



The soil-plant interface in *Megathyrus maximus* cv. Mombasa subjected to different doses of nitrogen in rotational grazing



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Abstract:

This work aimed to evaluate the effects of three nitrogen (N) doses on the morphogenic and structural characteristics, root mass (RM) and distribution in the soil profile, and penetration soil resistance of Mombasa guineagrass pastures managed with rotational stocking. The experimental design used randomized blocks with three N doses (100, 200, and 300 kg ha⁻¹) and three replicates. The criterion for interrupting the pastures' regrowth was the height of 80 to 90 cm of the canopy (90–95 % of light interception by the canopy). The animals were removed from the paddocks when the canopy reached 50 % of the pre-grazing height. Forage mass and accumulation, canopy morphogenic and structural

characteristics, RM and distribution in the soil profile, and soil resistance to penetration were evaluated. In pastures fertilized with 200 and 300 kg ha⁻¹ of N, the highest leaf appearance (0.090 and 0.081 leaves⁻¹ tiller⁻¹ d⁻¹), elongation rates (2.82 and 2.61 cm tiller⁻¹ d⁻¹) and highest daily forage accumulation (113.8 and 106.6 kg ha⁻¹d⁻¹) were observed. Using 300 kg ha⁻¹ of N promoted greater soil resistance to penetration at 10 cm of depth in the post-grazing (3.3 MPa). No effect of N doses was observed for RM ($P>0.05$). The pre- and post-grazing height control of animals in the paddocks therefore helped to maintain the pasture structure and avoid the soil compaction process. According to the results, it is concluded that 200 and 300 kg ha⁻¹ of N fertilization is a strategy for intensifying pastures.

Key words: Canopy height, Leaf appearance rate, Light interception, Root mass, Soil resistance.

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Introduction

Intensive grazing systems use cultivars with high forage production potential and good nutritional value that require investment in maintenance fertilization. *Panicum maximum* (Syn. *Megathyrsus maximum*) cv. Mombasa is the most used cultivar due to its high tillering and regrowth vigor after grazing^(1,2). This cultivar also has a production potential that can exceed 27 t ha⁻¹ yr^(3,4) and achieves nutritional values compatible with individual gains above 700 g animal day⁻¹⁽⁵⁾. Due to its growth habit and productive potential, this cultivar should be managed using intermittent stocking. Furthermore, the rest period must be interrupted when the forage canopy intercepts 90 to 95 % of the incident light⁽⁶⁾, and the animals' removal must occur when 50 % of the forage has been grazed^(4,7).

Nitrogen (N) fertilization enhances a pasture's production, as it acts directly on the morphogenic and structural characteristics of the forage plant⁽⁸⁾. The N increases the leaves' appearance and elongation rates and reduces the leaves' life span, and the phyllochron still stimulates the sprouting of axillary buds, increasing the production of tillers^(9,10). In this sense, morphogenesis study on fertilized pastures allows one to understand the physiological mechanisms of plant growth, as well as N's role as a modulator, regulator, and enhancer of this process.

Little research has been conducted on N's effects on the root system of pastures, especially in the tropics. However, N has been proven to influence root growth in periods

of higher rainfall⁽¹¹⁾, which can lead to a linear increase in root mass (RM)⁽¹²⁾. Nitrogen fertilization increases a pasture's productive capacity with a significant increase in the stocking rate^(13,14), which can compromise the soil's physical characteristics⁽¹⁵⁾.

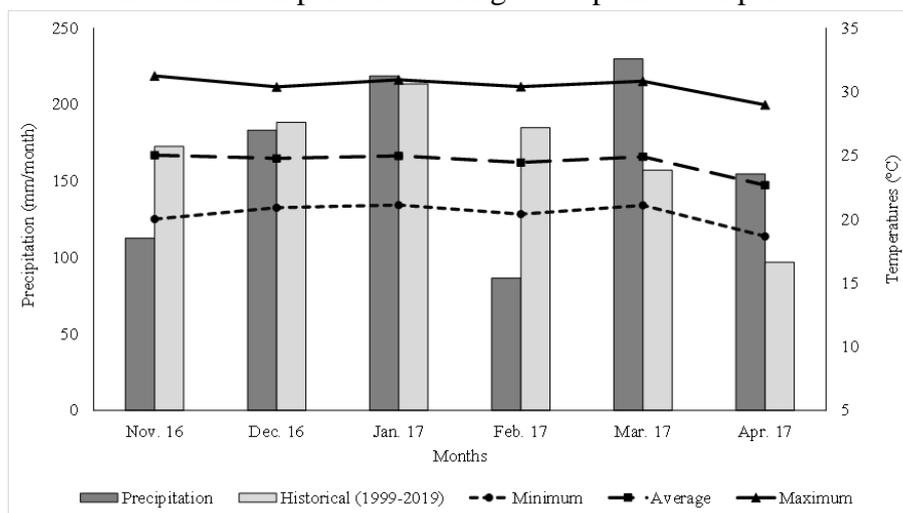
Much regarding the effects of animal trampling that results from grazing pressure on the soil's physical attributes—including soil compaction and soil penetration resistance (PR)—and root development remains to be investigated since a pasture's longevity is based on the soil's chemical, biological, and physical balance. This last factor determines the roots' ability to develop and exploit soils to absorb water and nutrients.

