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Water requirement and crop coefficients of sorghum in Apodi Plateau[1]

Necessidade hídrica e coeficientes de cultivo do sorgo nas condições da chapada do Apodi

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HIGHLIGHTS:

The equation to calculate Kc as a function of the normalized difference vegetation index exhibited an adjusted $R^2 = 0.92$.
The simple and dual crop coefficients show the importance of local adjustment, since the results are different from FAO 56.
The total evapotranspiration values of the crop show the importance of irrigation, especially during the dry season.

ABSTRACT: Sorghum is of significant economic importance for Northeastern Brazil, since it exhibits high growth rates in regions with irregular rainfall distribution and high temperatures, and is an alternative to corn, which has greater water requirements. Despite being a traditional crop in the region, there are few studies on irrigation management in the Apodi plateau. The aim of this study was to determine the evapotranspiration of the crop and the crop coefficient (Kc) for the different stages of sorghum growth in two cycles, and establish the relationship between the Kc and the normalized difference vegetation index (NDVI) obtained by radiometry. Two weighing lysimeters were used to estimate crop evapotranspiration (ETc). Reference evapotranspiration (ETo) was estimated by the Penman-Monteith method (FAO) and the crop coefficient determined using two methodologies: simple Kc and dual Kc. Total crop evapotranspiration in the two cycles was 452 and 557 mm. The ETc value was 23% higher in the second cycle compared to the first. The maximum Kc values for the first and second cycles were 1.21 and 1.35, respectively, using the dual Kc methodology. The linear relationship found between the Kc values and the NDVI allows monitoring and estimating the water requirements of the crop.

Key words: *Sorghum bicolor*, water consumption, water resources, irrigation management

RESUMO: O sorgo apresenta grande importância econômica para o Nordeste brasileiro, por ter alta capacidade em desenvolver-se em regiões com distribuição irregular de chuvas e alta temperatura, sendo uma alternativa à cultura do milho, que possui maior exigência hídrica. Apesar de ser uma cultura de tradição na região, há poucos estudos para o manejo da irrigação na chapada do Apodi. O objetivo desta pesquisa foi determinar a evapotranspiração da cultura, o coeficiente de cultivo para os diferentes estádios de crescimento do sorgo em dois ciclos e obter uma relação entre o Kc e o Normalized Difference Vegetation Index (NDVI) obtidos por radiometria. Para estimar a evapotranspiração da cultura (ETc) foram utilizados dois lisímetros de pesagem. A evapotranspiração de referência (ETo) foi estimada pelo método de Penman-Monteith (FAO) e o coeficiente de cultivo foi obtido por duas metodologias, Kc simples e Kc dual. Os valores da evapotranspiração total da cultura, nos dois ciclos, foram 452 e 557 mm. O valor da ETc foi 23% maior no segundo ciclo em relação ao primeiro. Os valores de Kc máximo obtidos para o primeiro e segundo ciclos foram 1,21 e 1,35, respectivamente, utilizando-se a metodologia do Kc dual. A relação linear encontrada entre os valores de Kc e o NDVI permite monitorar e estimar as necessidades hídricas da cultura.

Palavras-chave: *Sorghum bicolor*, consumo hídrico, recursos hídricos, manejo da irrigação

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Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is grown for its climate resilience and versatility in the production of grains and forage for animal feed, as well as the production of bioenergy in different regions of the world. Sorghum is considered the fifth most produced cereal in the world, after wheat, rice, corn and barley (FAOSTAT, 2018). Globally, the total planted area of sorghum was 42 million hectares in 2018, producing 59 million metric tons of grain (FAOSTAT, 2018).

According to Dias & Blanco (2010), sorghum is the most indicated cereal in the semiarid of Northeastern Brazil since it adapts well to the abiotic stresses in this region. Sorghum is grown by producers in Rio Grande do Norte state, Brazil, during the rainy season and under irrigation in the dry period. Despite being a traditional crop in the region, there are few studies on irrigation management in the Apodi Plateau.

The water requirements of the crop are typically calculated according to the FAO (Allen et al., 2006), which uses reference evapotranspiration (ETo) and a crop coefficient (Kc). The Kc values obtained by measuring evapotranspiration (ETc) several times with lysimeters and then relating it with ETo (Doorenbos & Pruitt, 1975) are available for a number of crops. Although major crops have been the object of many studies with lysimeters, the Kc values of crops with less economic importance are often estimated based on fewer studies and frequently where ETc is determined using less accurate alternative methods (López-Urrea et al., 2014).

