agriculture

Article

Nitrogen Fertilization Boosts Maize Grain Yield, Forage Quality, and Estimated Meat Production in Maize–Forage Intercropping

Bruno R. Gilli [1], Camila S. Grassmann [1], Eduardo Mariano [2] and Ciro A. Rosolem [1,*]

[1] School of Agricultural Sciences, São Paulo State University, Av. Universitária, 3780, Botucatu 18610-034, SP, Brazil; brunorosolengilli@gmail.com (B.R.G.); camila.grassmann@bayer.com (C.S.G.)
[2] Center for Nuclear Energy in Agriculture, University of São Paulo, Piracicaba 13416-000, SP, Brazil; emariano@cena.usp.br
* Correspondence: ciro.rosolem@unesp.br

Abstract: Crop–livestock integrated systems such as intercropping and crop rotation have been critical for sustainable agriculture, promoting land use intensification throughout the year. The success of these systems under no-till depends on numerous factors, and the choice of forage grass is paramount. In this study, maize grain yield, forage dry matter yield, bromatological quality, and estimated meat production were assessed in a field experiment where maize (*Zea mays* L.) was intercropped with Guinea grass (*Megathyrsus maximus* cv. Tanzania) and palisade grass (*Urochloa brizantha* cv Marandu) under N rates from 0 to 270 kg ha^{-1}. Nitrogen fertilization resulted in the highest forage dry matter yield, on average, 2.9-fold higher than the N-unfertilized treatments. The highest maize grain yield was obtained with 270 kg ha^{-1} of N, 48% higher than all other treatments. Guinea grass intercropped with maize and fertilized with 270 kg ha^{-1} of N resulted in an estimated meat production 27% higher than palisade grass at the same N rate. However, at the final cut, Guinea grass fertilized with 270 kg ha^{-1} of N led to the highest neutral detergent fiber, acid detergent fiber, and cellulose. While palisade grass seems to impose lower competition with maize, Guinea grass increases estimated meat production.

Keywords: *Megathyrsus maximus*; *Urochloa brizantha*; *Zea mays* L.; forage production; integrated agricultural system

Citation: Gilli, B.R.; Grassmann, C.S.; Mariano, E.; Rosolem, C.A. Nitrogen Fertilization Boosts Maize Grain Yield, Forage Quality, and Estimated Meat Production in Maize–Forage Intercropping. *Agriculture* **2023**, *13*, 2200. https://doi.org/10.3390/agriculture13122200

Academic Editor: José Manuel Rato-Nunes

Received: 17 October 2023
Revised: 21 November 2023
Accepted: 24 November 2023
Published: 25 November 2023

1. Introduction

The restoration of degraded areas and maximization of fertilizer use efficiency are essential factors for increasing sustainability in several agricultural systems [1]. The use of integrated systems such as the intercropping of maize (*Zea mays* L.) with tropical forages has been of great relevance for tropical agriculture allowing land use intensification, therefore decreasing deforestation [2]. The system enables cheap remediation of degraded pastures and provides plant residues essential for the success of systems under no-till [3]. After maize harvest, the forage grass remaining can be grazed or left in the field after chemical desiccation. The straw left on the soil surface offers soil covering and protection against erosion, averts extreme temperatures, decreases evapotranspiration, and improves nutrient cycling and soil physical characteristics preventing nutrient loss [4–6].

Nitrogen deficiency in crops is one of the most recurrent nutritional imbalances in integrated production systems [7]. In maize–forage grass intercropping, competition for N between species may compromise maize and/or forage production [8] and quality. Among the elements essential for grass species, N has been shown to promote the highest increases in forage production. The N uptake rate by these grasses is higher after the initial development and depends on environmental conditions, being higher in maize–forage intercropping than in monocropping systems [8]. Therefore, it is unknown whether the amount of N fertilizer recommended for single-cropped maize can meet the requirement of maize intercropped with forage grasses. Although intercropping systems may increase N use efficiency over monocropped maize [9], N fertilizer is still necessary to achieve high yield levels [10].

