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ARTICLE

RESEARCH ARTICLE

Residual heights alter forage production parameters and nutritional value of dwarf elephant grass [*Cenchrus purpureus* (Schumach.) Morrone]

Las alturas residuales alteran parámetros de producción de forraje y valor nutritivo del pasto elefante enano [*Cenchrus purpureus* (Schumach.) Morrone]

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Abstract: *Aim of study:* This study aims to ascertain the appropriate residual height for the dwarf elephant grass [*Cenchrus purpureus* (Schumach.) Morrone] 'Brs Kurumi' by concurrently evaluating its forage production, morphological composition, and nutritional value. *Area of study:* Rio Grande do Sul, Brazil. *Material and methods:* The dwarf elephant grass 'Brs Kurumi' was evaluated over four consecutive growing seasons in a randomized complete block design with five treatments and four replications. Treatments consisted of residual cutting heights (20, 30, 40, 50, and 60 cm), with a target management height of 80 cm. Parameters assessed included forage production and its morphological composition, population density of basal tillers, and nutritional value. *Main results:* The relationship between morphological components and nutritive value was highlighted. Residual cutting heights between 40 cm and 50 cm modified the pasture structure to balance the quantity [accumulated total dry matter production ranged from 8,242 kg/ha (40 cm) to 6,916 kg/ha (50 cm)], while nutritive value (crude protein content remained stable at 14.6% for both heights. *Research highlights:* Dwarf elephant grass 'Brs Kurumi' exhibited changes in forage production, morphology, and nutritional value across residual cutting heights. At recommended levels (50 cm and 40 cm, or 60% and 50% of the target height), the grass responded similarly to disturbance, suggesting that plants' phenotypic plasticity helped balance morphological components and nutritive value, facilitating to their adaptation to imposed residual heights and reflecting 'Brs Kurumi' ability to adjust its growth and sward structure to sustain adequate forage production, a high leaf proportion, and nutritive value.

Keywords: chemical compound; grazing management; phenotypic plasticity; sward structure; tropical grass.

Resumen: *Objetivo del estudio:* Este estudio tiene como objetivo determinar la altura residual adecuada para el pasto elefante enano [*Cenchrus purpureus* (Schumach.) Morrone] 'Brs Kurumi' mediante la evaluación simultánea de su producción de forraje, composición morfológica y valor nutricional. *Área de estudio:* Rio Grande do Sul, Brasil. *Material y métodos:* El pasto elefante enano 'Brs Kurumi' fue evaluado durante cuatro temporadas de crecimiento consecutivas en un diseño de bloques completos al azar, con cinco tratamientos y cuatro repeticiones. Los tratamientos consistieron en alturas residuales de corte (20, 30, 40, 50 y 60 cm), con una altura objetivo de manejo de 80 cm. Se evaluaron la producción de forraje y su composición morfológica, la densidad poblacional de macollos basales y el valor nutricional. *Resultados principales:* Se destacó la relación entre los componentes morfológicos y el valor nutritivo. Las alturas residuales de corte entre 40 cm y 50 cm modificaron la estructura del pasto para equilibrar la cantidad [la producción total acumulada de materia seca osciló entre 8,242 kg/ha (40 cm) y 6,916 kg/ha (50 cm)], mientras que el valor nutritivo (contenido de proteína bruta) se mantuvo estable en 14.6% para ambas alturas. *Aspectos destacados de la investigación:* El pasto elefante enano 'Brs Kurumi' presentó cambios en la producción de forraje, la morfología y el valor nutricional según las alturas residuales de corte. En los niveles recomendados (50 cm y 40 cm, equivalentes al 60% y 50% de la altura objetivo), la forrajera respondió de forma similar a la perturbación, lo que sugiere que la plasticidad fenotípica de las plantas ayudó a equilibrar los componentes morfológicos y el valor nutritivo. Esto facilitó su adaptación a las alturas residuales impuestas y reflejó la capacidad de 'Brs Kurumi' para ajustar su crecimiento y la estructura del dosel, manteniendo una producción de forraje adecuada, una alta proporción de hojas y buen valor nutritivo.

Palabras clave: compuestos químicos; estructura del dosel; manejo del pastoreo; pasto tropical; plasticidad fenotípica.

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Supplementary information ↓

1. INTRODUCTION

Elephant grass [*Cenchrus purpureus* (Schumach.) Morrone]; syn. *Pennisetum purpureum* (Schumach.) is one of the most important tropical forages for livestock production worldwide, owing to its high biomass yield and rapid regrowth (Singh, 2013; Pereira *et al.*, 2014). It is widely used in grazing and fodder systems, and supports both intensive and semi-intensive livestock systems in tropical and subtropical regions (Pereira *et al.*, 2014; Habte *et al.*, 2020). Its adaptability and nutritional potential in diverse environments, as demonstrated in studies across Africa and Asia, reinforce its value as a resilient and productive forage species (Habte *et al.*, 2020). Global germplasm evaluations have confirmed the wide genetic diversity and adaptability of elephant grass, reinforcing its role as a strategic forage for sustainable pasture-based livestock production systems (Muktar *et al.*, 2023).

