Crop coefficient estimated by degree-days for 'Marandu' palisadegrass and mixed forage

Coeficiente de cultivo estimado por grados-día para el pasto en empalizada 'Marandu' y el forraje mixto

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Abstract

Considering profitability in pasture-based systems, investigating parameters affecting crop coefficients for irrigation management becomes important. In this experiment, we determined the crop coefficient of 'Marandu' palisadegrass based on accumulated degree-days and estimated plant water consumption under single ('Marandu' palisadegrass) and mixed ('Marandu' palisadegrass + black oats + Italian ryegrass) cropping regimes. The research was conducted at the Luiz de Queiroz College of Agriculture in Piracicaba, São Paulo, Brazil, between 2016 and 2017. Evapotranspiration was assessed using weighing lysimeters while crop evapotranspiration was calculated using mean weight variation. Reference evapotranspiration and degree-days were estimated. Data were obtained from an automated weather station. Equations and regression models relating crop coefficient with accumulated degree-days were generated for two seasons (spring/summer and autumn/winter) and evaluated for two year-cycles, from 2015 to 2018. The results showed better prediction accuracy for the single cropping system in spring/summer 2017–18.

Keywords
degree-days evapotranspiration • water consumption • forage

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Resumen

Considerando la importancia económica de los pastos, existe una necesidad de investigar los parámetros que afectan los coeficientes de cultivo utilizados para el manejo del riego. En este experimento, nuestro objetivo fue determinar el coeficiente de cultivo del pasto 'Marandu' en función de la acumulación de grados-días y estimar el consumo de agua del cultivo puro (pasto 'Marandu') y del cultivo mixto (pasto 'Marandu' + avena negra + raigrás italiano) regímenes de cultivo. La investigación se llevó a cabo en la Escuela de Agricultura Luiz de Queiroz en Piracicaba/SP, Brasil, entre 2016 y 2017, en este periodo se registró la evapotranspiración utilizando lisímetros de pesaje. La evapotranspiración del cultivo se calculó utilizando la variación de peso promedio registrada por lisímetros. Los datos de una estación meteorológica automatizada se utilizaron para estimar la evapotranspiración de referencia y calcular los grados-días. Se generaron ecuaciones y modelos de regresión con relación al coeficiente de cultivo y los grados-días acumulados durante dos períodos estacionales (primavera/verano y otoño/invierno). Los modelos matemáticos se probaron durante dos ciclos anuales, de 2015 a 2018 y mostraron mejores resultados, en términos de precisión y exactitud, en el sistema de cultivo único en primavera/verano en los años 2017/18.

Palabras clave
grados-días • evapotranspiración • consumo de agua • forraje

Introduction

Intensive agriculture has improved productivity by investing in several crop-management practices, including irrigation and fertilization (12, 14, 36). Since pastures are major fodder sources for cattle in Brazil, intensification of pasture production turns key for the cultivation and management of this crop.

Occupying a vast territory, pastures are subjected to a wide range of environmental conditions, particularly temperature, light, and rainfall. Outranged environmental magnitudes for pasture production compromise vegetative development, expressed as low biomass accumulation and marked production seasonality (20, 23, 33). Meteorological conditions prevailing during winter impair tropical and subtropical forage crops, whereas spring/summer favor high forage productivity (25, 28).

In order to reduce fertilization and counteract low pasture yields during winter, cultivation of temperate forage species has been identified as an alternative for these cultivation systems. Good results have been reported for forage nutritional value and animal production (13). However, mixed cropping systems, where two or more species are co-cultivated using the overseeding method, cause changes in crop water requirements. Therefore, estimating these changes in irrigated pasture systems turns essential.

Adequate information on plant and microclimate interaction constitutes one major factor for accurate irrigation management (6, 29). Crop water requirements can be calculated after plant water losses through transpiration and soil evaporation, termed crop evapotranspiration (ET_c). Estimated reference evapotranspiration (ET_o) calculated using meteorological data, is then converted to ET_c using a crop coefficient (K_c) as a correction factor, while the precise ET_c can be determined using a weighing lysimeter (4).