Grasses and forage legumes are the main source of nutrients for ruminants. Thus, cattle raising depends on forage production, mainly grasses and legumes from pastures [5]. The right choice of adapted grass species and a better understanding of N fertilizer management can lead to higher forage yields and meat production. Palisade grass (*Urochloa brizantha*) and Guinea grass (*Megathyrsus maximus*) are among the grass species most grown in the tropics due to their high dry matter yields and palatability [11]. However, in addition to yield penalties, several edaphoclimatic factors such as shade can affect the forage quality [12]. Since grass forage production and quality are directly associated with direct sunlight interception by the leaves, the threshold of 95% of light interception (LI) in pastures has been used to define the moment of introducing cattle for grazing, resulting in subsequent improvements in dry matter yield and nutritional quality of the forage given the better cutting management.

Despite several studies on maize growth and yield when intercropped with forage grasses, there is a gap in the knowledge of the effects of maize and N fertilization on forage growth, yield, and quality. Therefore, an interdisciplinary study addressing maize–forage grass intercropping is critical to generate information for a better understanding of the agricultural system regarding the response of the forage species, grain crops, and N fertilization. We hypothesized that N fertilization increases maize yield and improves dry matter yield and quality of forage grass species, eventually increasing meat production. Therefore, our objectives were to (1) evaluate maize grain yield when intercropped with grasses; (2) assess dry matter yield and bromatological quality of forage; and (3) monitor the grass canopy LI after the maize harvest as affected by N fertilization and forage species in a short-term field experiment under tropical conditions.

2. Materials and Methods

2.1. Study Site

A rainfed maize–forage grass intercropping field experiment was carried out in Botucatu, State of São Paulo, Brazil (22°49′27.7″ S, 48°25′46.7″ W, 700 m a.s.l.) on a clay Rhodic Hapludox [13], with ≈70% kaolinite, ≈15% gibbsite, and small amounts of 2:1 clay minerals. The climate is Cwa (mesothermic), with wet summers and dry winters. The experiment started in December 2017. Three soil samples were randomly taken from each plot to a depth of 20 cm to determine particle size [14] and chemical properties [15] before the experiment setup. The soil had 190 g kg^{-1} of sand, 196 g kg^{-1} of silt, 614 g kg^{-1} of clay, pH ($CaCl_2$) 5.1, P 35.9 mg kg^{-3}, K 2.0 $mmol_c$ kg^{-3}, Ca 40.3 $mmol_c$ kg^{-3}, and Mg 23.4 $mmol_c$ kg^{-3}, H + Al 40.5 $mmol_c$ kg^{-3}, cation exchange capacity 106.2 $mmol_c$ kg^{-3}, and base saturation 62%. Total C and N were assessed by dry combustion using an elemental analyzer (CHNS-2000, Leco Corp., St. Joseph, MI, USA), and the soil had 17.7 g kg^{-1} of total C and 2.0 g kg^{-1} of total N. Moreover, mineral N forms were analyzed [16,17], and 5.1 mg kg^{-1} of $NH_4{}^+$-N and 2.3 mg kg^{-1} of $NO_3{}^-$-N were found. Additional information regarding site characteristics can be seen in [18]. To monitor climate parameters, a weather station 2.6 km away from the experimental site was used (Figure 1).

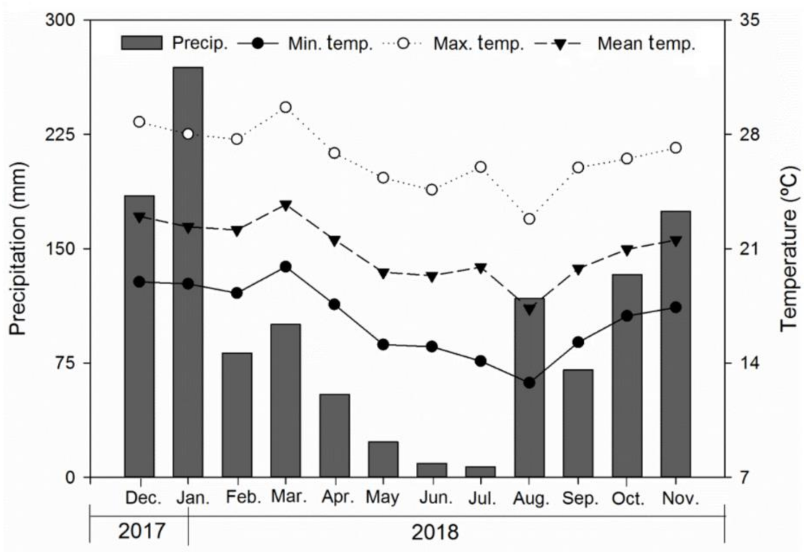

Figure 1. Monthly minimum, maximum, and average air temperatures and rainfall recorded during the growing season period (December 2017–November 2018).

