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ORIGINAL PAPER

Optimizing evapotranspiration and crop irrigation requirements of tropical forages cropping systems in Southern Brazil

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Abstract
Crop irrigation requirements are usually estimated based on crop evapotranspiration (ET_c) as determined by the reference evapotranspiration (ETo) and crop coefficient (K_c). There is a lack of knowledge on the irrigation requirements of tropical forage crops in Brazil, contrasting with the increasing use of irrigation in pastures. The effort of this study was to investigate what would be the water needs of tropical forages in Southern Brazil, based on a robust experimental database. The study was carried out in São Paulo State-Brazil using different forages species and their combinations [Guinea grass (GG); Guinea grass + black oat + ryegrass (GOR); Bermuda grass (BG), and Bermuda + black oat + ryegrass (BOR)]. The experimental fields were fully irrigated, and the Kc values were derived from ETc measurements on lysimeters; ETo was estimated using daily data from a nearby weather station and the standard FAO56 parameterization. Mean daily ETc values for GG, GOR, BG and BOR were 4.1, 2.9, 3.6, and 3.4 mm, respectively, and respective mean Kc values were 0.99, 0.90, 1.0, and 0.94. Average Kc values for all plots decreased as ETo increased, producing a negative Kc-ETo relationship, mainly when ETo reached values greater than 5 mm d^{-1}. This was most likely due to internal plant stomatal resistance to vapor release from the leaves diffusing to the atmosphere at high ETo. So, the time-based Kc curves described by FAO 56 manual should be adjusted for the analyzed crops considering different ranges of ETo to improve the required irrigation depth.

Keywords Irrigation management · Water resources · Crop coefficient

Introduction

Livestock is one of the main activities of Brazilian agribusiness with more than 200 million animals (IBGE 2021) in c.a. 160 million hectares of pastures. Pastures are Brazil's main soil use and are present in all six biomes of the country (Souza et al. 2020). Brazil is projected to remain the world's top exporter of beef, accounting for over one-third of global shipments. Brazil has the largest commercial bovine herd in the world, accounting for approximately 25 percent of beef exports by major traders (FAOSTAT 2023).

According to PRB (2022), the global population will reach almost 10 billion people in 2050, and food production is expected to increase by 35% to 56% to meet such demand (Dijk et al. 2021). The large territorial extension and favorable climate make Brazil a protagonist in producing and exporting food, fiber, and energy. However, the Brazilian agricultural frontiers are already limited, and the greater expansion of agricultural production must be related to the gain in productivity narrowing the yield gap (Marin et al. 2022). Thus, Brazil is an important country in global food security, but currently, nearly 53% of pastures present some level of degradation and severely degraded pastures represent 14% of the total area (Souza et al. 2020).

Usually, the average stocking density is equal to one animal unit per hectare in Brazil (450 kg) (IBGE 2021). However, stocking density can drop to 0.5 animal units per hectare in cases of degraded pasture. On the other hand, well-fertilized, irrigated, and rotated pastures, can support up to 10 animal units per hectare (Ribeiro et al. 2008). So, irrigation practice is an option to increase forage yields and consequently intensify Brazil's livestock sector, overcoming low yields and increasing land use efficiency. The expansion rate of irrigation has grown in Brazil, according to ANA (2021), and only 14% of agricultural lands in Brazil are currently irrigated. It is estimated to increase from 8.2 to 12 million hectares in the irrigated area by 2040.

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Despite Brazil being a country rich in freshwater compared to the rest of the world, its sources are poorly distributed, concentrated mostly in the northern region of the country, where there is practically no agriculture and sparsely populated. However, many agricultural fields in Brazil may not have enough water to be fully irrigated, such as Southern Brazil, where water scarcity is already an issue (Mattiuzi et al. 2019). So, one of the challenges is to improve irrigation efficiency to make proper advances in water resources related to irrigation management and, at the same time, assure high crop yields while preserving the water resources (Marin et al. 2019).

Crop irrigation requirements are commonly estimated through crop evapotranspiration (ETc), which is estimated based on reference evapotranspiration (ETo) from a standard surface of well-watered alfalfa or grass and then applying a suitable crop coefficient (Kc) (Allen et al. 1998). Thus, Kc is used to adjust ETc according to the local environment, crop growth characteristics, and soil type. While various methods exist to estimate ETc, the Penman–Monteith (Allen et al. 1998) method is extensively employed to determine ETo, combined with a published lists of Kc values for over a hundred agricultural crops, as described in Allen (2000).

Numerous studies conducted under various environments and cropping systems have been examined (Marin and Angelocci 2011; Nassif et al. 2014; Marin et al. 2016, 2019, 2020; Sobenko et al. 2018) following the FAO 56 approach (Allen et al. 1998), for improved irrigation management, it is advisable to utilize the average ETo values from the days preceding an irrigation event to adjust the Kc values. and the inverse ETo-Kc relationship is evidence for this recommendation, highlighting the overestimation of required irrigation depth for high ETo values., such overestimation could have negatively impact on the groundwater levels and increase the risk of nitrate leaching.

In this paper, we conducted an analysis using a comprehensive ground dataset collected for different forages systems to estimate Kc values to enhance the forage irrigation management, and to propose a modification in the Kc-ETo approach for these crops, hypothesizing that adjustments based on the inverse relationship Kc-ETo would lead to substantial water and energy savings for livestock in Brazil.

Material and methods

Study site

The study was carried out in the experimental area of the Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ/USP), in Piracicaba, SP, Brazil, at latitude 22°42′14″ S and longitude 47°37′21″ W, and altitude of 546 m above sea level (Fig. 1).

The climate in the region, classified based on the Köppen-Geiger classification (Peel et al. 2007) is considered as humid subtropical (Cwa), with hot and humid summers, along with dry winters.. The average annual temperature and precipitation are recorded at 21.7ºC and 1273 mm, respectively (http://www.leb.esalq.usp.br/leb/postocon.html). The experimental area consisted of four experimental plots of 12 × 12 m, with a total of 144 m^2 each, with a 4-m border. A weighing lysimeter was installed in the center of each plot (Fig. 2).

The soil in the experimental area is classified as Ferralsols soil (WRB 2015). The initial chemical and physical characteristics were determined before setting up the experiment (Table 1). Conventional soil preparation (plowing and harrowing) and weed control were carried out. Fertilization to correct soil fertility was carried out as recommended by Raij et al. (1997).

Then, dolomitic limestone (25% CaO, 17% MgO) was applied at a dosage of 4000 kg ha^{-1}, aiming to reach a base saturation percentage (V%) equal to 70%. One month after the application of limestone was applied 128 kg ha^{-1} of P_2O_5 (simple superphosphate), and potassium levels were corrected with initial fertilization, with a dose sufficient to reach 3.5% of the CEC (cation exchange capacity). Subsequently, fractional fertilization was carried out at each cultivation cycle, so that the potassium content reached 5–6% of the CEC. During the experiment, fractionated nitrogen fertilization with urea was applied immediately after each cycle, in order to apply 80 kg ha^{-1} of N in each fertilization, in the spring–summer period, and 50 kg ha^{-1} of N in the autumn–winter period.

