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Leaf area index and radiation extinction coefficient of a coffee canopy under variable drip irrigation levels

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ABSTRACT. The leaf area index (LAI) is relevant in studies of phenomena at different scales, such as for the leaf to canopy scale and the calculation of the extinction coefficient of photosynthetically active radiation (kPAR), providing input for the parameterization of physiological basis models. The objective of this work was to verify the variation of the LAI and the coffee kPAR subjected to different drip irrigation levels (130, 100, 70, and 40%) and to compare the data obtained from radiation bar linear sensors (SunScan) in the plants that received full irrigation with the values found by other LAI estimation methodologies. The study was conducted in Piracicaba, São Paulo State, Brazil, using the species *Coffea arabica* cv. Red Catuaí IAC 144; a drip irrigation system was adopted, with the irrigation controlled by tensiometry. The mean LAI values were higher in the L130 (irrigation level of 130%) and L100 (irrigation level of 100%) treatments than those with deficit irrigation depths. The mean kPAR values were lower for the L130 and L100 treatments than the values found in the deficit irrigation depth treatments. When comparing SunScan to other methodologies, the mean error (ME) and absolute mean error (AME) were high.

Keywords: *Coffea arabica*; LAI; SunScan; water deficit.

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Introduction

Water deficiency is a limiting factor responsible for most of the gap in coffee yield production because it affects several aspects of plant growth. The most visible effects of water stress are the reduction of plant size, leaf area and crop productivity. The degree of damage caused by the water deficit depends considerably on the phenological stage of the plant in which the stress occurs and on the duration of the stress (DaMatta & Ramalho, 2006; Silva et al., 2010; Costa et al., 2018).

A decrease in leaf area is one of the results of a water deficit and can be considered as the first defense against drought. Water stress not only limits the size of each leaf but also increases the leaf abscission rate (Farias, Fernandes, Azevedo, & Dantas Neto, 2008; Grisi et al., 2008).

The leaf area index (LAI) is an important variable used to estimate water, carbon and energy flows. This index is relevant in studies related to the knowledge of phenomena at different scales, such as for the leaf to canopy scale and the calculation of the extinction coefficient of photosynthetically active radiation (kPAR), providing important information for the parameterization of physiological basis models (Sasaki, Imanishi, Ioki, Morimoto, & Kitada, 2008; Taugourdeau et al., 2014).

In coffee trees, leaf volume variations associated with management decisions may influence the LAI dynamics. Despite its importance, determination of the LAI of coffee is not a simple task, since the methods proposed are often exhaustive, and in many cases, the destruction of plants is necessary. In general, these methods are developed from radiation penetration studies in the canopy and have limitations that provide underestimated LAI values (Silva et al., 2009; Rakocevic & Androcioli-Filho, 2010; Schleppi, Thimonier, & Walthert, 2011, Costa et al., 2019).

The search for methods that estimate the LAI of a coffee plant in a precise, non-destructive manner and that consider the particularities of the coffee culture that affect the LAI (such as irrigation management) is of great importance for the research community and may help guarantee confidence in productivity predictions (Antunes, Pompelli, Carretero, & DaMatta, 2008; Pocock, Evans, & Memmott, 2010; Ramirez & Zullo Júnior, 2010; Groenendijk et al., 2011).

The objective of this work was to verify the behavior of the LAI and the radiation extinction coefficient of coffee plants with different irrigation depths and to compare the data obtained from radiation bar linear sensors (SunScan-Delta-T Devices Ltd, London) in plants that received variable irrigation levels with the values calculated by other methodologies of LAI estimation.

Material and methods

Location and characterization of the experiment area

The experiment was carried out under greenhouse conditions located in the experimental area of the Biosystems Engineering Department, University of São Paulo, in Piracicaba / São Paulo State, Brazil. The geographical coordinates of the experiment area are as follows: 22° 42' 45" south latitude and 47° 37' 54" west longitude. The local altitude is approximately 543 meters.

The greenhouse had a total area of 160 m^2 and was 3 m high, with a transparent 150 micron polyethylene film cover and closed sides covered by a "type screen with 30% interception. The structure was supplied with 56 containers (500 L each), and at the bottom of each container was a 5-cm-thick layer of gravel coated with a geotextile blanket (Costa, Almeida, Coelho, Folegatti, & José, 2015; Costa et al., 2018). The soil used inside the containers is classified as a eutrophic Red Nitosol, clay phase, called "Luiz de Queiroz Series".