2.2. Treatments and Study Design

The experimental design was a split plot in randomized complete blocks with four replicates. We studied maize–forage grass intercrop systems under different N rates. Maize was intercropped with Guinea grass (*Megathyrsus maximus*, cv Tanzania) or palisade grass (*Urochloa brizanta*, cv marandyu). These intercrops were assigned to the main plots and 0, 90, 180, and 270 kg ha^{-1} of N were side-dressed as ammonium sulfate applied to maize + forage grass in subplots, which were 10 m long and 4.5 m wide.

2.3. Crop Management

Lime ($CaCO_3 \cdot MgCO_3$, 2000 kg ha^{-1}) and gypsum ($CaSO_4 \cdot 2H_2O$, 3600 kg ha^{-1}) were surface-applied in October 2017 to mitigate soil acidity and to add S to the system. Forage grasses and maize were planted simultaneously in December 2017 using a no-till planter with a row spacing of 0.45 m. Forage seeds were mixed with the base fertilizer (50 kg ha^{-1} of P as triple superphosphate and 40 kg ha^{-1} of K as KCl) and planted at a depth of 8 cm. It was used 12 kg ha^{-1} of pure live seeds of each grass, while maize (cv. hybrid 2B587PW, Dow AgroSciences, São Paulo, Brazil) was planted to a final stand of ≈42,000 plants ha^{-1}. The N fertilizer (granular ammonium sulfate) application was split twice, 30 kg ha^{-1} of N at planting, and the remaining was side dressed in the N-fertilized treatments at growth stage V4–V5 (five leaves with visible leaf collars [19]). At the same time, 50 kg ha^{-1} of K was also side-dressed as KCl. The N fertilizer was hand-applied to the soil surface in single-side banding (3 cm wide), ≈5 cm from the crop row. At maize physiological maturity (i.e., R6 growth stage; April 2018), three central rows (8.1 m^2) of the crop were machine harvested to estimate maize grain yield (MGY) and the stover remained in the field. The grasses were grown until November 2018, when glyphosate (2.9 kg ha^{-1} a.i.) was sprayed. Crop residues remained over the soil surface.

Forage grasses were randomly sampled at maize physiological maturity (April 2018) and mid-October/November 2018 just before chemical desiccation. At both sampling times, two samples per subplot were taken using 0.75 × 0.45 m (0.67 m^2) frames and oven-dried at 65 °C to constant weight to estimate forage dry matter yield (FDMY). The dry biomass was ground in a Wiley mill and passed through a 0.5 mm sieve for subsequent analysis.

2.4. Bromatological Analysis

Subsamples of the forage biomass collected in April and November 2018 were used for bromatological analysis. Briefly, the plant tissues were oven-dried to constant weight at 105 °C, and the mineral matter and crude protein contents were determined using micro-Kjeldahl distillation [20]. Acid detergent fiber (ADF), neutral detergent fiber (NDF), hemicellulose, cellulose, and lignin were analyzed according to [21].

2.5. Light Interception, SPAD Index and Height of Grasses

Following maize harvest, a microplot of 1.0 long $\times$ 0.5 m wide (0.5 m^2) was demarcated in each subplot, where the light interception (LI) of the remaining forage grasses was measured weekly at 11:00 am–1:00 pm, using a plant canopy analyzer (LAI 2000, LI-COR Biosciences, Lincoln, NE, USA), up to 95% LI. When each treatment reached 95% LI, the SPAD index was determined using a chlorophyll meter (SPAD-502 Plus, Konica Minolta Sensing, Osaka, Japan).

2.6. Estimated Meat Production

Although there was no grazing in the experiment, meat production was estimated using the Large Ruminant Nutrition System (LRNS) model. The LRNS model is based on the Cornell Net Carbohydrate and Protein System (CNCPS) version 5, as described in [22]. The parameters used to predict animal performance were Nelore breed, male, 450 kg body weight, 52% carcass yield, 22% body fat grading system, and continuous grazing. The following variables were used to estimate the meat production within the LRNS model: FDMY, mineral material, crude protein, ADF, NDF, hemicellulose, cellulose, and lignin of the forage grass.