In established pastures, the K_c varies depending on crop growth and landscape, such as after sowing, seed germination, or forage grazing (7, 17, 18, 27, 31). However, as the grazing cycle is defined by species, climate, and animal characteristics, this approach turns imprecise and avoided for tropical forage crops.

Air temperature is used to calculate degree-days, expressing available thermal units for crop growth. Accumulated degree-days (ADD) are also used to estimate the correct K_c for irrigation management. Thus, K_c-as estimated by ADD-varies with ambient temperature, influencing crop growth and cycle (16). Therefore, alternative methods for K_c estimation may be particularly useful for the dynamics of irrigated pastures. Therefore, in this study and using the weighing-lysimeter method, we aimed to measure K_c for growth cycles of 'Marandu' forage, a palisadegrass cultivar (*Urochloa brizantha*). The study took place during 2016 and 2017 and developed an adjustable regression model relating K_c and ADD during the four seasons, evaluated when applied to previous and subsequent years.

Materials and methods

Experimental site and soil classification
The field experiment was conducted at the Luiz de Queiroz College of Agriculture (ESALQ/USP), Piracicaba, São Paulo (latitude 22°42' S, longitude 47°38' W, altitude 546 m) in Brazil. The soil is classified as Ferralic Nitisol (38), with 48.6% clay, 32.5% sand, and 18.9% silt (0-0.4 m).

Soil chemical characteristics were determined prior experiment: pH = 5.1, $P_{(resin)}$ = 52 mg dm^{-3}, K = 0.69 cmol$_c$ dm^{-3}, Ca = 2.6 cmol$_c$ dm^{-3}, Mg = 1.4 cmol$_c$ dm^{-3}, H + Al = 3.65 cmol$_c$ dm^{-3}, Al = 0.2 cmol$_c$ dm^{-3}, and CEC = 8.34 cmol$_c$ dm^{-3}. Soil preparation included plowing and harrowing, weed control, Ph correction, and fertilization adjustment.

Forage cultivation
The experimental area included two, 144 m² plots. The area surrounding the experimental plots was covered with irrigated pastures and sugarcane. Only one close field had bare soil. Reading errors lead by bare soil, affecting evapotranspiration, were identified and excluded from daily calculations after verifying hot air mass entrances.

Initially, both plots were direct-seeded by broadcasting 15 kg ha^{-1} of 'Marandu' palisadegrass. Similar crop management practices were followed in both plots. After crop establishment (~70 days), the grass was cut to a standard height of 0.15 m above soil surface using a brush cutter. In autumn, one plot was kept for a single cropping system under 'Marandu' palisadegrass. Meanwhile, and to create a mixed cropping system, the other plot was direct-seeded (broadcasting) with 100 kg seeds ha^{-1} of black oats (*Avena strigosa* 'Embrapa 29 (Garoa)') and 60 kg seeds ha^{-1} Italian ryegrass (*Lolium multiflorum* 'Fepagro São Gabriel'). This created a pasture comprising three different forage crops during autumn and winter.

Cutting cycles were grouped according to seasons: summer (February to March 2016, and December 2016 to January 2017), autumn (April to June 2016), winter (July 2016 to October 2016), and spring (October to December 2016). After each cut, the plots were fertilized with 80 kg ha^{-1} urea during spring and summer and 50 kg ha^{-1} during autumn and winter. The Average total forage yield (*TFY*) was calculated as the sum of leaf and stem dry mass (DM), after kiln drying.

Forage cutting in the single-cropped plot ('Marandu' palisadegrass), was performed every 28 days during spring and summer, extended to 40 days during autumn and winter. In the mixed-cropped plot ('Marandu' palisadegrass + black oats + ryegrass), harvest was performed at intervals ranging from 24 to 40 days when the canopy had exceeding 95% light interception, measured with a LAI-2000 Plant Canopy Analyzer (LI-COR Environmental, Lincoln, Nebraska USA).