This species has five well-defined morphological groups (Singh, 2013). In this context, dwarf cultivars, such as 'Brs Kurumi', stand out for their suitability in pasture system, achieving dry matter (DM) yields between 10 and 20 t/ha/year (Alves *et al.*, 2023). These cultivars have been genetically improved to have shorter internodes to reduce overall plant height (Sollenberger *et al.*, 1989). The shortening of internodes also promotes the emergence of basal tillers, as shorter plants allow greater light penetration at the base of the sward, which contributes to better soil cover and a more uniform distribution of tussocks (Pereira *et al.*, 2014). Furthermore, increased light penetration at the base of the plant promotes continuous photosynthetic activity in the lower leaves, ensuring consistent growth and quality throughout the growing season and enhancing animal production. Sward structures that allow enable balanced integration of morphological components have a decisive impact on the efficiency of grazing production systems. Despite its forage potential, the use of elephant grass in pastures has been limited by challenges in controlling canopy structure during grazing (Gomide *et al.*, 2015). In this context, understanding how forage plants respond to changes imposed by management practices is fundamental because this response reflects phenotypic plasticity, a key factor in the rate at which plant communities adapt to disturbances (Mori & Niinemets, 2010).

In C_4 forage species, the conditions that prioritize the vertical gradient by balanced participation of morphological components (Schmitt *et al.*, 2019), nutritive value (Difante *et al.*, 2009) and persistence of the plant can be achieved by maintaining residual heights that do at or below 50% of the target management height (Schmitt *et al.*, 2019). The aim is to maintain a high proportion of high-quality green leaf material while minimizing the accumulation of lower-quality stems and dead material (Silva *et al.*, 2019).

Considering that a greater reduction in the height of dwarf elephant grass decreases the DM percentage of leaf blades, preventing efficient pasture regrowth (Dourado *et al.*, 2019; Silva *et al.*, 2021) and that a smaller reduction compromises grazing efficiency and lowers the nutritional value of the ingested forage (Sollenberger *et al.*, 2020), we hypothesized that dwarf elephant grass managed with residual heights between 40 and 50 cm would optimize both forage production parameters and nutritional value. In addition, few studies have simultaneously evaluated the different residual heights of dwarf elephant grass over extended periods. This study is distinguished by its assessment of the greatest number of residual heights to date, a relevant contribution considering that the species exhibits high phenotypic plasticity (Gomide *et al.*, 2015). Determining the optimal residual height of dwarf elephant grass also provides practical insights into the sustainable management of this species, enabling the adoption of strategies that promote persistence and support long-term animal productivity. Therefore, the present study was conducted to ascertain the appropriate residual height for the dwarf elephant grass 'Brs Kurumi' by concurrently evaluating its forage production, morphological composition, and nutritional value.

2. MATERIAL AND METHODS

2.1. Experimental site

The experiment was conducted in Cruz Alta, Rio Grande do Sul, Brazil (28°34'28.55"S, 53°36'50.83"W, 448 m a.s.l.), over four consecutive growing seasons (from August 15, 2019, to May 20, 2022), covering the spring, summer, and autumn seasons. The soil is classified an oxisol, specifically a Dystrophic Red Latosol (Santos *et al.*, 2018). Oxisols are strongly acidic soils composed of mineral materials at an advanced stage of weathering. They are typically very deep, with a sequence of A, B, and C horizons and minimal differentiation between sub-horizons (Santos *et al.*, 2018). Prior to experimentation, soil analyses from the 0–20 cm layer indicated the following properties: pH-H_2O: 6.1; pH-SMP: 6.5; clay content: 43.0%; P: 76.2 mg/dm³; K: 72.0 mg/dm³; organic matter: 3.4%; Al: 0.0 cmolc dm³; Ca: 4.6 cmolc/dm³; Mg: 2.1 cmolc/dm³; Base saturation: 73.2% and Al saturation: 0.0%.

The climate is humid subtropical (Cfa) (Moreno, 1961), with mean annual precipitation of 1,300 mm and mean annual air temperature of 20°C. Climatological data for the experimental period (observed average temperature and accumulated precipitation along with 30-year historical data) were obtained from a meteorological station at the National Institute of Meteorology (INMET) located in Cruz Alta. Air temperatures fell below 15°C (base temperature for dwarf elephant grass growth during several periods): August 2019 (14.2ºC), June (13.0ºC) to July/2020 (13.9ºC), May (14.9ºC) to July/2021 (13.6ºC) and May/2022 (14.2ºC) (Table 1). Accumulated precipitation during the experimental period were below the historical average in August, September, and December (2019); January to April and August to December (2020); February to April, June to July, September and November to December (2021); and January to February (2022) (Table 1).

Table 1. Average monthly rainfall (mm) and air temperature (°C) during the experimental period (2019-2022) and the long-term (30 yr) historical record. Cruz Alta, Rio Grande do Sul, Brazil.

Month	Rainfall (mm)					Temperature (°C)				
	Years					Years				
	2019	2020	2021	2022	30 yr. avg.	2019	2020	2021	2022	30 yr. avg.
Jan	-	157.2	183.2	60.0	158.5	-	24.1	23.5	26.7	24.3
Feb	-	34.0	65.2	50.4	127.0	-	22.9	22.5	24.7	23.5
Mar	-	19.6	104.0	220.6	124.1	-	24.4	21.9	21.6	22.8
Apr	-	38.2	46.4	195.6	143.0	-	19.2	19.9	18.9	20.1
May	-	200.6	215.4	217.8	147.9	-	15.7	14.9	14.2	16.5
Jun	-	279.4	138.6	-	146.7	-	13.0	12.6	-	14.6
Jul	-	211.0	14.0	-	139.2	-	13.1	13.5	-	13.7
Aug	72.6	107.6	164.2	-	119.6	14.2	15.8	16.3	-	15.7
Sep	83.2	83.6	161.6	-	165.0	16.5	17.6	17.7	-	16.6
Oct	329.4	37.8	239.0	-	190.8	20.0	20.9	19.2	-	19.5
Nov	222.4	52.0	26.6	-	150.9	22.2	22.0	22.8	-	21.7
Dec	23.4	121.6	57.0	-	141.4	24.6	23.7	24.5	-	23.9

2.2. Experimental design and treatments

The experimental design followed a randomized complete block design with five treatments and four replications. Treatments consisted of five residual heights (20, 30, 40, 50, and 60 cm).