Irrigation management

The irrigation system adopted was drip irrigation with a self-compensating emitter. Each vase had two drippers with an output flow rate of 8 L h^{-1}. This flow was divided into four points on the vase by mini-cuttings. The system was a pressurized centrifugal pump with an engine power of 0.5 hp. Uniformity tests were performed using the uniformity coefficients of CUC and CUD distribution, and uniformities of 97.4% and 94.8%, respectively, were obtained.

The irrigation management was based on matric potential readings, measured with 12 tensiometers installed at three depths (20, 40, and 60 cm) in four containers. Soil water matric potential readings were made with a digital puncture tensiometer calibrated against a mercury column vacuometer. There was a three-day interval between the readings, and data were collected from 7 to 8 o'clock, when the data variation was minimal. To perform the calculations of irrigation management, a spreadsheet was set up in Microsoft Excel®.

Experimental design and treatments

A randomized complete block design was used with four blocks and four irrigation levels. The experimental unit was represented by a vase with a plant. The irrigation levels applied were as follows: L130 - 130%, L100 - 100%, L70 - 70%, and L40 - 40%. The reference level (L100) kept the soil moisture at the field capacity (θcc) throughout the experiment, which corresponds to the 100% ETc replacement. The L40, L70, and L130 irrigation levels were variations in the applied fraction taken as reference to the L100 treatment.

The execution of these treatments was carried out over a 25 days period. This period of time was defined from a previous experiment showing that this period was sufficient for variation in the plant water potential; moreover, this period did not compromise the plants that would be used in future evaluations. The evaluations were carried out on adult plants (3 years old) of the species *Coffea arabica* cv. Red Catuaí IAC 144. After the application of the irrigation treatments, all the plants received full irrigation.

Evaluations and data analysis

SunScan equipment was used in order to evaluate the photosynthetically active incident radiation (PARi) in the plant canopy and is composed of a bar with 64 PAR radiation sensors measuring 1 meter in length, a handheld computer that stores the sensor readings and a solar radiation sensor (direct and diffuse) incident on the canopy (Figure 1a). The radiation sensors incident on the canopy register a reading at the same time as it is read with the sensor bar in the crop canopy. This makes it possible to calculate the percentage of radiation intercepted by the upper portions of the canopy and the percentage of non-intercepted radiation (incident radiation) at each point on the plant.

Readings were performed at 36 different points, defined by quadrants of a 20 cm x 30 cm spatial canopy grid, according to Figure 1b. With the data obtained, the PARi percentage was calculated at each point on the plant using Equation 1. From these data, PARi maps were prepared along the quadrants sampled on the plant.

$$PARi = \frac{PARcanopy}{PARtop}\,100 \qquad (1)$$

where: PARi – photosynthetically active radiation incident, %; PARcanopy – photosynthetically active radiation incident on a particular portion of the canopy, μmol m^{-2} s^{-1}; and PARtop – photosynthetically active radiation incident on the inner top of the greenhouse, μmol m^{-2} s^{-1}.