2.7. Statistical Analysis

Statistical analyses were performed using SAS (version 9.4M3, SAS Institute, Cary, NC, USA). ANOVA was run on experimental data from crop yield (FDMY and MGY), bromatological quality, and meat production considering a split plot scheme using the GLIMMIX procedure. Blocks were considered as random effects, while grass species and N rates were treated as fixed effects. Restricted maximum likelihood (ReML) was used to estimate the covariance parameters, while compound symmetry (CS) was adopted as the covariance structure based on the corrected Akaike information criterion (AICc). Skewed data were treated using lognormal distribution, and values were back-transformed. Means were compared using LSMEANS ($p \leq 0.05$) statement with the simulated adjustment. The LI data obtained following maize harvest until the forage cut (April–November 2018) were fit to linear or quadratic models using orthogonal polynomials using the REG procedure. The criteria for choosing a regression model were the significant fit ($p \leq 0.05$), the highest value of the coefficient of determination (R^2), and residual analysis.

3. Results

3.1. Forage and Maize Yields

Forage dry matter yields (FDMY) responded to N rates at both sampling times but were not affected by forage grass species (Figure 2A,B). At maize harvest, FDMY was 2.3- and 2.6-fold higher with the addition of 90 and 270 kg ha^{-1} of N, respectively, compared with the unfertilized control (Figure 2A). At the final cut, FDMY was 3.4- and 2.1-fold higher in the treatment with 240 kg ha^{-1} compared with the control and 180 kg ha^{-1} of N, respectively (Figure 2B). Conversely, maize grain yield (MGY) was highest when intercropped with palisade grass and fertilized with 270 kg ha^{-1} of N, while the N-unfertilized control resulted in the lowest yield, regardless of the forage grass (Figure 2C). When intercropped with Guinea grass maize responded up to 90 kg ha^{-1} of N, but with palisade grass, it responded up to 270 kg ha^{-1} of N.