2.3. Field experimentation

A total area of 154 m^2 was delineated and subdivided into 20 plots, each measuring 4 m^2 with 1 m pathways separating them. Dwarf elephant grass [*Cenchrus purpureus* (Schumach.) Morrone], syn. *Pennisetum purpureum* (Schumach.) 'Brs Kurumi' was planted on August 15, 2019. Plant establishment was monitored over a period of 20 days, during which replanting was performed as needed to maintain uniform stand density across the experimental units. Plants were established manually using vegetative cuttings, with a 0.8 m row spacing (4 rows/plot). Within each row, vegetative cuttings were planted at 0.40 m spacing, resulting in a total of 20 cuttings per plot. Whenever the canopy reached the target management height of 80 cm (Gomide *et al.*, 2015), the plots were harvested to the previously defined residual heights. Based on initial soil test results and recommendations for warm-season grasses (Comissão de Química e Fertilidade do Solo–RS/SC, 2016), basal monoammonium phosphate (MAP) was applied at 300 kg/ha [33 kg/ha of nitrogen (N) and 156 kg/ha of phosphate (P_2O_5)]. In addition, urea was applied annually, equivalent to 190 kg/ha of N, split into three applications during the vegetative phenological stage (at tillering, after the first evaluation, and after the third evaluation).

2.4. Evaluation of parameters

The experimental protocol began evaluations on December 10, 2019. In the following years, evaluations resumed in December, corresponding to the initial growth phase of dwarf elephant grass under the study conditions. Canopy height was measured weekly and evaluations were performed whenever a target management height of 80 cm was reached. All replicates within each treatment were harvested simultaneously to ensure consistency.

Annual evaluations concluded when the forage species indicated growth cessation, characterized by the absence of new leaf emergence in more than 50% of the experimental unit and the inability to reach the target management height. This period coincided with the months of March to May, depending on the treatment-specific regrowth dynamics observed during the evaluations. Annually, owing to unfavorable climatic conditions for the growth of dwarf elephant grass in subtropical climate regions, no field evaluations were conducted from June to November. From the target management height (80 cm), the mean number of harvests varied according to residual height. 3.5 ± 1.3 for 20 cm, 3.5 ± 1.3 for 30 cm, 4.5 ± 1.7 for 40 cm, 7.2 ± 2.7 for 50 cm, and 8.0 ± 2.9 for 60 cm. These means were determined post-hoc from the data collected during the experimental period.

Sampling of forage production, canopy height, basal tiller population density, and nutritional value was performed at two randomly selected representative points within each plot. After cutting, the samples were homogenized, and composite samples were collected to determine each variable. For sampling, a 0.25 m^2 quadrat was used whenever the canopy reached the target height of 80 cm, while maintaining the designated residual heights. The plots were then mown to the target residual height, and excess biomass was removed from the experimental area.

The average pre- and post-cut pasture heights were determined through measurements taken at five points per experimental unit before and after each evaluation, using a ruler graduated in centimeters. Samples were separated into leaf blade, stem (leaf sheath + stem), and dead material components and dried in a forced ventilation oven at 60°C for 72 hours, and subsequently weighed. At the conclusion of the experiment, the accumulated total dry matter (TDM, kg/ha), leaf blade dry matter (LDM, kg/ha), stem dry matter (SDM, kg/ha), and dead material (DMP, kg/ha) were calculated. The accumulated values for each variable were calculated by summing the total number of evaluations conducted annually. Basal tiller population density (TPD, tillers/m^2) was assessed by counting the number of basal tillers prior to each destructive harvest.

The samples for chemical compounds were homogenized and 300 g fresh weight subsamples were dried at 60 °C for 72 hours. The dried material was then ground in a mill with a 1 mm sieve and analyzed for DM (%) content. Subsequently, samples were returned to the oven at 105 °C for 12 hours to determine final DM concentration (Method 934.01; AOAC, 2005). The N concentration was determined using the Kjeldahl method, and crude protein (CP, %) was calculated as N × 6.25 (Method 984.13; AOAC, 2005). Neutral detergent fiber (NDF, %) and acid detergent fiber (ADF, %) analyses were performed according to the procedures described by Van Soest *et al.* (1991).

2.5. Statistical analysis

The data were subjected to both individual (results not shown) and joint analyses of variance (ANOVA). In the joint analysis, random effects were assumed for the blocks, year, and interaction between residual height and year, while all other factors were considered fixed. The adopted model is as follows:

$$Y_{ijk} = \mu + H_i + Y_j + B_k + HY_{ij} + E_{ijk.}$$

Where: Y_{ijk} is the observed value of cut *i* in block *k* and within year *j*; μ is the overall mean; Hi is the fixed effect of cutting height i (i = 1, 2, 3, 4 and 5); Yj is the fixed effect of year j (j = 1, 2 and 3); HY(ij) is the random effect of the interaction of height *i* with year *j*; Bk is the random effect of block k (k = 1, 2, 3 and 4); E_{ijk} is the experimental error. Assuming that:

$$\mathrm{H_i} \sim \mathrm{N}(0,); \mathrm{Y_j} \sim \mathrm{N}(0,); \mathrm{B_k} \sim \mathrm{N}(0,); \mathrm{H'Y_{ij}} \sim \mathrm{N}(0,); \mathrm{eE_{ijk}} \sim \mathrm{N}(0,)$$

Prior to interpreting the results, the ANOVA assumptions were verified. Residuals were tested for normality using the Shapiro–Wilk test, and homogeneity of variances among treatments was assessed using Levene's test, both at a 5% significance level. No significant deviations were detected; thus, data transformation was not required.

