MAPPING AND QUANTIFICATION OF WATER CONSUMPTION IN BEAN CROPS USING THE METRIC ALGORITHM

Jéfferson de Oliveira Costa[1], Rubens Duarte Coelho[2], Jefferson Vieira José[3], Carlos Alberto Quiloango-Chimarro[4], Wagner Wolff[5]

ABSTRACT: The evapotranspiration (ET) and crop coefficient (Kc) spatial variabilities are disregarded in traditional methods of evapotranspiration estimation based on lysimeters. With the development of remote sensing techniques, the estimative of ET on agricultural areas, in a spatialized way, has become possible through the use of algorithms based on the surface energy balance such as the METRIC and its automated version, featured on the Google Earth Engine Evapotranspiration Flux (EEFlux) platform. This study was conducted at a center pivot irrigated area located in the city of Primavera do Leste, MT, Brazil. Four growing cycles (2013, 2014, 2015 and 2017) of the species *Phaseolus vulgaris* (Carioca bean) and *Vigna unguiculata* (Caupi bean) were analyzed. Using images from the Landsat 8 satellite, within the EEFlux platform, the spatial variability of the actual evapotranspiration (ETa) and the Kc curve of these two species were determined. The water use efficiency (WUE) was also determined. The ETa for Carioca bean ranged from 4.28 to 6.91 mm d^{-1} and the Kc obtained ranged from 0.8 to 1.16. For Caupi bean, the ETa obtained ranged from 2.75 to 5.19 mm d^{-1} and the Kc obtained ranged from 0.86 to 1.29. The WUE of Carioca and Caupi beans, on average, was 0.52 and 0.31 kg m^{-3}, respectively. The method of estimating ETa and Kc mapped using the Google EEFlux platform made it possible to understand the spatial variability of these two variables.

KEYWORDS: Irrigation, *Phaseolus vulgaris*, *Vigna unguiculata*.

MAPEAMENTO E QUANTIFICANDO O CONSUMO HÍDRICO DA CULTURA DO FEIJÃO UTILIZANDO O ALGORITMO METRIC

[1] Researcher, Minas Gerais Agricultural Research Agency/EPAMIG, CEP 39525000, Nova Porteirinha, MG. E-mail: costajo@alumni.usp.br
[2] Full professor, University of São Paulo, ESALQ-USP, Piracicaba, SP
[3] Adjunct professor, Federal University of Acre, UFAC, Cruzeiro do Sul, AC
[4] PhD student, University of São Paulo, ESALQ-USP, Piracicaba, SP
[5] Data Scientist / Researcher, Bayer company, Piracicaba, SP

RESUMO: A variabilidade espacial da evapotranspiração (ET) e do coeficiente de cultura (Kc) é desconsiderada quando estes são obtidos por meio de lisímetros. Com o desenvolvimento das técnicas de sensoriamento remoto a estimativa da ET de áreas agrícolas, de forma espacializada, tornou-se possível por meio do uso de algoritmos baseados no balanço de energia da superfície como o Mapping Evapotranspiration at high Resolution using Internalized Calibration (METRIC) e sua versão automatizada, presente na plataforma Google Earth Engine Evapotranspiration Flux (EEFlux). O estudo foi realizado em uma área irrigada por pivô central localizada no município de Primavera do Leste, MT, Brasil. Foram analisados quatro ciclos de cultivo (2013, 2014, 2015 e 2017) das espécies *Phaseolus vulgaris* (feijão carioca) e *Vigna unguiculata* (feijão caupi). Usando imagens do satélite Landsat 8, dentro da plataforma EEFlux, determinou-se a variabilidade espacial da evapotranspiração atual (ETa) e a curva do Kc dessas duas espécies avaliadas. A eficiência do uso da água (EUA) para as duas espécies também foi determinada. A ETa para o feijão carioca variou entre 4,28 a 6,91 mm d^{-1} e o Kc obtido variou entre 0,8 a 1,16, em termos gerais. Para o feijão caupi, a ETa obtida variou entre 2,75 a 5,19 mm d^{-1} e o Kc obtido variou entre 0,86 a 1,29, em termos gerais. A EUA do feijão carioca e do feijão caupi, em média, foi de 0,52 e 0,31 kg m^{-3}, respectivamente. O método de estimativa de ETa e Kc espacializados utilizando a plataforma Google EEFlux possibilitou a compreensão da variabilidade espacial dessas duas variáveis.

