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Water productivity and production function in irrigated millet crop[1]

Função de produção e produtividade da água em cultura de milheto irrigado

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Abstract

Determining the function that correlates water productivity with crop yield is essential for the correct sizing and management of irrigated agricultural systems. The objectives of this study are to determine forage production (FP) of millet at different irrigation levels and water productivity. Two experiments were conducted using millet crop sown in the 2014/2015 growing season in Santiago, Rio Grande do Sul, Brazil, and in the 2015/2016 growing season in Santa Maria, Rio Grande do Sul. The experiments were carried out using a completely randomized block design with four repetitions and six irrigation regimes (0, 25, 50, 75, 100, and 125% of reference evapotranspiration-ETo). Dry matter (DM) production of plants collected at 50, 80, 110, and 140 days after sowing and water productivity were determined. Irrigation had a significant effect on millet FP (kg DM ha^{-1}) during the 2014/2015 and 2015/2016 growing seasons after adjusting the quadratic equation. The maximum technical efficiency in the two growing seasons was reached at 125% of ETo, with FP of 15,494.47 kg ha^{-1} and 14,779.50 kg ha^{-1}, respectively. Water productivity was not significantly different between treatments, yieldingan average of 1.86 kg DM m^{-3} and 1.69 kg DM m^{-3} in the two seasons, respectively. The curve of average FP estimated with the logistic equation accurately represents the total FP in the two seasons. Millet crop is susceptible to water deficits, and the irrigation regime of 125% ETo achieved the highest FP in both growing seasons. However, the adopted irrigation regimes did not significantly affect water productivity.

Key words: Forage production. Irrigation depths. *Pennisetum americanum* L.

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Resumo

A determinação da função de produção que relaciona a água com a produção da cultura é imprescindível para o correto dimensionamento e manejo de sistemas agropecuários irrigados. Os objetivos deste trabalho são a identificação da função de produção de forragem de milheto em relação às lâminas aplicadas e a determinação da produtividade da água. Foram realizados dois experimentos com a cultura do milheto semeados na safra agrícola 2014/2015 em Santiago, RS e na safra 2015/2016 em Santa Maria, RS. O delineamento experimental foi em blocos ao acaso com quatro repetições e seis lâminas de irrigação (0, 25, 50, 75, 100 e 125% da evapotranspiração de referência - ETo). Foi avaliada a produção de massa seca total acumulada de forragem, coletada aos 50, 80, 110 e 140 dias após a semeadura e determinou-se a produtividade da água. Observou-se efeito significativo para a produção de forragem de milheto (kg de MS ha^{-1}) nas duas safras agrícolas 2014/2015 e 2015/2016, ajustando-se equação quadrática. A máxima eficiência técnica entre os tratamentos foi encontrada, para as duas safras, na lâmina 125% da ETo com produção de forragem de 15.494,47 kg ha^{-1} e 14.779,50 kg ha^{-1}. A produtividade da água não diferiu estatisticamente para os distintos tratamentos em ambos os anos, com as médias gerais dos tratamentos em cada ano de 1,86 e 1,69 kg de MS m^{-3} nas safras de 2014/2015 e 2015/2016 respectivamente. A dinâmica de produção de massa seca acumulada, para a equação logística obtida com a média das duas safras representa com desempenho "ótimo" as produções de forragem acumuladas das duas safras agrícolas. A produção de forragem de milheto é suscetível a déficits hídricos, sendo a lâmina de 125% da ETo, a mais produtiva nas duas safras agrícolas. As lâminas de irrigação não influenciaram na produtividade da água.

Palavras-chave: Produção de forragem. Lâminas de irrigação. *Pennisetum americanum* L.

Introduction

Interannual climate variability, especially rainfall, decreases the yield and quality of forage crops (BANDINELLI et al., 2003). Water deficits significantly reduce the productivity of agricultural systems commensurate with their intensity and duration (RAY et al., 2015; VIVAN et al., 2015; PEREIRA et al., 2017). Irrigation is used to mitigate the effects of water deficits and ensure high forage yields (OLIVEIRA et al., 2015; KIRCHNER et al., 2017; KOETZ et al., 2017).