All experimental plots were irrigated with a conventional sprinkler system, operating via a sectoral mechanism at a flow rate of 590 L h^{-1} and running at a pressure of 245 kPa. The quantity of water applied was determined by weighing-lysimeter readings (in L/m² or mm), considering the lysimeter depth (z = 0.58 m) as the maximum crop root depth. In tropical forages, most roots are detected down to 0.60 m, and 70% of all roots are concentrated within the first 0.30 m depth (2, 21, 34).

An irrigation interval kept soil moisture content (SMC) over 70% (recommended for K_c estimate), between field capacity (θ_{fc}) and lowest soil water content (θ_{wp}). It was measured within 15 bars to standard atmospheric pressure (SMC ≥ 0.7 [$\theta_{fc} - \theta_{wp}$]), guaranteeing null soil water deficit, and accurate K_c data.

Evapotranspiration and accumulated degree-days
Crop evapotranspiration (ET_c) in the experimental plots was estimated using two lysimeters, made of a PVC box (500 L), of 1.22 m² and 0.58 m depth (26), with an automatic drainage system. Both sets were calibrated and controlled by a datalogger program (26). Lysimeter measurements were recorded every 15 min and converted into 1-day interval data. Values exceeding 0.20 mm in a 15 min interval, caused by excessive rainfall or evapotranspiration, were excluded. Brief periods of high evapotranspiration and consequent ET_c fluctuations arose during hot transient air masses originated from exposed soil and arriving mainly from the north, northwest, west, and occasionally, from the southwest.

Daily degree-days (DD_i) were calculated based on temperature (22). Equation 1 was used when crop basal temperature (T_b) was lower than minimum daily temperature (T_{min}), and eq. 2, when T_b exceeded T_{min}. Meteorological data were obtained from the ESALQ Meteorological Station, located 100 m from the experimental area. Data for $T_{min,}$ and T_{max} are shown in figure 1. Reference evapotranspiration (ET_o) (Penman-Monteith model, 2, 3) for different cycles is shown in table 1 (page 75).

$$DD_i = \frac{(T_{max} + T_{min})}{2} - T_b \tag{1}$$

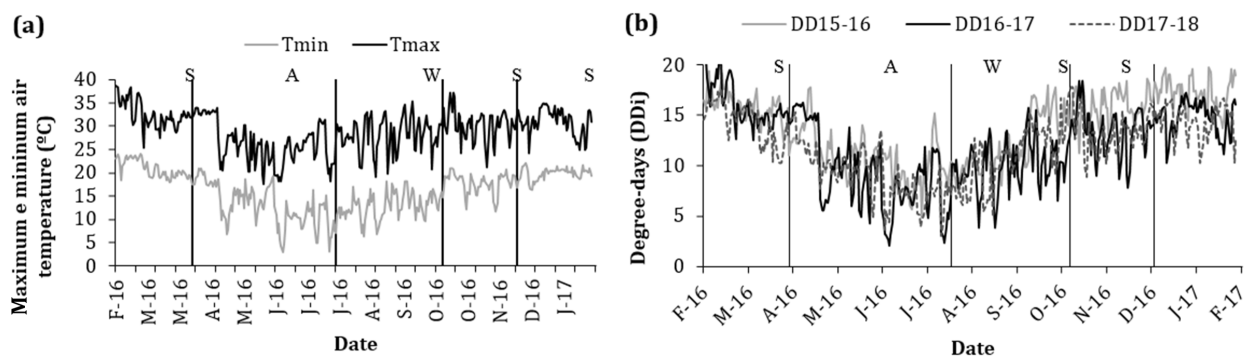$$DD_i = \frac{[(T_{max} - T_b)^2]}{2(T_{max} - T_{min})} \tag{2}$$

In equations 1 and 2:
DD_i = daily degree-days,
T_{max} = maximum daily temperature in °C,
T_{min} = minimum daily temperature in °C (figure 1a),
T_b = basal crop temperature for the single-cropped 'Marandu' palisadegrass plot, which was considered to be 10.6 °C (26). This same basal temperature was applied for plots with palisadegrass mixed with black oats and Italian ryegrass.

Graphs are divided sequentially according to season (Summer, Autumn, Winter, Spring).
En ambas figuras, los gráficos se dividen secuencialmente según estación (verano, otoño, invierno, primavera).

