ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.3, e275196, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n3e275196
Original Article

Using mining waste from the Fundão Dam in Mariana for Mombasa grass production[1]

Biomassa e demanda hídrica do capim mombaça em solo afetado pelo rompimento da Barragem do Fundão

Tayssa M. Franco[2*], Gloria M. R. Plazas[2], Vinícius L. Silva[2], Rubens A. de Oliveira[2], Marcus J. A. de Lima[3], Fernando F. da Cunha[2], Odilon G. Pereira[2], Paulo R. Cecon[2] & Carlos A. B. de Alencar[2]

[1] Research developed at Universidade Federal de Viçosa, Viçosa, MG, Brazil
[2] Universidade Federal de Viçosa, Viçosa, MG, Brazil
[3] Universidade Federal Rural da Amazônia, Capitão Poço, PA, Brazil

HIGHLIGHTS:

Efficient Mombasa grass production in ore tailings is achieved through optimal management with low soil moisture content.
The rupture of the Fundão Dam significantly reduced soil productivity in the affected regions.
The greatest water demand for Mombaça grass was obtained in autumn.

ABSTRACT: The collapse of the Fundão Dam in Mariana, MG, in 2015 introduced the challenge of using Technosol, a soil type formed by deposition of iron mining waste along the Doce River banks, for agricultural purposes. This study aimed to determine the optimal water depth for enhancing production of tropical forage, *Megathyrsus maximus* cv. Mombasa, when grown on iron ore tailings. Additionally, it sought to establish a crop coefficient applicable to the edaphoclimatic conditions of Viçosa, MG, Brazil. The experiment was conducted throughout the summer, fall, and winter of 2022, employing 21 drainage lysimeters. A completely randomized experimental design was adopted, featuring six treatment groups (plants in Technosol receiving water depths ranging from 20 to 120% of the crop's evapotranspiration, as derived from the control treatment), along with a control group (plants in Latosol with a depth of 100%), each with three repetitions. Our findings showed that irrigation must replace 40% of the crop evapotranspiration. Moreover, cultivating in Technosol resulted in a reduction of productive capacity by 37.39% during the summer/fall and fall seasons. For Mombasa grass grown in Oxisol, crop coefficients of 1.2 during the summer and 1.5 during the fall and winter are advised.

Key words: crop coefficient, evapotranspiration, irrigated pasture, mining tailings, *Megathyrsus maximus* (Jacq.)

RESUMO: O rompimento da Barragem do Fundão em Mariana, MG, ocorrida em 2015, trouxe o desafio de usar o Tecnossolo (tipo de solo) formado pela deposição do rejeito de mineração de ferro nas margens do Rio Doce para agricultura. O objetivo desta pesquisa foi obter a lâmina de água para otimizar a produção da forragem tropical *Megathyrsus maximum* cv. Mombaça, cultivada em rejeito de mineração de ferro e determinar seu coeficiente de cultura para as condições edafoclimáticas de Viçosa, MG. O experimento foi realizado durante as estações de verão, outono e inverno do ano de 2022, com a utilização de 21 lisímetros de drenagem. O experimento foi distribuído em delineamento inteiramente casualizado com 6 tratamentos (plantas em Tecnossolo com lâminas variando de 20 a 120% da evapotranspiração da cultura, obtida do tratamento-testemunha) e adição de uma testemunha (plantas em Latossolo com lâmina de 100%) com três repetições. Recomenda-se irrigação com reposição de 40% da evapotranspiração da cultura. O cultivo em Tecnossolo diminuiu a capacidade produtiva em 37,39% nos ciclos das estações do verão/outono e outono. Recomenda-se os coeficientes de cultura de 1,2 no verão e 1,5 no outono e no inverno, para o capim-Mombaça cultivado em um Latossolo.

Palavras-chave: coeficiente de cultura, evapotranspiração, pasto irrigado, rejeito de mineração, *Megathyrsus maximus* (Jacq.)

• Ref. 275196 – Received 28 May, 2023
* Corresponding author - E-mail: tayssa.menezes2015@gmail.com
• Accepted 26 Nov, 2023 • Published 04 Jan, 2024
Editors: Ítalo Herbet Lucena Cavalcante & Hans Raj Gheyi

Introduction

The catastrophic rupture of the Fundão Dam in Mariana, MG, Brazil, in 2015, resulted in the discharge of over 45 million m^3 of iron ore tailings onto the banks of the Doce River (Silva et al., 2019). This event led to the formation of a unique soil profile known as Technosol (Vicente et al., 2021), characterized by distinct physical-hydric, structural, and chemical properties compared to natural soils, which can impact plant growth and development (Santos et al., 2019; Batista et al., 2020).

Consequently, the challenge of harnessing Technosol for agricultural production emerged, necessitating research to generate knowledge and facilitate the implementation of agriculture in the affected areas. Achieving this goal entails not only selecting suitable plant species but also comprehending the dynamics of water within the soil-plant-atmosphere continuum. Using soil cover with forage species presents a promising solution, as these species typically exhibit excellent adaptability to adverse environments and tend to improve soil parameters (Oliveira et al., 2019; Bezerra et al., 2022).

Megathyrsus maximum cv. Mombasa, a grass variety that previously played a significant role in the dairy farming sector within the Iron Quadrangle region, demonstrated high responsiveness to fertilization and irrigation management, with peak productivity concentrated during the spring/summer season (accounting for 62.6% of the annual total) (Euclides, 2014; Jesus et al., 2021). The decline in production can be mitigated through irrigation application, as irrigated pasture can help attenuate the effects of climate seasonality, even though it cannot eliminate them entirely (Jesus et al., 2021).

Our primary goal was to determine the optimal water depth for enhancing the production of tropical forage *M. maximum* cv. Mombasa when cultivated on iron ore tailings. Additionally, we aimed to establish a crop coefficient applicable to the edaphoclimatic conditions of Viçosa, MG, Brazil.

Material and Methods

The study was conducted between October 27, 2021, and August 8, 2022, at the Irrigation Experimental Area of the Departamento de Engenharia Agrícola at the Universidade Federal de Viçosa - UFV, located in Viçosa, MG, Brazil, at geographic coordinates 20°46'08" S and 42°52'44" W, with an altitude of 675 m.

Iron ore tailings were sourced from the Germano Dam in Mariana, MG, Brazil, with the cooperation of the Renova Foundation, situated at geographic coordinates 20°13'01" S and 43°28'10" W, at an altitude of 893 m. These tailings were used to fill 18 of the 21 drainage lysimeters, each measuring 1.40 m in length, 1.00 m in width, and 0.90 m in depth.