Vital et al. (2015) and Orth et al. (2012) reported that several tropical forage species are used in Brazil, and one of the most prominent is millet (*Pennisetum americanum* L.), a grass with high forage potential, with yields of up to 20 tons. ha^{-1} and considerable resistance to water stress (PEREIRA FILHO, 2016). Irrigation increases soil water content, which increases forage dry matter (DM) production (SINGH; SINGH, 1995; SILVA et al., 2006). Furthermore, irrigation improves forage distribution throughout the year, allowing better planning of production systems and increasing crop yield per area (OLIVEIRA et al., 2016).

Analyzing the response of crops to different water levels is critical to define irrigation management and improve water utilization, and limited irrigation may be a good strategy to increase water efficiency (KRESOVIC et al., 2016; CHILUNDO et al., 2016). Therefore, determining the effects of variations in rainfall caused by climate change on forage production (FP) is crucial (GRANT et al., 2014). The quantification of this response is possible using the water balance method (PEREIRA et al., 2017), which considers water input and output during the cultivation period up to the depth of the root system (LIBARDI, 2005). The FAO-56 procedure is based on reference evapotranspiration on a grass surface (ETo), and this parameter can be estimated using the Penman-Monteith method (ALLEN et al., 1998). Daily crop evapotranspiration (ETc) was calculated considering the crop coefficient (Kc), and the influence of the water level was assessed by the soil moisture coefficient (Ks) (BERNARDO, 2006).

Bartero et al. (2013) showed that previous experiments in forage plants evaluated parameters such as DM but did not measure plant growth. Plant development is characterized by a phase of rapid growth, which tends to stabilize, and is adequately represented by logistic functions (REGAZZI, 2003). Plant response to a given input does not vary with its dose since plant production stabilizes after maximum doses tending to excess.

This study determined millet FP under different irrigation regimes and water productivity.

Materials and Methods

Two experiments were performed to determine water productivity in millet forage, the first in the 2014/2015 growing season in the experimental area of Fazenda Liberdade, in the municipality of Santiago (altitude, 439 meters; average annual rainfall, 1769 mm), Rio Grande do Sul, Brazil. There was a high variation in temperature in the study area during the experimental period, with an average minimum of 17.5 ºC, an average maximum of 27.8 ºC, average relative humidity of 82.3%, average wind speed of 2.2 m s^{-1}, and average daily solar radiation of 943.18 KJ m^2.

The second study was conducted in the 2015/2016 growing season in the experimental area of the UFSM Polytechnic College, in the municipality of Santa Maria (altitude, 122 meters; average annual rainfall, 1688 mm), Rio Grande do Sul. During the study period, this area presented a minimum average temperature of 16.8 °C, a maximum average temperature of 26.7 °C, average relative humidity of 82.5%, average wind speed of 2.0 m s^{-1}, and daily average solar radiation of 883 KJ m^2.

The climate of the region is temperate with subtropical characteristics and strong winters. According to Köppen-Geiger classification, the climate of the region is Cfa (humid subtropical), with irregular rainfalls throughout the year, especially in the summer, water deficits in summer due to high evapotranspiration, and rainfall usually does not meet the water demand of the plant (MORENO, 1961).

The soils of the study sites are classified as typical dystrophic Red Latosol (Cruz Alta Mapping Unit) and typical dystrophic Yellow Latosol (Santa Maria Mapping Unit), respectively, according to Streck et al. (2008).

The physical-hydrological characterization of the soils of the two experimental units was performed according to the methodologies proposed by EMBRAPA (2011). The total soil water retention capacity up to a depth of 0.50 m was 80.0 mm (Cruz Alta) and 83.3 mm (Santa Maria), indicating that the amount of water available to the plants was similar between these soils.

The experiments were carried out using a completely randomized block design with four repetitions and six irrigation levels (0, 25, 50, 75, 100, and 125% of ETo) measured using the FAO Penman-Monteith equation (ALLEN et al., 1998). ETo data were obtained from local automated weather stations. The first experiment was conducted in a Vantage PRO weather station (Davis), located approximately 200 meters from the experimental area (Santiago, Rio Grande do Sul).The second experiment was performed in a "Santa Maria" weather station, which belongs to the National Institute of Meteorology (Instituto Nacional de Meteorologia-INMET) and is located approximately 2,000 meters from the experimental area. Effective rainfall (ER) data obtained during the cultivation periods were compared with ER data from climatological normals obtained at the São Luiz Gonzaga and Santa Maria weather stations of INMET.