PALAVRAS-CHAVE: Irrigação, *Phaseolus vulgaris*, *Vigna unguiculata*.

INTRODUCTION

The estimation of plant water consumption is decisive for effective water management in agriculture. To plan the use and management of water in agricultural areas, knowledge of variables related to the climate, soil, and plants is essential. These variables include the reference evapotranspiration (ETo), crop coefficient (Kc), and crop evapotranspiration (ETc). Conventional techniques can be used to obtain these variables over a homogeneous surface; however, their accuracy may be limited owing to spatial variability and high cost. Hence, there is a need for more accurate and cost-effective methods to estimate these variables to improve agricultural water management.

In recent years, many remote sensing techniques have been used to quantify the evapotranspiration (ET) of agricultural areas on a large scale. Among the types of models and algorithms for obtaining ET, those based on surface energy balance are the most widely used.

Mapping Evapotranspiration at a high resolution using Internalized Calibration (METRIC) is one of the most widely used algorithms.

Studies conducted across different regions of the world have demonstrated that algorithms for estimating ET have shown satisfactory performance even with limited meteorological data. For instance, successful application of these algorithms can be found in studies conducted on cotton (JOSÉ et al., 2020), maize (COSTA et al., 2020), and coffee (COSTA et al., 2019). Traditional methods have been used to estimate ET and Kc in Carioca bean and Caupi bean cultivation areas in Brazil; however, the estimation of water consumption using the METRIC algorithm in the Google EEFlux version requires further investigation. It is expected that the use of remote sensing to estimate ET can improve irrigation management by considering the spatial variability of cultivated areas.

This research aimed to estimate the spatial distribution of ETa and the Kc curve of Carioca and Caupi beans, using the METRIC algorithm in the Google EEFlux version. Furthermore, we compared Kc estimates with FAO guidelines and other reference studies in Brazil and worldwide for Kc in bean crops.

MATERIAL AND METHODS

The study was conducted using data collected from a property located in the municipality of Primavera do Leste, Mato Grosso, Brazil (Figure 1). The property consisted of an irrigated area (central pivot) of approximately 130 ha, with a latitude of 15º13 S, longitude of 53º58'W, and an average altitude of 560 m. Two species of bean, *Phaseolus vulgaris* and *Vigna unguiculata*, were grown between 2013 and 2017.

The climate of the region is of type Aw (ALVARES et al., 2013), that is, tropical with dry winter season. The annual average temperature is 22.0°C and the average annual rainfall is 1784 mm. The difference between the precipitation of the driest month and the wettest month is 313 mm. The average temperature variation during the year is 4.5°C. The warmest month of the year is October with an average temperature of 23.4°C. During the month of July (the coldest month of the year) the average temperature is 18.9°C.