A PVC drainage network at the base of the lysimeters was covered with a 0.10 m thick gravel layer, followed by a sand layer of the same thickness. Subsequently, 18 lysimeters were filled with 0.65 m of iron ore waste with a density of 1.66 g cm^{-3}, and three lysimeters contained soil classified as Oxisol with a density of 1.07 g cm^{-3} (as detailed in Table 1). A 0.05 m space was left vacant around the edges, following the model adapted from Bernardo et al. (2019). Throughout the filling process, the original densities of the Oxisol and iron ore tailings were maintained.

Samples were collected from the 0-20 cm layer of both ore tailings and soil for physical-hydric and chemical characterization, as presented in Tables 1 and 2. Physical-hydric attributes, such as water retention at field capacity (FC) and permanent wilting point (PWP), were analyzed in the Laboratory of Soil Physics, while chemical analysis was conducted in the Laboratory of Soil, Plant Tissue, and Fertilizer Analysis, both affiliated with the Department of Soils at the Universidade Federal de Viçosa.

Liming was not necessary because base saturation (BS) values were 62.7 and 48.3% for soil and ore tailings, respectively (Table 2). The desired BS for Mombasa grass cultivation is 45% (Alvarez et al., 1999). Fertilization for establishment and maintenance followed the recommendations of Alvarez et al. (1999), with the quantities of N, P_2O_5, and K_2O applied detailed in Table 3.

Seeds of the tropical forage *Megathyrsus maximum* cv. Mombasa (Poaceae) with a pure live seed of 76% were evenly distributed in three furrows spaced 0.46 m apart within each

Table 1. Particle size distribution and physical-hydric analyses of ore tailings and Oxisol samples from the 0-20 cm depth layer

Sample	Coarse sand	Fine sand	Silt	Clay	FC	PWP	Dp	Ds	TP	TWA	Textural class
	(dag kg^{-1})				(g g^{-1})		(g cm^{-3})		(%)	(mm cm^{-1})	
Iron ore Tailing	10.8	58.3	24.4	6.5	0.15	0.06	2.78	1.66	40.00	1.6	Sandy loam
Oxisol	12.6	11.5	5.3	70.6	0.31	0.21	2.63	1.07	59.00	1.07	Clay

FC - water content at field capacity; PWP - water content at permanent wilting point; Dp - particle density; Ds - soil bulk density; TP - total porosity; TWA - total water availability in the soil

Table 2. Chemical characteristics of ore tailings and Oxisol samples from the 0-20 cm depth layer

Layer (0-20 cm)	pH H_2O	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	t	CEC	BS (%)
		(mg dm^{-3})			(cmolc dm^{-3})							
Iron ore Tailing	5.6	49.9	62.0	6.6	2.3	0.5	0.0	1.8	3.0	3.0	4.8	62.7
Oxisol	5.1	40.6	134.0	12.6	2.6	0.7	0.0	4.6	3.6	3.6	8.2	48.3
Layer (0-20 cm)	**SSI (%)**	**P-rem (mg dm^{-3})**	**S**	**B**	**Cu**	**Mn**	**Fe**	**Zn**	**Cr**	**Ni**	**Cd**	**Pb**
			(mg dm^{-3})									
Tailing	0.5	50.1	3.3	0.4	1.6	59.5	114.6	17.1	0.0	0.21	0.1	1.3
Oxisol	0.6	21.5	23.2	2.1	1.0	18.7	30.7	6.4	0.0	0.02	0.0	1.3

pH in water - ratio 1:2.5; P, Na, K, Fe, Zn, Mn, Cu, Cd, Pb, Ni, and Cr - Mehlich-1 extractor; Ca^{2+}, Mg^{2+}, and Al^{3+} - 1 mol L^{-1} KCl extractor; H+Al - 0.5 mol L^{-1} calcium acetate extractor at pH 7.0; SB - sum of exchangeable bases; t - effective cation exchange capacity; CEC - cation exchange capacity at pH 7.0; BS - base saturation; m - aluminum saturation index; SSI - sodium saturation index; P-rem - remaining phosphorus; S - monocalcium phosphate in acetic acid; B - hot water extractor

Table 3. Fertilization schedule and nutrient doses for Mombasa grass grown in Technosol and Oxisol

Fertilization period	Technosol			Oxisol		
	N*	P_2O_5	K_2O**	N	P_2O_5	K_2O
	(kg ha^{-1})					
Establishment	200	20	40	200	20	40
Maintenance	200	-	40	200	-	40

Sources: N* - ammonium sulfate; N - urea; K_2O - potassium chloride; K_2O** - application of potassium chloride when vegetation had covered 60% of the lysimeter areas

lysimeter. Sowing density adhered to the recommendation of 12.0 kg ha^{-1} by EMBRAPA (2001).

The experiment was designed with a completely randomized structure, featuring six treatment groups (L20, L40, L60, L80, L100, and L120%), along with a control treatment (S100%) with three replications each, totaling 21 experimental units. The six treatments consisted of varying irrigation depths for plants grown in Technosol (20, 40, 60, 80, 100, and 120% of the ETc from the control treatment). The control treatment involved plants cultivated in Oxisol without traces of iron mining residues and was irrigated daily with 100% ETc.

Several parameters were assessed, including forage dry matter productivity (FDM) in t ha^{-1}, irrigation water productivity (WP_{Irri}) in kg mm^{-1}, evapotranspiration curves (ETc and ETo) in mm d^{-1}, and the evolution of crop coefficient (Kc). A 500-g sample of fresh shoot biomass was collected from each cutting to calculate the production parameters.

Eqs. 1 and 2 were employed to calculate ETc and ETo, while Eqs. 3 and 4 were used to compute FDM and WP_{Irri}. Kc was calculated according to Eq. 5.

$$\mathrm{ETc} = \mathrm{I} - \mathrm{D} \tag{1}$$

where:

ETc - crop evapotranspiration (mm d^{-1});
I - applied irrigation depth (mm d^{-1}); and,
D - drained water depth (mm d^{-1}).

$$\mathrm{ETo} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T + 273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34 u_2\right)} \tag{2}$$

where:

ETo - reference evapotranspiration (mm d^{-1});
R_n - net surface radiation (MJ m^{-2} d^{-1});
G - soil heat flux density (MJ m^{-2} d);
T - air temperature at 2 m height (°C);
u_2 - wind speed at 2 m height (m s^{-1});
e_s - saturation vapor pressure (kPa);
e_a - is the partial vapor pressure (kPa);
Δ - slope of the saturation vapor pressure curve (kPa °C^{-1}); and,
γ - psychrometric coefficient (kPa °C^{-1}).

$$\%\mathrm{DM} = \frac{\left(\%\mathrm{ASE}\%\mathrm{ASA}\right)}{100} \tag{3}$$

where:

%DM - percentage of dry matter;
%ASA - percentage of sample dried at 55 °C in a forced-air circulation oven; and,
%ASE - percentage of sample dried at 105 °C without air circulation.

$$\mathrm{WP}_{\mathrm{Irri}} = \frac{\mathrm{FDM}}{\mathrm{TIW}} \tag{4}$$

where:

WP_{Irri} - irrigation water productivity (kg mm^{-1});
FDM - forage dry matter (kg); and,
TIW - total irrigation water (mm).

$$\mathrm{Kc}(t) = \begin{cases} \mathrm{Kc}_i, t \le t_1 \\ \mathrm{Kc}_i + \dfrac{\mathrm{Kc}_n - \mathrm{Kc}_i}{t_2 - t_1}\left(t - t_i\right), t_1 < t < t_2 \\ \mathrm{Kc}_n, t_2 \le t \le t_3 \\ \mathrm{Kc}_n + \dfrac{\mathrm{Kc}_f - \mathrm{Kc}_n}{t_4 - t_3}\left(t - t_3\right), t_3 < t \le t_4 \end{cases} \tag{5}$$

where:

t - days after cutting;
t_1 - equal to t_i;
t_2 - $t_1 + t_c$;
t_3 - $t_1 + t_c + t_n$ t_4; and,
t_4 - $t_1 + t_c + t_n + t_f$.