Regression analyses were performed to evaluate trends across cutting heights, and model selection was based on the significance of linear, quadratic, and cubic coefficients, tested using Student's t-test at the 5% significance level. Pearson's correlation coefficients between traits were also estimated and tested by Student's *t*-test at the 1% and 5% levels. The strength of correlations was interpreted according to the classification proposed by Silveira *et al.* (2021): null (r = 0), weak (0 < r ≤ 0.30), moderate (0.30 < r ≤ 0.60), strong (0.60 < r ≤ 0.90), very strong (0.90 < r < 1.00), and perfect (r = 1). To visualize the correlation structure, a network plot was constructed, in which the distance between traits was proportional to the absolute correlation value. Edges with |r| ≥ 0.40 were highlighted: positive correlations were shown in green and negative ones in red. All analyses were performed using GENES software (Cruz, 2016).

3. RESULTS

3.1. Forage production

The accumulated total DM production, LDM, SDM, DMP were fitted to the linear regression model as a function of residual height ($p<0.05$; Figure 1). The accumulated total DM production values ranged from 5,840 ± 1,575 (60 cm RH) to 10,395 ± 1,311 (20 cm RH) kg/ha, with a linear reduction of 113.8 ± 17.6 kg/ha per cm increase in residual height (R^2=0.70; Figure 1a). Leaf blade DM production ranged from 5,786 ± 1,566 (60 cm RH) to 8,326 ± 915.4 (20 cm RH) kg/ha and decreased at a rate of 64.7 ± 16.6 kg/ha per cm increase in residual height (R^2=0.46; Figure 1b). Stem material produced 384.0 ± 68.5 (60 cm RH) to 1,293 ± 394.5 (20 cm RH) kg/ha with a linear reduction of 34.1 ± 3.5 kg/ha per cm increase in residual height (R^2=0.84; Figure 1c). The quantity of senescent material harvested ranged from 55.0 ± 17.5 (60 cm RH) to 876.0 ± 309.5 (20 cm RH) kg/ha with a linear reduction of 17.9 ± 3.2 kg/ha per cm increase in residual height (R^2=0.63; Figure 1d).

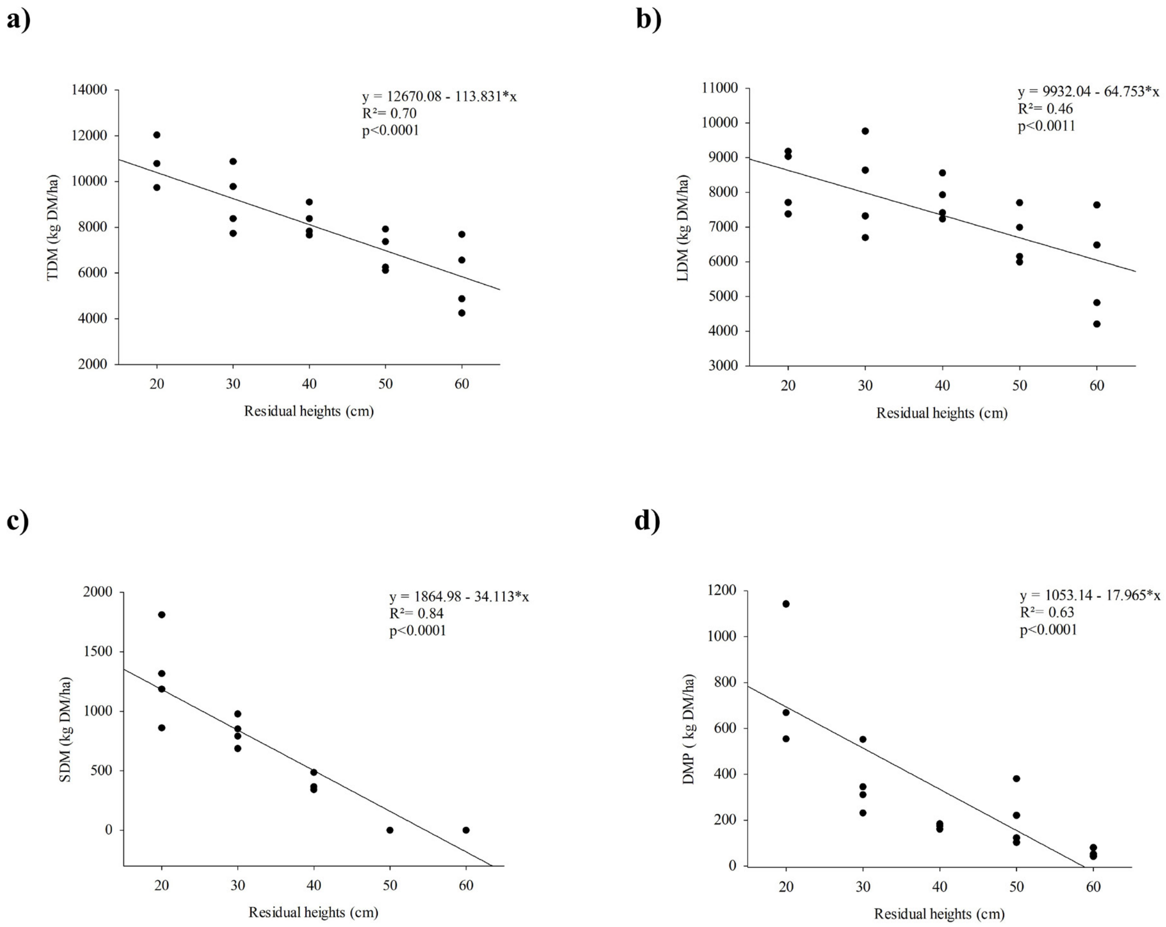


Figure 1. Agronomic characteristics of dwarf elephant grass 'Brs Kurumi' subjected to five different residual heights evaluated in Cruz Alta, Rio Grande do Sul, Brazil. TDM: accumulated total dry matter production (a); LDM: accumulated leaf blade dry matter production (b); SDM: accumulated stem dry matter production (c); DMP: accumulated dead material production (d).

