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 (Kc) 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. Kc values were determined from crop evapotranspiration (ETc) and reference evapotranspiration (ETo). ETc was estimated from the water balance between the periods of successive irrigations in which there was no precipitation, while ET0 was obtained using the Penman–Monteith equation parameterized by FAO. To describe the relationship between Kc and LAI, linear and nonlinear models were used. The logistic model was best for describing the Kc values as a function of LAI. The determined minimum, mean and maximum Kc values were 0.21, 0.57 and 0.80 respectively.

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

The study of variables, such as crop coefficient (Kc) – 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.

Kc is typically taken from the literature values and is affected by crop variety and growth stage¹². According to Volschenk¹³, knowledge of the Kc values for the initial, intermediate and final stages of a given crop cycle is necessary for the estimation of the crop evapotranspiration (ETc) curve throughout the crop cycle.

Gutiérrez and Meinzer¹⁴ obtained a Kc 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 Kc 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 (ET0) estimated using the FAO Penman–Monteith equation. Arruda et al.¹⁶ presented Kc 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 ETc and Kc of a coffee plant (Coffea arabica L.) four years after pruning using the water balance method, and obtained ETc between 1.23 and 4.39 mm d⁻¹ and Kc ranging from 0.59 to 1.16.

However, according to Lima and Silva¹⁸, the determination of irrigation depths using Kc may be prone to error if the conditions of the sites from which the Kc 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 Kc value cannot be established for all climatic situations; therefore, a crop coefficient should be determined for each stage of crop development¹⁹. According to Carr²⁰ in Zimbabwe an approach is used that allows Kc 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).
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.

The soil in the experimental site is classified as Dystroferric Red Latosol with a very clayey texture. 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. 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).

$$ET_c = I - \Delta A,$$  \hspace{1cm} (1)

where ET$_c$ is the crop evapotranspiration (mm), I the irrigation (mm) and $\Delta A$ is the storage variation (mm).

To determine ET$_o$ we used the Penman–Monteith equation parameterized by FAO$^{13}$.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma C_o\Delta u_2(e_v - e_a)}{\Delta + \gamma(1 + e_o u_2)},$$  \hspace{1cm} (2)

where ET$_o$ is the reference evapotranspiration (mm day$^{-1}$); $\Delta$ 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$^{-1}$), $\gamma$ 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$^{-1}$), $e_v$ the water steam saturation pressure (kPa); $e_a$ the partial steam pressure (kPa) and $C_o = 900$ 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:

$$K_c = \frac{\sum ET_c/\Delta t}{\sum ET_o/\Delta t},$$  \hspace{1cm} (3)

where ET$_c$ is the crop evapotranspiration (mm), ET$_o$ the reference evapotranspiration (mm) and $\Delta t$ 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) 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 $D$ was adjusted to the logistic model according to eqs (4) and (5) respectively, as given below

$$Y_{lh} = d_{lh} \left[1 + b_{lh} e^{(-c_{lh}t)}\right]^{-1},$$  \hspace{1cm} (4)

$$Y_{ld} = d_{ld} \left[1 + b_{ld} e^{(-c_{ld}d)}\right]^{-1},$$  \hspace{1cm} (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, \(a_{1Lh}, b_{1h} \) and \(c_{1h}\) are adjustment parameters of the logistic model for plant height, \(a_{1Dc}, b_{1D} \) and \(c_{1D}\) 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

\[
LA = 2\pi \left( \frac{DP^p DC^p + DP^p HP^p + DC^p HP^p}{3} \right)^{1/3},
\]

where \(LA\) is the leaf area (\(m^2 \) 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 \(2.5 \times 0.6\) m.

\[
LAI = LA \times \frac{N_p}{10,000},
\]

where \(LAI\) is the leaf area of the canopy (\(m^2 \) 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)).

\[
K_{cL} = a_{L} LAI + b_{L},
\]

\[
K_{cP} = a_{P} LAI^2 + b_{P} LAI + c_{P},
\]

\[
K_{cLg} = a_{Lo} \left[1 + b_{Lo} e^{-c_{Lo} LAI}\right]^{-1},
\]

\[
K_{cGo} = a_{Go} e^{-b_{Go} c_{Go} LAI},
\]

where \(K_{cL}\) is the \(K_c\) value (dimensionless) predicted by the linear model, \(K_{cP}\) the \(K_c\) value (dimensionless) predicted by the polynomial model, \(K_{cLg}\) the \(K_c\) value (dimensionless) predicted by the logistic model, \(K_{cGo}\) the \(K_c\) value (dimensionless) predicted by the Gompertz model, \(a_L\) and \(b_L\) are parameters of adjustment of the linear equation; \(a_P, b_P\) and \(c_P\) 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

\[
R^2 = 1 - \frac{SQ_{R}}{SQ_{tot}},
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum (O_i - E_i)^2},
\]

\[
E_f = \frac{\left[\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (O_i - E_i)^2\right]}{\sum_{i=1}^{n} (O_i - \bar{O})^2},
\]