Uniform irrigations were administered in all treatments during the initial phase of the experiment (a 68-day establishment period) to replace 100% of ETc, using a manual watering can. Subsequently, plants were cut at a height of 0.15 m, and varying irrigation depths were applied until the conclusion of the experiment.

Covers consisted of metallic structures with transparent plastic film, equipped with two side gutters to collect and channel rainwater to the border. Plastic film was rolled up and secured to the metallic framework in the absence of rainfall. Daily meteorological data, including temperature, relative humidity, wind speed, and solar radiation, were retrieved from the digital database of the Instituto Nacional de Meteorologia - INMET, with its automatic meteorological station situated 750 m horizontally and 24 m vertically from the experimental area.

Drainage water was collected daily between 7 and 9 a.m. from the lysimeters containing soil (control treatment, identified as S100%), as they received 40% more ETc irrigation. Following collection, mean quantification of drained water was determined via the gravimetric method, employing a Toledo PRIX 3/16 scale. ETc and reference evapotranspiration values were calculated over a 24-hour interval using Eqs. 1 and 2, respectively (Allen et al., 2006).

After implementing the treatments, the cutting criterion for the subsequent four cycles was established as maintaining the pasture's height within the range of 0.90 to 1.00 m in the lysimeters containing Oxisol. Subsequently, all lysimeters underwent systematic grass cutting, with samples being collected for analysis from that point onward. Notably, a practice of mixing drained water with irrigation water was adopted and applied to the respective lysimeters to minimize nutrient loss through leaching.

Daily Kc values were determined by dividing the average of three daily crop evapotranspiration values, obtained through water balance in the three lysimeters filled with Oxisol, by the daily reference evapotranspiration values, calculated using the Penman-Monteith FAO-56 equation.

The method proposed by Doorenbos & Pruitt (1977), which comprises four distinct periods [initial (t_i), growth (t_c), intermediate (t_n), and final (t_f)] in days, along with the initial (Kc_i), intermediate (Kc_n), and final (Kc_f) stages of the crop coefficients (Kc), was employed as per Eq. (5).

Firstly, FDM was estimated by reducing the moisture content of the samples in a forced-air circulation oven, using the INCT-CA G-001/1 method (Detmann et al., 2012). Subsequently, dry matter (%DM) was calculated for samples with high moisture content, such as fresh forage, in accordance with Eq. (3).

Dry matter productivity (%DM) was employed to estimate forage dry matter productivity (FDM) (t ha^{-1}) and irrigation water productivity (WP_{Irri}) (kg mm^{-1}). WP_{Irri} was determined using a formula adapted from the method developed by Mota et al. (2020), as presented in Eq. 5.

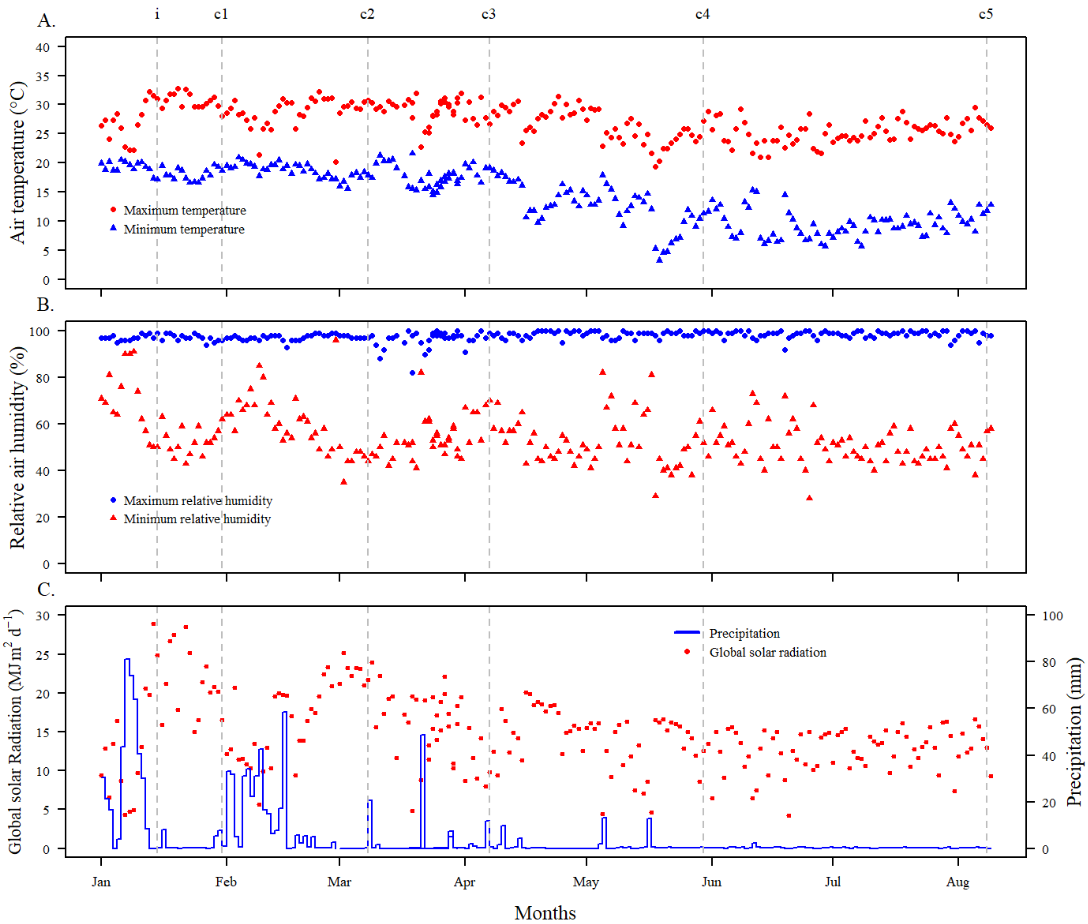
Data were subjected to normality and homoscedasticity assumptions, followed by analysis of variance and Dunnett's mean test (5% significance level) to compare plants cultivated in iron ore tailings with the control treatment. There was no statistical comparison between cycles; instead, individual comparisons were made for each cycle. Statistical software SPEED Stat (Carvalho et al., 2020) was used for these analyses.