The following research questions were formulated for this work: How does N fertilization affect morphogenic and structural characteristics and forage accumulation? Will pastures that receive higher N doses be more compacted when the PR method evaluates them? Would correct pasture management (based on the 95% LI) associated with moderate grazing intensity be able to reduce the compaction effect on root development? In search of answers, the objective was to evaluate the effects of fertilization using three different N doses on the morphogenic and structural characteristics, RM and distribution in the soil profile, and soil penetration resistance of Mombasa guineagrass pastures managed with rotational stocking.

Material and methods

Experiment location and edaphoclimatic monitoring

The experiment was conducted at Embrapa Beef Cattle, Campo Grande, MS (20°27'S, 54°37'W and an altitude of 530 m) from November 2016 to April 2017. According to the Köppen classification, this region has a tropical savanna climate (Aw) with seasonal rainfall distribution. The Embrapa Beef Cattle weather station, located approximately 4 km from the experimental area, recorded the rainfall and minimum average, and maximum temperatures (Figure 1).

Figure 1: The monthly average and historical precipitation and minimum, average, and maximum temperatures during the experimental period

The experimental area's soil is classified as Red Latosol and has clay contents around 30 %⁽¹⁶⁾. Before the experiment began, the soil was sampled in the 0–10, 0–20, and 20–40 cm layers for chemical evaluation (Table 1). Based on the soil analysis results and the proposed production system, the pastures were fertilized in coverage with 80 kg ha⁻¹ of P₂O₅ and 80 kg ha⁻¹ of K₂O in November 2016.

Table 1: The chemical characteristics of the experimental area's soil at depths of 0–10, 0–20, and 20–40 cm in pastures of Mombasa guineagrass fertilized

Doses	Depth (cm)	pH CaCl ₂	PMg dm ⁻³	MOg dm ⁻³	K cmol dm ⁻³	Ca	Mg	Ca+Mg	Al	H	Al+H	S	T	V %
N100	0–10	5.53	4.34	44.03	0.43	4.08	1.18	5.27	0.00	3.47	3.47	5.69	9.16	62.17
	0–20	5.56	3.89	42.38	0.32	4.18	1.15	5.33	0.00	3.49	3.49	5.66	9.15	61.88
	20–40	5.47	1.47	28.38	0.19	2.06	0.97	3.23	0.00	3.15	3.15	3.42	6.57	51.96
N200	0–10	5.50	5.89	37.92	0.38	3.87	1.17	5.03	0.00	3.25	3.25	5.42	8.66	62.54
	0–20	5.53	4.64	37.24	0.35	3.83	1.18	5.02	0.00	3.10	3.10	5.37	8.46	63.39
	20–40	5.33	1.87	25.62	0.19	2.22	1.42	3.63	0.00	2.98	2.98	3.83	6.80	56.36
N300	0–10	5.27	4.06	40.08	0.41	3.45	1.10	4.55	0.00	4.25	4.25	4.96	9.21	53.93
	0–20	5.33	3.85	39.46	0.26	3.48	1.08	4.57	0.00	3.93	3.93	4.83	8.76	55.22
	20–40	5.42	1.33	32.64	0.13	2.32	0.97	3.28	0.00	3.15	3.15	3.42	6.56	52.33

N100 = 100 kg ha⁻¹ yr⁻¹ of N; N200 = 200 kg ha⁻¹ yr⁻¹ of N; and N300 = 300 kg ha⁻¹ yr⁻¹ of N.

Experimental design and conduction

The 13.5 ha experimental area was divided into three blocks of 4.5 ha each; each block was then divided into three 1.5 ha modules and these into six 0.25 ha paddocks. The experimental design used completely randomized blocks, with three treatments and three repetitions (modules). The treatments were Mombasa guineagrass pastures fertilized with doses of 100 (N100), 200 (N200), and 300 (N300) kg ha⁻¹ of N.

