, such as crop coefficient (K_c) – which, according to Allen *et al.*[11], numerically expresses the relationship between potential and reference evapotranspiration – has physical and biological significance since it depends on the leaf area, architecture (aerial part and root system), plant cover and plant transpiration.

K_c is typically taken from the literature values and is affected by crop variety and growth stage[12]. According to Volschenk[13], knowledge of the K_c values for the initial, intermediate and final stages of a given crop cycle is necessary for the estimation of the crop evapotranspiration (ET_c) curve throughout the crop cycle.

Gutiérrez and Meinzer[14] obtained a K_c value of 0.58 for coffee plants with approximately one year of planting, and average values of 0.75 and 0.79 for coffee plants with two to four years of age. For coffee plants with adequate management and height of 2–3 m in sub-humid climate, Allen *et al.*[15] proposed a K_c value between 0.90 and 0.95 in the absence of weeds and 1.05 and 1.10 in the presence of weeds, adopting the reference evapotranspiration (ET_o) estimated using the FAO Penman–Monteith equation. Arruda *et al.*[16] presented K_c values between 0.73 and 0.75 in the first year of planting and from 0.87 to 0.93 in years 7 and 8 respectively.

Sato *et al.*[17] determined ET_c and K_c of a coffee plant (*Coffea arabica* L.) four years after pruning using the water balance method, and obtained ET_c between 1.23 and 4.39 mm d^{-1} and K_c ranging from 0.59 to 1.16.

However, according to Lima and Silva[18], the determination of irrigation depths using K_c may be prone to error if the conditions of the sites from which the K_c values obtained and those where the crops are grown are different, and the water consumption of the crops may be overestimated or underestimated.

A single K_c value cannot be established for all climatic situations; therefore, a crop coefficient should be determined for each stage of crop development[19]. According to Carr[20], in Zimbabwe an approach is used that allows K_c to vary according to age, size and planting arrangement of the trees, defined as the relationship between the canopy cover area and the area occupied by the plant (leaf area index, LAI).

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Thus, the present aims to evaluate the single K_c for drip-irrigated Arabica coffee Catiguá MG-3, and provide a mathematical description as a function of LAI for the southern Minas Gerais region, Brazil.

Material and methods

The study was conducted in the coffee sector of the Department of Agriculture of the Federal University of Lavras (UFLA), in the municipality of Lavras, Minas Gerais, Brazil. The geographical coordinates of the area are 21°14′S lat. and 44°58′W long., with an average altitude of 910 m amsl. The climate of the region is of the Cwa-type, according to the Köppen classification (mesothermal with mild summers and winter drought). The average annual precipitation is 1460 mm, average annual temperature is 20.4°C. The potential evapotranspiration (ETP) and actual evapotranspiration (ETR) for the coffee crop vary from 899 to 956 mm and from 869 to 873 mm respectively[21].

The soil in the experimental site is classified as Dystroferic Red Latosol with a very clayey texture[8]. The planting of coffee cv. Catiguá MG-3 was carried out in May 2007 at a spacing of 2.5 × 0.6 m (6666 plants ha^{-1}). The liming, implantation and post-plant fertilization were carried out based on the recommendations of Ribeiro *et al.*[22]. A weather station was installed in the experimental site for daily monitoring of air temperature, relative humidity, atmospheric pressure, wind speed, precipitation and solar radiation.

The experiment comprised of 36 experimental plots. Each plot had three lines with ten plants in each line, and the eight central plants were considered as useful. In each planting line, a lateral line was installed with self-compensating drippers (flow rate of 3.75 l h^{-1}), ensuring the formation of a continuous wet strip along the 0.6 m wide rows of plants.

The timing of irrigation was defined based on water tension in the soil. In six experimental plots, tensiometers were installed at depths of 0.10, 0.25, 0.40 and 0.60 m, and readings were taken daily using a digital puncture meter. Irrigation in 2007 and 2008 was performed when the average tensiometer readings installed at 0.10 and 0.25 m indicated a tension of 20 kPa. The irrigation depth used for this tension was 13.6 mm and irrigation time was 2 h and 48 min. From 2009, irrigation was based on the tensiometer readings installed at a depth of 0.60 m. The irrigation depth employed was defined considering the average of the tensiometer readings and the water retention curve in the soil, increasing the soil moisture to field capacity condition.