Results and Discussion

Five growth cycles of Mombasa grass were analyzed from January 16 to August 8, 2022. Crop (ETc) and reference (ETo) evapotranspiration values were collected in all cycles for subsequent crop coefficient (Kc) calculation. However, grass biomass samples for forage production and quality analysis were only collected in the first four cycles since plants had not reached cutting height. This may have been due to susceptibility of C4 plants to low temperatures and light (Santos et al., 2020) during certain seasons, leading to a reduction in growth.

The five cycles and their corresponding periods and seasons were as follows: cycle 1 - January 16 to 31 (summer), cycle 2 - February 1 to March 8 (summer), cycle 3 - March 9 to April 7 (summer/fall), cycle 4 - April 8 to May 30 (fall), and cycle 5 - May 31 to August 8 (fall/winter).

Meteorological data, including global solar radiation, rainfall, relative air humidity, and temperature (Figures 1A, B, and C), were analyzed for all five crop cycles. Understanding



i - beginning of treatments; c_1 - cycle 1; c_2 - cycle 2; c_3 - cycle 3; c_4 - cycle 4; and c_5 = cycle 5

Figure 1. Daily variations in maximum (°C) and minimum (°C) mean air temperatures (A), maximum (%) and minimum (%) mean air relative humidity (B), global solar radiation (MJ m^2 d^{-1}), and rainfall (mm) (C) during five cultivation cycles of Mombasa grass from January to August 2022

the effects of these meteorological elements is crucial for assessing their impact on crop evapotranspiration, crop coefficient, production parameters, and forage quality.

According to the climatological normal (1991 to 2020) for Viçosa, accumulated monthly rainfall ranged from 99.2 (October) to 236 mm (January) in the rainy season and from 7.7 (July) to 58 mm (April) in the dry season (INMET, 2022). Figure 1C highlights that January 2022 was atypical, with an accumulated rainfall of 438.23 mm, 185.6% higher than the climatological normal.

In February (cycle 2), accumulated rainfall was also high (374 mm), 220% higher than the climatological normal maximum (116.9 mm), with rainfall being distributed throughout the cycle. In April (end of cycle 3 and entire cycle 4), accumulated rainfall was 32.4 mm, which is 44.3% lower than the climatological normal (58 mm). In July, which covered half of cycle 5, accumulated rainfall was about 6 mm, which is 22% lower than the climatological normal (7.7 mm) (INMET, 2022).

Figure 1C also displays the daily values of global solar radiation during cultivation cycles. Cycle 1 showed a maximum value of 29.0 MJ m^2 d^{-1} and a minimum of 15.1 MJ m^2 d^{-1}. Cycle 2 exhibited a variation from 25.5 to 5.6 MJ m^2 d^{-1}. In cycle 3, maximum reached 24.0 MJ m^2 d^{-1}, while minimum was 5.0 MJ m^2 d^{-1}. These values ranged from 25.0 to 4.5 MJ m^2 d^{-1} in cycle 4 and 16.7 to 4.5 MJ m^2 d^{-1} in cycle 5.

Global solar radiation variations were 13.9, 19.9, 19.0, 20.5, and 12.2 MJ m^2 d^{-1} for each respective cycle, differing in 50.6% from the beginning to the end of the experiment. Hence, perenniality and productivity of forage grasses can be influenced by cultural practices and climate factors, such as rainfall (directly related to relative air humidity, given that the lysimeters were covered), radiation, and temperature, among other factors (Silva et al., 2021). Variables like radiation and temperature directly influenced total duration of each cycle, with a significant difference observed, for instance, between cycle 1 (16 days) and cycle 5 (69 days).

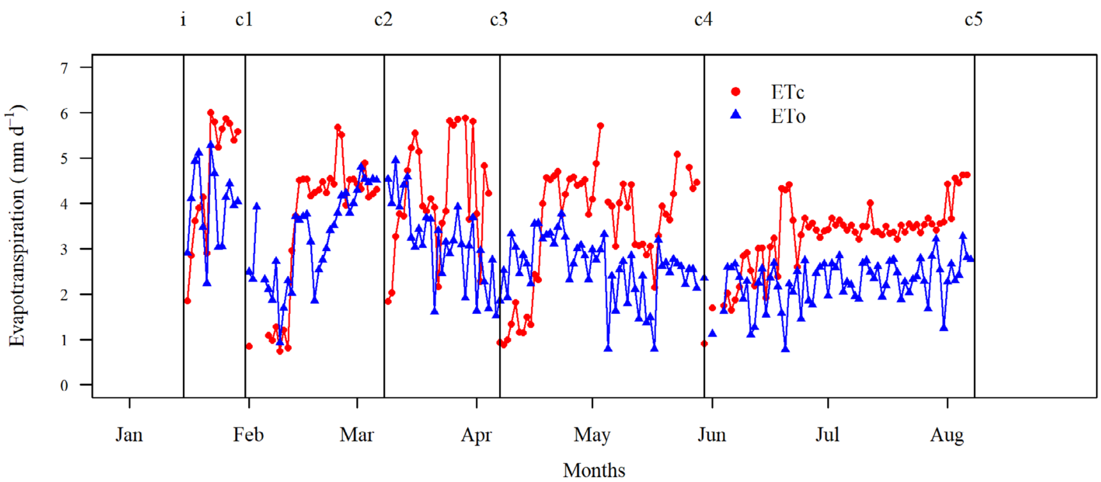
According to the climatological normal from 1991 to 2020, the mean relative air humidity (RH%) in Viçosa, MG was 80.1% in January, 78.9% in February, 82.4% in March, 82.85% in April and May, and 82.15% from April to May, June, and July (INMET, 2022). Conversely, the mean RH% values during cycles 1 and 2 were 79.0 and 83%, respectively, which were close to the climatological normal (80.1 and 78.9%, respectively). Cycles 3 and 4 exhibited values of 77.6 and 75.5%, respectively, which were 6.5 and 8.89% lower than the climatological normal. Lastly, the mean relative humidity in cycle 5 was 74.63, 9.15% lower than the climatological normal. Additionally, the maximum average RH% values during the five cycles were around 93%, while the lowest values recorded in each cycle were 45.0, 38.0, 40.5, 30.0, and 29% for cycles 1, 2, 3, 4, and 5, respectively.