Basal tiller population density was fitted to the linear regression model as a function of residual height ($p<0.05$; Figure 2). There was 46.0 ± 3.0 (60 cm RH) to 89.0 ± 12.2 (20 cm RH) tillers/m^2 with a linear reduction of 0.9 ± 0.2 tillers/m^2 for every cm increase in residual height (R^2=0.64; Figure 2).

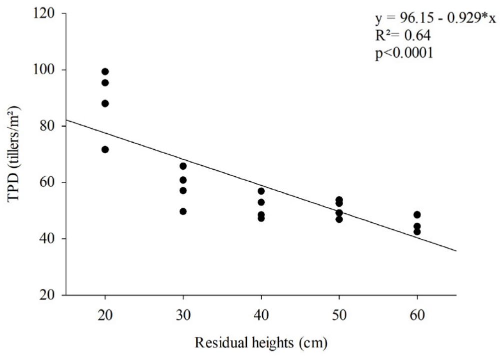


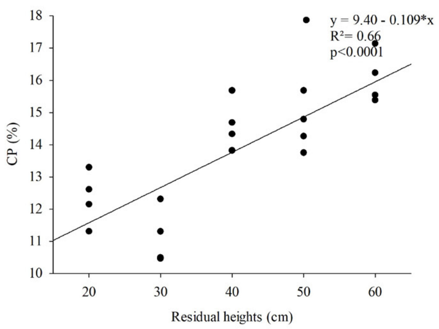
Figure 2. Agronomic characteristics of dwarf elephant grass 'Brs Kurumi' subjected to five different residual heights evaluated in Cruz Alta, Rio Grande do Sul, Brazil. TPD: basal tiller population density.

Accumulated total DM production had an average contribution of more than 80.0% from LDM, with values below 12.4% from SDM, and 8.4% from DMP. Reductions in TDM (19.2%) and LDM (16.0%) were greatest when pastures had residual heights of 40 and 50 cm. It was not possible to quantify the percentage reduction for SDM because it was not recorded for residual heights ≥ 50 cm.

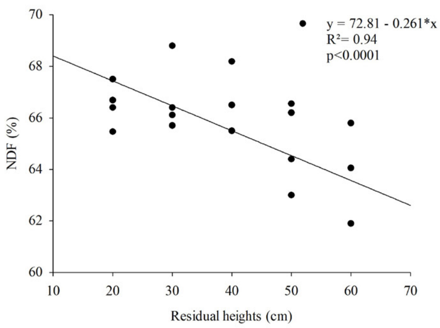
3.2. Nutritive value

Crude protein, NDF, and ADF levels were fitted to the linear regression model as functions of residual height ($p<0.05$; Figure 3). Crude protein values increased from 11.1 ± 0.9 % (20 cm RH) to 16.1 ± 0.8% (60 cm RH) with a linear rate of increase of 0.11 ± 0.01% per cm as residual height increased (R^2=0.66; Figure 3a). Neutral detergent fiber decreased from 66.9 ± 2.9% (20 cm RH) to 56.4 ± 3.6% (60 cm RH) with a linear reduction of 0.26 ± 0.07% per cm as residual height increased (R^2=0.94; Figure 3b). Acid detergent fiber also decreased as residual height was increased from 33.1 ± 1.9% (20 cm RH) to 29.8 ± 1.9% (60 cm RH) at the rate of 0.09 ± 0.03% per cm (R^2=0.88; Figure 3c).

a)



b)



c)

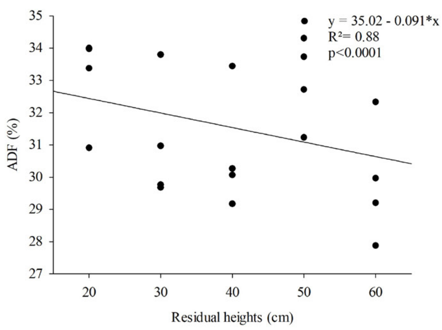


Figure 3. Nutritive value of dwarf elephant grass 'Brs Kurumi' subjected to five different residual heights evaluated in Cruz Alta, Rio Grande do Sul, Brazil. CD: crude protein (a); NDF: neutral detergent fiber (b); ADF: acid detergent fiber (c).

The correlation network analysis (Figure 4) revealed associations among the measured variables. Correlation coefficients (r) ranged from a moderate negative value of −0.83 (CP and SDM; p≤0.01) to strong positive value of 0.96 (TDM and LDM; p≤0.01); 0.96 (TDM and SDM; p≤0.01). In addition, the correlations of medium magnitude −0.86 (TDM and CP; p≤0.01); 0.88 (TDM and DMP; p≤0.01); 0.86 (TDM and TPD; p≤0.01) and 0.70 (LDM and TPD; p≤0.05) stand out.