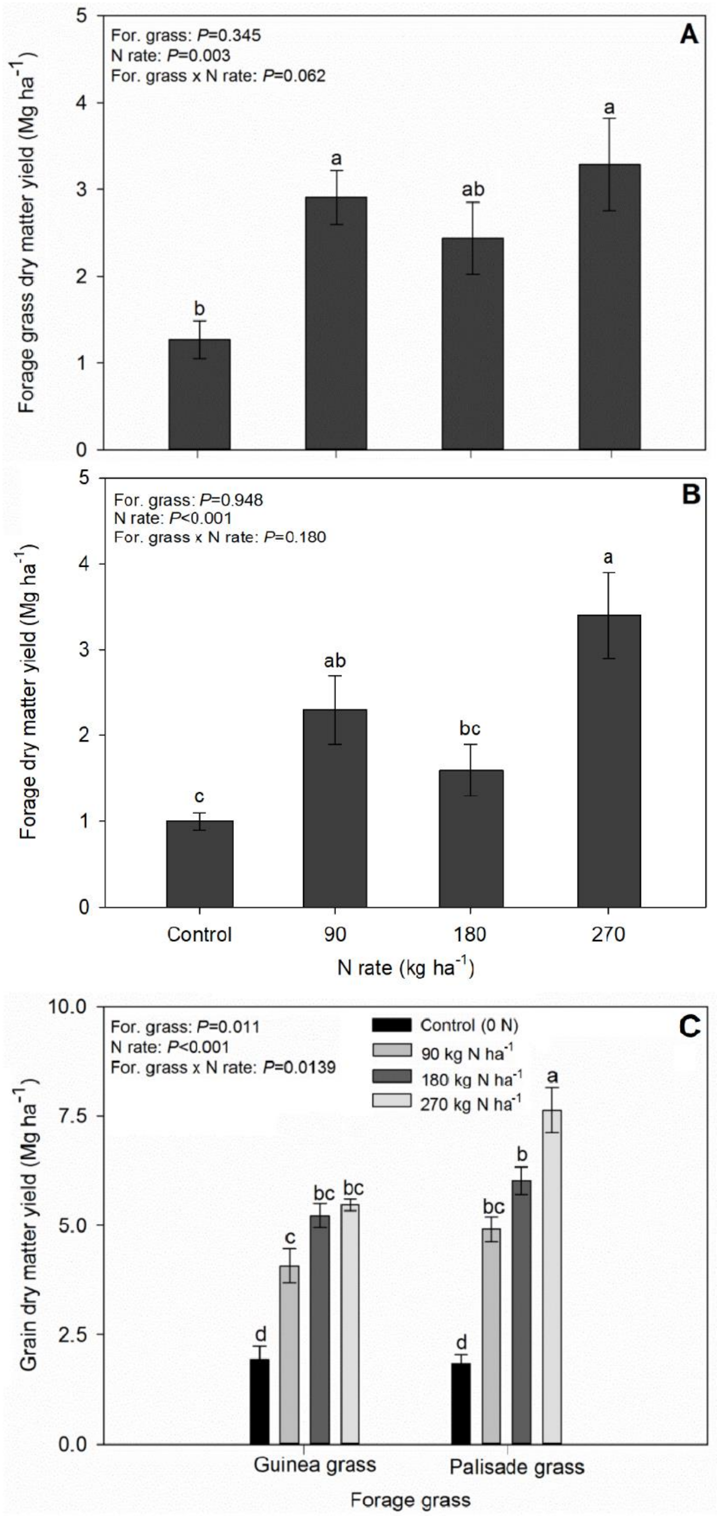

Figure 2. Forage dry matter yield at maize harvest in April (**A**) and in November 2018 (**B**), and maize grain yield (**C**). The error bars represent the SEM (n = 8 for panels (**A**,**B**) and 4 for panel (**C**)). Different lowercase letters indicate differences at $p \leq 0.05$.

3.2. Forage Light Interception and SPAD Index

After maize harvest, the forage LI evolution over time was fitted using linear models; as expected, this index increased along the growth cycle, with the R^2 coefficient ranging from 0.89 to 0.96, with no visible effect of N rate and grass species (Figure 3A,B). The SPAD index measured at 95% of LI was 1.4-fold higher in the N-fertilized treatments, on average, compared with the unfertilized control (Figure 3C).