Undisturbed soil samples were collected before the implementation of the experiment to determine the texture and water retention curve (Camargo et al. 2009), and adjusted according to Van Genuchten (1980) (Table 2). The depths sampled were 0.10, 0.20, 0.30, 0.40, 0.50, and 0.60 m (Table 5), in accordance with the effective depth of root system (0.60 m) and irrigation management, which was the same as for the lysimeters, and thus a total soil water storage capacity (WSC) of 49.3 mm was obtained in the soil profile, to a depth of 0.60 m.

The irrigation system used was conventional sprinkler irrigation using 12 m × 12 m spacing (emitters x lines), with four sprinklers per plot set at an angle of 90º, with an applied flow of 1771 $L.h^{-1}$ and an application intensity of 12.3 mm h^{-1}. The irrigation water depths were determined from the data collected in the weighing lysimeters. The area was irrigated with a fixed irrigation shift to raise soil moisture to field capacity (Θ_{FC}). The irrigation time varied based on the water consumption of the crop, which was measured in the lysimeters, and the intensity of the sprinkler application. The depletion factor (f) used was 0.60 for pastures according to Allen et al. (1998). Even though irrigation was carried out in a fixed irrigation shift, if the soil moisture reached the critical point, irrigation was anticipated to avoid water deficit.

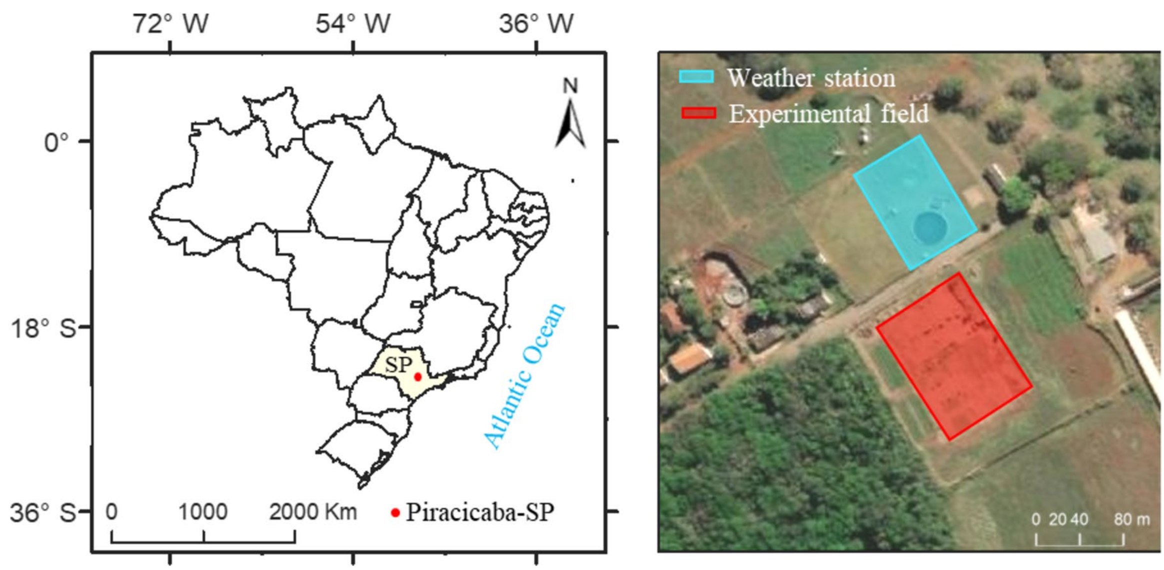


Fig. 1 Spatial distribution of the study site in Piracicaba, SP, Brazil

Lysimeter-based evapotranspiration measurement

To measure crop evapotranspiration (ETc) and crop coefficient (Kc), weighing lysimeters were constructed. Each lysimeter consisted of a circular PVC box, with a volume of 500 L, upper and lower diameters of 1.22 m and 1.0 m, respectively, and a height of 0.58 m, and a weighing structure composed of circular steel plate, triangular steel support, and three load cells for weighing. Before installing the lysimeters, the responses of the load cells and the drainage system were tested for one week for each lysimeter separately, in addition to the calibration of the drainage system. After carrying out the tests, the lysimeters were installed in each cultivation plot in cylindrical openings in the soil with a radius of 0.7 m and 1.0 depth m. The system automation consisted of a data acquisition unit through a data logger that received and stored information from the lysimeters. Field calibrations showed adjustments with significant correlation between mass variations and voltage response. More details on the construction, testing and calibration of lysimeters are available in Sanches (2018).

The crop evapotranspiration (ETc) estimation was made through the balance of water inflows and outflows, obtained from the difference in weight of the lysimetric system, according to Eq. 1.

$$ETc = Varm + P + I - Vd \tag{1}$$

where ETc is the crop evapotranspiration (mm d^{-1}); Varm is the storage variation (mm d^{-1}); P is the precipitation (mm d^{-1}); I is the irrigation (mm d^{-1}); Vd is the drainage variation (mm d^{-1}).

Daily reference evapotranspiration (ETo) using the PM-FAO-56 (Allen et al. 1998) was obtained (Eq. 2) from data from the automatic meteorological station at ESALQ/USP, located about 50 m from the study area.

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

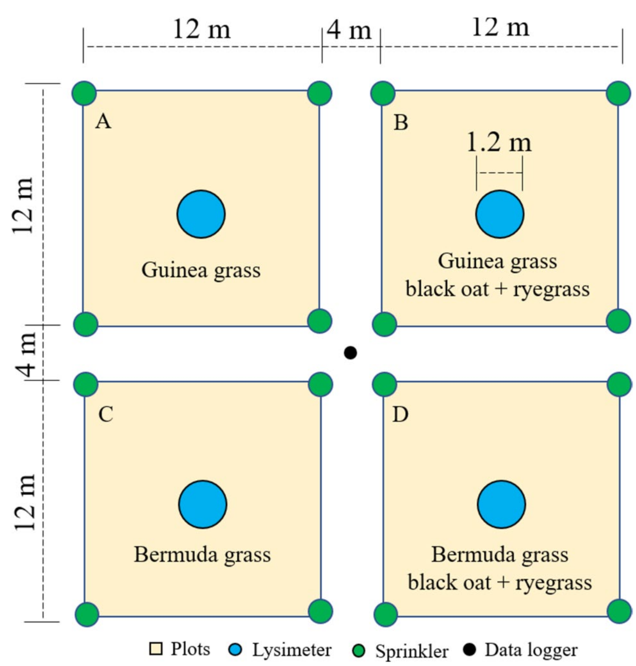


Fig. 2 Distribution of experimental plots Guinea Grass (**A**); Guinea Grass + Black Oat + Ryegrass (**B**); Bermuda Grass (**C**); and Bermuda Grass + Black Oat + Ryegrass (**D**) with the sprinklers (green circles), forage grown and lysimeters (blue circles) in the study field