Figure 1A illustrates the maximum and minimum mean temperatures during the cultivation cycles, ranging from 33.0 to 16.0 °C in cycle 1, 32.0 to 15.5 °C in cycle 2, 32.0 to 14.5 °C in cycle 3, 31.0 to 4.0 °C in cycle 4, and 29.0 to 6.0 °C in cycle 5. Mombasa grass is a tropical forage plant with a C4 metabolism, demanding in temperature and light, with an optimal temperature range of 30 to 35 °C but tolerating a minimum of 19 °C (Valente et al., 2011). Studies suggest that tropical forage grasses develop better under high-temperature conditions (Leal et al., 2020).

Figure 2 presents the daily values of reference evapotranspiration and crop evapotranspiration for Mombasa grass plants grown in the Oxisol during five cultivation cycles.

The maximum accumulated ETo values were 55.3, 106.8, 96.0, 132.3, and 274.7 mm in cycles 1, 2, 3, 4, and 5, respectively. The maximum accumulated ETc values were 64.6, 108.1, 110.3, 168.9, and 216.7 mm in cycles 1, 2, 3, 4, and 5, respectively. This indicates that as the cycle duration increased, so did the water demand of the grass. The mean daily ETo values were 3.68, 3.05, 3.2, 2.54, and 3.98 mm d^{-1}, while ETc values reached 4.3, 3.08, 3.67, 3.24, and 3.14 mm d^{-1}, corresponding to cycles 1, 2, 3, 4, and 5, respectively.

Reference evapotranspiration exceeded crop evapotranspiration during the first week after cutting, with maximum mean values of 4.5 and 2.5 mm d^{-1} in cycle 1 and cycle 5, respectively. Crop evapotranspiration at the end of the first week after cutting



i - beginning of treatments; c_1 - cycle 1; c_2 - cycle 2; c_3 - cycle 3; c_4 - cycle 4; and c_5 - cycle 5

Figure 2. Daily variation in reference evapotranspiration (ETo) and crop evapotranspiration (ETc) for Mombasa grass plants grown in an Oxisol during five cultivation cycles for the edaphoclimatic conditions in Viçosa, MG, Brazil, from January to August 2022

exceeded reference evapotranspiration, reaching maximum mean values higher than 5 mm d^{-1} in the first three cultivation cycles and maximum mean values of 3.5 mm d^{-1} in cycle 4.

Crop evapotranspiration was lower in the initial days of each cycle due to the significant reduction in leaf area after cutting, resulting in reduced water demand by the crop. However, as time progressed, ETc increased to support the plants' full vegetative development (Schwenck et al., 2020).

Figures 3A, B, C, D, and E display the results of the crop coefficient (Kc) for Mombasa grass (days after cutting) grown in the Oxisol during five crop cycles, covering the summer, fall, and winter seasons.

Cycle 1 (Figure 3A) exhibited an initial Kc (Kc_i) of 0.71, a medium Kc (Kc_n) of 1.43, and a final Kc (Kc_f) of 0.46. Cycle 2 (Figure 3B) displayed Kc values of 0.46, 1.26, and 0.56 in the initial, medium, and final periods, respectively. Cycle 3 (Figure 3C) had an initial Kc (Kc_i) of 0.46, a medium Kc (Kc_n) of 1.3, and a final Kc (Kc_f) of 0.47. Cycle 4 (Figure 3D) presented initial, medium, and final Kc values of 0.47, 1.56, and 0.6, respectively. Cycle 5 (Figure 3E) had the following Kc values: Kc_i = 0.6 and Kc_n = 1.5; the final Kc was not calculated in this cycle, as there was no subsequent cut.

It is worth noting that Cycle 1 was short, lasting only 16 days, while Cycles 2 and 3 were of medium duration, spanning 35 and 29 days, respectively. Cycles 4 and 5 were longer, lasting 57 and 69 days, respectively. This variation in cycle duration may have been primarily influenced by temperature fluctuations across different seasons, with Cycles 4 and 5 experiencing minimum mean temperatures below the 19 °C threshold tolerated by tropical forage grasses.

A study conducted in Piracicaba, SP, Brazil, indicated that Mombasa grass plants exhibited medium-length cycles when the minimum mean temperature was above 15 °C. However, these cycles extended to an average of 69 days when temperatures were lower, highlighting the seasonality of forage grass production (Mota et al., 2020). In the present study, this seasonality, characterized by a sharp reduction in growth and forage production, occurred from late fall to early winter.

Figure 3 also illustrates that the behavior of the crop coefficient (Kc) remained similar despite variations in cycle duration. In general, Kc followed a medium trend of starting at 0.5 in the initial Kc during the first week, followed by an increase to a mean Kc of 1.4, with oscillations of ±0.2, before reaching a final mean Kc of 0.5. Alencar et al. (2009) determined a practical mean Kc of 0.8 for forages under grazing conditions and observed that the Kc of Mombasa grass was 37.5% lower in the first week after cutting and 75% higher in the stabilization period compared to the results obtained in this research. The increase in Kc during the stabilization period may have been influenced by the oasis effect (Bernardo et al., 2019).

Furthermore, although Kc remained high in comparison to the single Kc for forages, as mentioned earlier, its values did not significantly differ from those obtained in a study with a 12 x 12 m border area for the same crop in Piracicaba, SP, Brazil. In