The irrigation schedule was fixed at seven days, and the irrigation level was calculated by the difference between the sum of ETo values and the sum of ER during the study period. ER was calculated according to the surface runoff coefficient proposed by Millar (1978), which was 70% in both experimental areas.

The soil water balance was obtained considering daily inputs (ER and irrigation) and outputs (runoff, deep drainage, and crop evapotranspiration) up to a root system depth of 0.5 m. Crop evapotranspiration (0, 25, 50, 75, 100, and 125% of ETc) was calculated by multiplying ETo values by Kc (ALLEN et al., 1998) and Ks (BERNARDO, 2006). Input data were ER (total rainfall minus surface runoff) and irrigation levels in each experimental area.

The experiments consisted of 24 experimental units. The size of each unit was 4 x 4 m, which corresponds to an area of 16 m^2 plus the margins. Irrigation was performed using a sprinkler irrigation system, and the applied water levels were controlled by opening and closing the irrigation lines. The application rates were determined using the Christiansen Uniformity Coefficient.

Millet crop (cultivar ADR500) was sown in November 2014 and November 2015 in a no-tillage system, with inter-row spacing of 0.36 m, 10-15 kg seeds ha^{-1}, and a sowing depth of 3 cm, as recommended by the seed suppliers (GONTIJO NETO, 2006). Fertilization was performed for an expected forage yield of 20,000 kg ha^{-1} of DM, as recommended in the Fertilization and Liming Manual for the states of Rio Grande do Sul and Santa Catarina (COMMITTEE ON SOIL CHEMISTRY AND FERTILITY [COMISSÃO DE QUÍMICA E FERTILIDADE DO SOLO - CQFS RS/SC, 2004]). Cultivation was performed with standardized cuttings at 50, 80, and 110 days after sowing (DAS). The cuts were made at the height of 0.15 m from the soil surface, and cover fertilization was performed with urea after each cut.

To evaluate the forage yield of millet crop, plants were collected in a linear interval of 0.5 m at a height of 0.15 m from the soil surface at 50 DAS (first cut), 80 DAS (second cut), 110 DAS (third cut), and 140 DAS (fourth and last cut). The samples were transferred to the laboratory and dried for 72 hours (or until constant weight) in an oven with forced air circulation at 65 °C. After drying, DM was measured on a precision scale, and the values obtained in the cuts were summed to obtain total production (extrapolated to hectare). To measure water productivity (kg of DM m^{-3}), FP was divided by the volume of water applied, and the values were extrapolated to hectare (kg of DM ha^{-1}). The results were analyzed using SISVAR software (FERREIRA, 2011) at a level of significance of 5% and subjected to regression analysis.

To obtain the crop growth curve, the logistic model (REGAZZI, 2003) was adjusted to total FP data at maximum technical efficiency (MTE) in each growing season (125% of ETo) and in both seasons (125% of ETo). The model was defined by $Y = a / (1 + \exp(b - c.x))$, where Y is total FP, X is total water level (ER + irrigation), and a, b, and c are the parameters used for adjusting the equation. The fit of the models was evaluated by the coefficient of determination (R^2). Data analysis was performed using software Table Curve 2D version 2.03 (Jandel Scientific).