Figure 1. a. Minimum (Tmin) and maximum (Tmax) air temperatures during 2016 - 2017. **b.** Daily degree-days (DD) during 2015 - 2016 (DD15-16), 2016 - 2017 (DD16-17), and 2017 - 2018 (DD17-18) in Piracicaba, São Paulo, Brazil.

Figura 1. a. Temperaturas mínimas (Tmin) y máximas (Tmax) del aire durante 2016 - 2017; **b.** Los grados-días (DD) diarios durante los períodos 2015 -2016 (DD15-16), 2016 - 2017 (DD16-17) y 2017 - 2018 (DD17-18) en Piracicaba, São Paulo, Brasil.

It should be noted that *ADD* was also estimated for the original cropping cycles (28 days for spring/summer and 40 days for autumn/winter), with 11 productive cycles for single-cropped 'Marandu' palisadegrass and five cycles of the same forage in the overseeded mixed-cropping regime ('Marandu' palisadegrass + black oats + ryegrass).

The summed DD values for each cropping cycle comprised all accumulated degree-days (*ADD*). The K_c values were obtained as ET_c/ET_o. Daily values of K_c were averaged over 4-day intervals obtaining mean daily values and reducing possible distortions due to water flow within the lysimeters. The K_c values of the studied forage crops were grouped as follows: single-cropped pasture during spring-summer (Sp/Su) and autumn-winter (A/W), and the overseeded mixed-cropped pasture during A/W. Subsequently, daily K_c means were correlated with *ADD* for each cutting cycle verifying if *ADD* could be used in K_c determinations.

Single cropping cycles are divided sequentially according to season (Su = summer, A = autumn, W = winter, Sp = spring).

Los ciclos para un solo cultivo se dividen secuencialmente según la temporada (Su = verano, A = otoño, W = invierno, Sp = primavera).

	Date cycles (month/day)	ET_o (mm cycle^{-1})	ET_o (min-max daily)
Su	02/11 – 03/09/2016	90.6	0.9 - 5.3
Su	03/10 - 04/06/2016	101.6	1.4 - 5.3
A	04/07 - 05/04/2016	100.3	1.1 - 4.9
A	05/05 – 06/13/2016	79.6	0.6 - 3.3
A	06/14 – 07/23/2016	97.8	1.2 - 3.7
W	07/24 - 09/01/2016	143.4	1.2 - 4.8
W	09/02 - 10/11/2016	164.5	1.0 - 5.9
Sp	10/12 - 11/08/2016	118.4	0.5 - 6.7
Sp	11/09 - 12/06/2016	122.1	0.9 - 6.3
Su	12/07/2016 - 01/03/2017	128.2	2.9 - 6.4
Su	01/04 - 01/31/2017	120.2	0.7 - 6.1
Date cycles (month/day)		**ET_o (mm cycle^{-1})**	**ET_o (min-max daily)**
05/05 -06/13/2016		79.6	0.6 - 3.3
06/14 - 07/11/2016		67.2	1.2 - 3.7
07/12 - 08/04/2016		66.8	1.2 - 4.0
08/05 -09/05/2016		123.2	1.7 - 4.8
09/06 - 10/07/2016		129.1	0.8 - 5.6

Statistical analysis

K_c and *ADD* data were correlated using SigmaPlot software for regression analysis, with equations adjusted for the entire experimental period according to seasons. For 2015-2016 and 2017-2018 periods (prior and after the experiment, respectively), climate data was collected from a weather station located near the experimental area. For both periods, second-order polynomial models (K_c *vs. ADD*) were generated ($R^2 \geq 0.97$). K_c was estimated according to eq3, based on the calculated *ADD* in the simulated sequences for 2015-2016 and 2017-2018.

$$K_c = a + b \cdot ADD + c \cdot ADD^2 \qquad (3)$$

Degree-days were counted from February 11, 2016 to January 31, 2017 (355 days), according to the original experimental period. The same periods were adopted for 2015-2016 and 2017-2018.