The N fertilization was divided into two applications for the N100 treatment and three applications for the N200 and N300 treatments. The first N dose was applied in November, along with P and K (80 kg ha⁻¹ of P₂O₅ and 80 kg of K₂O). The N source used was urea, applied until the end of March (rainy season) and only when the animals left the paddocks. The grazing method used was rotational stocking with a variable stocking rate (put-and-take). Canopy heights of 80 to 90 cm and 40 to 50 cm were adopted as pre- and post-grazing conditions⁽⁶⁾, respectively, for all N doses evaluated. Fifty-four (54) crossbred steers of the Angus x Nellore breed, with the age and initial weight of 10 months and 300 kg, were used to lower the pastures, and performance evaluations were not performed for this experiment. The animals received mineral supplementation *ad libitum*.

Forage canopy estimated variables

The forage canopy height (cm), before and after grazing, was determined using a graduated ruler at 40 random points per paddock. The height of each point corresponded to the canopy height around the ruler, and the average of these points represented the average canopy height in each paddock.

For the forage mass estimation, before and after grazing, a paddock from each module was chosen at random, and nine 1 m² samples were cut close to the ground level in each grazing cycle⁽⁴⁾. The same paddock was sampled throughout the experimental period. The samples were weighed and divided into two subsamples: One was dried at 65 °C until constant weight to determine the total dry matter. The other was manually subdivided into leaf (leaf blade), stem (sheath and stem), and dead material, dried at 55 °C until constant weight, and weighed. The percentage of each component was determined to estimate the leaf:stem ratio.

The forage accumulation rate was calculated using the difference between the forage mass in the current pre-grazing and the previous post-grazing, considering only the green portion (leaf and stem), divided by the number of days between samples. The total forage accumulation during the experimental period was the sum of the forage accumulation of all grazing cycles.

At the beginning of each paddock rest period, 10 tillers in each experimental unit were marked to determine morphogenic and structural characteristics. The tillers were marked in two paddocks per module, totaling 18 paddocks (six paddocks for each N dose evaluated). Measuring individual leaves and tillers allowed to evaluate the following factors: leaf appearance rate (LAR; leaves tiller⁻¹ d⁻¹), or the number of leaves per tiller divided by the number of days in the evaluation period; phyllochron (days), or the inverse of LAR; leaf elongation rate (LER; cm tiller⁻¹ d⁻¹), or the sum of leaf blade elongation divided by the number of days in the evaluation period; stem elongation rate (SER; cm tiller⁻¹ d⁻¹), or the sum of stem elongation divided by the number of days in the evaluation

period; final leaf length (FLL; cm tiller⁻¹), or the leaf blades' fully expanded average length; leaf senescence rate (LSR; cm tiller⁻¹ d⁻¹), or the relationship between the sum of the leaf blades' senescent lengths in the tiller and the number of days in the evaluation period; green leaves number (GLN), or the number of expanding and expanded leaves, disregarding the senescent leaves of each tiller; leaf life span (LLS; days), or the period of time from the leaf appearance until its death, estimated using the equation $LLS = GLN \times \text{Phyllochron}^{(17)}$.

The tiller population density (TPD) was estimated by counting tillers in three 1 m² (number of tillers per m²) areas per experimental unit. The locations of these points were chosen to represent the average pasture condition at the time of the assessment. These areas were kept fixed and marked with a wooden stake and were changed only when they no longer represented the average pasture condition. Tilling counting was performed during the pre-grazing condition.

Soil estimated variables

The dry RM was evaluated by collecting eight samples from two paddocks of each module, using a cylindrical auger 4.8 cm wide and 10 cm high, from March 20 to 24, 2017. Four samples were collected under the tussocks and four outside the tussocks. Each sample was subsampled at depths of 0–10, 0–20, 20–30, and 30–40 cm. The samples of moist soil + root were packed in identified plastic bags.

The soil + root samples were washed with running water using sieves with 2 and 1 mm screens, separating the soil from the RM. The roots were dried in an oven at 60 to 65 °C for 72 h and then weighed to determine the dry matter content. To assess soil moisture, a soil sample deformed by an experimental module was collected⁽¹⁸⁾. The soil moisture values were used to adjust the dry RM calculations (kg ha⁻¹) and the root distribution in the soil profile.

Soil penetration resistance (PR) was estimated using the Falker PenetroLOG - PLG 1020 (electronic soil compaction meter) from March 15 to April 17, 2017. The PR assessments were performed in 10 positions in the two central paddocks of each module before and after grazing. Additionally, on the same day that the PR assessments were completed, samples were collected to determine soil moisture at depths of 0–15, 15–30, 30–45, and 45–60 cm for later correction of the PR values⁽¹⁹⁾.