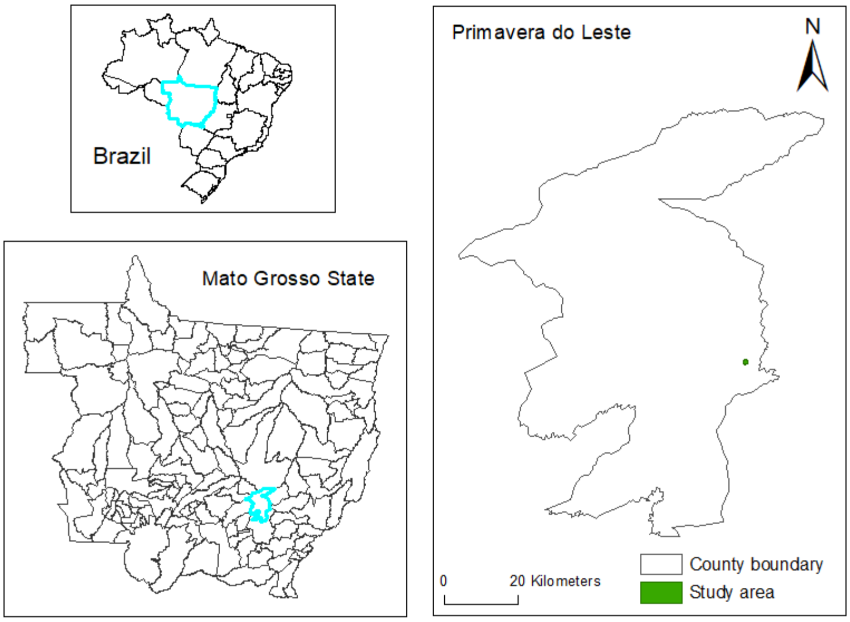

Figure 1. Location of the study area, details of the State of Mato Grosso, the municipality of Primavera do Leste and the area of the center pivot analyzed.

The relief is flat and the predominant soils of the region are dystrophic Red Latosols, which have low natural fertility, varying from deep to very deep, permeable, clayey and very clayey texture. In the region the vegetation of the Cerrado biome predominates (LOPES & GUILHERME, 2016).

Field data collected from four bean crops, including two years of Carioca bean and two years of Caupi bean were used in this study (Table 1). Both species were sown in two different seasons, in similar planting areas and growing cycles. Yield data from each crop were also used to calculate the water use efficiency (WUE) under different conditions.

Table 1. Characterization of the crops of Carioca bean (*Phaseolus vulgaris*) and Caupi bean (*Vigna unguiculata*) in the study area (Primavera do Leste - MT), throughout the years of 2013 and 2017.

Crop*	Planting date	Harvest date	Cycle (days)	Production** (Mg)	Productivity (Mg ha^{-1})
Carioca bean	07/08/2013	11/01/2013	86	329.33	2.52
Caupi bean	03/03/2014	06/06/2014	95	191.12	1.46
Caupi bean	04/12/2015	07/17/2015	96	153.10	1.17
Carioca bean	05/26/2017	08/24/2017	90	502.50	2.84

* in the years of planting of Carioca bean the cultivar Pérola was used and in the years of planting of the Caupi bean the cultivar Nova era was used; ** the total production was obtained in an area of 130.68 hectares, referring to the area irrigated by the central pivot irrigation system; Mg - Megagram; ha - hectares.

The WUE was calculated using the productivity data of the bean crop, as well as the data of the water consumption of the crop along its respective cycles, according to Equation 1 (GEERTS & RAES, 2009).

$$WUE = Y/10\ ET_{ac} \quad (1)$$

Where: WUE is the water use efficiency, (kg m^{-3}); Y is the bean yield, (kg ha^{-1}); and ETac is the total ET throughout the growing cycle, (mm).

As for the remote data, images of the sensors were used OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) of Landsat 8 satellite, scene path 225 and row 71 over the years 2013, 2014, 2015 and 2017 (Table 2). The satellite used has 16-day temporal resolution and 30-meter space resolution, according to the United States Geological Survey (USGS). These images were used to complement the field data and provide a more comprehensive understanding of the water-use patterns of crops.

Table 2. Landsat 8 satellite passage dates in which images of Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) were considered for the present study.

Carioca bean		Caupi bean	
2013	2017	2014	2015
August 26	June 18	March 22	April 26
September 11	July 4	April 7	May 28
September 27	July 20	May 9	June 13
October 13	August 5	May 25	June 29

The images of the Landsat 8 satellite used in this study were processed on Earth Engine Evapotranspiration Flux (EEFlux / METRIC version 0.20.2). The actual ET is calculated as a residual of the surface energy balance (ALLEN et al., 2007), according to Equation 2.

$$LE = Rn - H - G \quad (2)$$

Where: LE is the latent heat flux (referring to the energy used in the evapotranspiration process), (W m^{-2}); Rn is liquid radiation, (W m^{-2}); G is the heat flux in the soil, (W m^{-2}); and H is the sensible heat flux, (W m^{-2}).