Using the generated regression models, K_c values were estimated for these years. Estimation accuracy was evaluated by the mean error (*ME*; eq 4), the root mean square error (*RMSE*; eq 5), Willmott's concordance index *d* (37), and confidence index *c* (10, eq 6 and 7).

$$ME = \left(\frac{1}{n}\right) \sum_{i=1}^{n} (E_i - O_i) \qquad (4)$$

$$RMSE = \sqrt{\left[\left(\frac{1}{n}\right) \sum_{i=1}^{n} (E_i - O_i)^2\right]} \qquad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n} (E_i - O_i)^2}{\sum_{i=1}^{n} \left(|E_i - \overline{O}| + |O_i - \overline{O}|\right)^2} \qquad (6)$$

$$c = \sqrt{R^2} \times d \qquad (7)$$

In the equations:
n = the number of data points,
E_i = the estimated data,
O_i = the observed data.

RESULTS

Regression curves for K_c means *vs. ADD* in single-cropped 'Marandu' palisadegrass were divided into two periods: Sp/Su and A/W, as shown in figure 2. For both periods, second-order polynomial models (K_c vs. *ADD*) were generated ($R^2 \geq 0.97$). During A/W, maximum K_c ($K_{c\,max}$ = 0.82) was obtained at an *ADD* of 160 °C·days (°C × days, degree-days), whereas in Sp/Su, $K_{c\,max}$ reached 0.90 at an *ADD* of 280 °C·days (figure 2).
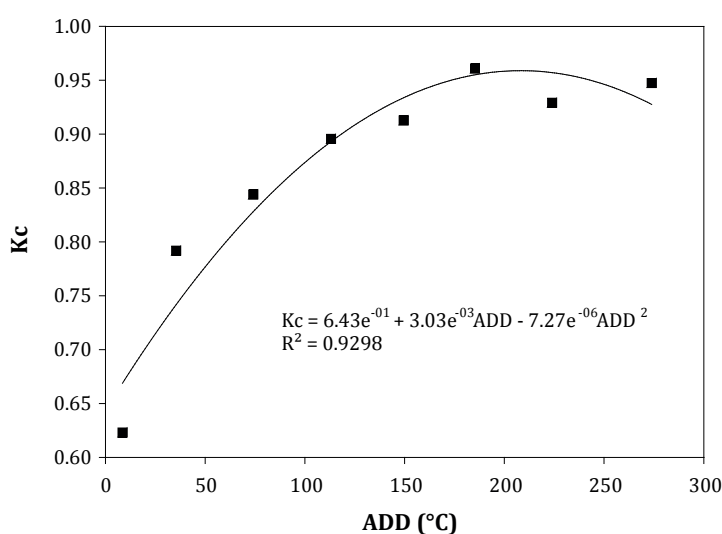

Kc = $6.43e^{-01}$ + $3.03e^{-03}$ADD - $7.27e^{-06}$ADD ^{2}
R^2 = 0.9298

Figure 2. Empirical models for accumulated degree-days (ADD) and crop coefficient (*Kc*) during spring (Sp) and summer (Su) (ADD_{SpSu} *vs. Kc_{SpSu}*) (●); and autumn (A) winter (W) (ADD_{AW} *vs. Kc_{AW}*) (○). Equation parameters (a, b, c) and coefficient of determination (R^2) for single-cropped Marandu palisadegrass during the experimental period February 2016 to January 2017; Piracicaba, São Paulo, Brazil.

Figura 2. Modelos empíricos de coeficiente de cultivo (Kc) y grados-días acumulados (ADD) durante la primavera (Sp) y el verano (Su) (ADD_{SpSu} vs. Kc_{SpSu}) (●); y otoño (A) invierno (W) (ADD_{AW} vs. Kc_{AW}) (○). Parámetros de la ecuación (a, b, c) y coeficiente de determinación (R^2) para el pasto Marandu de un solo cultivo durante el experimento (febrero de 2016 a enero de 2017); Piracicaba, São Paulo, Brasil.