The ET_c (mm) was determined in a simplified manner (eq. (1) below) and internal drainage was not considered because it was during periods without rainfall. The capillary rise was taken as zero due to the deep water table. Surface run-off was assumed to be zero because the area where the coffee plants were grown was practically flat, and during the period of analysis there was no precipitation (drip irrigation does not favour surface run-off).

$$ET_c = I - \Delta A, \tag{1}$$

where ET_c is the crop evapotranspiration (mm), I the irrigation (mm) and ΔA is the storage variation (mm).

To determine ET_o we used the Penman–Monteith equation parameterized by FAO[15].

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{(T+273)} u_2 (e_s - e_a)}{\Delta + \gamma(1 + c_d u_2)}, \tag{2}$$

where ET_o is the reference evapotranspiration (mm day^{-1}); Δ is the slope of the steam pressure curve (kPa $°C^{-1}$), R_n the liquid radiation on the surface of the crop (MJ m^{-2} d^{-1}), G the sensitive heat flow in the soil (MJ m^{-2} d^{-1}), γ the psychrometric coefficient (kPa $°C^{-1}$), T the average air temperature at 2 m height (°C), U_2 the wind speed at 2 m height (m s^{-1}), e_s the water steam saturation pressure (kPa); e_a the partial steam pressure (kPa) and C_n = 900 s m^{-1} and C_d = 0, 34 mm s^3 Mg^{-1} d^{-1} are the constants defined for the reference crop.

The K_c values were determined as follows

$$K_c = \frac{\sum ET_c/\Delta t}{\sum ET_o/\Delta t}, \tag{3}$$

where ET_c is the crop evapotranspiration (mm), ET_o the reference evapotranspiration (mm) and Δt is the interval between successive irrigations calculated on days (d) during the period when there was no precipitation.

The height (H) and crown diameter (D_c) of the plants were measured bimonthly, totalling 18 evaluation periods in the first three years (January, March, May, July, September and November) and three evaluation periods in 2013 (January, April and June). The plant height was measured from the stem of the plants to the apical bud of the stems using graduated ruler, and crown diameter was measured with a measuring tape in the cross-sectional direction of the planting line. The temporal evolution of the average values of H and D_c was adjusted to the logistic model according to eqs (4) and (5) respectively, as given below

$$Y_{Lh} = a_{Lh}\left[1 + b_{Lh} e^{(-c_{Lh} t)}\right]^{-1}, \tag{4}$$

$$Y_{LD} = a_{LD}\left[1 + b_{LD} e^{(-c_{LD} t)}\right]^{-1}, \tag{5}$$

where Y_{Lh} is the average value of plant height (m) estimated by the logistic model, Y_{LD} the average value of canopy diameter (m) estimated by the logistic model, a_{Lh}, b_{Lh} and c_{Lh} are adjustment parameters of the logistic model for plant height, a_{LD}, b_{LD} and c_{LD} are adjustment parameters of the logistic model for canopy diameter, and t is the time (days) that has elapsed since the planting of seedlings in the field (DAP).

Based on the values of mean plant height (H), canopy diameter (D_{c}) and distance between plants in the planting rows (SD), we estimated the evolution of the canopy leaf area values using eq. (6) below, which represents half of the surface area of an ellipsoid

$$\mathrm{LA} = 2\pi\left(\frac{\mathrm{DP^P DC^P + DP^P H^P + DC^P H^P}}{3}\right)^{1/P}, \quad (6)$$

where LA is the leaf area ($\mathrm{m^2\ plant^{-1}}$), DP the distance between plants in the planting line (m), DC the canopy diameter (m), H the plant height (m) and $P = 1.6075$.

The LAI was calculated by the functional relationship between the leaf area and the area available to the plants given a spacing of 2.5×0.6 m.

$$\mathrm{LAI} = \mathrm{LA}\frac{N_{\mathrm{p}}}{10,000}, \quad (7)$$

where LA is the leaf area of the canopy ($\mathrm{m^2\ plant^{-1}}$) and N_{p} is the number of plants per hectare.