Table1 Chemical characteristics of the soil in the experimental area

Layer	pH	P	K	Ca	Mg	H+Al	Al	V	CEC
m	–	mg.dm^{-3}	cmol$_c$.dm^{-3}					%	cmol$_c$.dm^{-3}
0–0.20	5.3	72	0.94	3.9	1.8	3.1	0.2	68	9,7
0.20–0.40	4.9	31	0.44	1.3	1.0	4.2	0.2	39	7.0

pH: hydrogen potential. P: phosphorus. K: potassium. Ca: calcium. Mg: magnesium. H+Al: hydrogen+aluminum. Al: aluminum. CEC: cation exchange capacity

where ETo is the reference evapotranspiration (mm d^{-1}), Rn is the radiation on the surface of the crop (MJ.m^{-2}.d^{-1}), G is the density of the heat flux of soil (MJ.m^{-2}.d^{-1}), T is the temperature of the air at a height of 2 m (ºC), u_2 is the wind speed at a height of 2 m (m s^{-1}), es is the saturation vapor pressure (kPa), ea is the actual vapor pressure (kPa), es-ea is the deficit of the saturated vapor pressure (kPa), D is the tangent to the saturated vapor curve (kPa), Δ is the slope vapor pressure curve (kPa. ºC^{-1}), and γ is the psychrometric constant (kPa. ºC^{-1}).

By obtaining the crop evapotranspiration (ETc) and reference evapotranspiration (ETo) values, the relationship between the two allowed obtaining the crop coefficient (Kc) values for forage plants during the regrowth cycles through the ratio between ETc and ETo.

To comprehend variations in Kc values in response to atmospheric confitions, for each experimental lysimeter (grown forage) and cropping cycle, a comparison of the relationships between ETo-Kc and ETc-ETo data was performed. Additionally, for each experimental lysimeter, considering all cultivation cycles, the mean Kc for the intervals lower than 2 mm d^{-1}, 2–3 mm d^{-1}, 3–4 mm d^{-1}, 4–5 mm d^{-1}, and greater than 5 mm d^{-1} of the ETo were measured so that it could be defined one Kc for each level of atmospheric demand, this approach has been observed in Marin et al. (2019) and Sobenko et al. (2018). The new Kc and ETc values found in this study based on the ETo values were further compared with the Kc values proposed by the FAO (Allen et al. 1998).

Forage planting and sowing

To streamline crop management, forage planting and sowing in each lysimeter were carried out on different dates spaced by 15 days. Bermuda grass (Cynodon spp) seedlings were planted on November 16, 2015, and Guinea grass (Panicum maximum cv) was sown on November 29, 2015. One Bermuda grass seedling was used every 0.5 m^2, with 288 seedlings per experimental plot, totaling 576 seedlings in the experimental area. For Guinea grass, seeds were used in a proportion equivalent to 20 kg ha^{-1}. The first day of December was adopted for the beginning of ETc data collection, with two days for Guinea grass germination and approximately 15 days for the establishment of Bermuda´s stolon.

The experimental plots were separated as follows: plots A and B with Guinea grass and plots C and D with Bermuda grass. With the intention of minimizing variability in forage supply, annual forage crops are often grown in rotation with pastures or form part of double- or triple-cropping forage systems (Chapman et al. 2014). So, subsequently, during the autumn/winter period, plots B and D were sown with black oat (cultivar Drizzle 29)+ryegrass (cultivar São Gabriel). On February 12th and 19th, 2016, after the forage standardization cut occurred (0.35 m high for Guinea grass, and 0.10 m high for Bermuda grass), the cultivation cycles of Guinea grass and Bermuda grass began, respectively, and on April 29th and May 6th, 2016, the over-sowings (black oats+ryegrass) were carried out in Bermuda grass and Guinea grass, respectively, with the cycles shown in Table 3. Tropical forages used in pastures grow rapidly. Then, there were several forage-cutting cycles throughout the year (from 21 to 40 days).

Results and discussion

The total precipitation for the experimental period (February/2016 to February/2017) was 1539 mm with a maximum volume of 336 mm (January/2017), and a minimum of 2.4 mm (July/2016). The monthly average temperature was 22.2 °C with a minimum value in June/2016 (16.7 °C), and

Table 2 Physical characteristics of the soil in the experimental area

Layer	Sand	Silt	Clay	Ds	Θ_{FC}	Θ_{WP}	WSC
m	%			mg. m^{-3}	cm^3 cm^{-3}		mm
0–0.20	35.7	19.2	45.1	1.47	0.39	0.29	29.4
0.20–0.40	29.3	18.7	52.0	1.61	0.38	0.29	30.0
0.40–0.60	25.6	13.4	61.0	1.48	0.42	0.34	23.8
Average	30.2	17.1	52.7	1.52	0.40	0.31	27.7

Ds: Bulk soil density $\Theta_{FC:}$ Moisture at field capacity. $\Theta_{WP:}$ Moisture at the permanent wilting point. WSC: soil water storage capacity

Table 3 Forage cultivation period for each cultivation cycle and experimental plot

Crop Cycle	Plot A[1]	Plot B[2]	Plot C[3]	Plot D[4]
1	02/12 – 03/11/2016	–	02/19 – 03/18/2016	–
2	03/12 – 04/08/2016	–	03/19 – 04/08/2016	–
3	04/09 – 05/06/2016	–	04/09 – 04/29/2016	–
4	05/07 – 06/15/2016	05/07 – 06/15/2016	04/30 – 06/01/2016	04/30 – 06/01/2016
5	06/16 – 07/25/2016	06/16 – 07/21/2016	06/02 – 07/01/2016	06/02 – 06/28/2016
6	07/26 – 09/03/2016	07/22 – 08/22/2016	07/02 – 08/06/2016	06/29 – 07/22/2016
7	09/04 – 10/01/2016	08/23 – 09/23/2016	08/07 – 09/08/2016	07/23 – 08/12/2016
8	10/02 – 10/29/2016	–	09/09 – 10/11/2016	08/13 – 08/09/2016
9	10/30 – 11/25/2016	–	10/12 – 11/01/2016	09/09 – 10/14/2016
10	11/26 – 12/19/2016	–	11/02 – 11/22/2016	–
11	12/20 – 01/16–2017	–	11/23 – 12/13/2016	–
12	01/17 – 02/13/2017	–	12/14 – 01/04/2017	–
13	–	–	01/05 – 01/25/2017	–
14	–	–	01/26 – 02/15/2017	–

[1]Guinea grass; [2]Guinea grass + black oat + ryegrass; [3]Bermuda grass; [4]Bermuda + black oat + ryegrass

a maximum in February/2016 (27.5 °C). Average relative humidity equals 75.9% and is similar over the entire period. Average net radiation of 8.53 $MJ.m^{-2}.d^{-1}$ with a minimum in June/2016 (4.16 $MJ.m^{-2}.d^{-1}$) due to the cloudiest days, and a maximum in February/2017 (12.06 $MJ.m^{-2}.d^{-1}$).