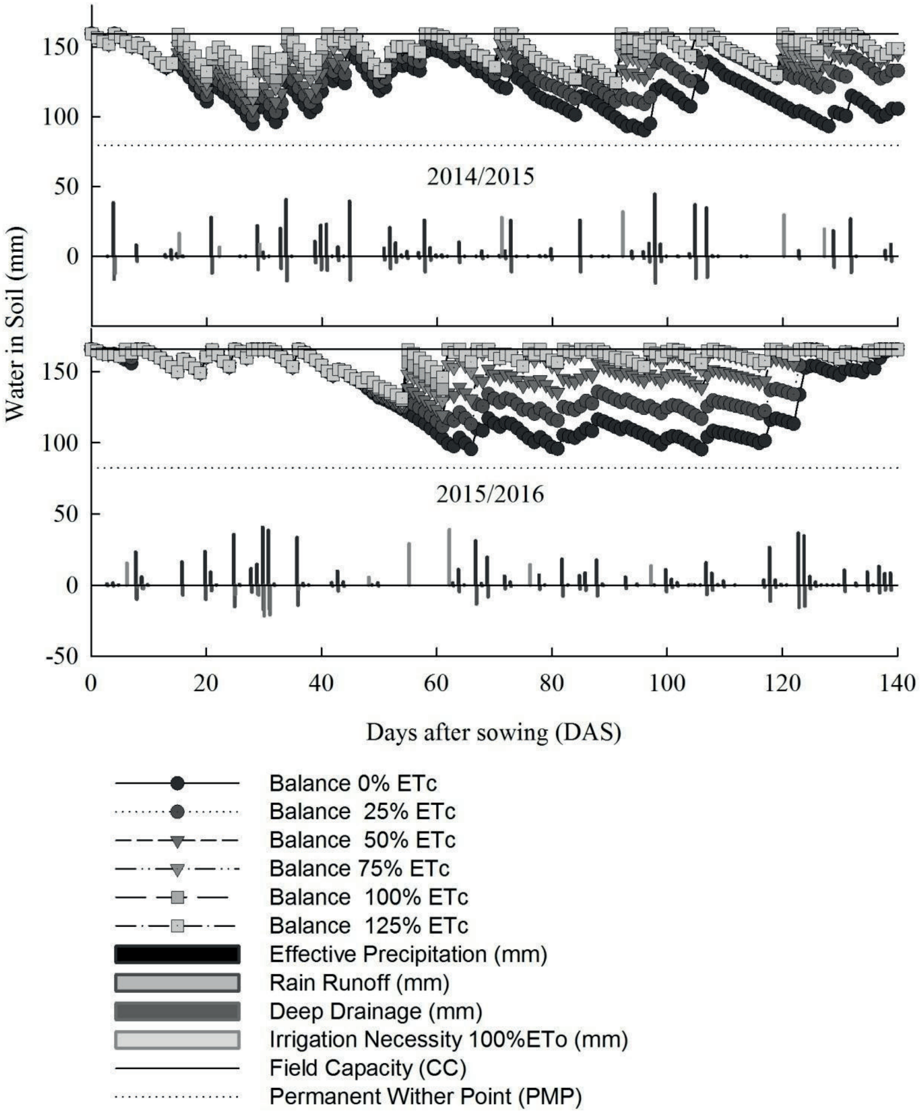
The adjusted equation (averages at 125% of ETo in the 2014/2015 and 2015/2016 growing seasons) was evaluated by the linear regression $y = a + bx$, in which the dependent variable was total FP in each treatment (0, 25, 50, 75, 100, and 125% of ETo) and each season, and the independent variable was total FP estimated by the equation. The statistical indicators were Pearson's correlation coefficient (r) and the concordance or accuracy index (d) proposed by Willmott (1981), and performance was evaluated by the confidence coefficient proposed by Camargo and Sentelhas (1997).

Results and Discussion

ER was 652.12 mm and 624.82 mm during the 2014/2015 and 2015/2016 growing seasons, respectively. ER was higher than climatological normals in the study regions (465.3 mm and 426.7 mm, respectively), indicating that some seasons might have less and irregular rainfall, which might reduce FP and compromise production when volumes were smaller than 400 mm during the growth cycle, and during periods of excess water, which are as detrimental as water deficit.

Rainfall distribution during the cultivation periods was heterogeneous, with drought periods requiring irrigation (Figure 1). In the 2014/2015 season, 141.37 mm of water was applied in the regime of 100% of ETo, distributed in seven irrigation events. In the 2015/2016 season, 117.46 mm of water was applied in the regime of 100% of ETo, distributed in seven irrigation events. Tardin et al. (2013) found that water stress caused by drought decreased FP. Cunha et al. (2008) have shown that pasture evapotranspiration usually exceeds ER in some cultivation seasons, and irrigation is required to increase productivity and profitability.