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
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; 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 E\(_{\text{To}}\), 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 E\(_{\text{To}}\), E\(_{\text{Tc}}\) and \(K_c\) 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 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

<table>
<thead>
<tr>
<th>Period</th>
<th>( \text{ET}_o/\Delta t ) (mm d(^{-1}))</th>
<th>( \text{ET}_c/\Delta t ) (mm d(^{-1}))</th>
<th>( K_c )</th>
<th>Leaf area index (LAI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13–29 August 2007</td>
<td>2.8998</td>
<td>0.6323</td>
<td>0.2180</td>
<td>0.08</td>
</tr>
<tr>
<td>4 September–17 October 2007</td>
<td>3.5072</td>
<td>0.7382</td>
<td>0.2105</td>
<td>0.11</td>
</tr>
<tr>
<td>28 April–28 May 2008</td>
<td>2.0113</td>
<td>0.7728</td>
<td>0.3842</td>
<td>0.61</td>
</tr>
<tr>
<td>19–26 August 2008</td>
<td>2.8449</td>
<td>0.8100</td>
<td>0.2847</td>
<td>1.18</td>
</tr>
<tr>
<td>2–5 September 2008</td>
<td>3.1913</td>
<td>0.7620</td>
<td>0.3321</td>
<td>1.42</td>
</tr>
<tr>
<td>18 May–1 June 2009</td>
<td>1.8099</td>
<td>0.4701</td>
<td>0.7851</td>
<td>3.25</td>
</tr>
<tr>
<td>14 July–17 August 2009</td>
<td>3.1495</td>
<td>1.1115</td>
<td>0.3529</td>
<td>1.37</td>
</tr>
<tr>
<td>28 August–3 September 2009</td>
<td>4.2586</td>
<td>1.4145</td>
<td>0.3321</td>
<td>1.42</td>
</tr>
<tr>
<td>31 August–6 September 2010</td>
<td>3.4162</td>
<td>1.7902</td>
<td>0.5240</td>
<td>2.44</td>
</tr>
<tr>
<td>10–14 September 2010</td>
<td>3.4226</td>
<td>1.6380</td>
<td>0.4786</td>
<td>2.47</td>
</tr>
<tr>
<td>4–9 February 2011</td>
<td>4.2286</td>
<td>2.5927</td>
<td>0.6131</td>
<td>2.87</td>
</tr>
<tr>
<td>28 June–8 July 2011</td>
<td>1.4547</td>
<td>1.1422</td>
<td>0.7851</td>
<td>3.25</td>
</tr>
<tr>
<td>12–19 July 2011</td>
<td>1.5978</td>
<td>1.2973</td>
<td>0.8119</td>
<td>3.27</td>
</tr>
<tr>
<td>28 July–2 August 2011</td>
<td>3.1954</td>
<td>2.1580</td>
<td>0.6754</td>
<td>3.31</td>
</tr>
<tr>
<td>9–16 August 2011</td>
<td>2.6428</td>
<td>1.7119</td>
<td>0.6478</td>
<td>3.34</td>
</tr>
<tr>
<td>6–20 September 2011</td>
<td>3.2211</td>
<td>2.1796</td>
<td>0.6767</td>
<td>3.42</td>
</tr>
<tr>
<td>28 February–2 March 2012</td>
<td>4.1034</td>
<td>2.0534</td>
<td>0.5374</td>
<td>3.78</td>
</tr>
<tr>
<td>27–31 July 2012</td>
<td>2.0873</td>
<td>1.5007</td>
<td>0.7190</td>
<td>4.07</td>
</tr>
<tr>
<td>6–9 October 2012</td>
<td>3.6339</td>
<td>1.9865</td>
<td>0.5467</td>
<td>4.19</td>
</tr>
<tr>
<td>18–25 April 2013</td>
<td>2.3626</td>
<td>1.9378</td>
<td>0.8202</td>
<td>4.49</td>
</tr>
<tr>
<td>10–20 May 2013</td>
<td>2.1570</td>
<td>1.8088</td>
<td>0.8386</td>
<td>4.52</td>
</tr>
<tr>
<td>20–27 June 2013</td>
<td>1.8524</td>
<td>1.1357</td>
<td>0.6131</td>
<td>4.57</td>
</tr>
<tr>
<td>1–9 August 2013</td>
<td>3.3667</td>
<td>2.4104</td>
<td>0.7160</td>
<td>4.63</td>
</tr>
</tbody>
</table>