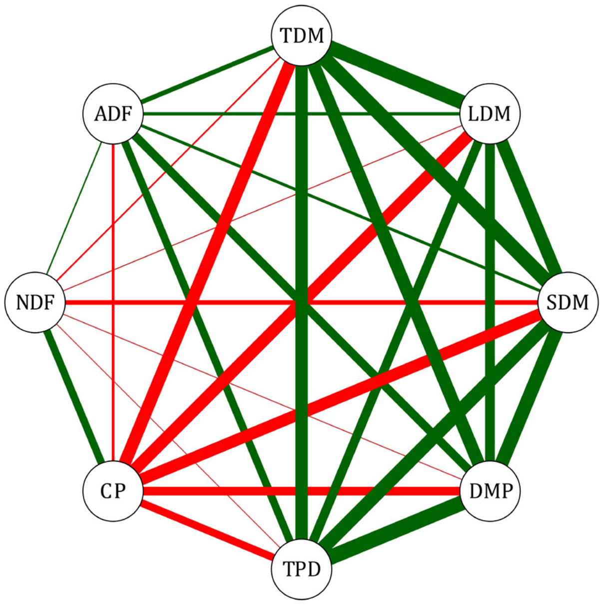


Figure 4. Correlation network among agronomic traits of dwarf elephant grass 'Brs Kurumi' subjected to different residual heights evaluated in Cruz Alta, Rio Grande do Sul, Brazil.

TDM: accumulated total dry matter production; LDM: accumulated leaf blade dry matter production; SDM: accumulated stem dry matter production; DMP: accumulated dead material production; TPD: basal tiller population density; CD: crude protein; NDF: neutral detergent fiber; ADF: acid detergent fiber.

Principal Component Analysis (PCA) revealed that the first two principal components (PC1: λ = 5.65; PC2: λ = 1.48) sufficiently explained the relationship between morphological composition and nutritive value variables, as both components had eigenvalues greater than 1. Together, the first two principal components retained 89.2% of the total information from the original variables. Principal Component 1 (PC1) captured 70.7% of the total variance present in the dataset. The variables that demonstrated the strongest positive contributions to PC1 were total dry matter (TDM), shoot dry matter (SDM) (loadings of 0.41), dry matter production (DMP) (0.39), total plant dry matter (TPD), and leaf dry matter (LDM) (0.38). Conversely, crude protein (CP) showed a strong negative contribution (−0.37). The positive and negative signs reflect the orientation of variable loadings in the Cartesian plane (Figure 5). The second principal component (PC2) accounted for 18.5% of the variability contained in the original variables, and the variables closest to the PC2 axis were NDF (0.71), ADF (0.59), CP (0.26), and TPD (0.18) (Figure 5). PC1 primarily captured variations related to morphological components, with TDM, SDM, and TPD contributing positively and CP contributing negatively. Conversely, PC2 was primarily influenced by the nutritive components, and NDF, ADF, CP, and TPD showed positive associations. As illustrated in Figure 5, distinct associations were observed between residual forage height and multiple forage quality and production parameters. Specifically, a 20 cm residual height was positively correlated with ADF, TDN, DMP, TDM, LDM, and SDM. Conversely, the 40 and 50 cm residual heights were associated with CP and NDF. Notably, residual heights of 30 and 60 cm displayed limited or weak associations with the studied variables.

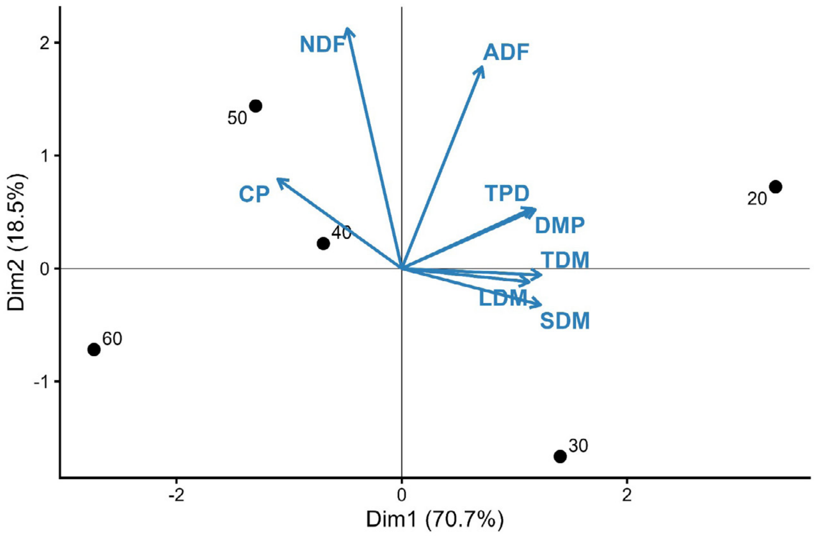


Figure 5. Principal components analysis (PCA) biplot based on the first two principal components for five residual heights (20, 30, 40, 50 and 60 cm) evaluated in Cruz Alta, Rio Grande do Sul, Brazil. Variables include: TDM, accumulated total dry matter production; LDM, accumulated leaf blade dry matter production; SDM, accumulated stem dry matter production; DMP, accumulated dead material production; TPD, basal tiller population density; CD, crude protein; NDF, neutral detergent fiber; ADF, acid detergent fiber.

4. DISCUSSION

This study confirmed the hypothesis that the morphological components and nutritive value of dwarf elephant grass 'Brs Kurumi' can be modified through management practices involving different residual heights. This confirms previous research on other erect forage plants, such as sorghum [*Sorghum bicolor* (L.) Moench] and ryegrass (*Lolium multiflorum* L.) which have also shown responsiveness to residual height management (Fonseca *et al.*, 2013; Comassetto *et al.*, 2020). Ward structure refers to the spatial distribution and arrangement of the aerial parts of plants, characterized by traits that vertically and horizontally express the quantity of available forage (Laca & Lemaire, 2000). Therefore, it is justified to examine and report responses that characterize the behavior of pasture structural variables.