A drop in the air temperature in the fall/winter seasons (May to June) was observed, and there were several days with temperatures below 12 °C, generally indicated as a limit to the growth of tropical grasses (Andrade et al. 2016), which might limit the growth of Bermuda and Guinea grasses. Pasture production is largely governed by climate variability, which ultimately influences soil moisture, atmospheric temperature, and solar radiation, affecting plant physiology and growth processes (Radcliffe and Baars 1990; Chapman et al. 2009). Considering the climatological normal (from 1917–2022), January is the hottest month in the region with an average of 24.6ºC and July the coldest with 17.6ºC (ESALQ 2023), Fig. 3.

The amount of rainfall and irrigation applied for each lysimeter, and crop cycle varied over the crop cycles (Fig. 5). It is noted that rainfall was poorly distributed during the cultivation cycles for all lysimeters, being scarce during the winter season (from May to September). Thus, irrigation played an important role in avoiding water stress and ensuring high forage yields.

In the lysimeter cultivated with Guinea grass (Fig. 5A), it presented a total of 1458 mm of precipitation and 570 mm irrigated for the 12 cultivated cycles, with cycles 5, 6, and 7 presenting the highest irrigated depths in the driest season of the year and, in the cycle 3 due to an atypical drought for the period, practically all the water came from irrigation (90 mm).

For the lysimeter grown with Guinea grass with overseeding (Fig. 5B), the total precipitation for the four cycles was 325 mm and 285 mm irrigated. Cycle 1 presented the highest precipitation volume (256 mm) representing almost

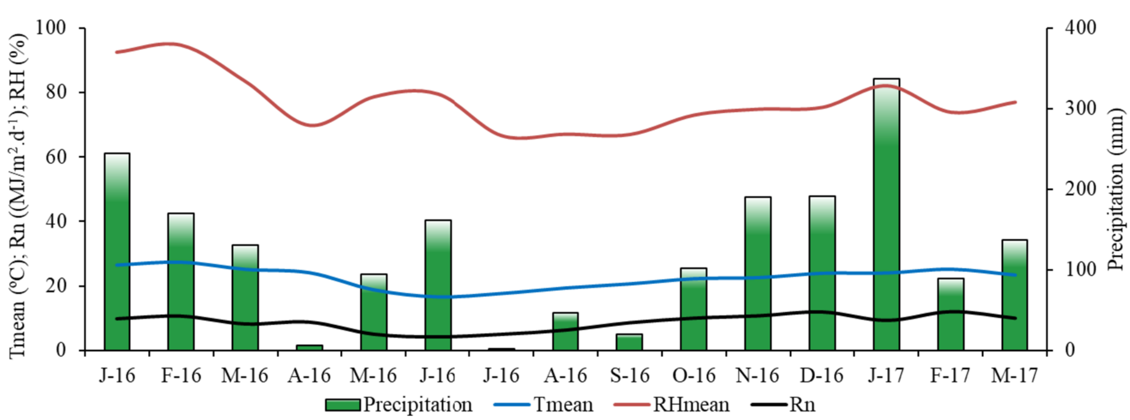


Fig. 3 Precipitation, relative humidity (RH), mean temperature (Tmean) and net radiation values (Rn) during the experimental period

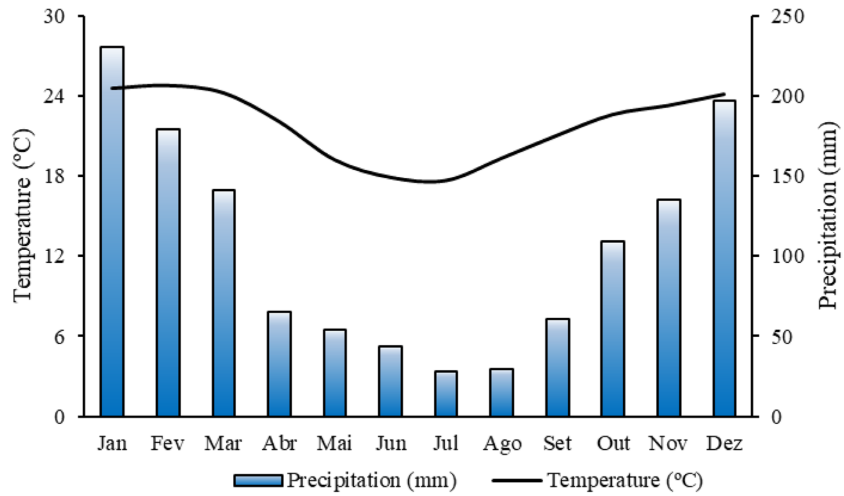


Fig. 4 Mean monthly precipitation and temperature considering the climatological normal (from 1917–2022) for the region of study

Table 4 Average daily crop evapotranspiration (ETc), reference evapotranspiration (ETo), and crop coefficient (Kc) for each plot

Plot	N° cycles	ETc total mm	Mean ETc mm d^{-1}	ETo mm	ETo mm d^{-1}	Mean Kc
A	12	1469	4.1	1437	4.0	0.99
B	4	401	2.9	433	3.1	0.90
C	14	1294	3.6	1403	3.9	1.03
D	6	563	3.4	563	3.4	0.94

Bermuda grass (A), Bermuda grass + black oat + ryegrass (B), Guinea grass (C), and Guinea grass + black oat + ryegrass (D)