Statistical analysis

Statistical analysis of the forage mass and accumulation rate data was conducted using a mathematical model that contained the random block effect and the fixed effects of treatments, seasons, and the interactions between them. For all analyses, the mixed procedure available at the SAS Institute (1996) was used. The comparison of means was performed using the Tukey test, adopting a 5% probability. In the case of significant interactions, the comparison of means was performed using the probability of the difference and the Tukey test at 5%.

Principal components (PCs) evaluated the data concerning the morphogenic and structural characteristics: the data set was standardized, which means that each descriptor presented zero mean and unit variation. This analysis allowed to reduce the space of the original variables in a smaller set, preserving the maximum of the data's original variability. All statistical analyses were conducted using software R version 3.6.1.

For RM and soil PR, a randomized block design in a split-plot arrangement was adopted. The residual effect of the N doses was allocated to the plot and the depths to the subplot. The following model was used:

$$Y_{ijk} = \mu + D_i + B_j + \alpha_{ij} + P_k + (D \cdot P)_{ik} + \beta_{ijk}$$

Y_{ijk}= value observed in dose i, block j, and depth k;

μ= overall average effect;

D_i= dose effect i (i = 100, 200, and 300);

B_j= block effect j;

α_{ij}= random error effect attributed to the parcel;

P_k= depth effect k; (D*P)_{ik} = the effect of the interaction between dose and depth; and

β_{ijk}= random error assigned to the subplot.

When significant according to the F test, the effect of doses was analyzed using the Tukey test and the effect of depths with the Scott-Knott test, both at 5% probability.

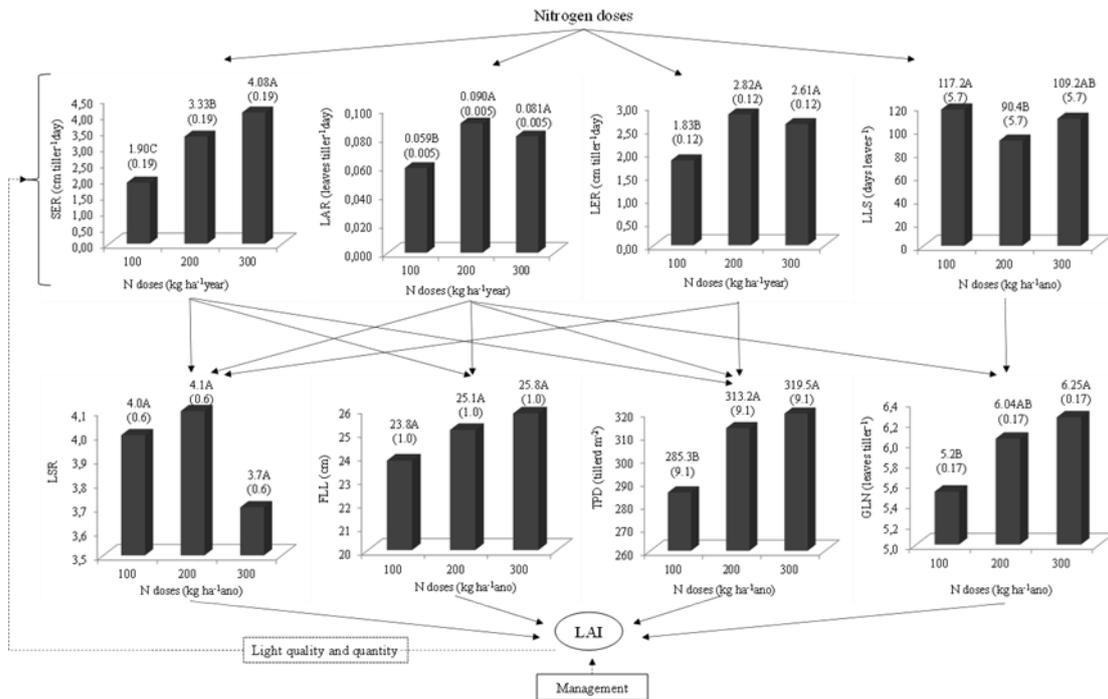
Results

Morphogenic and structural characteristics

Fertilization with N200 and N300 promoted the highest LAR and LER compared to fertilization with N100 (Figure 2). The LSR was high in pastures fertilized with N100,

and it was the same in pastures fertilized with N200 and N300 (Table 3). Moreover, pastures fertilized with N100 demonstrated the lowest SER, pastures fertilized with N300 the highest SER, and pastures fertilized with N200 an intermediate SER (Figure 2).