In the mathematical description of K_{c} dependence of a coffee plantation on LAI, we used the following models: linear (eq. (8)), polynomial (eq. (9)), logistic (eq. (10)) and Gompertz (eq. (11)).

$$K_{\mathrm{c}_{li}} = a_{li}\mathrm{LAI} + b_{li}, \quad (8)$$

$$K_{\mathrm{c}_{\mathrm{Po}}} = a_{\mathrm{Po}}\mathrm{LAI}^2 + b_{\mathrm{Po}}\mathrm{LAI} + c_{\mathrm{Po}}, \quad (9)$$

$$K_{\mathrm{c}_{\mathrm{Lo}}} = a_{\mathrm{Lo}}\left[1 + b_{\mathrm{Lo}}\mathrm{e}^{(-c_{\mathrm{Lo}}\mathrm{LAI})}\right]^{-1}, \quad (10)$$

$$K_{\mathrm{c}_{\mathrm{Go}}} = a_{\mathrm{Go}}\mathrm{e}^{[-b_{\mathrm{Go}}\mathrm{e}^{(-c_{\mathrm{Go}}\mathrm{LAI})}]}, \quad (11)$$

where $K_{c_{li}}$ is the K_{c} value (dimensionless) predicted by the linear model, $K_{c_{\mathrm{Po}}}$ the K_{c} value (dimensionless) predicted by the polynomial model, $K_{c_{\mathrm{Lo}}}$ the K_{c} value (dimensionless) predicted by the logistic model, $K_{c_{\mathrm{Go}}}$ the K_{c} value (dimensionless) predicted by the Gompertz model, a_{li} and b_{li} are parameters of adjustment of the linear equation; a_{Po}, b_{Po} and c_{Po} are parameters of adjustment of the polynomial equation, a_{Lo}, b_{Lo} and c_{Lo} are parameters of adjustment of the logistic model, a_{Go}, b_{Go} and c_{Go} are the parameters of adjustment of the Gompertz model.

The parameters of the models were adjusted to the observed values using the Solver tool of Microsoft Excel. The coefficient of determination (R^2), root mean square error (RMSE) and model efficiency (E_{f}) were the other statistical indices used to evaluate the performance of the models according to the following equations

$$R^2 = 1 - \frac{SQ_{\mathrm{R}}}{SQ_{\mathrm{tot}}}, \quad (12)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - E_i)^2}, \quad (13)$$

$$E_{\mathrm{f}} = \frac{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(O_i - E_i)^2\right]}{\sum_{i=1}^{n}(O_i - \bar{O})^2}, \quad (14)$$

where SQ_{R} is the sum of squared residuals, SQ_{tot} the sum of total squared, n the number of data and O_i the observed value, $\bar{O}$ the average of the estimated values and E_i is the estimated value.

Results and discussion

Figure 1 shows the average values of water tension in the soil measured by using a tensiometer at depths of 0.10, 0.25, 0.40 and 0.60 m between May 2007 and August 2013. Note that the average soil water tension data oscillated during the period. The tensiometers located at 0.10 and 0.25 m depth showed peaks reaching, tension values of 60 kPa. This occurred due to the greater concentration of the root system in the upper layers of soil, promoting greater reduction in water content. Ronchi *et al.*[23] examined the development of the root system of four cultivars of Arabica coffee under different spatial arrangements, and found that the root proportions in the surface layers (0.1 m) were higher than in the lower layers of the soil (0.4 m).

The tensiometers located at 0.4 and 0.6 m present small oscillations of tension, mostly remaining below 20 kPa, indicating that the irrigation management adopted has helped maintain adequate humidity of the soil for full development of the coffee plant.