Figure 1. Water balance considering crop evapotranspiration, effective rainfall, runoff, deep drainage, and the need for irrigation (100% ETo) up to a soil depth of 0.50 m under different irrigation regimes (0, 25, 50, 75, 100, and 125% of ETc) during the 2014/2015 and 2015/2016 growing seasons.

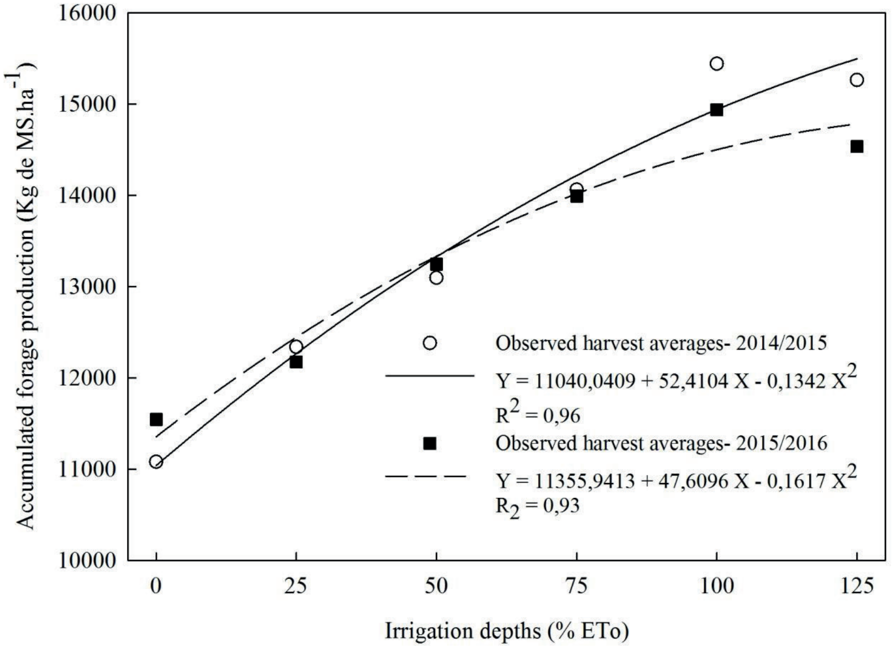


Deep drainage and runoff events also occurred during the cultivation periods, and irrigation (100% of ETo) was necessary. Water was applied as irrigation in different treatments, resulting in different soil moisture concentrations and different crop evapotranspiration (ETc) values.These differences were mainly due to the variation in Ks, corresponding to 0.86-1.00 in the first season and 0.91-1.00 in the second season.

The amount of water in the soil was higher in treatments with higher irrigation levels. In the control treatment (0% of ETc), where water was not replaced by irrigation, the amount of water in the soil approached the permanent wilting point (PWP), which justifies the differences in productivity between treatments because the soil water depletion levels necessary to decrease millet FP are approximately 60% of the total available water (difference between field capacity and PWP) (ALLEN et al., 1998).

There was a significant effect of irrigation on millet FP at a level of significance of 5% in the two growing seasons. The quadratic equation was adjusted with a coefficient of determination of 95.55% and 93.13%, respectively (Figure 2). The MTE in the two growing seasons was reached at 125% of ETo, corresponding to FP of 15,494.47 and 14,779.50 kg ha^{-1}, respectively, and these values were 28.75% and 23.16% higher than those of the control treatments, respectively. Similarly, Heringer and Moojen (2002) evaluated the effect of nitrogen doses on millet production in Santa Maria, Rio Grande do Sul, and found that total FP was 8,862 and 17,403 kg ha^{-1} of DM at a dose of 0 and 450 kg ha^{-1} of nitrogen, respectively.

Figure 2. Millet forage production under different irrigation regimes during the 2014/2015 and 2015/2016 growing seasons.



Dantas et al. (2016) analyzed FP in *Brachiaria brizantha* under different irrigation regimes in four cuts in autumn and winter in Jaboticabal, state of São Paulo, Brazil, and found a quadratic response, with coefficient of determination of 0.73 in autumn and 0.94 in winter, and maximum FP of 2,359 kg ha^{-1} and 1,756 kg ha^{-1} at the irrigation levels of 267 and 269 mm, respectively.