In this experiment, residual height served as the structural factor. The main components of forage production that form the vertical structure of the canopy (TDM, LDM, SDM, and DMP) and horizontal structures represented by TPD, all decreased with increasing residual height. These results confirm that the forage sward structure of dwarf elephant grass 'Brs Kurumi' can be modified through management practices that apply appropriate target heights in relation to different residual heights. TPD was the primary variable among the evaluated parameters, as it contributed meaningfully to both principal components in the Cartesian plane of the PCA. This characteristic reinforces the species' potential for persistence, since TPD is directly related to its ability to renew and persist across management cycles and indirectly to the pasture's nutritive value. In this context, understanding the relationships among the evaluated parameters facilitates the practical identification of an optimal residual height that balances productivity, nutritive value, and longevity of 'Brs Kurumi'.

Previous studies have reported that elephant grass cultivars maintained at residual heights ranging from 10 to 70 cm produced varying proportions of leaf blades and stems (Pereira *et al.*, 2013; Pereira *et al.*, 2018; Rosa *et al.*, 2023). For the 'Brs Kurumi', despite a limited number of studies to date addressing morphological composition, it was observed that maintaining a residual height of 50% of the target management height (80–40 cm) resulted in contributions of 92% from leaf blades and 8% from stems (Rosa *et al.*, 2023). These findings corroborate with the results obtained in the experiment which showed a similar distribution (95% contribution from leaf blades and 5% from stems). Comprehensive studies examining the relationship between the structural characteristics and nutritive value are essential for understanding the productive potential of this cultivar. In this context, the present study stands out for its detailed evaluation of these parameters, providing critical information for improving management strategies, and ultimately, enhance animal production.

Correlations between forage production traits TDM and LDM confirmed the importance of leaf blade production in total accumulated DM production. Leaf blades were also identified as the plant component preferentially selected by grazing animals (Hodgson, 1990). The high contribution of LDM to TDM production was similar to that obtained for other dwarf elephant grass cultivars (Gomide *et al.*, 2015; Rosa *et al.*, 2023). LDM, SDM, and TPD were the main components of forage production and, as expected, were highly correlated with TDM. These findings confirm the necessity of monitoring these variables in experimental protocols designed to optimize sward structure to ensure adequate forage production, efficient utilization, and long-term plant persistence. Perennial C_4 grasses undergo stem elongation during the vegetative and reproductive development phases of development (Pereira *et al.*, 2014). Insights into this characteristic have guided the development of management practices that promote the maintenance of pasture structures conducive to high nutritive value (Silva *et al.*, 2019) and forage utilization.

Monitoring the basal TPD is important for perennial C_4 grasses due to its role in maintaining soil cover and ensuring pasture persistence (Pereira *et al.*, 2015). The correlations between TDM and TPD, LDM, and TPD favored greater forage DM production and greater tillering. This is explained by the fact that each newly formed leaf initiates a bud with the potential to develop into a new tiller (Skinner & Nelson, 1992). However, the results indicate that the TDP decreases as the residual height increases. This is related to increased competition for light in the forage canopy, which affects tiller mortality (Pereira *et al.*, 2015). Therefore, the challenge in maintaining optimal elephant grass height lies in striking a balance where adequate basal TPD and overall nutritional value (e.g., maximizing digestible nutrients while managing fiber content) are preserved without compromising pasture persistence due to excessive light competition at higher residual heights. The composition of the aerial part of the plant has a considerable effect on the nutritive value of forage, and consequently, the potential for animal production. In the present study, CP increased as the residual height increased. CP values ranged from 14.3% at a residual height of 50 cm (80–50 cm management) to 17.8% at 40 cm (80–40 cm management) in 'Brs Kurumi', aligning with trends observed in previous studies (Alves *et al.*, 2023; Rosa *et al.*, 2023). The efficiency of forage conversion into animal products depends on the balance between pasture productivity and nutritional value. Therefore, although CP was the only variable in this study that increased with higher residual height, the overall results indicate that other parameters related to morphological composition and nutritive value also play a fundamental role in producing the amount of forage required to ensure daily dry matter intake without compromising animal nutritional requirements.

As the residual height increased, less stem material was present in the harvested material. The presence of stems was detectable up to a residual height of 40 cm, corresponding to the removal of 50% of the initial height. The NDF and ADF values reported in this study were similar to those found in previous studies on 'Brs Kurumi'. (Alves *et al.*, 2023; Rosa *et al.*, 2023). This highlights the importance of adopting management practices for this cultivar to minimize the presence of stems, as elephant grass naturally contains a considerable fraction of this structure. This aspect directly affects the nutritive value of the available forage and the efficiency of forage intake, reinforcing the need for management practices that promote a higher proportion of leaf blades within the pasture canopy. The results demonstrated a positive correlation between TDM and SDM and negative correlations between CP and TDM and between CP and SDM. This condition in C_4 forages should be observed, as increases in forage DM production are often accompanied by N dilution in the plant, which in turn directly affects CP concentration (Lemaire & Gastal, 1997). It is important to consider that grazing 'Brs Kurumi' at low residual heights may reduce CP concentrations, potentially impairing animal performance. Furthermore, an increase in stem material reduces forage nutritional value for grazing livestock and may have adverse effect on bite formation during grazing (Euclides *et al.*, 2019). The positive correlation between TDM and DMP confirms the need for management practices that intensify forage production efficiency and reduce losses due to senescence and accumulation of dead material (Pereira *et al.*, 2014).