During the evaluation period (May 2007–August 2013) the average monthly minimum value of air temperature was 16.7°C in July, while the average monthly maximum value was 24.9°C in February. The average monthly minimum value of relative humidity was 68.50% in August, and the average monthly maximum value was 85.66% in December. The accumulated annual average precipitation was 1526.2 mm, with 86.0% distributed from October to March, which corresponds to the local rainy season. The year 2009 experienced the highest accumulated annual

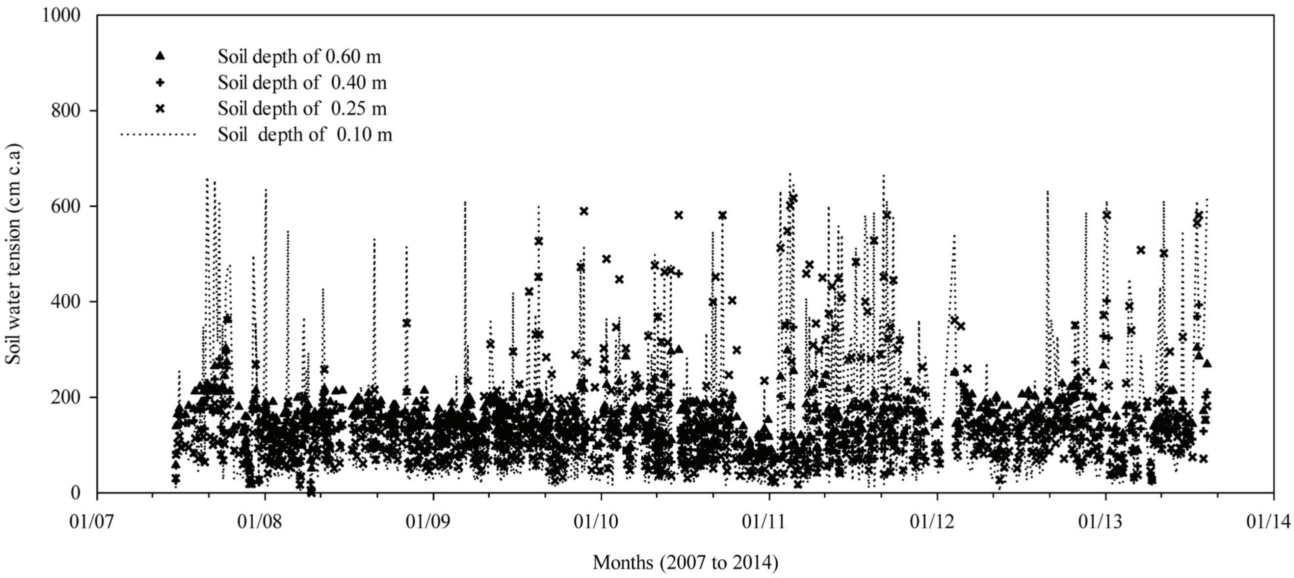

Figure 1. Water tension in the soil at depths of 0.10, 0.25, 0.40 and 0.60 m between May 2007 and August 2013.

Table 1. Adjustment parameters of the logistic model for plant height (m) and canopy diameter (m) of drip-irrigated coffee plants as a function of assessment time

Plant height (m)				Diameter of plant canopy (m)			
Logistic model (eq. (10))				Logistic model (eq. (10))			
a_{Lh}	b_{Lh}	C_{Lh}	R^2	a_{LD}	b_{LD}	C_{LD}	R^2
2.0898	7.7438	0.002014	0.9355	1.9683	7.7412	0.00285	0.8911

rainfall of 1811.5 mm. The average wind speed at 2.0 m above the ground surface over the six years of study was 0.5 m s^{-1}. The highest monthly average values were recorded in 2009, registering 2.3, 2.2 and 2.4 m s^{-1} for January, July and August respectively. In June, the lowest solar radiation (Rs) values were observed; 124, 130, 136, 108, 114 and 127 W m^{-2} for the years 2008, 2009, 2010, 2011, 2012 and 2013 respectively. The highest values of solar radiation were observed in November; 266, 335, 284, 267, 284 and 257 W m^{-2} for 2008, 2009, 2010, 2011, 2012 and 2013 respectively.

June recorded the lowest average value of ET_o, wind speed (0.2 m s^{-1}), air temperature (17.5°C) and solar radiation (124 W m^{-2}). For a given location, lower the solar radiation, air temperature and wind speed, and higher the relative humidity of air, lower is the rate of evaporation and transpiration since these climate parameters provide energy for vaporization and removing water vapour from the surface.