EEFlux uses the Landsat thermal band and shortwave bands to estimate the surface energy balance and to estimate the amount of vegetation, albedo and surface roughness. The current version of EEFlux employs automated image calibration. EEFlux is calibrated by assigning values for EToF for the 'hot' and 'cold' parts (pixels) of the surface temperature spectrum of the scene.

To calculate the reference evapotranspiration (ETo), the maximum and minimum temperatures, solar radiation, wind speed, relative humidity, and precipitation from the meteorological station located in the study area were used. The Penman-Monteith method (FAO 56) was used to estimate the ETo for the days of the satellite passages, following the methodology adopted by Allen et al. (1998) using the REF-ET software version 2.01.14.

Using the ETo values obtained, the crop coefficient (Kc) for each phenological phase (I, II, III and IV) of the Carioca and Caupi bean plants was estimated. Specifically, the Kc values were derived by dividing the daily actual evapotranspiration (ETa) by the corresponding daily ETo. The term Kc was used throughout the work to represent what is actually Kc multiplied by the soil water stress coefficient (Ks) (ALLEN et al., 2007), that is, the soil was considered to be in the capacity of field on the days evaluated.

Descriptive statistical analyses of ETa and Kc data were conducted. This included an examination of the mean values for each period of the bean cycle considered in this study. The values of Kc of the Carioca and Caupi beans were compared to the Kc of the FAO-56 recommendations (ALLEN et al., 1998) and by reference studies in Brazil and the world (Table 3).

Table 3. Development conditions of the crop coefficient (Kc) studies of Carioca and Caupi beans, and the values used in the comparison of Kc of the beans estimated by METRIC (EEFLUX) with Kc recommended by these reference studies.

References	Dp	Variety	Irrigation system	Countries	
Allen et al. (1998)	**	**	*	EUA	Carioca bean
Albuquerque and Andrade (2011)	**	**	*	Brazil	Carioca bean
Mendonça et al. (2007)	24	UENF 47	Conventional sprinkler	Brazil	Carioca bean
Medeiros et al. (2001)	14 28	Carioca 80-SH	*	Brazil	Carioca bean
Bastos et al. (2008)	16	BR-17 Gurguéia	Conventional sprinkler	Brazil	Caupi
Souza et al. (2005)	10	Setentão	Micro sprinkler	Brazil	Caupi
Murga-Orrillo et al. (2016)	20	Nova era	Conventional sprinkler	Brazil	Caupi
Saraiva and Souza (2012)	**	**	*	Brazil	Caupi

Dp - planting density (plants m^{-2}); * not specified; ** general conditions of cultivation.

RESULTS AND DISCUSSION

On the selected dates of I, II, III and IV phases of Carioca bean in 2013, the average ETa values were 6.07, 6.91, 6.71 and 5.69 mm d^{-1}, respectively (Table 4). In 2017, the representative dates of the initial, intermediate, and final phases of the Carioca bean had average ETa values of 4.65, 4.96, 428 and 5.21 mm d^{-1}, respectively. The average ETo values on the representative dates of I, II, III and IV phases of Carioca beans grown in 2013 were 7.40, 6.06, 5.78 and 7.11, respectively. In 2017, the representative dates of I, II, III and IV phases of Carioca beans had average ETo values of 5.81, 4.23, 3.93 and 6.28, respectively. Similarly, the average Kc values on the representative dates of I, II, III and IV phases of Carioca beans grown in 2013 were 0.86, 1.14, 1.16 and 0.80, respectively. In 2017, the representative dates of I, II, III and IV phases of Carioca beans had average Kc values of 0.80, 1.12, 1.09 and 0.86, respectively. The cumulative evapotranspiration (ETac) during the growing cycle in 2013 was 685.73 mm d^{-1}, while in 2017, it was 426.49 mm d^{-1}. In addition, water use efficiency (WUE) in 2013 and 2017 was 0.37 and 0.67 kg m^{-3}, respectively.