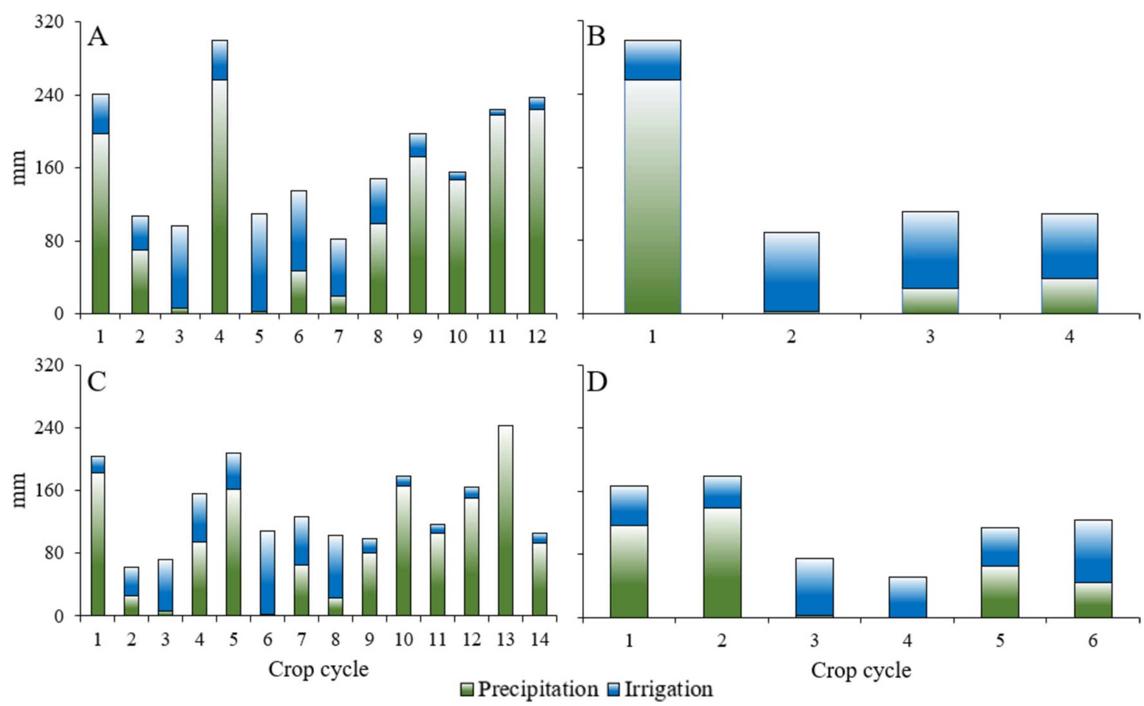
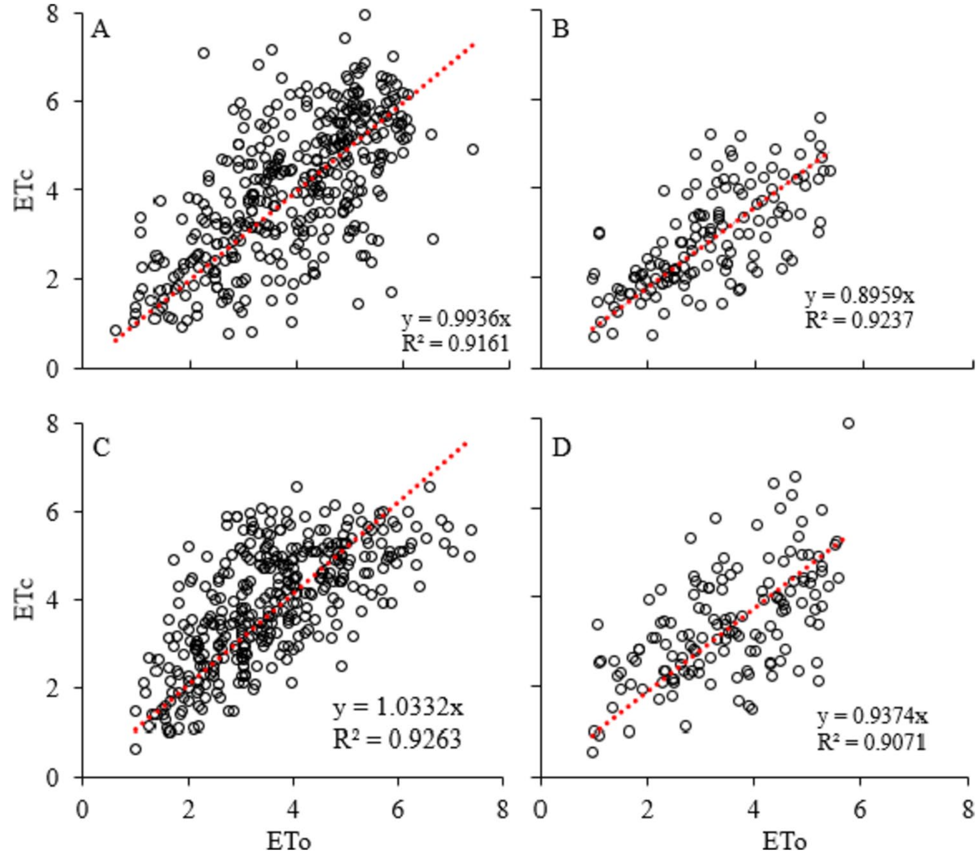


Fig. 5 Precipitated and irrigated volumes for Bermuda grass (**A**), Bermuda grass + black oat + ryegrass (**B**), Guinea grass (**C**), and Guinea grass + black oat + ryegrass (**D**)

Fig. 6 Correlation between reference evapotranspiration (ETo) and crop evapotranspiration (ETc) for Bermuda grass (**A**), Bermuda grass + black oat + ryegrass (**B**), Guinea grass (**C**), and Guinea grass + black oat + ryegrass (**D**)



80% considering the four cycles, while cycle 2 presented only 2.40 mm with the highest irrigation required (86 mm).

The lysimeter grown with Bermuda grass (Fig. 5C) had a total of 1400 mm of precipitation and about 550 mm from irrigation with cycle 13 having the highest volume of precipitation (242 mm) and no irrigation, while cycle 6 had only 2.40 mm and required the largest irrigated volume (106 mm).

In relation to the lysimeter grown with Bermuda grass with overseeding (Fig. 5D), the 6 cultivated cycles presented a total of 367 mm of precipitation and 343 mm of irrigation depth. Cycles 3 and 4 practically did not have water from precipitation and the applied irrigation was 72 mm and 51 m, respectively, to meet the water demands of the forages.

We observed the major source of variability over the study period was rainfall, particularly during fall/winter. The climatological normal (from 1917–2022) shows July as the driest month with 28.2 mm and January the wettest with 231.8 mm (ESALQ 2023), Fig. 4.

This variation in rainfall largely influences pasture growth and quality, impacting on stocking rates, and management of feed supply and demand by supplementary feeding and the use of fertilizer (Chapman et al. 2013). Yet, studies have shown that irrigation can double the pasture yield compared to non-irrigated land, enabling intensification and expansion of farm systems or land use change from less intensive sheep or beef farms to higher value dairying (Clark et al. 2007; Martin et al. 2006; Thorrold et al. 2004; Wilcock et al. 2011) (Fig. 5).

Table 5 Crop coefficient values (Kc) for each experimental plot according to reference evapotranspiration intervals (ETo)

Plots	Daily reference evapotranspiration interval (ETo in mm.d^{-1})				
	< 2 mm	2 – 3 mm	3 – 4 mm	4 – 5 mm	> 5 mm
Plot A[1]	1.34	1.17	1.12	0.98	0.93
Plot B[2]	1.23	0.96	0.94	0.81	0.85
Plot C[3]	1.32	1.05	0.96	0.90	0.84
Plot D[4]	1.47	1.14	0.98	0.92	0.83
Average	1.34 ± 0.1	1.08 ± 0.09	1.00 ± 0.08	0.90 ± 0.07	0.86 ± 0.05

[1]Guinea grass; [2]Guinea grass + black oat + ryegrass; [3]Bermuda grass; [4]Bermuda + black oat + ryegrass