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 \( R^2 \)

<table>
<thead>
<tr>
<th>Model</th>
<th>( a_{Li} )</th>
<th>( b_{Li} )</th>
<th>RMSE</th>
<th>( E_f )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear model (eq. (11))</td>
<td>0.1197</td>
<td>0.2198</td>
<td>0.0930</td>
<td>0.9999</td>
<td>0.7964</td>
</tr>
<tr>
<td>Polynomial model of the second degree (eq. (12))</td>
<td>( a_{po} )</td>
<td>( b_{po} )</td>
<td>( c_{po} )</td>
<td>RMSE</td>
<td>( E_f )</td>
</tr>
<tr>
<td>Polynomial model of the second degree (eq. (12))</td>
<td>( a_{po} )</td>
<td>( b_{po} )</td>
<td>( c_{po} )</td>
<td>RMSE</td>
<td>( E_f )</td>
</tr>
<tr>
<td>Logistic model (eq. (13))</td>
<td>0.7984</td>
<td>1.1426</td>
<td>0.7776</td>
<td>0.0875</td>
<td>0.9999</td>
</tr>
<tr>
<td>Gompertz model (eq. (14))</td>
<td>( a_{Go} )</td>
<td>( b_{Go} )</td>
<td>( C_{Go} )</td>
<td>RMSE</td>
<td>( E_f )</td>
</tr>
<tr>
<td>Gompertz model (eq. (14))</td>
<td>( a_{Go} )</td>
<td>( b_{Go} )</td>
<td>( C_{Go} )</td>
<td>RMSE</td>
<td>( E_f )</td>
</tr>
</tbody>
</table>

\[ \text{Figure 2.} \] Crop coefficient \( (K_c) \) as a function of leaf area index (LAI) for Arabica coffee plants.
height varying from 2 to 3 m. These results also corroborate the data obtained by Arruda et al.\textsuperscript{15}. For drip-irrigated coffee plants, Flumingnan et al.\textsuperscript{27} recommend $K_c$ values of 0.76 and 0.91 for $E_{T_o} \geq 3.0$ and $<3.0$ mm day\textsuperscript{-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.\textsuperscript{25} for LAI $< 1.5$ and lower for LAI $> 1.5$. According to Pereira et al.\textsuperscript{25}, 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\textsuperscript{14}, and Pereira et al.\textsuperscript{25} evaluated the $K_c$ and LAI values of the irrigated coffee plant. Figure 3 shows a comparison of the results observed in this study with those obtained by Gutiérrez and Meinzer\textsuperscript{14}, and Pereira et al.\textsuperscript{25}. In the study by Gutiérrez and Meinzer\textsuperscript{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\textsuperscript{2} m\textsuperscript{-2}. The $K_c$ values for LAI $< 1.5$ m\textsuperscript{2} m\textsuperscript{-2} were higher than those obtained by Pereira et al.\textsuperscript{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\textsuperscript{14} presented $K_c$ values for LAI up to 7.5 m\textsuperscript{2} m\textsuperscript{-2}, and in this study, the highest LAI value was approximately 5 m\textsuperscript{2} m\textsuperscript{-2}. Thus, the data of Gutiérrez and Meinzer\textsuperscript{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 $a_{L_o} = 0.80$ 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\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.

1. Arantes, K. R., Faria, M. A. and Rezende, F. C., Recovery of the coffee tree (Coffea arabica L.) after reception, submitted to different

Figure 3. $K_c$ as a function of LAI in the present study compared to those obtained by Pereira et al.\textsuperscript{25}, and Gutiérrez and Meinzer\textsuperscript{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\textsuperscript{14}.

ACKNOWLEDGEMENTS. We thank Consórcio Pesquisa Café, the Research Support Foundation of the State of Minas Gerais (FAPEMIG) and the Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil for financial support.

Received 20 April 2020; revised accepted 14 November 2021

doi: 10.18520/cs/v122/i1/70-76