Table 4. Values of actual evapotranspiration (ETa), reference evapotranspiration (ETo), crop coefficient (Kc), accumulated evapotranspiration (ETac) in the Carioca bean and Caupi bean cycle and water use efficiency (WUE) for the different periods studied.

Carioca bean								
Year	2013				2017			
Month/Day	August 26	September 11	September 27	October 13	June 18	July 4	July 20	August 5
ET_a (mm d^{-1})	6.07	6.91	6.71	5.69	4.65	4.96	4.28	5.21
ET_o (mm d^{-1})	7.40	6.06	5.78	7.11	5.81	4.23	3.93	6.28
K_c	0.82	1.14	1.16	0.80	0.80	1.12	1.09	0.86
ET_{ac} (mm)	685.73				426.49			
WUE (kg m^{-3})	0.37				0.67			

Caupi bean								
Year	2014				2015			
Month/Day	March 22	April 7	May 9	May 25	April 26	May 28	June 13	June 29
ET_a (mm d^{-1})	5.19	4.95	4.48	2.75	4.29	3.91	4.16	4.35
ET_o (mm d^{-1})	6.03	4.46	3.47	3.09	5.43	3.31	3.68	5.06
K_c	0.86	1.11	1.29	0.89	0.79	1.18	1.13	0.86
ET_{ac} (mm)	434.19				440.21			
WUE (kg m^{-3})	0.34				0.27			

The ETa values for Caupi beans varied across the different stages of growth in 2014 and 2015. For instance, in 2014, the average ETa values were 5.19, 4.95, 4.48 and 2.75 mm d^{-1} during the I, II, III and IV phases of the crop, respectively. In 2015, the corresponding values were 4.29, 3.91, 4.16 and 4.35 mm d^{-1}. The average ETo values on the representative dates of I, II, III and IV phases of Carioca beans grown in 2014 were 6.03, 4.46, 3.47 and 3.09, respectively. In 2015, the representative dates of I, II, III and IV phases of Carioca beans had average ETo values of 5.43, 3.31, 3.68 and 5.06, respectively. The average Kc values for the Caupi beans varied across different stages of growth. For example, in 2014, the Kc values were 0.86, 1.11, 1.29 and 0.89 during the I, II, III and IV phases of the crop, respectively. The corresponding Kc values in 2015 were 0.79, 1.18, 1.13 and 0.86. The total ETa for Caupi bean cultivation during the growth cycle was 434.19 mm d^{-1} in 2014 and 440.21 mm d^{-1} in 2015. Furthermore, the WUE for Caupi bean cultivation was found to be 0.34 kg m^{-3} in 2014 and 0.27 kg m^{-3} in 2015.

Santana et al. (2014) obtained ETc values of Carioca beans using the soil water balance method in the Uberaba-MG region, which also showed variations as a function of the periods evaluated within the cycle (days after sowing) and the type of planted cultivar. The results of Medeiros et al. (2005) and Medeiros et al. (2016), in a study of Carioca beans in Campinas-SP, also corroborate the variability of ET values presented in this study. The results of Souza et al. (2005), Bastos et al. (2008) and Saraiva & Souza (2012) in studies with Caupi bean in the northeast region of Brazil, also corroborate with the variability of ET values presented in this work for this crop.

Medeiros et al. (2004) obtained Kc values of the Carioca bean using three different ETo estimation methods, in the Campinas-SP region, which presented a variability as a function of the leaf area index (LAI) and the ETo estimation method. Results found by Allen et al. (2005) and Tasumi et al. (2005), in studies with bean crop, also corroborate with the variability of Kc values presented. Results found by Souza et al. (2005), Bastos et al. (2008) and Saraiva & Souza (2012) in studies with Caupi bean in the northeast region of Brazil, also corroborate with the variability of Kc values presented in this work for this crop.