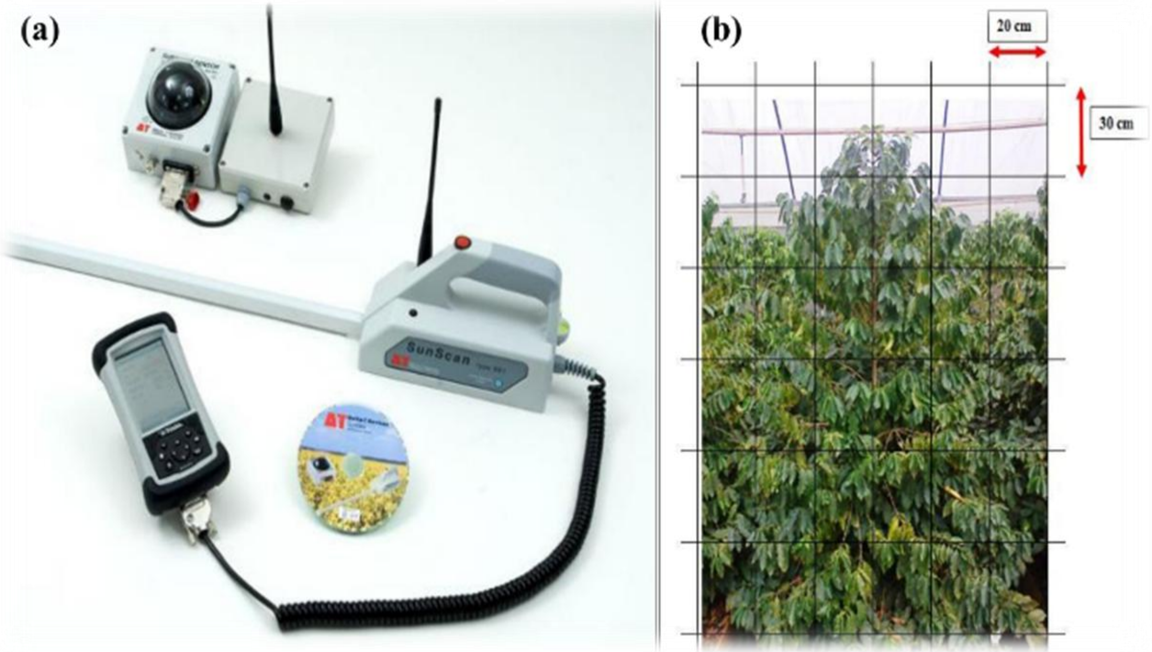

Figure 1. SunScan equipment used to measure the fraction of photosynthetically active incident radiation (PARi) (a); Quadrant scheme evaluated in the plant canopy (b).

The mean value was also calculated between the points sampled in the upper, middle and lower third of the canopy, thus defining an average for each portion of the plant. In this situation, Tukey's averages test was performed at 5% probability using Sisvar software.

The leaf area index (LAI) was determined at the same 36 points on the plants, defined by 20 x 30 cm quadrants placed across the canopy. With these data, the averages were calculated between the points sampled in the upper, middle and lower third of the canopy, thus defining an average for each portion of the plant. Tukey's averages test was then performed at 5% probability with Sisvar software (Ferreira, 2011).

The kPAR was determined from the PARi and LAI measured by the SunScan system, using Equation 2:

$$\mathrm{kPAR} = -\frac{\ln\left(\frac{\mathrm{PARt}}{\mathrm{PARi}}\right)}{\mathrm{LAI}} \qquad (2)$$

where: PARt – photosynthetically active radiation transmitted below the upper third of the plant, MJ m^{-2}; PARi – photosynthetically active radiation incident above the canopy, MJ m^{-2}; and LAI – index of leaf area, dimensionless.

The LAI (SunScan methodology) and kPAR obtained for plants under the full irrigation level (L100) were compared with values calculated by other methods and authors. The comparison was made using the mean error (ME) and the absolute mean error (AME).

Results and discussion

For the PARi percentage maps of the quadrants sampled in the coffee tree canopy, different color patterns were observed as a function of the irrigation level treatments and the portions of the plant. In the map in Figure 2a, created from the mean data of plants subjected to the L130% treatment, it was found that the percentage of PARi was approximately 90% in the upper quadrants. In the middle and lower quadrants, this value was approximately 35% and 4%, respectively. The map of the plants subjected to the L100% treatment (Figure 2b) presented a similar pattern to the map of the plants subjected to the L130% treatment.