The plant height and canopy diameter data were adjusted using the logistic model. Table 1 lists the parameters of the adjustment equation. As can be seen from the table, the model represents 93.55% of the plant height data. The representativeness of the model for the canopy diameter variable was low, with R^2 of 0.8911. The parameters a_{Lh} and a_{Ld} represent the upper asymptote and indicate the growth of the variable. During the study period, the height of coffee cv. 'Catiguá MG-3' was around 2.10 m, and thus can be classified among the small cultivars. With respect to canopy diameter, the maximum value obtained by the model (around 2 m) indicates that the spacing adopted between the rows has not yet promoted the closure of the rows. Pereira *et al.*[24], while evaluating the height of coffee plants cv. Rubi MG1192 using the Gompertz model, reported a maximum height of around 2 m.

The daily ET_o and ET_c data, K_c and calculated LAI values, obtained between May 2007 and August 2013, during periods when there was no rainfall, illustrate 23 intervals with irrigation (Table 2).

As can be seen from the table, the lowest value of K_c (0.21) was registered in 2007, approximately five months after planting, while the highest observed value was 0.84, and the average value was 0.53. The LAI value ranged from 0.08 to 4.63. The average K_c values showed an increasing trend during the evaluation period following the average K_c values increased during the evaluation period following the LAI trend, which may have promoted an increase in transpiration rate. K_c value of 1.04 and LAI of 2.98 were obtained by Pereira *et al.*[25] at 40 months after

Table 2. Observed values of K_c for drip-irrigated Arabica coffee in the southern region of Minas Gerais, Brazil, obtained between August 2007 and August 2013

Period	$ET_o/\Delta t$ (mm d^{-1})	$ET_c/\Delta t$ (mm d^{-1})	K_c	Leaf area index (LAI)
13–29 August 2007	2.8998	0.6323	0.2180	0.08
4 September–17 October 2007	3.5072	0.7382	0.2105	0.11
28 April–28 May 2008	2.0113	0.7728	0.3842	0.41
19–26 August 2008	2.8449	0.8100	0.2847	0.59
2–5 September 2008	3.1913	0.7620	0.2388	0.61
18 May–1 June 2009	1.8099	0.4701	0.2597	1.18
14 July–17 August 2009	3.1495	1.1115	0.3529	1.37
28 August–3 September 2009	4.2586	1.4145	0.3321	1.42
31 August–6 September 2010	3.4162	1.7902	0.5240	2.44
10–14 September 2010	3.4226	1.6380	0.4786	2.47
4–9 February 2011	4.2286	2.5927	0.6131	2.87
28 June–8 July 2011	1.4547	1.1422	0.7851	3.25
12–19 July 2011	1.5978	1.2973	0.8119	3.27
28 July–2 August 2011	3.1954	2.1580	0.6754	3.31
9–16 August 2011	2.6428	1.7119	0.6478	3.34
6–20 September 2011	3.2211	2.1796	0.6767	3.42
28 February–2 March 2012	4,1034	2.2053	0.5374	3.78
27–31 July 2012	2.0873	1.5007	0.7190	4.07
6–9 October 2012	3.6339	1.9865	0.5467	4.19
18–25 April 2013	2.3626	1.9378	0.8202	4.49
10–20 May 2013	2.1570	1.8088	0.8386	4.52
20–27 June 2013	1.8524	1.1357	0.6131	4.57
1–9 August 2013	3.3667	2.4104	0.7160	4.63

Table 3. Adjusted values of the parameters of the linear, second-degree polynomial, logistic and Gompertz models, and the fit quality indicators RMSE, E_f and R^2