Mean minimum K_c values ($K_{c\,min}$) determined at the beginning of the study periods were 0.50 for Sp/Ss and 0.67 for A/W. *ADD* values for spring and autumn were 375.82 °C·days and 355.25 °C·days, respectively (figure 2). ET_c was largely ranged during Sp/Su (0.54-6.57) than during the A/W (0.64-5.62), as shown in table 2, page 77.

K_c mean values obtained in the present study were lower than those previously reported, but observed K_{cmax} under 'Marandu' palisadegrass in summer, reached 1.20. In addition, except for cycle 1 (establishment), each cycle reached a similar productive potential to that observed by other authors (table 2, page 77). The *TFY* values for the single-cropping system in each season were 13927.9 kg DM ha^{-1} (summer), 5803.6 kg DM ha^{-1} (spring), 5624.6 kg DM ha^{-1} (autumn), and 4187.8 kg DM ha^{-1} (winter). These values sum a total of 29543.9 kg DM ha^{-1} yr^{-1} in the single-cropping system. The *TFY* in the mixed-cropping system was 11343.74 kg DM ha^{-1} as recorded in a 155-day period (table 2, page 77).

Table 2. Reference evapotranspiration (ETo) and crop evapotranspiration for single-cropped 'Marandu' palisadegrass (ETc_sc) and for palisadegrass overseeded with black oats and Italian ryegrass (ETc_o), and total forage yield (*TFY*) in kg of dry mass (DM) per each period from 2016 to 2017 in Piracicaba/SP, Brazil.

Tabla 2. Evapotranspiración de cultivos para pasto Marandu de un solo cultivo (ETc_sc) y para pasto Marandu sobre sembrado con avena negra y de raigrás italiano(ETc_o) y rendimiento total de forraje (TFY) en kg materia seca (DM) para cada período de 2016 a 2017 en Piracicaba/SP, Brasil.

Cycles for single cropping are sequentially divided according to season (Su = summer, A = autumn, W = winter, Sp = spring).

Los ciclos para un solo cultivo se dividen secuencialmente según la temporada (Su = verano, A = otoño, W = invierno, Sp = primavera).

single-cropped palisadegrass				
	Date cycles (month/day)	$ET_c sc$ (mm cycle^{-1})	$ET_c sc$ (min-max daily)	*TFY* (kg DM ha^{-1} cycle^{-1})
Su	02/11 – 03/09/2016	74.1	1.7 - 3.8	1708.3
Su	03/10 - 04/06/2016	65.6	1.3 - 3.4	2542.9
A	04/07 - 05/04/2016	83.9	2.0 - 4.0	2307.1
A	05/05 – 06/13/2016	--	--	1998.8
A	06/14 – 07/23/2016	--	--	1318.7
W	07/24 - 09/01/2016	127.6	1.8 - 4.1	1617.3
W	09/02 - 10/11/2016	129.3	1.2 - 5.2	2570.5
Sp	10/12 - 11/08/2016	101.9	1.6 - 6.5	2580.8
Sp	11/09 - 12/06/2016	106.8	2.1 - 5.7	3222.8
Su	12/07/2016 - 01/03/2017	116.2	1.5 - 8.0	4951.5
Su	01/04 - 01/31/2017	90.0	1.0 - 7.2	4725.2
palisadegrass overseeded with black oats and Italian ryegrass				
	Date cycles (month/day)	$ET_c o$ (mm cycle^1)	$ET_c o$ (min-max daily)	*TFY* (kg DM ha^{-1} cycle^{-1})
	05/05 -06/13/2016	81.0	0.9 - 4.4	1827.37
	06/14 - 07/11/2016	65.4	0.2 - 4.6	1735.87
	07/12 - 08/04/2016	69.9	1.8 - 4.4	2748.9
	08/05 -09/05/2016	105.5	1.6 - 5.0	2554.8
	09/06 - 10/07/2016	111.3	1.8 - 5.1	2476.8

In figure 3 (page 78), mean K_c for palisadegrass mixed of black oats and Italian ryegrass was similar to that obtained for the single-cropped system. However, at the end of the cycle, K_c values did not decrease, as previously seen for the single-cropped pasture during AW (figure 2, page 76).