In recent years, few studies have focused on measuring the ETc of sorghum (López-Urrea et al., 2016; Sousa et al., 2020) and obtaining new crop coefficients for areas where sprinkler irrigation is used. Thus, there is a need to determine the ETc of sorghum and its crop coefficients (Kc) under different climate and agronomic conditions. Several studies have shown a relation between NDVI and Kc (Kamble et al., 2013; Alface et al., 2019).

Thus, the aims of this study were to determine the water requirements of irrigated sorghum using a weighing lysimeter, and its respective simple and dual Kc for the soil and climatic conditions of the Apodi Plateau in order to establish the relation between Kc and the NDVI obtained by radiometry.

Material and Methods

The study was conducted on an experimental farm belonging to the Agricultural Research Company of Rio Grande do Norte (EMPARN), in the municipality of Apodi, Brazil (5º 37' 38" S, 37º 49' 55" W and 150 m above sea level). Based on Köppen's climate classification, the climate is BSh (hot semiarid), with average rainfall and temperature of 893 mm $year^{-1}$ and 27.1 °C, respectively, according to the National Meteorological Institute (INMET, 2009).

The soil in the study area was classified as Inceptisol, with sandy clay loam texture (570 g kg^{-1} of sand, 90 g kg^{-1} of silt and 340 g kg^{-1} of clay), field capacity of 0.1700 kg kg^{-1}, permanent wilting point of 0.1133 kg kg^{-1}, global density of 1.20 kg dm^{-3}, particle density of 2.71 kg dm^{-3} and total porosity of 0.5558 m^3 m^{-3}.

The study was conducted during April 4, 2012 (Julian day JD 95) and July 24, 2012 (JD 206), and between October 12, 2012 (JD 286) and January 12, 2013 (JD 12), corresponding to two cycles. The area cultivated on the experimental farm was 3.6 ha, with the 'BRS Ponta Negra' sorghum variety, using 0.10 m spacing between plants and 0.75 m between rows. Irrigations consisted of a conventional sprinkling system.

Two weighing lysimeters were installed in the area in order to obtain the ETc (crop evapotranspiration), calculated as the difference between the loss of lysimeter weight due to evapotranspiration and gain from rainfall, irrigation or dew, divided by the area of the lysimeter (2.7 m^2). The lysimeters were installed on load cells connected to a CR3000 datalogger (Campbell Scientific, Inc., Logan, Utah, USA) programmed to take measurements every 60 s and output data every 10 min.

The soil in the lysimeter was the same that was dug up for its installation in the ground. Each lysimeter was 2.7 m long, 2.3 m wide and 1.7 m deep. The system makes it possible to read the ETc in the lysimeter with a resolution of 0.04 mm. The lysimeters were weighed daily in order to identify individual reading errors not explained by the entry and loss of water. Data collected during rainfall, weighing and calibration were not used to calculate crop evapotranspiration.

The ETo values were estimated by the FAO 56 Penman-Monteith equation 1 (Allen et al., 2006), using the meteorological data of an INMET weather station, located on an experimental farm 750 m from the study area.

$$ETo = \frac{0.408\Delta(Rn - G)\gamma \frac{900}{T_{ave+273}} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where:

- ETo - reference evapotranspiration, mm day^{-1};
- Rn - net radiation, MJ m^{-2} day^{-1};
- G - soil heat flux density, MJ m^{-2} day^{-1};
- T_{ave} - average daily temperature at a height of 2 m, ºC;
- u_2 - average daily wind speed at a height of 2 m, m s^{-1};
- e_s - average daily saturation vapor pressure, kPa;
- e_a - average current daily vapor pressure, kPa;
- Δ - slope of the vapor pressure curve at T_{ave}, kPa ºC^{-1}; and,
- γ - psychometric constant, kPa °C^{-1}.

The Kc values were obtained from the quotient of ETc and ETo, according to Eq. 2.

$$Kc = \frac{ETc}{ETo} \quad (2)$$

The Kc obtained in each phenological phase was compared with those indicated by FAO 56 methodology (Allen et al., 2006).