Animals were not included in the present study. However, previous studies with animals indicated that, irrespective of the forage species, removing 40–50% of the initial canopy height optimizes DM intake rates in grazing animals (Fonseca *et al.*, 2012, 2013; Mezzalira *et al.*, 2014), as the presence of stems acts as a vertical barrier to the grazing process. In the present study, residual heights of 40 and 50 cm were close to the values described by these authors. According to Schmitt *et al.* (2019), for directly grazed elephant grass pastures, forage removal > 50% is difficult to maintain in practice because of the plant's architecture. Although our study did not involve grazing animals, the observed changes in morphological composition, particularly the [e.g., higher leaf percentage at 40–50 cm, or increased stem percentage at 20 cm] are critical as they directly influence forage quality and potential intake dynamics under grazing conditions. Higher leaf proportions are known to facilitate greater bite mass and intake rates in grazing animals (Fonseca *et al.*, 2013, 2012), suggesting that these residual heights would likely optimize forage intake for 'Brs Kurumi'.

In the present study, principal component analysis (PCA) revealed a distinct separation between morphological components and nutritive value parameters in the dwarf elephant grass 'BRS Kurumi' subjected to varying residual heights (Figure 5). This information is important because the presentation of pasture to grazing livestock affects their forage intake behavior and efficiency (Fonseca *et al.*, 2012, 2013; Mezzalira *et al.*, 2014). The combined eigenvalues of the first two principal components explained a minimum of 80% of the total variance (Morrison, 1976). For these components, eigenvalues above one was obtained, indicating that each retained a substantial proportion of information from the original variables (Kaiser, 1958). PC1 comprised variables related to the structural attributes of dwarf elephant grass. A positive relationship was observed between TDM and SDM, highlighting the importance of examining the morphological components contributing to TDM (Figures 4 and 5). In tropical forage species, TDM may not correctly predict pasture conditions because a significant increase in stem accumulation within the biomass alters pasture structure and can obscure meaningful indicators of forage quality (Montagner *et al.*, 2008).

A residual height of 20 cm was more strongly associated with the morphological components that contributed to structural changes in the pasture, characterized by increased proportions stems, dead material, and ADF, thus reducing the leaf:stem ratio and diminished nutritive value of the forage. The dwarf elephant grass 'Brs Kurumi' managed under these conditions, if offered to animals, could reduce animal performance not only because of higher fiber content, but also because of increased proportions of stem and dead material in the forage canopy (Mezzalira *et al.*, 2013). Residual heights of 40 and 50 cm were associated with higher levels of CP and NDF in the forage available for animals to ingest. In addition, the forage structure of these swards contains more leaf material, which facilitates faster grazing and positively influences forage intake and animal performance (Amaral *et al.*, 2013).

The magnitude of adaptive changes should be considered when selecting management practices involving different residual heights. Maintaining residual heights between 20 and 30 cm proved to be less ideal, as the plants required a longer recovery period to reach their target management height, corroborating the results found in the literature for residual heights ranging from to 30–35 cm (Pereira *et al.*, 2013; Sousa *et al.*, 2013). In a study on 'Brs Kurumi' elephant grass managed under grazing conditions, a residual height of 30 cm was recommended as ideal (Gomide *et al.*, 2014). However, as previously discussed this residual height was not favorable under the conditions of the present study. The fact that the survey covered four consecutive growing seasons reinforces the robustness of our results. Furthermore, the 30 cm height showed no association with the other evaluated variables in the PCA, indicating that this recommendation may not be appropriate under the conditions studied here. Moreover, under these management conditions, dwarf elephant grass 'Brs Kurumi' exhibited lower nutritive value compared to the forage produced at higher residual heights. In the present study, for the residual heights recommended within the standard for maintaining residuals between 60% and 50% of the target management height (50 cm and 40 cm), dwarf elephant grass exhibited a similar response to the disturbance imposed by these residual height levels. In this context, the plants' phenotypic plasticity probably favored a balance between the morphological components and nutritive value, contributing to adaptation to the imposed residual height conditions. This response and the observed phenotypic plasticity reflect the ability of 'Brs Kurumi' to adjust its growth and canopy structure to maintain adequate forage production, high leaf proportion, and nutritive value.

5. CONCLUSION

Residual height significantly affected the forage production, morphological composition, and nutritional value of the dwarf elephant grass 'Brs Kurumi'. Our results indicated that maintaining residual heights between 40 and 50 cm provides an optimal balance, promoting a high leaf-to-stem ratio, favorable nutritional quality (characterized by higher crude protein and lower fiber content), and adequate forage production. Although lower residual heights (e.g., 20 cm) showed some advantages in terms of nutritive value, these were offset by increased stem and dead material as well as slower sward recovery, which may compromise pasture persistence and animal intake. The phenotypic plasticity observed in 'Brs Kurumi' at depths of 40 and 50 cm highlights its adaptability to these management strategies, making practical recommendations for sustainable pasture management focused on maximizing the nutritive value of forage.

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Supplementary material

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Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Authorship contribution statement

Juliana M. Machado: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Dinah P. Abbott-Rodrigues: Visualization, Writing – original draft, Writing – review & editing.

Adriano Mantovani-Tolfo: Conceptualization, Investigation.

Alexandra L. Bandeira-Calgaro: Investigation.

Andréa Dos Santos-Pereira: Investigation.

Iohan Souza-Da Silva: Investigation.

Paula Montagner: Investigation, Writing – original draft.

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Diógenes Cecchin-Silveira: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft.

Competing interests

The authors have declared that no competing interests exist.

Statement on the use of Artificial Intelligence

Not applicable.

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