Pereira Filho (2016) has shown that millet is resistant to water deficits and can complete the growth cycle with an annual rainfall of less than 300 mm. However, millet crops reach their productive potential only in the absence of water shortage and in the presence of good rainfall distribution (VIVAN et al., 2015). Pimentel et al. (2016) observed that water supply was a determining factor for the development of forage species. Antoniel et al. (2016) reported that FP is remarkably increased in irrigated pastures. Kirchner et al. (2019) worked with irrigated sorghum crop in Santa Maria, Rio Grande do Sul, and found that FP increased by 2,600 kg ha^{-1} at 100% of ETo compared with a control treatment (0% of ETo).

There were no significant differences in water productivity between treatments, with average yields of 1.86 and 1.69 kg of DM m^{-3} in the 2014/2015 and 2015/2016 growing seasons, respectively. However, in both growing seasons, water productivity increased by 12.12% and 4.00% at 100% of ETo when compared to the control treatment (0% of ETo) (Table 1), indicating higher water use efficiency (WUE) in both seasons by better utilization of the nutrients applied by cover cropping and better physiological activity by better harnessing solar radiation for the synthesis of photoassimilates.

Table 1. Effective rainfall (mm), irrigation levels (mm), and water productivity (kg DM m^{-3}) in each treatment (% ETo) during the 2014/2015 and 2015/2016 growing seasons.

Treatment (% ETo)	Effective rainfall (mm)	Irrigation level (mm)	Water productivity (kg de MS m^{-3})
		2014/2015 growing season	
125	638.54	176.71	1.87
100		141.37	1.98
75		106.03	1.89
50		70.69	1.85
25		35.34	1.83
0		0.00	1.74
		2015/2016 growing season	
125	624.82	146.83	1.63
100		117.46	1.75
75		88.10	1.72
50		58.73	1.73
25		29.37	1.66
0		0.00	1.68

Melo (2006) worked with sorghum and millet plants grown in pots and found comparatively higher water productivity values under different irrigation regimes (0, 25, 50, 75, and 100% of soil field capacity), and plant growth was higher at 25, 50, and 75% of field capacity for both cultures after 45 days of cultivation. Water productivity was 4.1 kg and 2.7 kg of DM m^{-3} for millet at an irrigation level of 75% and 100% of ETo, respectively.

Parizi et al. (2009) evaluated five irrigation levels (0, 60, 80, 100, and 120% of ETo) in corn crop in Santiago, Rio Grande do Sul, and observed that WUE values were higher (3.46 kg DM m^{-3}) at 100% of ETo and lower (3.0 kg of MS m^{-3}) at 120% ETo, i.e., WUE tended to decrease as the water level increased.

At different total water levels (ER + irrigation) during the 140 days of cultivation, daily water consumption varied from 5.92 to 4.66 mm day^{-1} at 125% and 0% of ETo, respectively, in the 2014/2015 growing season, and 5.51 to 4.46 mm day^{-1} at 125% and 0% of ETo, respectively, in the 2015/2016 growing season. Muller et al. (2002) found that maximum daily water consumption was approximately 8 $mm.day^{-1}$ for FP of Mombaça grass in São Desidério, Bahia, Brazil.

The curves for total FP (DM ha^{-1}) according to the total water level are shown in Figure 3. Table 2 presents the adjustment parameters of equations a, b, and c, upper and lower limits, and the coefficients of determination (R^2).

Figure 3. Logistic model-adjusted curves (Y=a/(1+exp(b-c.x))) for total forage production of millet (Y-axis) with maximal irrigation efficiency (125% of reference evapotranspiration) during the 2014/2015 and 2015/2016 growing seasons, and average e forage production values at different irrigation levels (mm) (X-axis).