Figure 2: The morphogenic and structural characteristics of the canopy of Mombasa guineagrass fertilized with nitrogen (N) doses



The values in parentheses indicate the standard error of the mean. SER= stem elongation rate; LAR= leaf appearance rate; LER= leaf elongation rate; LLS= leaf life span; LSR= leaf senescence rate; FLL= final leaf length; TPD= tiller population density; GLN= green leaves number; LAI= Leaf area index.

Pastures fertilized with N100 also had the lowest TPD, while pastures fertilized with N200 and N300 had the highest TPD (Figure 2). The FLL did not differ between the N doses. Pastures that received N100 revealed the lowest GLN per tiller, whereas pastures that received N300 revealed the highest; the N200 dose promoted intermediate GLN values. The leaf:stem ratio did not differ for the evaluated N doses. Finally, the phyllochron and LSR were higher in pastures fertilized with N100 and lower in pastures fertilized with N200 or N300 (Table 2).

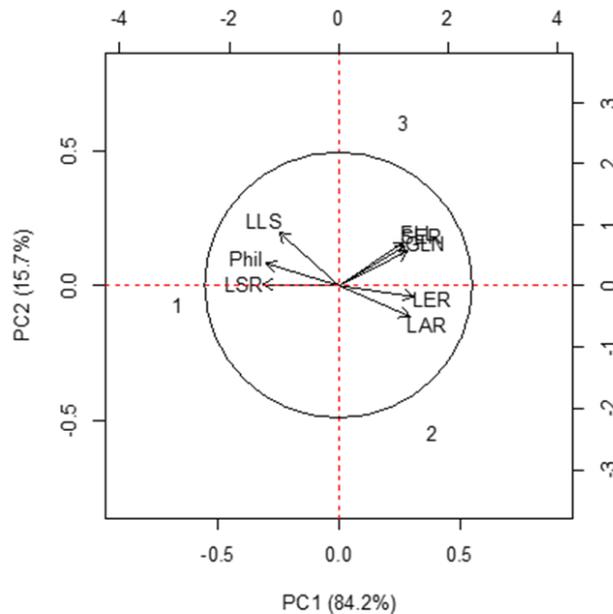
Table 2: Phyllochron and leaf senescence rate (LSR) averages in Mombasa guineagrass pastures fertilized with N doses

Variables	N doses (kg ha ⁻¹)			P-value
	100	200	300	
Phyllochron, days	18.6 ^a	11.3 ^b	12.9 ^b	0.0001
LSR, cm tiller ⁻¹ d ⁻¹	1.09 ^a	0.72 ^b	0.73 ^b	0.0001

^{ab} Distinct lowercase letters on the same line differ according to the Tukey test ($P>0.05$).

The PC analysis indicated that only two PCs explained 99 % of the variation in the data set. The first PC explained 84.2 % of the total data variation and aspects related to the tissues' appearance (Figure 3). In this PC, the LAR was positively associated with the FLL, LER, GLN, and SER and negatively associated with the phyllochron, FLL, and LSR. In addition, the LAR, FLL, LER, GLN, and SER indicated a high association with the N200 and N300 doses. In the second PC, which explained 15.7 % of the data variation, a positive association between the phyllochron, LLS, GLN, FLL, and SER and a negative association between these variables and the LAR and LER were observed. In this PC, the phyllochron, LLS, GLN, FLL, and SER were associated with the N300 dose and the LAR and LER with the N200 dose. The LSR demonstrated neutrality by N doses.

Figure 3: Biplot of the first principal component (x-axis) and the second principal component (y-axis)



FLL= final leaf length; Phil= filocron; LAR= leaf appearance rate; LER= leaf elongation rate; GLN= number of green leaves; LSR= leaf senescence rate; LLS= leaf life span; SER= stem elongation rate.

Canopy height, forage mass, and accumulation rate

The pre- and post-grazing heights approximated the predetermined targets for the three N doses evaluated. The height averages were 81.6 (\pm 1.61) cm in the pre-grazing condition and 44.7 (\pm 1.21) cm in the post-grazing condition (when the animals left the paddocks). Mombasa guineagrass pastures fertilized with N300 revealed the highest daily forage accumulation rate (Table 3) and the shortest grazing and resting periods, whereas pastures fertilized with N100 revealed the longest grazing and resting periods. Those fertilized with N200 presented intermediate values.