Regarding ETac, Bastos et al. (2008) found lower values (288.5 mm) for the Caupi bean in the northeast, and similar results were obtained by Murga-Orrillo et al. (2016). Bozkurt & Mansuroglub (2018) estimated the water consumption for the bean crop cycle and found values of 358 mm in the fall season and 533 mm in the spring season in Hatay Province, Turkey. Satriani et al. (2016) showed that ETac was 299.4 mm for the whole growing season. As for WUE, similar values were found by Doorenbos & Kassam (1979), 0.3 to 0.6 kg m^{-3} for bean, when 300 to 500 mm of water is used throughout the cycle. Soureshjani et al. (2019) found WUE values of 0.5 to 1.3 kg m^{-3} for beans subjected to water stress. WUE variation may be related to different amounts of water applied, the effects of climatic conditions, and the amount and type of fertilizer used (FAN et al., 2018).

Figure 2 shows the average values of Kc of Carioca bean (A) and Caupi bean (B) throughout their respective growth cycles including the Kc obtained in this study (Kc METRIC) as well as other Kc curves found in literature. The average Kc values for Carioca beans in the two years analyzed (2013 and 2017) increased from a minimum value in the initial phase (0.81) to a maximum value in the intermediate phase (1.13). This trend was expected because of an increase in leaf area (maximum values in the intermediate phases).

It was observed that the average Kc for Carioca beans obtained through the METRIC algorithm (Google EEFlux) was similar to the FAO Kc value (ALLEN et al., 1998) in the intermediate phase. However, it was different in the initial and final phases, which is consistent with the results of Tasumi et al. (2005). Thus, it is important to estimate the local Kc values. Differences in Kc values may be attributed to differences in the date of emergence, land use management, rainfall, leaf area, and atmospheric conditions such as air temperature, wind speed, and vapor pressure deficit (KAMBLE et al., 2013).

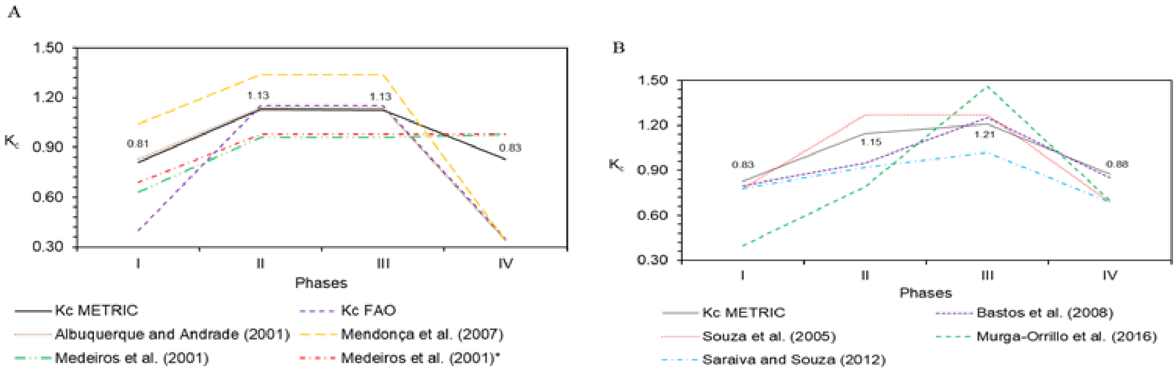

Figure 2. Kc curves of Carioca (A) and Caupi (B) beans, using the METRIC algorithm in the Google EEFlux version compared with other reference studies in Brazil and worldwide.

The Kc values of the Caupi bean obtained using the METRIC (Google EEFlux) algorithm was closest to the Kc values obtained in other studies conducted in Brazil (ALBUQUERQUE & ANDRADE, 2011; Mendonça et al., 2007; Medeiros et al., 2001). However, the Kc values reported by Murga-Orillo et al. (2016) differed significantly from the other four Kc curves. According to these authors, the Kc of Caupi bean may differ from these values because of local soil conditions and ETo estimation methods. Overall, estimation of ETa and Kc via remote sensing is a valuable tool that can be used in irrigation management.