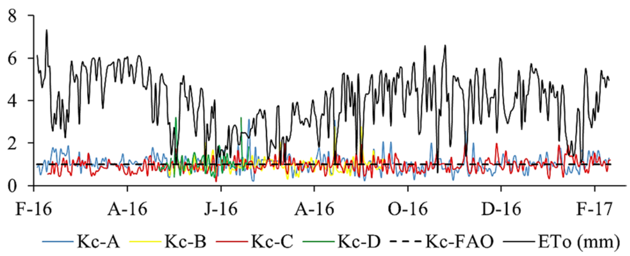


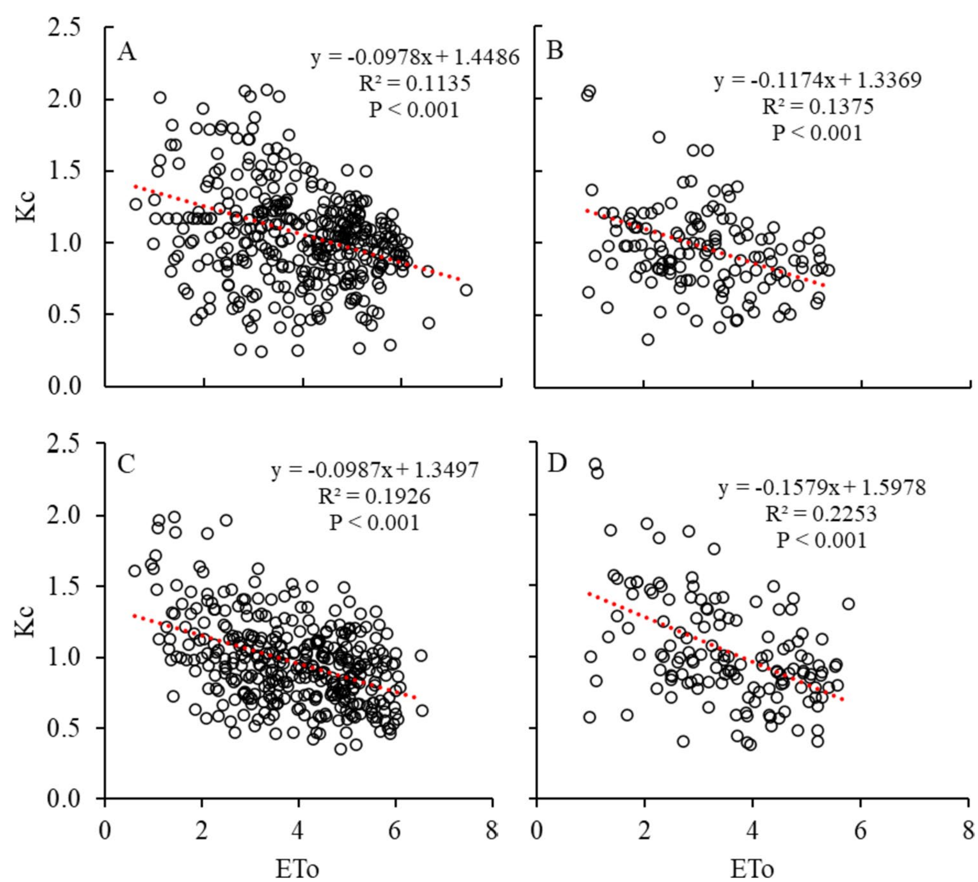
Fig. 7 Crop coefficient (Kc, dimensionless) from the plots cultivated with Bermuda grass (**A**), Bermuda grass + black oat + ryegrass (**B**), Guinea grass (**C**), and Guinea grass + black oat + ryegrass (**D**), Kc-FAO, and reference evapotranspiration (ETo, mm)

Mean Kc values (Fig. 6), represented by the angular coefficient between ETc and ETo of the line forced to pass through the origin for lysimeters A, B, C, and D were similar, with values of 0.99, 0.90, 1.03, and 0.94, respectively, reasonably agreed to the standards values of Kc recommended by the FAO 56 paper (Allen et al. 1998), and for all lysimeters, the $R^2 > 0.90$. Despite the similar average Kc values considering all forage cuts, the plot B (Bermuda grass + black oat + ryegrass had lowest ETc, resulting the lowest Kc (0.90).

Average daily ETc and ETo (Table 4) were higher in plots A and C due to the lower temperatures in plots C and D cultivated in the autumn and winter season. For plot A (Bermuda grass) the total ETc was 1469 mm with an average of 4.1 mm d^{-1}. In plot B (Bermuda grass with overseeding in autumn/winter) there were a total of 401 mm with an average of 2.9 mm d^{-1}. In plot C (Guinea grass) there were 1403 mm total and 3.9 mm d^{-1}. For Plot D (Guinea grass with overseeding in autumn/winter) the total ETo was 563 mm, with an average of 3.4 mm d^{-1}.

Irrigation requirement is mostly based on Allen et al. (1998) adopting Kc for forage after establishment (first cutting) equal to 1 (ETc is equal to ETc). This Kc mid coefficient for hay crops is an overall average Kc mid coefficient that averages Kc for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late-season period of the growing season. As shown in Fig. 7, about 53% of daily Kc values from FAO is greater than measured Kc considering all the plots over cuttings. This has a significant consequence when the irrigation management relies on the Kc-FAO approach to meet the water demand of the forages. Over-irrigation depth occurs, predominantly during periods of high atmospheric demand

Fig. 8 Correlation between reference evapotranspiration (ETo) and crop coefficient (Kc) for Bermuda grass (**A**), Bermuda grass + black oat + ryegrass (**B**), Guinea grass (**C**), and Guinea grass + black oat + ryegrass (**D**)



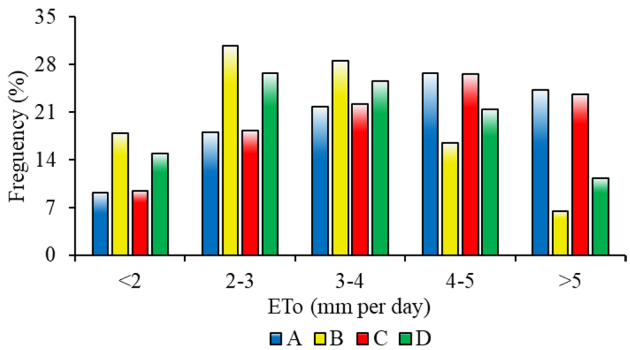


Fig. 9 Distribution of reference evapotranspiration (ETo) for Bermuda grass (**A**), Bermuda grass + black oat + ryegrass (**B**), Guinea grass (**C**), and Guinea grass + black oat + ryegrass (**D**)

(high ETo), leading to potential crop yield loss, adverse environmental impacts, and increased pumping expenses..

Despite irrigation ensuring appropriate soil water content in the root zone throughout all seasons, K_c values decreased as the ETo values increased for all the plots. This evidence can be observed through the negative slope (Fig. 8) considering all the forage cutting for each plot. Similar results were observed in Brazil and Australia for sugarcane, even under high soil water content and regardless of the canopy cover level (Marin et al. 2020). This highlights the need to adopt a variable Kc of pasture for irrigation scheduling with a range of ETo.