Table 3: The forage accumulation rate; pre- and post-grazing heights; and grazing and resting period averages in Mombasa guineagrass pastures fertilized with nitrogen (N) doses

Variables	N doses (kg ha ⁻¹)			P-value
	100	200	300	
Grazing period, days	6.5 (0.16) ^a	5.6 (0.16) ^{ab}	5.1 (0.14) ^b	0.0001
Rest period, days	30.9 (0.88) ^a	27.5 (0.84) ^b	24.6 (0.82) ^c	0.0001
FAR, kg ha ⁻¹ d ⁻¹	86.2 (3.1) ^c	106.6 (3.8) ^b	113.8 (3.5) ^a	0.0001

FAR= Forage accumulation rate.

^{abc} Distinct lowercase letters on the same line differ ($P < 0.05$); values in parentheses are the standard error of the mean.

The forage mass ($5,670 \pm 121$ kg ha⁻¹); leaf (67.9 ± 2.1 %), stem (17.3 ± 1.3 %), and dead material (14.8 ± 1.1 %); and leaf:stem ratio (3.9 ± 0.6) did not differ between the N doses in the pre-grazing. N doses also did not affect the forage mass and the percentages of leaf, stem and dead material in post-grazing, with average values and their standard errors of: $3,544 \pm 109$ kg ha⁻¹, 67.9 ± 2.1 %, 31.1 ± 1.7 , 41.5 ± 3.5 %, for forage mass, leaf, stem and dead material, respectively.

Mechanical penetration resistance of the soil and root mass

No interaction between the N doses and soil depths ($P=0.1397$) occurred for mechanical PR of the soil. Furthermore, the N doses had no effect on the PR ($P=0.4693$), with an average of 2.2 ± 0.16 MPa. However, in pre-grazing, a soil depth effect ($P=0.0001$) occurred on the PR. The highest PR was observed in the 10 cm layer (2.77 ± 0.06 MPa), followed by the 5–20 cm layers. Lower PRs were observed deeper in the soil.

In post-grazing, an interaction between the N doses and soil depths ($P=0.0001$) did occur for PR (Table 4). Up to 10 cm of depth, a higher PR was observed in pastures fertilized with N300 compared to those fertilized with N100 and N200. In the 15 cm layer, the PR did not differ by N doses. Conversely, in the 20–35 cm layers, the PR was higher in

pastures fertilized with N300 and lower in pastures fertilized with N200; those fertilized with N100 remained unaffected. After 40 cm of depth, no difference in PR between N levels was observed.

Table 4: Mechanical penetration resistance (MPa) of the soil submitted to different nitrogen (N) doses in Mombasa guineagrass pastures during post-grazing

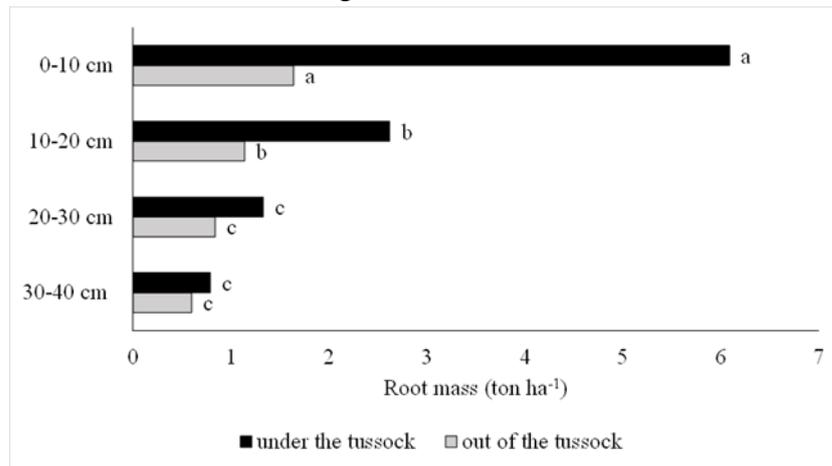
Depth (cm)	N doses (kg ha ⁻¹)		
	100	200	300
5	2.5 ^{ba}	2.5 ^{ba}	3.4 ^{aA}
10	2.7 ^{ba}	2.7 ^{ba}	3.3 ^{aA}
15	2.2 ^{aB}	2.2 ^{aB}	2.7 ^{aB}
20	2.5 ^{abA}	2.1 ^{bB}	2.9 ^{aB}
25	2.4 ^{abB}	1.9 ^{bC}	2.6 ^{aB}
30	2.2 ^{abB}	1.7 ^{bC}	2.4 ^{aC}
35	2.1 ^{abB}	1.6 ^{bD}	2.2 ^{aD}
40	1.9 ^{aC}	1.6 ^{aD}	2.0 ^{aD}
45	1.8 ^{aC}	1.5 ^{aD}	1.8 ^{aE}
50	1.6 ^{aD}	1.5 ^{aD}	1.7 ^{aE}
55	1.6 ^{aD}	1.4 ^{aD}	1.6 ^{aE}
60	1.5 ^{aD}	1.4 ^{aD}	1.5 ^{aE}

^{ab} Averages followed by distinct lowercase letters on the same line differ ($P < 0.05$).