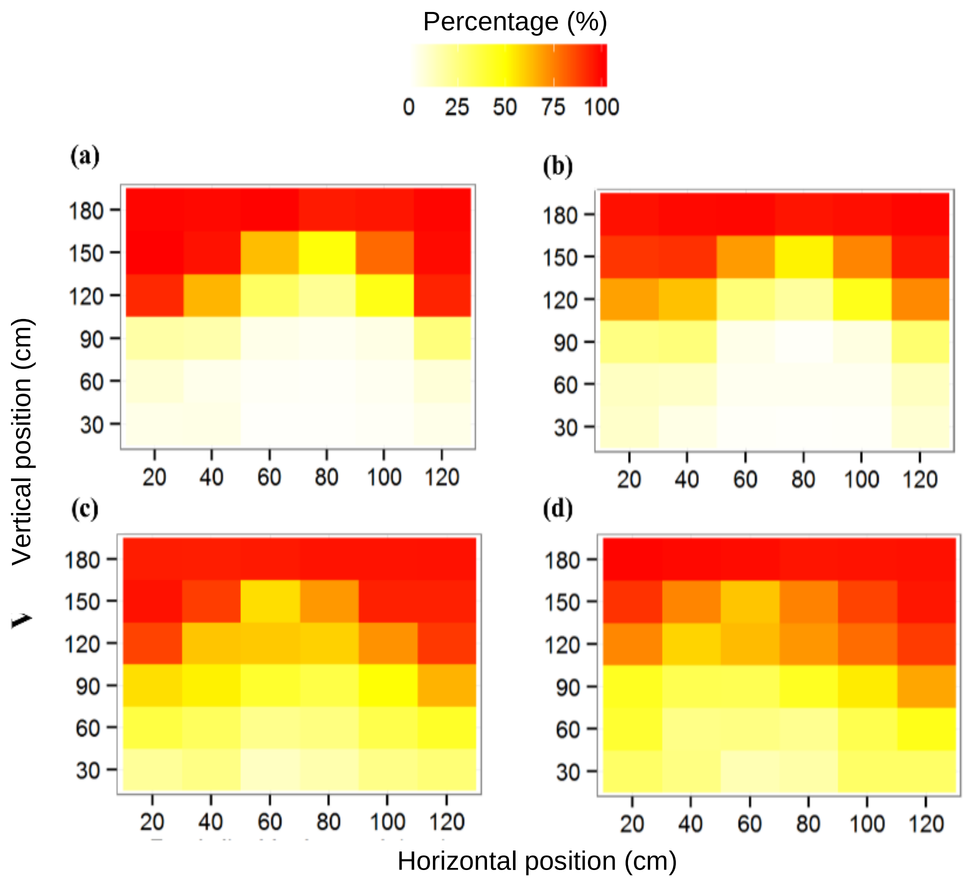

Figure 2. Maps of the percentage of photosynthetically active incident radiation (PARi) in each quadrant sampled in the coffee canopy. Map with the average PARi of the plants subjected to the L130% treatment (a); Map with the average PARi of the plants subjected to the L100% treatment (b); Map with the average PARi of the plants subjected to the L70% treatment (c); and Map with the average PARi of the plants subjected to the L40% treatment (d).

For the maps of the plants subjected to the L70% (Figure 2c) and L40% (Figure 2d) treatments different patterns were verified in relation to the maps of the plants subjected to the L130% and L100% treatments. In these maps of plants subjected to treatments with deficit irrigation depths, it was verified that the percentage of PARi was approximately 90% in the upper quadrants, and in the middle and lower quadrants, this value was approximately 60% and 27%, respectively.

The percentage of PARi in the upper, middle and lower third of plants subjected to different irrigation depths differed significantly at a 5% probability level by Tukey's test (Figure 3). As expected, it was observed that in all irrigation depths, the percentage of PARi was higher in the upper third than in the middle and lower third. These percentages were also higher in the middle third than in the lower third at all irrigation depths.

These results are consistent with those of Marin et al. (2003), who established that in the canopy tops, a vertical gradient of irradiance in the canopy is formed through the attenuation of solar radiation, and with the results of Righi et al. (2008), who verified a horizontal gradient of irradiance, according to the dimensions of the rocks and the incident angle of the solar radiation.

Analyzing the percentage of PARi in the upper third, it was verified that it was not significantly different in the different irrigation levels. In the middle and lower third, the percentage of PARi in the L130% and L100% treatments was significantly different from the L70% and L40% treatments.

This difference presented by treatments with deficit irrigation levels was possibly caused by the defoliation of the upper portions of the plant, which allowed an increase in the percentage of PARi in the middle and lower portions.

These results are in agreement with Pilau and Angelocci (2014), who affirmed that the vertical and horizontal gradients of irradiance in the canopy are continuously altered by variations of the leaf area caused by the environmental conditions or the processes of conduction of the coffee tree that interfere directly in the interception of the solar radiation.