CONCLUSIONS

The Google EEFlux platform proved to be a valuable tool for estimating actual evapotranpiration (ETa) and crop coefficient (Kc) at different stages of development of Carioca and Caupi bean plants, providing insights into their spatial variability. This method has the potential to contribute to a better understanding of the water requirements of these two bean species and to improve irrigation management in irrigated cropping systems.

The trend of the different Kc curves of the bean crop obtained using the METRIC methodology is similar to that of other reference studies in Brazil and worldwide. Carioca and Caupi beans showed average water use efficiency (WUE) values of 0.52 and 0.31 kg m^{-3}, respectively.

REFERENCES

ALBUQUERQUE, P. E. P.; ANDRADE, C. L. T. 2001. **Planilha eletrônica para a programação da irrigação de culturas anuais**. Sete Lagoas: Embrapa Milho e Sorgo, 14p. Circular Técnica, 10.

ALLEN, R. G.; PEREIRA, L. S.; RAES, D.; SMITH, M. 1998. **Crop evapotranspiration-Guidelines for computing crop water requirements-FAO**. Irrigation and drainage paper 56: FAO, Rome, Italy.

ALLEN, R. G.; PEREIRA, L. S.; SMITH, M.; RAES, D.; WRIGHT, J. L. 2005. FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. **Journal of irrigation and drainage engineering**, 131: 2-13.

ALLEN, R. G.; TASUMI, M.; TREZZA, R. 2007. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)-Model. **Journal of Irrigation and Drainage Engineering**, 133: 380-394.

ALVARES, C. A.; STAPE, J. L.; SENTELHAS, P. C.; GONÇALVES, J. L. M.; SPAROVEK, G. 2013. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, 22: 711-728.

BASTOS, E. A.; FERREIRA, V. M.; SILVA, C. D.; ANDRADE JÚNIOR, A. D. 2008. Evapotranspiração e coeficiente de cultivo do feijão-caupi no Vale do Gurguéia, Piauí. **Irriga**, 13: 182-190.

BOZKURT, S.; MANSUROGLU, G. S. 2018. Responses of unheated greenhouse grown green bean to buried drip tape placement depth and watering levels. **Agricultural Water Management**, 197: 1-8.

COSTA, J. O. 2019. **Spatial variability of water consumption of irrigated crops using remote sensing [Thesis]**. Piracicaba, University of São Paulo.

COSTA, J. O., COELHO, R. D., WOLFF, W., JOSÉ, J. V., FOLEGATTI, M. V., FERRAZ, S. F. B. 2019. Spatial variability of coffee plant water consumption based on the SEBAL algorithm. **Scientia agrícola**, 76: 93-101.

COSTA, J. O.; JOSÉ, J. V., WOLFF, W., OLIVEIRA, N. P. R., OLIVEIRA, R. C., RIBEIRO, N. L., COELHO, R. D., SILVA, T. J. A., BONFIM-SILVA, E. M., SCHLICHTING, A. F.

2020. Spatial variability quantification of maize water consumption based on Google EEflux tool. **Agricultural Water Management**, 232, 106037.

DOORENBOS, J.; KASSAM, A. H. 1979. **Yield response to water. Irrigation and drainage**. paper 33: 257.

FAN, Y.; WANG, C.; NAN, Z. 2018. Determining water use efficiency of wheat and cotton: A meta-regression analysis. **Agricultural Water Management**, 199: 48-60.

GEERTS, S.; RAES, D. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. **Agricultural Water Management**, 96: 1275-1284.

JOSÉ, J. V., OLIVEIRA, N. P. R., SILVA, T. J. A., BONFIM-SILVA, E. M., COSTA, J. O., FENNER, W., COELHO, R. D. 2020. Quantification of cotton water consumption by remote sensing. **Geocarto International**, 35(16), 1800-1813.