^{AB} Distinct uppercase letters in the same column differ ($P < 0.05$).

Standard error of the mean = 0.102.

No interaction effect between N doses and soil depths occurred for the RMs ($P > 0.05$). In addition, no N dose effect was observed for the RMs under (2.70 ± 0.595 t/ha of DM) or outside (1.05 ± 0.230 t/ha of DM) the tussocks ($P > 0.05$), which differed by the sampled layers (Figure 4). The largest RMs were observed in the 0–10 cm layer, followed by the 10–20 cm layer; the 20–30 and 30–40 cm layers had the lowest RMs, with no differences between them. The sum of all sampled layers revealed 10.82 t ha⁻¹ of root DM in the space under and 4.22 t/ha of root MS outside the tussocks.

Figure 4: Root mass inside and between Mombasa guineagrass tussocks fertilized with nitrogen doses

ab Different letters compare depths in the same position according to the tussock.

Discussion

Nitrogen fertilization influences the morphogenic and structural characteristics of the canopy of Mombasa guineagrass^(9,10,20). Indeed, different responses to the N doses used has been observed. For instance, high N doses led to increases in LAR and LER^(9,10,21). Nitrogen also stimulates a systematic effect on leaf growth: as N nutrition increases, the LAR increases as well. Moreover, N increases cell production in growing leaves, altering cell division and expansion rates⁽²²⁾ and thus affecting the LER. Pastures fertilized with N100 therefore had a lengthier leaf elongation due to their lower supply of this nutrient. As N becomes more available to a plant, its LER increases, increasing its final leaf size and ultimately decreasing its useful life⁽²³⁾. Mombasa guineagrass pastures that received higher N doses (200 and 300 kg ha⁻¹) reached the pre-grazing target of 80–90 cm more quickly than those that received a lower N dose (100 kg ha⁻¹) due to their shorter phyllochron, or the time necessary for two consecutive leaves to appear. The higher N doses may have favored the recovery of the leaves' photosynthetic apparatus of Mombasa guineagrass soon after defoliation, reducing the phyllochron and the time the pastures needed to recover.

The reductions in LLS due to N fertilization necessitated adjusting grazing management practices to harvest the forage at the appropriate time, which the evolution of the LAR, LER, and LSR can determine. The different pastures' grazing and rest periods resulted from adjusting the grazing management to achieve the appropriate forage use condition.

Using N in fertilization strategies favors the growth and accumulation rate of forage by increasing the rates of enzymatic reactions and the metabolism of forage plants⁽²³⁾. As the forage accumulation increases, the leaf area index also increases, promoting the shading

of leaves and tillers at the pasture base⁽²⁴⁾. In their search for light, the stems elongate, and the younger, more photosynthetically efficient leaves are exposed at the top of the canopy^(20,25,26). Grazing management with pasture condition control enabled forage harvesting when the number of stems did not harm the canopy structure, since no variation between the leaf and stem percentages occurred in the pre-grazing, even with differences in the LAR, SER, and FLL (Figure 2) by the N doses evaluated.

Since the canopy's morphogenic characteristics influence its structural characteristics⁽²⁷⁾, the effects of the different N doses were observed in most structural variables. The LAR directly determines the TPD, as each new leaf that emerges represents a phytomer, which is formed by the leaf blade, ligule, sheath, node, internode, axillary buds, and roots⁽²⁸⁾. Each phytomer can generate a new tiller, whose appearance is regulated by the quantity and quality of the light that reaches the base of the canopy⁽²⁹⁾. The largest number of tillers is thus responsible for the largest forage production, observed in pastures fertilized with the highest N doses. Conversely, grazing management determines the canopy's opening or closing, influencing tiller appearance and mortality rates⁽²⁵⁾.

While green leaves per tiller is a genetically determined variable, an additional 0.73 leaves tiller⁻¹ were observed in pastures fertilized with N300 and 0.52 leaves tiller⁻¹ in pastures fertilized with N200 compared to those that received N100. Due to N's effect on the LAR, the GLN also increased⁽³⁰⁾, expressing the maximum plant genetic potential.

The FLL and leaf:stem ratio are responsive to defoliation intensity and can be classified as morphological mechanisms of escape that plants present in response to defoliation⁽²⁹⁾. In this experiment, the same pre- and post-grazing heights were used for all N doses applied, which determined the same grazing intensity, represented by 50 % utilization of the pre-grazing height. This grazing intensity is considered moderate⁽⁷⁾ and may have contributed to the leaves' length not differing by the N doses used.