Regarding the inverse Kc–ETo relationship, this evidence has been observed in various other crops under high evaporative demand conditions (representing high ETo values) (Marin et al. 2019). One plausible explanation is that the crop canopies restrict water loss by partially or completely closing the stomata under high evaporative demand conditions, allowing the plants to maintain a favorable internal water balance even with optimum water content in the soil profile and high atmospheric demand (Boyer 1982; Ciais et al. 2005; Franks 2013; Vinya et al. 2013). Previous studies for maize (Tardieu et al. 1993), soybean (Teare and Kanemasu 1972) and wheat (Neukam et al. 2016) mention that the stomatal closure is dependent on the conditions of high air temperatures and vapor-pressure deficits. Thus, results observed in Brazil for forages are consistent with these studies with p-value < 0.001 for all the plots, indicating that the environmental variables increase plant resistance to water transport, limiting water transpiration at high atmospheric demands, thus creating an inverse relationship between ETo-Kc.

The inverse relationship Kc-ETo holds significant importancefor irrigation management, as a reduction in the Kc values as ETo increases (Fig. 8), implies a high atmospheric water demand from crop fields. Past studies (Allen et al. 2006, 2011; Allen and Pereira 2009) have assessed and proposed improvements in the FAO-56 methods (Allen et al. 1998) in the estimation of ETo and Kc values. Nevertheless, our study reveals that the Kc–ETo inverse correlation occurred for all the plots with different forages analyzed. Consideration of this inverse correlation could also change the irrigation strategies under high ETo and could result in a reduction of estimated water consumed for irrigated crop forages in Brazil. Marin et al. (2019) obtained the same inverse ETo-Kc relationship for coffee, citrus, sugarcane, maize, soybean, wheat, and potato. These justifications are based on ETo values greater than 4 mm d^{-1} (Fig. 9), which corresponds to approximately 50% of the growing seasons for plot A, 22% for plot B, 30% for plot C, and 32% for plot D, and such high ETo values are usually correlated when irrigation is highly required, indicating that the time-based Kc curves following FAO 56 paper (Allen et al. 1998) are not applicable for forages in Brazil, and for practical irrigation management, Kc suggestions should be adapted to avoid overestimation of irrigation depth, thus decreasing energy costs, but without yield losses.

Table 5 shows proposed values for Kc in different ETo ranges over the cutting cycles. For all of them, Kc values decreased as the ETo increased, which may represent an interesting way to improve water management under sprinkler irrigation for crop forages and an important way to save water for extensive irrigated pastures. For Kc values when ETo greater than 4 mm d^{-1}, it decreased, on average, by 10%, and 14% for ETo greater than 5 mm d^{-1} compared to Kc-FAO recommendation and Kc recommendations for practical irrigation management should be based on the average ETo values of the previous days of the irrigation management following the Table 5.

Based on these results, adjusting Kc values downward under high atmospheric demand would improve water security for meat production in irrigated pastures, especially where precipitation amounts are low and in regions with water pumping limitations as in the case of the Midwest region in Brazil. However, conducting long-term studies in various climates conditions, varieties, and soil types could enhance the findings of this study, collaborating in decision-making to improve irrigation management.

Conclusions

This study primarily aimed to analyze the ETo-Kc relationship under high atmospheric demand in Brazil. It also proposed a modification to the Kc-ETo approach to prevent overestimating irrigation requirements for crop forages.

We found that average seasonal Kc values were similar between forage systems. However, Guinea grass had the lowest Kc during the hot period (summer) with high

ETo. We observed that K_c values decreased under high water requirements for Bermuda grass and Guinea grass systems, creating an inverse ETo-K_c relationship. Therefore, for practical purposes, Kc recommendations should consider this finding and adjust the Kc values based on the ETo values for forages to avoid overirrigation.

The findings of this research align with irrigated agriculture strategies for rational water use for high-producing forages varieties, thereby assisting farmers save water and electricity and preserving the groundwater and the ecosystem in Brazil.

Long-term studies that consider various climates, soil types, and types of forages are crucial. These studies should involve comprehensive analyses of biomass and crop water productivity, with a particular focus on the potential reduction of irrigation depth while maintaining comparable biomass production.

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Data Availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interest/competing interests The authors declare that they have no conflict of interest.

References

Allen RG (2000) Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. J Hydrol 229(1–2):27–41. https://doi.org/10.1016/S0022-1694(99)00194-8

Allen RG, Pereira LS (2009) Estimating crop coefficients from fraction of ground cover and height. Irrig Sci 28:17–34. https://doi.org/10.1007/s00271-009-0182-z

Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder R, Itenfisu D, Steduto P, Berengena J, Yrisarry JB, Smith M, Pereira LS, Raes D, Perrier A, Alves I, Walter I, Elliott R (2006) A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. Agric Water Manage 81(1–2):1–22. https://doi.org/10.1016/j.agwat.2005.03.007

Allen RG, Pereira LS, Howell TA, Jensen ME (2011) Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric Water Manag 98:899–920. https://doi.org/10.1016/j.agwat.2010.12.015

Allen RG, Raes D, Smith M (1998) Crop Evapotranspiration: Guidelines for Computing Crop Requirements. Irrig. Drain. Pap. No. 56. FAO, Rome, Italy

Ana (National Water and Sanitation Agency) (2021) Atlas irrigação. Uso da água na agricultura irrigada, 2nd ed. Brasília, DF, p. 66

Andrade AS, Santos PM, Pezzopane JRM, De Araujo LC, Pedreira BC, Pedreira CGS, Marin FR, Lara MAS (2016) Simulating tropical forage growth and biomass accumulation: an overview of model development and application. Grass Forage Sci 71(1):54–65

Boyer JS (1982) Plant productivity and environment. Science 218:443–448

Camargo OA, Moniz AC, Jorge JA, Valadares JMA (2009) Chemical Analysis Methods, Mineralogical and Physical Soil of the Agronomic Institute of Campinas, 106th edn. Agronomic Institute of Campinas, Campinas

Chapman DF, Cullen BR, Johnson IR, Beca D (2009) Interannual variation in pasture growth rate in Australian and New Zealand dairy regions and its consequences for system management. Anim Prod Sci 49:1071–1079

Chapman DF, Hill J, Tharmaraj J, Beca D, Kenny SN, Jacobs JL (2014) Increasing home-grown forage consumption and profit in non-irrigated dairy systems. 1. Rationale, systems design and management. Anim Prod Sci 54:221–233. https://doi.org/10.1071/AN12295

Chapman DF, Rawnsley RP, Cullen BR, Clark DA (2013) Inter-annual variability in pasture herbage accumulation in temperate dairy regions: causes, consequences, and management tools. In 'Proceedings 22nd International Grassland Congress'. 15–19 September 2013, Sydney. pp 798–805. (International Grassland Congress)

Ciais P, Reichstein M, Viovy N et al (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529–533

Clark DA, Caradus JR, Monaghan RM, Sharp P, Thorrold BS (2007) Issues and options for future dairy farming in New Zealand. New Zealand J Agric Res 50(2007):203–221

Dijk MV, Morley T, Rau ML, Saghai Y (2021) A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nat Food 2:494–501. https://doi.org/10.1038/s43016-021-00322-9