In the initial phase, the Kc varies primarily due to soil evaporation. The estimate was obtained using Eq. 3 (Allen et al., 2006):

$$Kc_{ini} = Kc_{ini(1)} + \left(\frac{I - 10}{40 - 10}\right)\left[Kc_{ini(2)} - Kc_{ini(1)}\right] \quad (3)$$

where:

Kc_{ini} - crop coefficient in the initial phase;

$Kc_{ini(1)}$ and $Kc_{ini(2)}$ - Kc_{ini} obtained on the FAO 56 graphs (Allen et al., 2006); and

I - average water infiltration, mm.

The Kc of the following phases was estimated using dual Kc methodology (Allen et al., 2006), according to Eq. 4:

$$Kc = K_{cb} + K_e \quad (4)$$

where:

K_{cb} - basal crop coefficient; and,

K_e - soil evaporation coefficient.

In climates where the minimum relative air humidity (RH_{min}) is other than 45% or where wind velocity is greater or less than 2 m s^{-1}, K_{cbave} and $K_{cbfinal}$ values above 0.45 must be adjusted using Eq. 5 (Allen et al., 2006)

$$K_{cb} = K_{cb(tab)} + \left[0.04\left(u_2 - 2\right) - 0.004\left(UR_{min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (5)$$

where:

$K_{cb(tab)}$ - K_{cbave} or $K_{cbfinal}$ (if ≥ 0.45) tabulated by FAO 56 (Allen et al., 2006);

u_2 - average daily wind speed at a height of 2 m, m s^{-1};

RH_{min} - daily average minimum relative air humidity, %; and,

h - average plant height, m.

K_e was calculated using the soil surface conditions, according to Eq. 6:

$$K_e = K_r\left(K_{cmax} - K_{cb}\right) \leq f_{ew} K_{cmax} \quad (6)$$

where:

K_r - dimensionless evaporation reduction coefficient;

K_{cmax} - maximum Kc after irrigation or rainfall; and,

f_{ew} - exposed and wetted soil fraction.

The normalized difference vegetation index (NDVI) values were calculated from Landsat 7-ETM + images, according to Eq. 7:

$$NDVI = \frac{\rho_{nir} - \rho_r}{\rho_{nir} + \rho_r} \quad (7)$$

where:

ρ_{nir} - near infrared reflectance; and,

ρ_r - red reflectance.

The images used to obtain the NDVI data were taken on 12/05/2012, 28/05/2012, 13/06/2012, 19/10/2012, 20/11/2012, 06/12/2012 and 22/12/2012. These images were selected since there was no cloud cover in the study area, making them suitable for processing.

Results and Discussion

Table 1 shows a summary of the meteorological conditions for the two cycles. The average temperature (T_{ave}), relative air humidity (RH), wind speed (W) and global radiation (Rg) were 29.1/29.7 °C; 57.3/49.1%; 2.7/3.9 m s^{-1} and 23.2/25.9 MJ m^{-2} day^{-1} for the first and second cycles, respectively. Rainfall (RF) was scarce during the two cycles (58.6 and 0.2 mm, respectively), demonstrating the importance of irrigation in this region to ensure crop development.

Figure 1 shows an increase in 'BRS Ponta Negra' sorghum biomass in terms of dry weight production and plant height during two phenological crop cycles. Dry weight yield was 25 and 30 t ha^{-1}, in the first and second cycles, respectively. Garofalo & Rinaldo (2013) assessed the response of sorghum to four irrigation treatments in Southern Italy, obtaining a maximum production of 41 t ha^{-1}. However, in a study conducted in central Spain, with two cycles, López-Urrea et al. (2016) reported a yield of 23 and 26 t ha^{-1} for sorghum H-133, results similar to those obtained here. Costa et al. (2017) studied the growth and production of the first rebudding of 'BRS Ponta Negra' sorghum in Upanema, Brazil, observing a yield of 22 t ha^{-1}.

In the first and second cycles, sorghum height reached 1.7 and 2.1 m, 88 and 70 days after planting, respectively. Vale & Azevedo (2013) assessed the yield and quality of 'BRS Ponta Negra' sorghum, obtaining a plant height of 2.2 m.