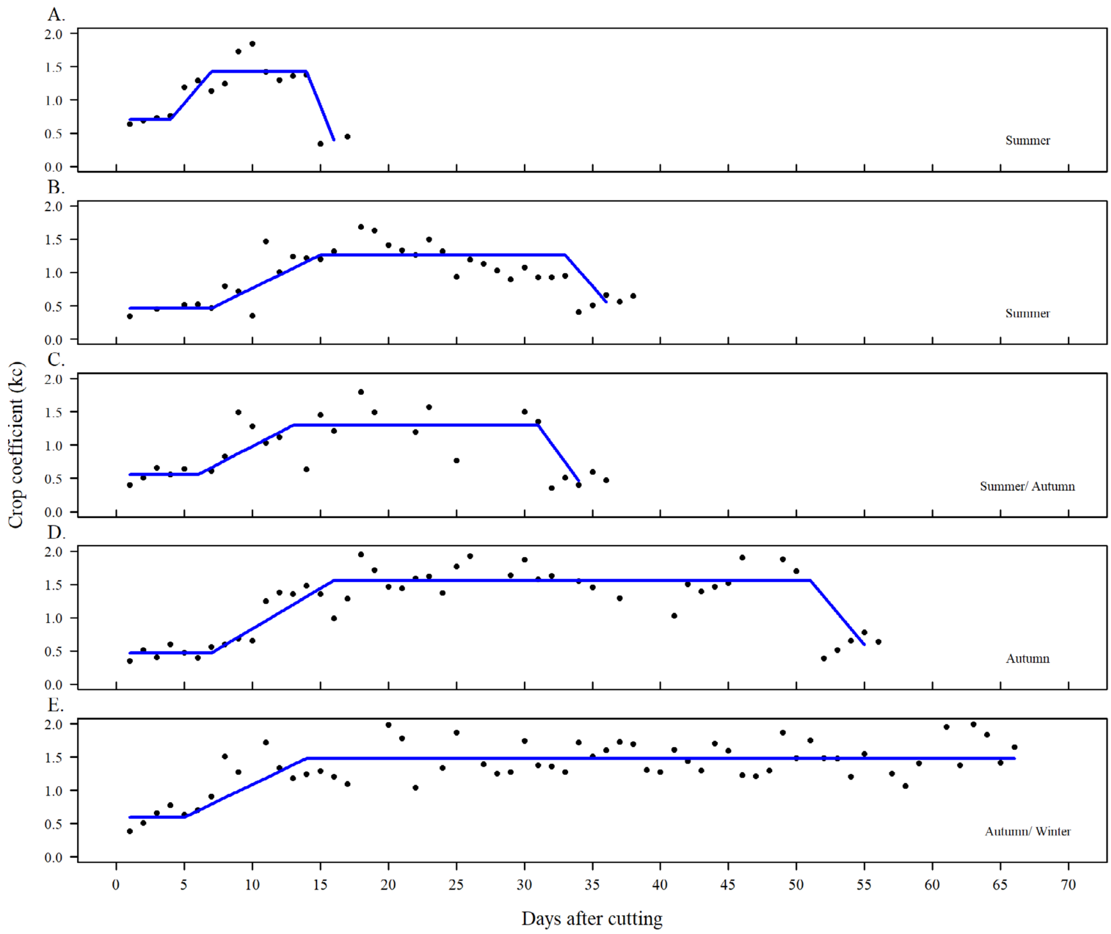


Figure 3. Crop coefficient (Kc) evolution for Mombasa grass grown in an Oxisol during five cultivation cycles (A - cycle 1, B - cycle 2, C - cycle 3, D - cycle 4, and E - cycle 5) and their respective seasons for the edaphoclimatic conditions in Viçosa, MG, Brazil

that study, Kc ranged from 0.58 to 1.4 at 32 days after cutting, with peaks reaching up to 1.7 (Sanches et al., 2017).

In summary, the results obtained in this research, combined with those from the aforementioned studies, suggest the importance of managing irrigation to apply smaller depths of water at the beginning of regrowth, followed by an increase in irrigation depth during the growth period stabilization. This period starts between the tenth and fifteenth day after regrowth and continues until the next cut.

A similar variation in Kc, ranging from 0.7 (at 7 days after cutting) to 1.2 (at 20 days after cutting), was observed in Mombasa grass plants grown in the semi-arid region of Minas Gerais (Mota et al., 2020). Despite the similarity in Kc results, differences were noted in the number of days required to reach the mean Kc. It is essential to consider that the coefficient for the same crop can be influenced by both cycle length and local climate conditions (Bernardo et al., 2019).

The parameters for dry matter productivity (FDM) and irrigation water productivity (WP_{Irri}) underwent normality and homoscedasticity assessments. In terms of the analysis of variance, the FDM data exhibited statistically significant differences only in cycle 4 at $p \leq 0.01$, while WP_{Irri} differed across all cycles at $p \leq 0.01$. The coefficient of variation for FDM ranged from 16.55 to 24.21% in cycles 2 and 4, respectively, while the variation in WP_{Irri} was 15.13 and 21.06% in cycles 4 and 3, respectively. Subsequently, Dunnett's mean test was applied, as shown in Table 4.

From the first to second cycle, FDM in the control (S100%) reduced on average by 11.6%. Plants grown in ore tailings receiving 100 and 120% ETc had their yields reduced by 10.01% and 11.62%, respectively. Finally, FDM of plants grown in treatments L20 and L40% reduced, on average, by 33.33 and 22.67%, respectively.

Considering the averages of each cycle, the control treatment showed a reduction in FDM by 4.06% between cycle 3 and 4, while FDM in L100% reduced by 37.39%. Conversely, L20 and L40% showed FDM reductions by 25.20 and 23.45%, respectively.

The significant reductions in forage dry matter productivity observed in plants subjected to various irrigation depths were primarily attributed to the soil type (Technosol). Technosol possesses a notably higher total water availability (TWA = 1.6 mm cm^{-1}), indicating its capacity for effective water retention, in contrast to the Oxisol used in the control treatment (TWA = 1.07 mm cm^{-1}). Consequently, the higher the TWA, the greater the water reservoir available to plants, which, in turn, enhances nutrient absorption.

Nevertheless, the dry matter productivity exhibited a significant decline throughout the cycles, even when the soil with the highest TWA was employed, particularly in the experimental plots where the deepest irrigation depths (L100 and L120%) were implemented. This outcome may be attributed to the high density of Technosol (1.66 g cm^{-3}), which surpasses that of the Oxisol in the control treatment by 35.5% (1.07 g cm^{-3}). Therefore, the Technosol exhibits a greater susceptibility to compaction, especially when subjected to higher water volumes.

Typically, soils with a higher susceptibility to compaction are characterized by the presence of finer and more expansive particles, such as clay soils. However, in the case of Technosol, despite its sandy loam texture, it exhibited higher density, potentially attributed to the significant content of silt material in its composition (24.4 dag kg^{-1}). Silt particles fall within an intermediate size range (0.004 to 0.06 mm), situated between sand and clay particles (Sari et al., 2017). These silt particles tend to accumulate in thin and porous layers within the soil, leading to increased compaction and hindering both water infiltration and soil aeration.

The decline in global solar radiation, temperature, and relative air humidity were also contributing factors affecting forage production in cycle 4. While plants with a C4 metabolism exhibit high tolerance to elevated radiation and temperature levels, their growth is notably influenced by lower values of these climatic variables. Furthermore, alongside the direct impact of climate, soil type plays a pivotal role, encompassing factors such as texture, structure, permeability, and water retention capacity. Hence, the interplay between soil texture, climatic conditions, and irrigation practices becomes a pivotal determinant in the fluctuation of FDM productivity (Kirchner et al., 2019).

In general, the highest efficiencies in terms of irrigation water productivity (WP_{Irri}) were observed at the lowest irrigation depths (L20, L40, and L60%) during cycles 1, 2, and 4. However, this pattern only held true in cycle 3 for plants subjected to treatments with water depths equivalent to 20 and 40% of ETc.