Linear model (eq. (11))					
	a_{li}	b_{li}	RMSE	E_f	R^2
	0.1197	0.2198	0.0930	0.9999	0.7964
Polynomial model of the second degree (eq. (12))					
a_{po}	b_{po}	c_{po}	RMSE	E_f	R^2
–0.0122	0.1775	0.1810	0.0903	0.9999	0.8078
Logistic model (eq. (13))					
a_{Lo}	b_{Lo}	C_{Lo}	RMSE	E_f	R^2
0.7984	1.1426	0.7776	0.0875	0.9999	0.8195
Gompertz model (eq. (14))					
a_{Go}	b_{Go}	C_{Go}	RMSE	E_f	R^2
0.8898	1.5461	0.4632	0.0891	0.9999	0.8129

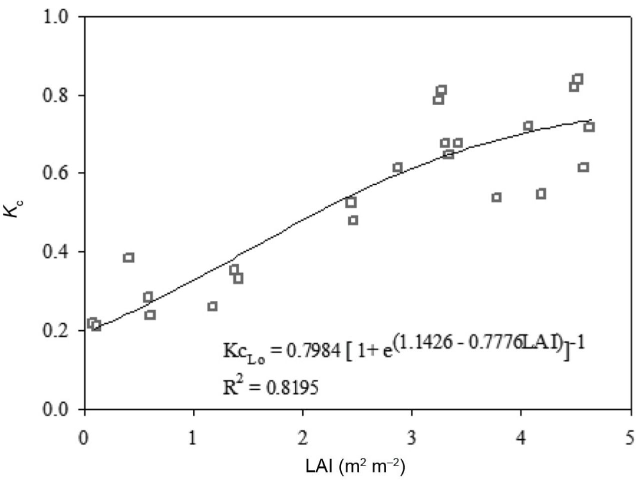

Figure 2. Crop coefficient (K_c) as a function of leaf area index (LAI) for Arabica coffee plants.

planting, considering sprinkler irrigation and a spacing of 2.5 m × 1.0 m. Flumingnan and Faria[26] reported that the average K_c determined in the first year can be attributed practically to evaporation loss since in this phase the crop covers a small portion of the land. In the second year, the increase in K_c average was related, in particular, to the evolution of LAI, which increased continuously (from 0.02 to 5), with greater increments in the second year, thus increasing transpiration.

Table 3 shows the mathematical description of K_c as a function of LAI. The four different models presented approximately equal values for RMSE (0.09) and E_f (1.00), signalling a good performance of the models, despite the logistic model presenting the highest coefficient of determination ($R^2 = 0.82$). Thus, the logistic model was used to describe the K_c values as a function of LAI (Figure 2). According to this model, the a_{Lo} parameter, which represents the maximum K_c that can be achieved; was estimated to be 0.80, and in the last evaluation the coffee plant was six years old and approximately 2.09 m tall.

Allen *et al.*[15] proposed K_c values between 0.90 and 0.95 for coffee plantations with adequate handling and height varying from 2 to 3 m. These results also corroborate the data obtained by Arruda *et al.*[16]. For drip-irrigated coffee plants, Flumingnan *et al.*[27] recommend K_c values of 0.76 and 0.91 for $ET_o \geq 3.0$ and <3.0 mm day^{-1} respectively.

Figure 2 shows K_c values as a function of LAI and the logistic model adjustment equation. These K_c values are higher than those obtained by Pereira *et al.*[25] for LAI < 1.5 and lower for LAI > 1.5. According to Pereira *et al.*[28], a factor that can shift the K_c curve up or down is the frequency of irrigation, which increases/decreases the direct evaporation through the soil surface due to greater/lesser surface wetting. Thus, this observed difference can probably be associated with the irrigation system adopted as well as the cultivar used and the site where the experiments are conducted.

Gutiérrez and Meinzer[14], and Pereira *et al.*[25] evaluated the K_c and LAI values of the irrigated coffee plant. Figure 3