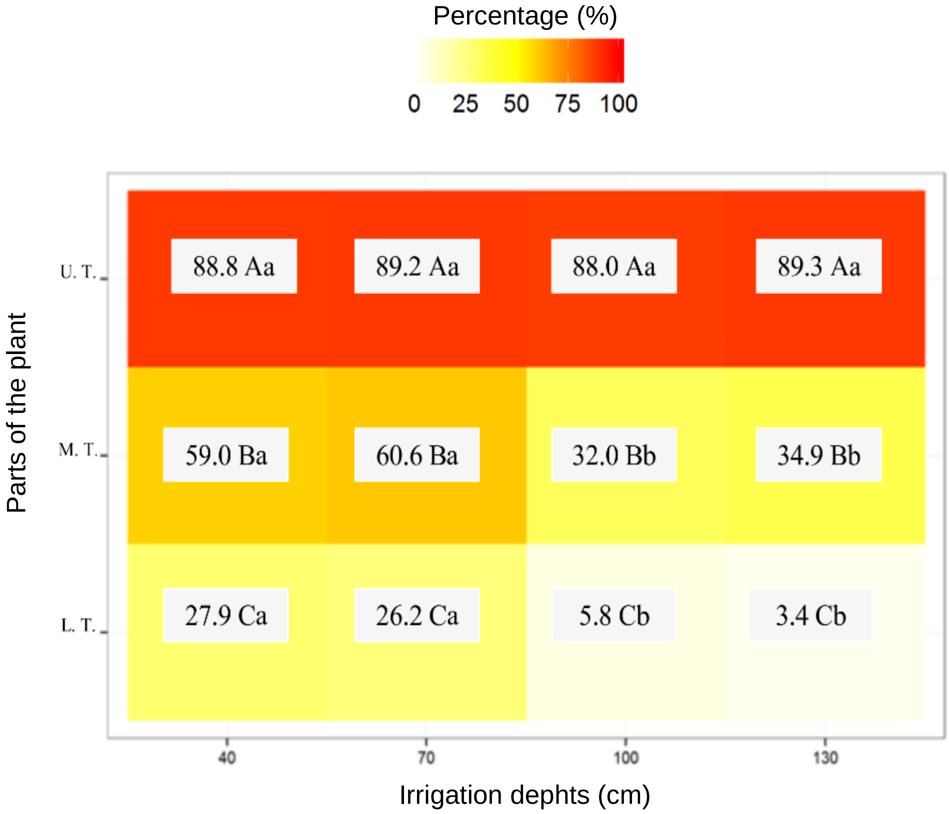

Figure 3. Percentage of photosynthetically active incident radiation (PARi) in the upper third (UT), middle third (MT) and lower third (LT) of plants subjected to different irrigation depths (L130%, L100%, L70%, and L40%). Distinct capital letters within the same irrigation depth and distinct lowercase letters within the same plant part differ from each other at a 5% probability level by Tukey's test.

The mean kPAR and LAI values of the three parts of the coffee plant subjected to different irrigation levels can be seen in Table 1. As expected, the LAI of the upper third was smaller than the LAI of the middle and lower thirds. In the upper part of the plant, the LAI found was 1.78 on average, and in the middle and lower portion, the values found, on average, were 3.83 and 6.5, respectively. According to Cunha and Volpe (2010), the attenuation of solar radiation is a function of the LAI because the increase of the intercepted photosynthetically active radiation is always related to the increase in the LAI.

For the lower part of the coffee tree, the LAI was higher in the plants subjected to the L130 and L100 treatments than in the plants that received the irrigation depths of 70% and 40%. In the middle third, the LAI found was not differentiated in the plants subjected to the L40, L70, and L100 treatments, and the highest LAI value found in that portion was for the plants that received an irrigation depth of 130%. In addition, in the upper third of the plants, there was no difference among the LAI values of the plants subjected to the four treatments.

The average LAI (for the whole plant) values found for the plants that received the L130, L100, L70, and L40 treatments were 4.7, 4.2, 3.7, and 3.5, respectively. The mean LAI values were higher for the plants subjected to the L130 and L100 treatments than the values found in coffee trees that received deficit irrigation depths (70% and 40%).

For the plants receiving the L130, L100, L70, and L40 treatments, kPAR values of 0.24, 0.29, 0.74, and 0.93, respectively, were found. The mean kPAR values were lower for the plants subjected to the L130 and L100 treatments than the values found in the coffee trees that received deficit irrigation depths (70% and 40%).

It was observed for the coffee trees with the different treatments that the kPAR decreases as a function of the LAI increase. This occurs because the interception of the photosynthetically active radiation is directly related to the LAI of the crop, so the radiation flux decreases exponentially with the increase of leaf area within the canopy (Cunha & Volpe, 2010).

Table 1. The leaf area index (LAI) and extinction coefficient of photosynthetically active radiation (kPAR) of the coffee tree subjected to different irrigation levels.