The K_c *vs. ADDa* equation (figure 2, page 76 and figure 3, page 78) was used for K_c estimates based on calculated *ADD* in the simulated sequences for the years 2015-2016 and 2017–2018, as shown in table 3 (page 78). The estimated K_c resulted in R^2 exceeding 0.92 for both Sp/Su and A/W periods, resulting in greater accuracy (higher coefficient *d*) and lower error in the Sp/Su estimation. Regarding the second year, 2017-2018, R^2 exceeded 0.95, improving the Sp/Su estimation (table 3, page 78).

Error analysis determined the Willmott's index (table 3, page 78). Mean errors (*ME*) were negative, indicating differences between model estimations and observed data in the field experiment. Observed values were higher than estimated values (with the largest error of 0.0641) in the single-cropped system during A/W. In the same period, the largest root mean square error (*RMSE*) was 0.11.

During the experimental year, *ADD* values reached approximately 404 °C·days (DD during spring and summer, and 360 °C·days during autumn and winter. In the previous annual period (2015-2016), mean values for Sp/Su and A/W were 443 and 438 °C·days, respectively, whereas in the subsequent annual period (2017-2018), ADD reached 383 and 379 °C·days, respectively.
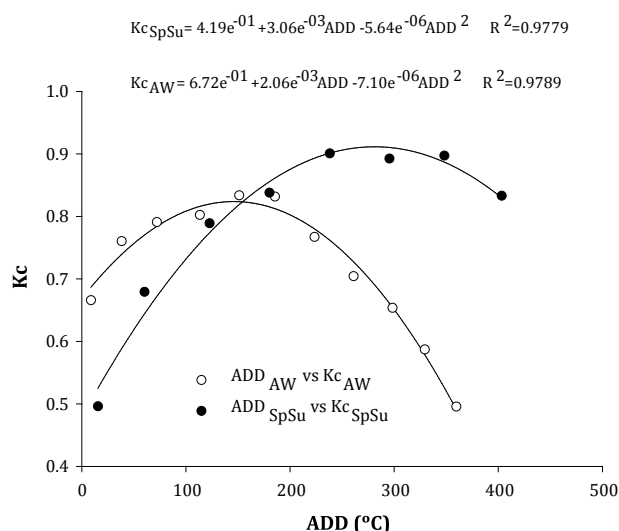
$$Kc_{SpSu} = 4.19e^{-01} + 3.06e^{-03}ADD - 5.64e^{-06}ADD^2 \quad R^2 = 0.9779$$

$$Kc_{AW} = 6.72e^{-01} + 2.06e^{-03}ADD - 7.10e^{-06}ADD^2 \quad R^2 = 0.9789$$

Figure 3. Empirical models of accumulated degree-days (ADD) and crop coefficient (K_c) during autumn/winter for palisadegrass mixed of black oats and Italian ryegrass (■), Piracicaba, São Paulo, Brazil.

Figura 3. Modelos empíricos de coeficiente de cultivo (K_c) y grados-días acumulados (ADD) durante el otoño/invierno para pastos mixtos de avena negra y raigrás italiano (■), Piracicaba, São Paulo, Brazil.

Table 3. Determination coefficient (R^{2*}), Willmott's index (d), Camargo and Sentelhas, (1997) index (c), mean error (ME), and root mean squared error (RMSE) of empirical models of K_c estimated from accumulated degree-days over 2 years. Observed *vs.* simulated K_c values for Piracicaba/SP, Brazil.

Tabla 3. Coeficiente de determinación (R^{2*}), índice de Willmott (d), Camargo y Sentelhas, (1997) índice (c), error medio (ME) y error cuadrático medio (RMSE) de modelos empíricos de Kc estimados a partir de grados-días acumulados durante 2 años. Valores de Kc observados *versus* simulados para Piracicaba/SP, Brasil.