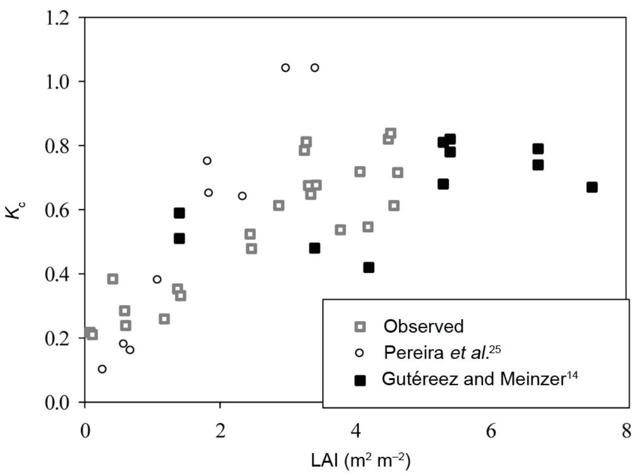

Figure 3. K_c as a function of LAI in the present study compared to those obtained by Pereira *et al.*[25], and Gutiérrez and Meinzer[14].

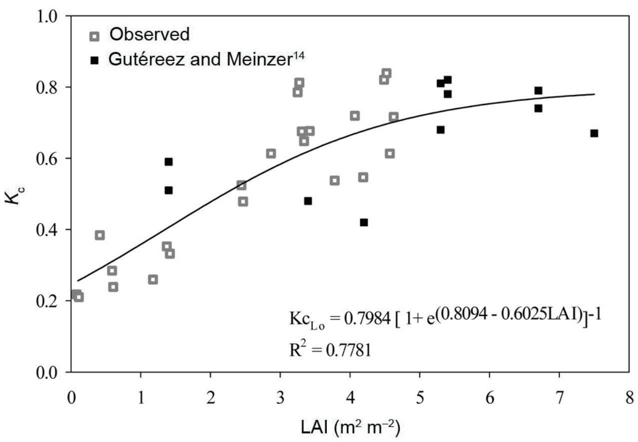

Figure 4. K_c as a function of LAI for drip-irrigated Arabica coffee using data from the present study and the results obtained by Gutiérrez and Meinzer[14].

shows a comparison of the results observed in this study with those obtained by Gutiérrez and Meinzer[14], and Pereira *et al.*[25]. In the study by Gutiérrez and Meinzer[14] on a commercial drip-irrigated coffee plantation in Hawaii, USA, the K_c values showed a certain similarity for LAI close to 5 $m^2 m^{-2}$. The K_c values for LAI < 1.5 $m^2 m^{-2}$ were higher than those obtained by Pereira *et al.*[25] for coffee irrigated by sprinklers.

At the beginning of crop development there is total exposure of the soil to climatic factors, as well as high irrigation frequency, and wet soil exposure due to the small leaf area of the coffee plants, which induces an increase in the evapotranspiration rate. Therefore, the divergence among K_c values would be due to the dependence of this parameter on local atmospheric conditions such as air temperature, wind speed, relative humidity and solar radiation.

Gutiérrez and Meinzer[14] presented K_c values for LAI up to 7.5 $m^2 m^{-2}$, and in this study, the highest LAI value was approximately 5 $m^2 m^{-2}$. Thus, the data of Gutiérrez and Meinzer[14] were incorporated with those obtained in the present study and a new function was generated considering the two sets of data (Figure 4). The value of $a_{Lo} = 0.80$ was considered, which represents the maximum K_c value predicted by the logistic model. The K_c values as a function of LAI showed a significant adjustment, in which the model explains 77.81% of the results presented after incorporation of data obtained by Gutiérrez and Meinzer[14]. It has been verified that the K_c values for coffee increases in the growth phase until it reaches the maximum value of LAI, thereafter maintaining certain stability in its values, with some fluctuations due to physiological processes and crop management. According to Rezende *et al.*[29], LAI increases with the planting density and is variable throughout the year, significantly influenced by harvest, and the occurrence of diseases and pests.

According to Flumingnan *et al.*[27], transpiration in the coffee production phase is the main component of evapotranspiration due to increase in LAI. In the crop production phase, K_c can assume lower values than in the formation phase, because depending on the conditions of atmospheric demand, stomatal closure occurs, limiting water loss to the atmosphere.

Conclusion

In this study, the logistic and Gompertz models proved a better fit and, according to quality evaluators, helped describe LAI of the coffee plant over time.

The logistic model best described the K_c values as a function of LAI, with a maximum value of 0.80 for 6-year-old coffee plant which was approximately 2.09 m in height.

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