Table 1. Monthly summary of meteorological variables during two cycles with 'BRS Ponta Negra' sorghum in the Apodi Plateau

Cycle/Month	T_{ave} (°C)	RH (%)	W (m s^{-1})	Rg (MJ m^{-2} day^{-1})	RF (mm)
1st cycle					
April 4-30	28.4	63.1	2.4	25.4	27.8
May	29.4	58.2	2.5	23.9	28.2
June	29.5	53.4	2.9	22.7	0
July 1-24	29.0	54.6	2.9	20.9	2.6
Average	29.1	57.3	2.7	23.2	58.6
2nd cycle					
October 12-31	29.0	46.7	3.7	26.0	0
November	29.6	46.5	4.0	26.3	0
December	29.8	52.3	3.8	26.6	0
January 1-12	30.2	50.8	4.2	24.6	0.2
Average	29.7	49.1	3.9	25.9	0.2

T_{ave} - Average temperature; RH - Relative air humidity; W - Wind speed; Rg - Global radiation; RF - Rainfall

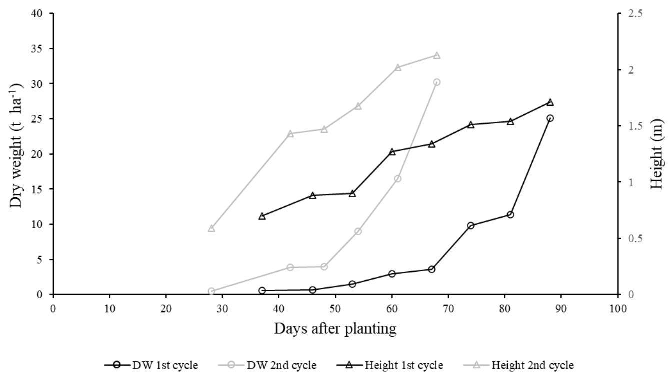


Figure 1. Dry weight (DW) production and plant height of 'BRS Ponta Negra' sorghum during the first and second cycles in the Apodi Plateau

Figure 2 presents the daily ETo and ETc data. During the two cycles, ETo demonstrated significant variability, with maximum values of 6.5 and 9.0 mm day^{-1} and minimum of 3.4 and 4.9 mm day^{-1}, and averages of 5.4 and 7.9 mm day^{-1}, for the first and second cycles, respectively.

At the end of each cycle, total ETo values for the first and second cycles were 607 and 736, respectively. The higher values found in the second cycle are likely due to the fact that higher pressure deficit (lower relative air humidity), wind speed, average temperature and global radiation occurred in the second semester compared to the first.

In regard to ETc, higher values were observed during the flowering phase, with total ETc of 452 and 557 mm at the end of the first and second cycles, respectively. The 23% higher ETc value in the second cycle was due to the greater atmospheric evapotranspirative demand, as a function of the higher values of the meteorological variables mentioned earlier. Lopéz-Urrea et al. (2016) assessed the evapotranspiration of sorghum in central Spain, finding values of 721 and 691 mm in 2007 and 2010, respectively, higher than those reported here, likely due to the greater evapotranspiration demand during the experiment. According to Wani et al. (2012), the water consumed by sorghum over 110-130 days varies between 450 and 750 mm.

Table 2 presents the duration of the phenological phases (simple Kc) from lysimeter data, and FAO 56 dual Kc (Allen et al., 2006), for each phase of the two crop cycles of 'BRS Ponta Negra' sorghum.

The maximum Kc values obtained for the first and second cycles were 1.21 and 1.35, respectively, using dual Kc methodology. In phase IV, a larger difference was observed in lysimeter Kc values between the two cycles (0.70 and 1.10), likely because the first cycle is longer (26 days) than the second