ESALQ, University of São Paulo, Biosystem Engineering (2023) Meteorological station of Piracicaba, SP. http://www.leb.esalq.usp.br/leb/postocon.html. Accessed Apr 2023

Faostat (Food and Agriculture Organization of the United Nations, Food and Agriculture Statistics) (2023) Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL. Accessed Apr 2023

Franks PJ (2013) Passive and active stomatal control: either or both? New Phytol 198:325–327

Ibge (Brazilian Institute of Geography and Statistics) (2021) Bovine Herd (Oxen and Cows). https://www.ibge.gov.br/explica/producao-agropecuaria/bovinos/br. Accessed Apr 2023

Marin FR, Angelocci LR (2011) Irrigation requirements and transpiration coupling to the atmosphere of a citrus orchard in Southern Brazil. Agric Water Manag 98:1091–1096. https://doi.org/10.1016/j.agwat.2011.02.002

Marin FR, Angelocci LR, Nassif DSP, Costa LG, Vianna MS, Carvalho KS (2016) Crop coefficient changes with reference evapotranspiration for highly canopy-atmosphere coupled crops. Agric Water Manag 163:139–145. https://doi.org/10.1016/j.agwat.2015.09.010

Marin FR, Angelocci LR, Nassif DSP, Vianna MS, Pilau FG, Silva EHFM, Sobenko LR, Gonçalves AO, Pereira RAM, Carvalho KS (2019) Revisiting the crop coefficient–reference evapotranspiration procedure for improving irrigation management. Theor Appl Climatol 138:1785–1793. https://doi.org/10.1007/s00704-019-02940-7

Marin FR, Inman-Bamber G, Silva TGF, Nassif DFP, Carvalho KS (2020) Sugarcane evapotranspiration and irrigation requirements in tropical climates. Theor Appl Climatol 140:1349–1357. https://doi.org/10.1007/s00704-020-03161-z

Marin FR, Zanon AJ, Monzon JP, Andrade JF, Silva EHFM, Richter GL, Antolin LAS, Ribeiro BSMR, Ribas GG, Battisti R, Heinemann AB, Grassini P (2022) Protecting the Amazon forest and reducing global warming via agricultural intensification. Nat Sustain 5:1018–1026. https://doi.org/10.1038/s41893-022-00968-8

Martin RJ, Stevens DR, Thomas SM, Zyskowski RF, Moot DJ, Fraser TJ (2006) Improving water use efficiency on irrigated dairy farms

in Canterbury. Proc NZ Grassland Assoc 68(2006):155–159. https://doi.org/10.33584/jnzg.2006.68.2654
Mattiuzi CDP, Marques GF, Medellín-Azuara J (2019) Reassessing water allocation strategies and conjunctive use to reduce water scarcity and scarcity costs for irrigated agriculture in Southern Brazil. Water 11:1140. https://doi.org/10.3390/w11061140
Nassif DSP, Marin FR, Costa LG (2014) Evapotranspiration and transpiration coupling to the atmosphere of sugarcane in southern Brazil: scaling up from leaf to field. Sugar Tech 16:250–254. https://doi.org/10.1007/s12355-013-0267-0
Neukam D, Böttcher U, Kage H (2016) Modelling wheat stomatal resistance in hourly time steps from micrometeorological variables and soil water status. J Agron Crop Sci 202:174–191. https://doi.org/10.1111/jac.12133
Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644. https://doi.org/10.5194/hess-11-1633-2007
PRB (Population Reference Bureau) (2022) 2022 world population data sheet. https://2022-wpds.prb.org/data-sheet-download/
Radcliffe J, Baars J (1990) The productivity of temperate grasslands. In 'Ecosystems of the world. 17B Managed grasslands. Analytical studies.' Amsterdam, Elsevier, pp 7–17
Raij B van, Cantarella H, Quaggio JA, Furlani AMC (1997) Recomendações de adubação e calagem para o estado de São Paulo, 3rd ed. IAC, Campinas
Ribeiro EG, Fontes CAA, Palieraqui JGB, Martins, Cóser, Santanna NF (2008) Effect of irrigation, during dry and rainy season, on stocking rate, intake and performance of steers grazing 'Mombaça' guineagrass and 'Napier' elephantgrass. R Bras Zootec 37(9). https://doi.org/10.1590/S1516-35982008000900005
Sanches AC (2018) Crop coefficient (Kc) and water consumption, productive and biometric factors of tropical grasses in exclusive cultivation and overseeding with winter forages. Doctorate thesis. USP/ESALQ
Sobenko LR, Souza TT, Gonçalves AO, Bianchini VJM, Silva EHFM, Souza LT, Marin FR (2018) Irrigation requirements are lower than those usually prescribed for a maize crop in southern Brazil. Exp Agric 2018:1–10. https://doi.org/10.1017/S0014479718000339
Souza CM Jr, Shimbo JZ, Rosa MR, Parente LL, Alencar AA, Rudorff BFT, Hasenack H, Matsumoto M, Ferreira LG, Souza-Filho PWM, de Oliveira SW, Rocha WF, Fonseca AV, Marques CB, Diniz CG, Costa D, Monteiro D, Rosa ER, Vélez-Martin E, Weber EJ, Lenti FEB, Paternost FF, Pareyn FGC, Siqueira JV, Viera JL, Neto LCF, Saraiva MM, Sales MH, Salgado MPG, Vasconcelos R, Galano S, Mesquita VV, Azevedo T (2020) Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth engine. Remote Sens 12:2735. https://doi.org/10.3390/rs12172735
Tardieu F, Zhang J, Gowing DJG (1993) Stomatal control by both [ABA] in the xylem sap and leaf water status: a test of a model for draughted or ABA-fed field-grown maize. Plant Cell Environ 16:413–420. https://doi.org/10.1111/j.1365-3040.1993.tb00887.x
Teare ID, Kanemasu ET (1972) Stomatal-diffusion resistance and water potential of soybean and sorghum leaves. New Phytol 71:805–810. https://doi.org/10.1111/j.1469-8137.1972.tb01959.x
Thorrold BS, Bright KP, Palmer CA, Wastney ME (2004) Modelling the effects of irrigation reliability on pasture growth in a dairy system in Canterbury. Proc N Z Grassl Assoc 66:31–34
Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:(5). https://doi.org/10.2136/sssaj1980.03615995004400050002x
Vinya R, Malhi Y, Fisher JB, Brown N, Brodribb T, Aragão LEOC (2013) Xylem cavitation vulnerability influences tree species' habitat preferences in miombo woodlands. Oecologia 173:711–720
Wilcock RJ, Nash D, Schmidt J, Larned ST, Rivers MR, Feehan P (2011) Inputs of nutrients and fecal Bacteria to freshwaters from irrigated agriculture: case studies in Australia and New Zealand. Environ Manage 48:198–211. https://doi.org/10.1007/s00267-011-9644-1
WRB (World reference base for soil resources 2014) (2015) International soil classification system for naming soils and creating legends for soil maps. Update 2015. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i3794en/I3794en.pdf. Accessed Apr 2023