During the vegetative period, the N demand tends to be linearly associated with the LER so that luxury N uptake occurs only after a leaf has expanded completely and is originated predominantly through the translocation of the canopy's bottom leaves⁽³¹⁾. Fertilizations with 200 and 300 kg ha⁻¹ yr⁻¹ of N were most likely to satisfy the nutrient demand and promoted greater speeds of appearance and elongation of the plant's shape and organs until the grazing frequency determined by height was reached. The N fertilization of tropical grasses increases the forage accumulation^(32,33,34). It is thus essential to adjust the stocking rate for each N dose applied to allow grazing animals to consume the forage produced.

In addition to the stocking rate, the grazing and rest periods differed by N doses, reflecting the different forage growth rates due to the availability of N for the plants. Pastures that received the lowest N dose (100 kg ha⁻¹ yr⁻¹) needed 6.3 more days of rest than those that received the highest N dose (300 kg) and 3.4 more than those that received the intermediate N dose (200 kg).

Grazing management adjustments were made to maintain the pre- and post-grazing target heights, regardless of the N dose applied; the forage mass and the pasture components percentage were therefore similar for the three N doses applied. The grazing intensity was satisfactorily controlled, maintaining the canopy condition. Conversely, the different forage accumulation for the three N doses determined the grazing frequency, reflecting in the rest periods. The pre- and post-grazing height control allowed to use the increase in biomass accumulation that N fertilization provides.

The highest N dose ($300 \text{ kg ha}^{-1} \text{ yr}^{-1}$) delivered the highest forage accumulation, with shorter grazing and rest periods for the pastures. Greater forage accumulation thus demanded a higher stocking rate so that the post-grazing goal (40–50 cm) could be reached, which was reflected in the increased grazing pressure.

The increases in stocking rate and grazing pressure that result from intensification (N fertilization) are strongly related to soil compaction in pastures^(35,36) due to the pressure that the animals' hooves exert. The intensity of this pressure depends on the body mass, the hoof area, and the kinetic energy exerted on the soils⁽¹⁵⁾, increasing the soil density due to the loads and pressure applied. The PR is directly related to the stocking rate⁽³⁷⁾, which was a determining factor in increasing PR in the pastures that received N300 in the post-grazing period. Notably, in the soil's superficial layers (0–10 cm), most grass roots are concentrated^(38,39). A PR greater than 2.5 MPa at these depths can therefore limit the development of roots^(37,40).

Although pastures that received N300 indicated PR values above 2.5 MPa in layers 0–10 cm deep in the post-grazing period, the stocking rate that the different N fertilizations provided does not seem to have affected the RM. This finding indicates that the intermittent stocking method that uses the put-and-take technique, which involves using a variable number of animals for load adjustment⁽⁴¹⁾, could efficiently control the grazing pressure, keeping it within what is considered ideal.

In addition, pastures demonstrated excellent regrowth vigor and high forage accumulation despite the PR values that could be impeding the pastures' development. Compaction reduces soil pores when larger pores are lost or reduced in size⁽⁴²⁾; however, grasses seem to adjust the diameter of their roots to fill porous spaces in their search for water and nutrients⁽⁴³⁾. The roots' elongation during this search thus seems to have a soil unpacking function during the pastures' regrowth, justifying the absence of N's effect on the soil's PR in the pre-grazing period.

While some research suggests that a reduction in the RM of forage grasses occurs due to the increase in N doses, even in periods with greater rainfall^(11,44), this research determined that the adopted management criterion (80–90 cm of pre-grazing and 40–50 cm of post-grazing heights) could guarantee the regrowth and the maintenance of the forage accumulation without compromising the root system. In fact, the remaining leaf area index (after grazing) has an important relationship with the RM so that more severe

defoliation intensities can reduce RM and growth^(12,45). In this experiment, the defoliation intensity was considered moderate (50 % of the plant's aerial part was removed) and within the grazing resistance limits considered ideal for plant use⁽⁴⁶⁾, which means that the remaining leaf area index could guarantee the full reestablishment of the plant's aerial and root parts.

Conclusions and implications

Nitrogen fertilization influences the growth of Mombasa guineagrass pastures, as well as their morphogenic and structural characteristics. Such changes affect the penetration resistance of the roots to the soil, which can promote soil compaction if grazing management is not strategically controlled. Pre- and post-grazing height control is a management alternative that allows one to not only maintain the canopy structure but also avoid the compaction process, preserving the dry roots matter in the soil, regardless of the intensification level.

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