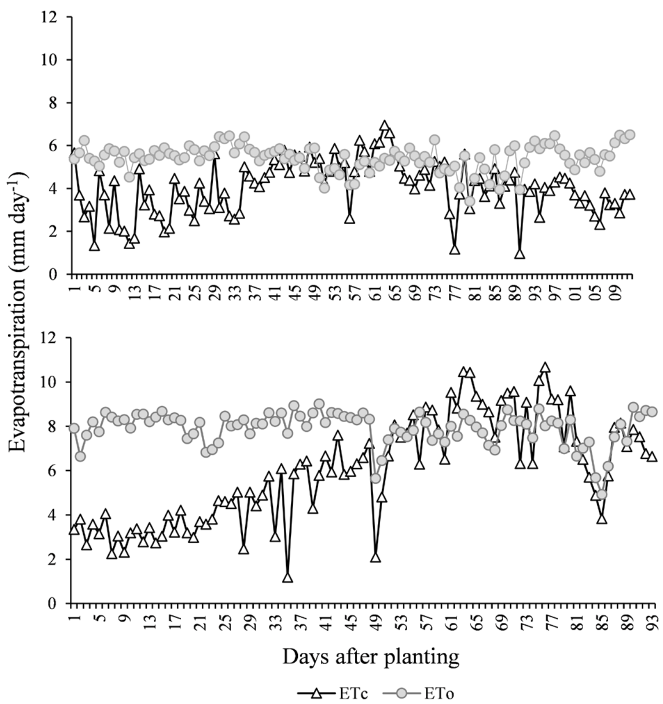


Figure 2. Variation in crop evapotranspiration (ETc) of 'BRS Ponta Negra' sorghum and reference evapotranspiration (ETo) as a function of days after planting, in the first (A) and second cycle (B)

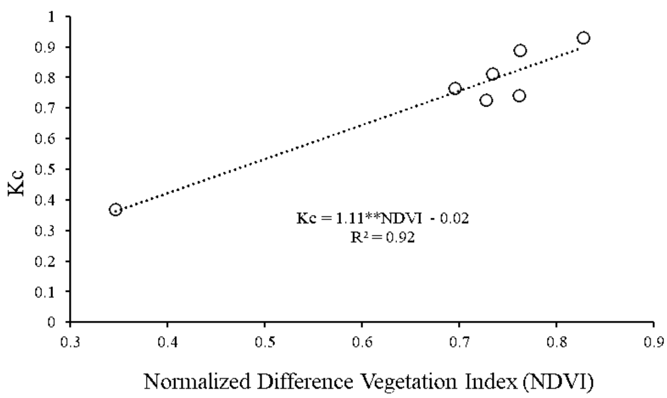
Table 2. Duration of phenological phases and average crop coefficient (Kc) of 'BRS Ponta Negra' sorghum during the two crop cycles in the Apodi Plateau

Phase	Duration (days)	Lysimeter Kc	Dual Kc (FAO 56)
1st cycle/2nd cycle			
I - Initial	24/21	0.54/0.40	0.46/0.45
II - Vegetative growth	30/32	0.83/0.68	0.84/0.90
III - Flowering	32/26	0.94/1.14	1.21/1.35
IV - Physiological maturity	26/13	0.70/1.10	1.01/1.16

(13 days). Table 2 shows that the Kc obtained in this study were lower than those found by FAO 56 (Allen et al., 2006) and Martinez Cruz et al. (2015), in Tucson, Arizona. Thus, in general terms, if water consumption is related to the Kc, the 'BRS Ponta Negra' variety may require less water than those used by the authors. However, the use of water alone is not the only factor to consider, given that commercial yield per unit of water use (water yield/productivity) must also be taken into account (Martinez Cruz et al., 2015).

Figure 3 shows the linear relation between NDVI and simple Kc during the first and second cycles, for 'BRS Ponta Negra' sorghum. The linear relation data between NDVI and simple Kc from the first and second cycles were combined into a single graph due to the lower number of NDVI data during the study (three and four images for the first and second cycles, respectively). There was a high correlation between simple Kc values and the NDVI. The coefficient of determination (R^2) was 0.92. Thus, the adjusted model explained 92% of Kc variability. In a study conducted in three provinces of Saudi Arabia, Mahmound & Gan (2019) used the data from different crops to acquire the linear correlations between Kc and NDVI, obtaining a simple linear regression (Kc = 0.19 x NDVI + 0.74), with R^2 = 0.915.

Numerous studies obtained satisfactory results in predicting Kc from NDVI, using linear regression models in different agricultural areas (Bezerra et al., 2010; Er-raki et al., 2013; Kamble et al., 2013; Mahmound & Gan, 2019).



** - Significant at $p \leq 0.01$ according to the t-test

Figure 3. Linear relation between the normalized difference vegetation index and simple Kc in two cycles of 'BRS Ponta Negra' sorghum, in the Apodi Plateau

Conclusions

1. High water requirement was observed for the sorghum crop, totaling 452 and 557 mm in the first and second cycles, respectively.

2. The simple and dual Kc values for the sorghum crop in the Chapada Plateau should be adjusted locally, since the Kc results were different from those reported in the literature.

3. Simple Kc can be estimated as a function of the normalized difference vegetation index (NDVI), making it possible to estimate the water requirements of the sorghum crop based on satellite images.

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