2015/16	R²*	d	c	ME	RMSE
spring/summer	0.9296	0.9797	0.9446	-0.0098	0.0361
autumn/winter	0.9248	0.8630	0.8300	-0.0641	0.1059
intercropped	0.9569	0.9597	0.9307	-0.0016	0.0384
2017/18	R²	d	c	ME	RMSE
springer/summer	0.9754	0.9937	0.9814	-0.0009	0.0205
autumn/winter	0.9589	0.9625	0.9425	-0.0276	0.0452
intercropped	0.9569	0.9767	0.9388	-0.0077	0.0299

DISCUSSION

The decreasing K_c values for single-cropped 'Marandu' palisadegrass during autumn and winter (figure 2, page 76) may be related to low biomass accumulation and extensive leaf senescence during this phase, leading to reduced tropical forage production and lower water requirements. In this regard, some authors have shown that even in irrigated cropping systems, biomass yield in colder seasons (A/W) is approximately 50% lower than that produced during warmer periods (1).

The coefficients of determination (R^2) for the observed *vs.* estimated data in 2017-2018 were higher than those in 2015-2016, keeping high accuracy for both periods. According to the categories for the *c* index (10), the present model can be considered *excellent*, except for simulations obtained for A/W, 2015-2016.

The Sp/Su and A/W periods showed a different ADD value for $K_{c\ max}$ obtention, with a greater maximum for Sp/Su. Other related studies on tropical forages have presented $K_{c\ max}$ values of 1.04 to 1.25 for *Megathyrsus maximus* 'Tanzania'; 1.04 to 1.54 for *Megathyrsus maximus* 'Mombaça'; and 1.33 for *Urochloa brizantha* 'Piatã' (5, 9, 15, 19). In our study, curves of K_c *vs. ADD* were constructed by grouping mean K_c values for Sp/Su, resulting in an average $K_{c\ max}$ value of 0.90, while the original data indicated a $K_{c\ max}$ value of 1.27. This difference can be explained by the plant -atmosphere interaction-a concept known as coupling-observed by other authors (30, 32) throughout the year. During the beginning of the Sp/Su cycles, high temperatures may have resulted in the crop-atmosphere decoupling, making evapotranspiration largely determined by solar radiation, resulting in lower K_c values. This differs from the beginning of the A/W period, when temperature, solar radiation, air humidity and cloud cover tend to be lower. These physiological parameters need to be more accurately determined in future studies. Literature on tropical pasture reports the optimum and maximum temperatures for vegetative development to be 40 °C, and 45 °C, respectively (24). Thus, given that maximum daily temperature recorded over the studied years was between 37.3 °C and 38.7 °C an influence on growth is not considered a significant factor in this study.

During autumn and winter, K_c models for the intercropped forage showed different behaviors compared to the models for single-cropped 'Marandu' palisadegrass (figure 3, page 78). In a well-managed intercropped system, water use efficiency (in terms of forage yield and water consumption) may be higher than in a single-cropped system (11, 39). Furthermore, the use of climatically adapted species may guarantee stable productivity through the intercropping cycles (35).

Estimation models applied to the 2016–2017 experimental cycle of K_c versus *ADD* for single-cropped 'Marandu' palisadegrass in the Sp/Su and A/W periods showed high precision ($R^2 \geq 0.97$). In addition, during winter, the mixed-cropping system reached an $R^2 \pm 0.93$.

When these equations were tested against two other experimental-year data sets considering ADD value as an input parameter, they showed high precision (R^2 between 0.93 and 0.98), accuracy (*d* values from 0.86 to 0.99), and confidence (*c* values between 0.83 and 0.98). A higher error was detected during A/W given that, during this period, the tropical pastures showed major productivity variances. K_c and *ADD* in pasture-irrigation management can be widely adopted given their versatility to cope with grazing rotation (8).

Conclusions

Seasonal *Kc* was measured by the weighing-lysimeter method for growth cycles of the palisadegrass 'Marandu' cultivar and the overseeded pasture of palisadegrass, black oat, and Italian ryegrass. When tested via regression modeling and estimated by accumulated degree-days (*ADD)* this model showed accurate results. The equations developed for the spring/summer season and the intercropped system showed higher correlations than autumn/winter. The models can be used to estimate K_c with *ADD,* only requiring minimum and maximum air temperature measurements for *Kc* estimate, easy in irrigation management.

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