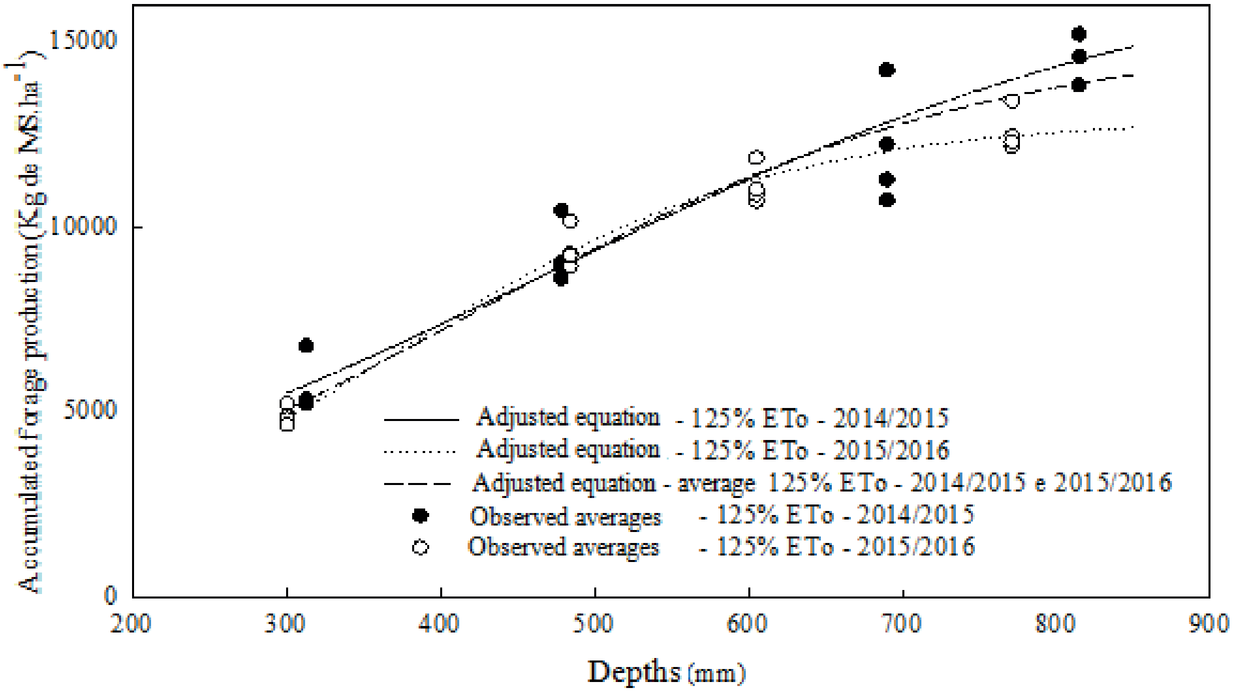


Table 2. Averages, upper limits (UL), and lower limits (LL) of parameters a, b, and c, and coefficient of determination of the logistic model as a function of the total water level (effective rainfall + irrigation) at the irrigation regime of 125% of reference evapotranspiration during the 2014/2015 and 2015/2016 growing seasons and averages of the two seasons.