Parts of the plant	LAI SunScan			
	Irrigation levels (%)			
	130	100	70	40
Lower third	7.5 Aa	6.8 Aa	6.1 Ab	5.6 Ab
Middle third	4.7 Ba	4.0 Bb	3.4 Bb	3.2 Bb
Upper third	2.0 Ca	1.8 Ca	1.6 Ca	1.7 Ca
LAI mean	4.7 a	4.2 a	3.7 b	3.5 b
kPAR mean	0.24 b	0.29 b	0.74 a	0.93 a

LAI - Index of leaf area; kPAR - extinction coefficient of photosynthetically active radiation. Distinct capital letters within the same irrigation depth and distinct lowercase letters within the same plant part differ from each other at a 5% probability level by Tukey's test

A comparison of the LAI and kPAR values obtained from the SunScan system with values found from other methodologies (Cunha & Volpe, 2010; Favarin, Dourado Neto, García, Villa Nova, & Favarin, 2002; Marin et al., 2003) can be observed in Table 2.

Using one of the equations adjusted by Favarin et al. (2002), an LAI of 2.96 was found; in comparison, the LAI found from the SunScan system had a ME of -1.24 and an AME of 1.24. A second equation also fitted by Favarin et al. (2002) found an LAI of 4.86; in comparison, the LAI found from the SunScan system had a ME and AME of 0.66.

Cunha and Volpe (2010) studied the cultivar Obatã IAC 1669-20, aged 5 years and planted with a 3.5 x 0.5 m spacing, and found an LAI of 2.5 for coffee; in comparison, the LAI obtained from the SunScan system had a ME and AME of 0.70.

Table 2. Comparison of leaf area index (LAI) and extinction coefficient of photosynthetically active radiation (kPAR) obtained from the SunScan system with values found from other methodologies.

Citation	Cultivate	Age	Spacing	LAI	ME	AME
Favarin et al. (2002)[1*]	Mundo Novo IAC 388-17	2.5 years	2.5 x 1.0 m	2.96	-1.24	1.24
Favarin et al. (2002)[2*]				4.86	0.66	0.66
Cunha and Volpe (2010)	Obatã IAC 1669-20	5 years	3.5 x 0.5 m	2.50	0.70	0.70
Marin et al. (2003)	Mundo Novo Apuatã	4 years	2.5 x 1.0 m	5.29	1.09	1.09
Citation	Cultivate	Age	Spacing	LAI	ME	AME
Cunha and Volpe (2010)	Obatã IAC 1669-20	5 years	3.5 x 0.5 m	0.54	0.25	0.25
Marin et al. (2003)	Mundo Novo Apuatã	4 years	2.5 x 1.0 m	0.79	0.50	0.50

[1]The equation $LAI = 0.0134 + 0.7276Di^2Hd$ was used; [2]The equation $LAI = -0.5786 + 0.6201Di$ (Di2 + 4Hd2) 0.5 was used; * In both situations, it was considered that Di = 1.5 m and Hd = 1.8 m; LAI - leaf area index; kPAR - extinction coefficient of photosynthetically active radiation; ME - mean error; AME - absolute mean error.

Marin et al. (2003) studied the cultivar Mundo Novo Apuatã, aged 4 years and planted with a 2.5 x 1.0 m spacing, and found an LAI of 5.29 for the coffee tree; in comparison, the LAI obtained from the SunScan system presented an AME and ME of 1.09. According to Barbosa et al. (2012), the LAI estimation methods used for coffee trees (*Coffea arabica* L.) present limitations related to the representation of crop particulates that affect LAI in time and space, which may explain the difference in LAI values when using different LAI methodologies.

Regarding the comparison of the kPAR, Cunha and Volpe (2010) found a kPAR of 0.54 for the coffee tree; in comparison, the kPAR obtained from the SunScan system presented a ME and AME of 0.25. Additionally, Marin et al. (2003) found a kPAR of 0.79 for the coffee tree; in comparison, the kPAR obtained from the SunScan system presented an ME and an AME of 0.50.

Conclusion

The average LAI values found for the plants receiving the L130, L100, L70, and L40 treatments were 4.7, 4.2, 3.7, and 3.5, respectively. The LAI was higher in the L130 and L100 treatments. The mean kPAR was lower for the L130 and L100 treatments than the values found for the deficit irrigation depths.

Based on the comparison of using the SunScan system versus that of other methodologies, the ME and

AME were high, which can be explained by the limitations of the methods related to the representation of cultivation particularities that affect the LAI in time and space.

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