JOSÉ, J. V., OLIVEIRA, N. P. R., SILVA, T. J. A., BONFIM-SILVA, E. M., COSTA, J. O., SOUSA, H. H. F., 2019. Spatial-temporal dynamics of biome Cerrado using different vegetation indexes. **Aust. J. Crop Sci.**, 13, 1438-1446.

KAMBLE, B.; KILIC, A.; HUBBARD, K. 2013. Estimating crop coefficients using remote sensing-based vegetation index. **Remote sensing**, 5: 1588-1602.

LOPES, A. S.; GUILHERME, L. R. G. 2016. Career Perspective on Soil Management in the Cerrado region of Brazil. **Advances in Agronomy**, 137: 1-72.

MEDEIROS, G. A.; ARRUDA, F. B.; SAKAI, E. 2004. Relações entre o coeficiente de cultura e cobertura vegetal do feijoeiro: erros envolvidos e análises para diferentes intervalos de tempo. **Acta Scientiarum. Agronomy**, 26: 513-519.

MEDEIROS, G. A.; ARRUDA, F. B.; SAKAI, E. 2005. Crop coefficient for irrigated beans derived using three reference evaporation methods. **Agricultural and Forest Meteorology**, 135: 135-143.

MEDEIROS, G. A.; ARRUDA, F. B.; SAKAI, E.; FUJIWARA, M. 2001. The influence of crop canopy on evapotranspiration and crop coefficient of beans (*Phaseolus vulgaris* L.). **Agricultural Water Management**, 49: 211-224.

MEDEIROS, G. A.; DANIEL, L. A.; FENGLER, F. H. 2016. Growth, development, and water consumption of irrigated bean crop related to growing degree-days on different soil tillage systems in Southeast Brazil. **International Journal of Agronomy**, 1: 1-8.

MENDONÇA, J. C.; SOUSA, E. F.; BERNARDO, S.; SUGAWARA, M. T.; PEÇANHA, A. L.; GOTTARDO, R. D. 2007. Determinação do coeficiente cultural (Kc) do feijoeiro (*Phaseolus vulgaris* L.) em Campos dos Goytacazes, RJ. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 11: 471-475.

MURGA-ORRILLO, H.; ARAÚJO, W. F.; ROCHA, P. R. R.; SAKAZAKI, R. T.; DIONISIO, L. F. S.; POLO-VARGAS, A. R. 2016. Evapotranspiração e coeficiente de cultivo do feijão-caupi cultivado em solo do cerrado submetido à cobertura morta. **Irriga**, 21:172-187.

SANTANA, M. J. D.; LEMOS, L. B.; SOUZA, S. S. D.; CAMPOS, T. M.; SILVA, F. M. D.; BORGES, R. D. 2014. Estimated production and evapotranspiration of irrigated bean cultivars. **Engenharia Agrícola**, 34: 1089-1103.

SARAIVA, K. R.; SOUZA, F. DE. 2012. O efeito das mudanças climáticas nas necessidades hídricas do feijão-caupi no Curu-Pentecoste utilizando o modelo “ISAREG”. **Revista Brasileira de Agricultura Irrigada**, 6: 8-13.

SATRIANI, A.; LOPERTE, A.; SOLDOVIERI, F. 2015. Integrated geophysical techniques for sustainable management of water resource. A case study of local dry bean versus commercial common bean cultivars. **Agricultural Water Management**, 162: 57-66.

SOURESHJANI, H. K.; NEZAMI, A.; KAFI, M.; TADAYON, M. 2019. Responses of two common bean (*Phaseolus vulgaris* L.) genotypes to deficit irrigation. **Agricultural Water Management**, 213: 270-279.

SOUZA, M. D. S. M.; BEZERRA, F. M. L.; MARIA, E. 2005. Coeficientes de cultura do feijão caupi na região litorânea do Ceará. **Irriga**, 10: 241-248.

TASUMI, M.; ALLEN, R. G.; TREZZA, R.; WRIGHT, J. L. 2005. Satellite-based energy balance to assess within-population variance of crop coefficient curves. **Journal of Irrigation and Drainage Engineering**, 131: 94-109.