It is important to emphasize that water productivity must be analyzed in conjunction with FDM since these variables do not always exhibit a direct proportionality. WP_{Irri} was

Table 4. Coefficient of variation (CV) and mean values for forage dry matter productivity (FDM) and irrigation water productivity (WP_{Irri}) for comparison of S100% to the other treatments (L20, L40, L60, L80, L100, and L120%) in four cultivation cycles

Treatment	S100%	L20%	L40%	L60%	L80%	L100%	L120%	CV (%)
				FDM (t ha^{-1})				
Cycle 1	7.07	9.72	9.79	8.64	9.07	7.49	7.74	17.11
Cycle 2	6.25	6.48	7.57	6.85	6.15	6.74	6.84	16.55
Cycle 3	7.38	4.84	5.84	6.28	6.31	5.99	6.1	16.61
Cycle 4	7.08	3.62*	4.47*	4.27*	3.69*	3.75*	4.24*	24.21
				WP_{Irri} (kg mm^{-1})				
Cycle 1	90.85	624.48*	314.29*	184.92*	145.55	96.14	80.75	16.73
Cycle 2	40.84	211.60*	123.60*	74.51*	50.24	44.05	35.05	15.55
Cycle 3	48.65	191.47*	115.47*	82.84	62.42	39.5	38.4	21.06
Cycle 4	14.54	85.27*	56.25*	33.47*	21.67	7.7	19.95	15.13

Means followed by an asterisk (*) in the row differ from the standard treatment (Oxisol - S) at a 0.05 probability level by the Dunnett's test. S100% - 100% replacement of ETc in control treatment (Oxisol); L20% - 20% replacement of ETc; L40% - 40% replacement of ETc; L60% - 60% replacement of ETc; L80% - 80% replacement of ETc; L100% - 100% replacement of ETc and L120% - 120% replacement of ETc in Technosol (ore tailings) notably higher in the treatment involving irrigation depths of 20%. Nevertheless, the L20% treatment struggled to sustain FDM production levels comparable to those achieved by the treatment with soil and 100% ETc. In contrast, the treatment with water depth equivalent to 40% of ETc consistently displayed higher values for both WP_{Irri} and FDM productivity throughout the cycles.

For instance, in cycle 4, the highest WP_{Irri} value was attained with water depths equivalent to 20% of ETc. However, it is worth noting that this treatment led to a substantial 48.8% reduction in FDM compared to the control treatment.

Consequently, the treatment with a 40% replacement depth (L40%) delivered not the highest but the most balanced WP_{Irri} and FDM outcomes. This implies that the L40% replacement depth conserves 60% of the water needed for irrigation while maintaining satisfactory forage dry matter production. Importantly, this treatment did not significantly differ from the control treatment in most cultivation cycles, thus ensuring the economic viability of this irrigated pasture. Additionally, daily irrigation management may have played a role in lowering WP_{Irri} values for treatments with water depths equivalent to 80, 100, and 120% of ETc, particularly when 100% of ETc was applied (Kirchner et al., 2019).

The comparison between water depths equivalent to 20% and 40% of ETc highlights the potential of the L40% treatment. Its lower moisture content effectively minimized direct water evaporation from the soil, all the while not negatively impacting FDM production (Silva et al., 2021). In a similar vein, Martin et al. (2012) conducted an evaluation of water use efficiency in corn plants (which also exhibit C4 metabolism) for silage production and concluded that the optimal silage productivity was achieved through moderate deficit irrigation, specifically at 50% of ETc. In the context of contemporary global climate change, C4 metabolism crops demonstrate resilience and sustainability, playing a vital role in ensuring food security, nutrition, and the livelihoods of farmers (Karnatam et al., 2023).

Conclusions

1. Efficient production and irrigation water productivity for Mombasa grass cultivated in a Technosol are achieved when managed with a water replacement rate of 40% of the crop evapotranspiration.

2. The study highlights that the Technosol reduced the productive capacity by 37.39% during the summer/fall and fall seasons when compared to the control treatment.

3. Based on the management practices employed in this research, the recommended mean crop coefficient values are 1.2 during the summer and 1.5 during the fall and winter for Mombasa grass cultivation in Oxisol.

Literature Cited

Alencar, C. A. B. D.; Cunha, F. F. D.; Martins, C. E.; Cóser, A. C.; Rocha, W. S. D. D.; Araújo, R. A. S. Irrigação de pastagem: Atualidade e recomendações para uso e manejo. Revista Brasileira de Zootecnia, v.38, p.98-108, 2009. https://doi.org/10.1590/S1516-35982009001300012

Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M.; Evapotranspiración del cultivo: guías para la determinación de los requerimientos de agua de los cultivos. Rome: FAO, v.298, p.1-5, 2006. http://www.fao.org/docrep/009/x0490s/x0490s00.htm

Alvarez V, H. V.; Ribeiro, A. C. Calagem. In: Ribeiro, A. C.; Guimarães, P.T.G.; Alvarez V., H. V. (coord.) Recomendações para o uso de corretivos e fertilizantes em Minas Gerais, Viçosa: Comissão de Fertilidade do Solo do Estado de Minas Gerais. 1999. Cap.8, p.43-61.

Batista, É. R.; Carneiro, J. J.; Pinto, F. A.; Santos, J. V. dos.; Carneiro, M. A. C. Environmental drivers of shifts on microbial traits in sites disturbed by a large-scale tailing dam collapse. Science of the Total Environment, v.738, p.1-12, 2020. https://doi.org/10.1016/j.scitotenv.2020.139453

Bernardo, S.; Soares, A. A.; Mantovani, E. C. Manual de irrigação. 8.ed. Viçosa: UFV, 2019. 625p.

Bezerra, R. C. A.; Santos, A. R. M. dos; Cordeiro, L. R. B. A.; Souza, J. C. G. de.; Nascimento, D. B. do.; Nogueira, J. C.; Calaça, J. dos S. G.; Fonsêca, G. R. F. da.; Lucena, R. R. L. de.; Leite, M. L. D. M. V. Indicadores de eficiência biológica e habilidade competitiva em sistemas consorciados de plantas forrageiras xerófilas: uma revisão. Research, Society and Development, v.11, p.1-13, 2022. http://dx.doi.org/10.33448/rsd-v11i15.37107

Carvalho, A. M. X. de; Mendes, F. Q. Speed Stat: Um programa de planilhas gratuito, intuitivo e minimalista para análises estatísticas de experimentos. Melhoramento de Culturas e Biotecnologia Aplicada, v.20, e327420312, 2020.

Detmann, E. M. A.; Souza, S. C. Valadares Filho, A. C., Queiroz, T. T.; Berchielli, E. O.; Saliba, L. S.; Cabral, D. S; Pina, M. M.; Ladeira.; Azevedo, J. A. G. Métodos para análise de alimentos. 1.ed. Visconde do Rio Branco: Suprema, 2012. 214p.

Doorenbos, J.; Pruitt, W. O. Guidelines for predicting crop water requirements. Rome: FAO, 1977. 154p. FAO Irrigation and Drainage Paper

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. Formação e manejo de pastagens de Capim-Mombaça em Rondônia. 1.ed. Rondônia: Embrapa Centro de Referência Agroflorestal de Rondônia, 2001. 2p.