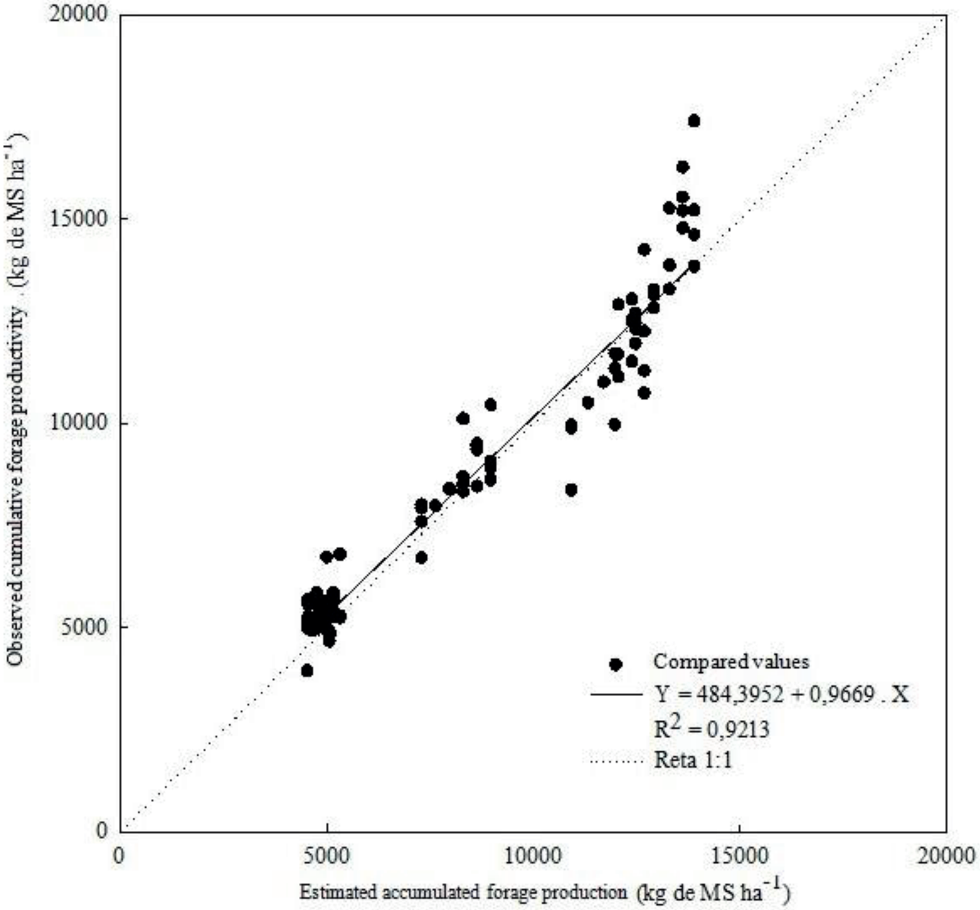
Treatment	**Equation parameters**			
	a	**b**	**c**	**R²**
UL	19933.66	2.85	0.0065	
125% of ETo in 2014/2015	17494.67	2.15	0.0046	0.93
LL	15055.68	1.45	0.0026	
UL	13760.42	3.45	0.0096	
125% of ETo in 2015/2016	12958.98	2.92	0.0080	0.98
LL	12157.53	2.39	0.0064	
UL	17252.64	3.05	0.0078	
125% of ETo in both growing seasons	15220.31	2.47	0.0059	0.93
LL	13187.98	1.89	0.0040	

Total FP in the treatments with MTE (125% of ETo) at the upper and lower limits of the confidence interval (Table 2) was higher during the 2014/2015 growing season than in the 2015/2016 growing season, i.e., the upper limit in the 2015/2016 season was not within the confidence interval of the 2014/2105 season. However, there was no significant difference between the average of the two seasons compared to the value of each season, and the limits of parameter "a" were within the confidence interval of the average of the two seasons. For parameter "b," the equations for total FP according to the irrigation level were similar, and the parameter limits of all equations were within their confidence intervals.

Muller et al. (2002) used a nonlinear model to explain the FP of Mombaça grass at different daily irrigation levels in a 30-day interval and found that production was 5,800 kg ha^{-1} and water consumption was approximately 8 mm.day^{-1}. The authors concluded that the model could be used to forecast FP.

The curves obtained with the averages estimated by the equations using an irrigation regime of 125% of ETo during the 2014/2015 and 2015/2016 growing seasons and the averages obtained in field experiments (0, 25, 50, 75, 100, and 125% of ETo) are shown in Figure 4. The coefficient of determination (R^2) was 92.13%, and the angular coefficient (b) was 0.97. The performance of the adjusted logistic model was classified as optimal, indicating that the model could be used to accurately determine total millet FP as a function of the total water level (ER + irrigation).

Figure 4. Comparison of total millet forage production estimated by the equation (at 125% of reference evapotranspiration) during the 2014/2015 and 2015/2016 growing seasons and total forage production measured under different irrigation regimes (0, 25, 50, 75, 100, and 125% ETo) during the two seasons.



The results show that the proposed logistic model can be used to estimate millet FP. Dourado Neto et al. (2005) determined total FP in the aerial structures of maize plants and predicted grain yield using mathematical-physiological models. Similar results were obtained by Gomes et al. (2014), who studied the same region and proposed mathematical models for simulating FP and soybean yield, and found that performance using these two parameters was good and excellent, respectively.

Conclusions

Millet crop is susceptible to water deficits, and an irrigation level of 125% ETo yielded the highest FP in the 2014/2015 and 2015/2016 growing seasons.

The adopted irrigation regimes did not significantly affect water productivity.

The adjusted logistic equation (average for the two growing seasons at 125% ETo) can be used to measure millet FP accurately.

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