Euclides, V. P. B. Manejo do capim-Mombaça para períodos de águas e seca. Embrapa Gado de Corte; Campo Grande: MS. 2014. Available on: <https://www.embrapa.br/en/busca-de-noticias/-/noticia/2118000/artigo-manejo-do-apim-mombaca-para-periodos-de-aguas-e-seca>. Accessed on: Jan. 2023.

INMET - Instituto Nacional de Meteorologia. Normal climatológica (1991 - 2020), 2022. Available on: <https://clima.inmet.gov.br/GraficosClimatologicos/DF/83377>. Accessed on: Jan. 2023.

Jesus, F. L. F. de; Sanches, A. C.; Souza, D. P. de; Mendonça, F. C.; Gomes, E. P.; Santos, R. C.; Santos, J. E. O.; da Silva, J. L. B. Seasonality of biomass production of irrigated Mombaça 'Guinea grass'. Acta Agriculturae Scandinavica, v.71, p.156-164, 2021. https://doi.org/10.1080/09064710.2020.1863456

Karnatam, K. S.; Mythri, B.; Nisa, W. U.; Sharma, H.; Meena, T. K.; Rana, P.; Vikal, Y.; Gowda, M.; Dhillon, B. S.; Sandhu, S. Silage maize as a potent candidate for sustainable animal husbandry development - perspectives and strategies for genetic enhancement. Frontiers in Genetics, v.14, p.1-24, 2023. https://doi.org/10.3389/fgene.2023.1150132

Kirchner, J. H.; Robaina, A. D.; Peiter, M. X.; Torres, R. R.; Mezzomo, W.; Ben, L. H. B.; Pimenta, B. D.; Pereira, A. C. Funções de produção e eficiência no uso da água em sorgo forrageiro irrigado. Revista Brasileira de Ciências Agrárias, v.14, p.1-9, 2019. https://doi.org/10.5039/agraria.v14i2a5646

Leal, V. N.; Santos, E. A.; Almada, E. D. B de.; Noll, M.; Machado, R. L. Agronomic performance of elephant grass cultivars under irrigation: a systematic review. Revista Biodiversidade, v.19, p.160-167, 2020. https://periodicoscientificos.ufmt.br/ojs/index.php/biodiversidade/article/view/10824

Martin, J. D.; Carlesso, R.; Aires, N. P.; Gatto, J. C.; Dubou, V.; Fries, H. M.; Scheibler, R. B. Irrigação deficitária para aumentar a produtividade da água na produção de silagem de milho. Irriga, v.1, p.192-205, 2012. https://doi.org/10.15809/irriga.2012v1n01p192

Mota, V. J. G.; Oliveira, F. G.; Gomes, V. M.; Monção, F. P.; Mota Filho, V. J. G. Determinação do coeficiente de cultura do capim-mombaça manejado em diferentes estações do ano no semiárido mineiro. Irriga, v.25, p.170-183, 2020. https://doi.org/10.15809/irriga.2020v25n1p170-183

Oliveira, L. B. de; Silva, M. A. J. da; Santos, E. M. Interação entre espécies forrageiras nativas e cultivadas em condições de semiárido. Arquivos de Ciências Veterinárias e Zoologia da UNIPAR, v.22, p.127-138, 2019. https://doi.org/10.25110/arqvet.v22i4.6949

Sanches, A. C.; Souza, D. P. de; Jesus, F. L. de F.; Mendonça, F. C.; Maffei, R. G. Consumo de água de forrageiras tropicais no período de formação de pastagem. Revista Brasileira de Agricultura Irrigada, v.11, p.1-11, 2017. https://doi.org/10.7127/rbai.v11n200606

Santos, A. R. M. dos; Gomes, F. J.; Ximenes, E. S. O. C; Aragão, W. F. D. X; Silva, A. C. D. Efeito do ambiente luminoso em forrageiras de clima tropical em sistemas silvipastoris. Nativa. Pesquisas Agrárias e Ambientais, v.8, p.633-642, 2020. https://doi.org/10.31413/nativa.v8i5.10883

Santos, O. S. H.; Avellar, F. C; Alves, M.; Trindade, R. C.; Menezes, M. B.; Ferreira, M. C.; França, G. S.; Cordeiro, J.; Sobreira, F. G.; Yoshida, I. M.; Moura, P. M.; Baptista, M. B. Scotti, M. R. Understanding the environmental impact of a mine dam rupture in Brazil: Prospects for remediation. Journal of Environmental Quality, v.48, p.439-449, 2019. https://doi.org/10.2134/jeq2018.04.0168

Sari, V.; Pereira, M. A.; Castro, N. M. dos R.; Kobiyama, M. Efeitos do tamanho da partícula e da concentração de sedimentos suspensos sobre a turbidez. Engenharia Sanitária Ambiental, v.22, p.213-219, 2017. https://doi.org/10.1590/S1413-41522016144228

Schwenck, V. A. X.; Queiroz, L. da S.; Garcia, A. D. B.; Jesus L. K. de.; Arndt, S.; Oliveira, E. M. de. Coeficiente de cultura por lisímetria da variedade de sorgo forrageiro SF-15 (*Sorghum bicolor* L). Revista Brasileira de Agricultura Irrigada, v.14, p.3960-3967, 2020.

Silva, L. I. da; Campos, M; C. C.; Brito, W. B. M.; Cunha, J, M. da; Lima, A. F. L. de; Santos, L. A. C. dos; Hassane, A. L. Spatial variability of soil erodibility in pastures and forest areas in the municipality of Porto Velho, Rondônia. Revista Ambiente & Água, v.16, p.1-18, 2021. https://doi.org/10.4136/ambi-agua.2750

Silva, M. Z.; Cayres, D. C.; Souza, L. A. M. de. Desastre socioambiental e Termo de Transação e Ajustamento de Conduta (TTAC) como instrumento de política pública: o caso da Barragem do Fundão. Civitas: Revista de Ciências Sociais, v.19, p.464-488, 2019. https://doi.org/10.15448/1984-7289.2019.2.30227

Silva, P. L.; Melo, M. C.; Camargo, D. D. Camargo, D. D.; Fernandes, M. F.; Drumond, L. C. D. Efeito de lâminas de irrigação subsuperficial na extração de nutrientes e produtividade em pastagem. Irriga, v.26, p.732-744, 2021. https://doi.org/10.15809/irriga.2021v26n4p732-744

Valente, T. N. P.; Lima, E. da S.; Henriques, L. T. de.; Machado Neto, O. R.; Gomes, D. Í.; Sampaio, C. B.; Costa, V. A. C. Anatomia de plantas forrageiras e a disponibilidade de nutrientes para ruminantes: revisão. Veterinária e Zootecnia, v.18, p.347-358, 2011. https://repositorio.unesp.br/handle/11449/141104

Vicente, N. M. de F.; Sperber, C. F.; Carneiro, M. A. C. Dia D do Rio Doce: Um olhar científico sobre o maior desastre socioambiental do Brasil. 1.ed. Lavras: UFLA, 2021. 246p.