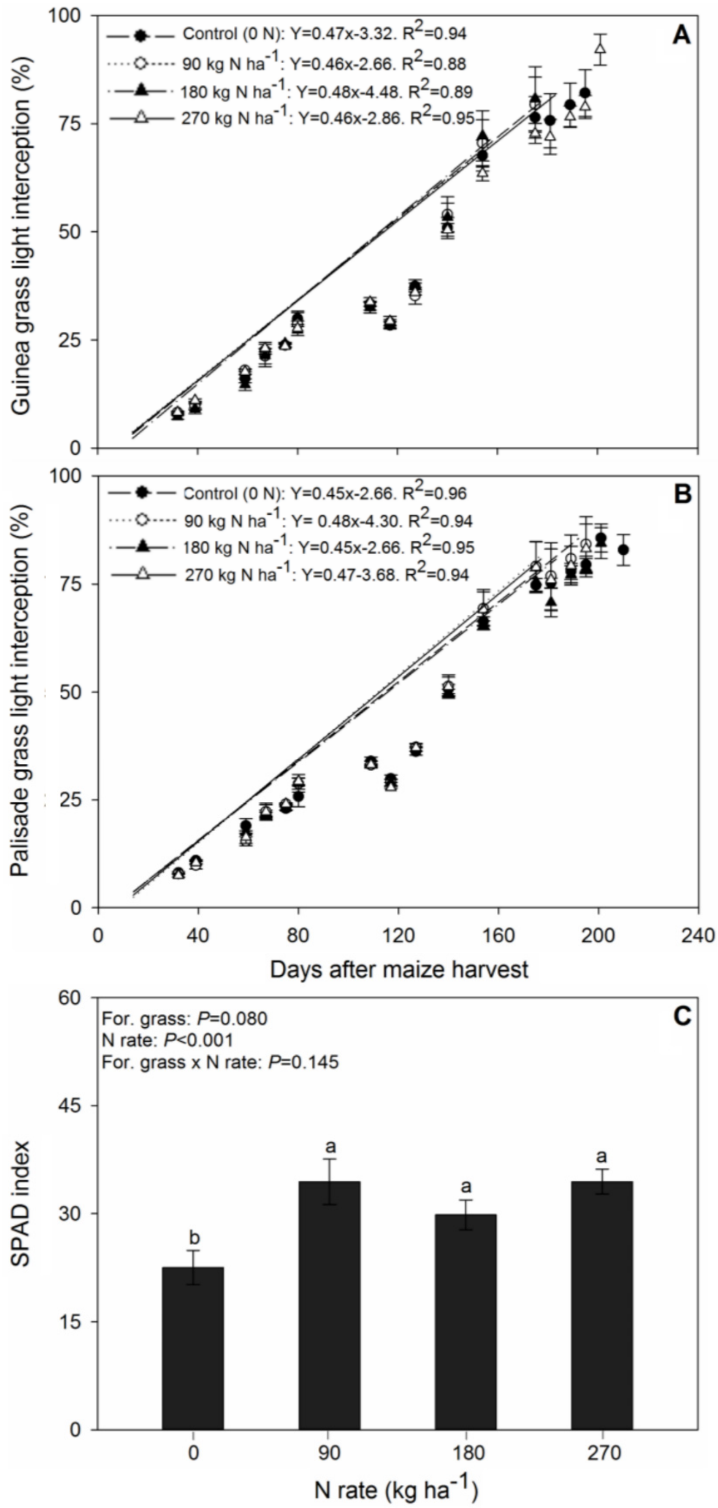

Figure 3. Light interception in Guinea grass (**A**) and palisade grass (**B**) from 14 d after maize harvest until the forage grass reached 95% of LI (April–November 2018); SPAD index in forage grass cut occurred in November 2018 (**C**). The error bars represent the SEM (n = 4, 4, and 8 for panels (**A**,**B**), and (**C**), respectively). Different lowercase letters indicate significant differences at $p \leq 0.05$.

3.3. Forage Quality

There was no interaction of the grass species with N rates on forage quality at both sampling times (Tables 1 and 2). At maize harvest, the mineral material of Guinea grass was 1.2-fold higher than that of palisade grass, with no effect of the grass species on crude protein, NDF, ADF, and hemicellulose (Table 1). The crude protein, NDF, ADF, and hemicellulose were affected by N addition. For crude protein, the highest N input (270 kg ha^{-1} of N) was, on average, 1.3-fold higher than the remaining N rates. For NDF and ADF, the N-fertilized treatments did not differ and were, on average, 1.1- and 1.2-fold higher than the unfertilized control. Hemicellulose was, on average, 1.1-fold higher in the control in comparison with the addition of 90 and 270 kg ha^{-1} of N. At the final cut, Guinea grass had higher NDF, ADF, and cellulose compared with palisade grass (Table 2). In addition, the crude protein was 1.4-fold higher in the N-fertilized treatments compared with the unfertilized control.

Table 1. Bromatological quality of forage grass at maize harvest. The error bars represent the SEM (n = 16, 8, and 4 for forage grasses, N rate, and forage grass × N rate, respectively).

Forage Grass	**N Rate kg ha^{-1}**	**MM %**	**CP**	**NDF**	**ADF**	**HEM**
Guinea grass	-	9.3 ± 0.2 a	5.4 ± 0.2	76 ± 1	45 ± 1	31 ± 1
Palisade grass	-	7.9 ± 0.3 b	6.2 ± 0.3	74 ± 1	43 ± 1	31 ± 1
		p = 0.018	p = 0.104	p = 0.083	p = 0.097	p = 0.411
-	Control	8.8 ± 0.3	5.2 ± 0.2 b	72 ± 1 b	39 ± 1 b	33 ± 1 a
-	90	9.0 ± 0.4	5.7 ± 0.3 b	77 ± 1 a	46 ± 1 a	31 ± 1 b
-	180	8.4 ± 0.5	5.4 ± 0.3 b	76 ± 1 a	45 ± 1 a	31 ± 1 ab
-	270	8.1 ± 0.4	7.1 ± 0.3 a	76 ± 1 a	46 ± 1 a	30 ± 1 b
		p = 0.056	p < 0.001	p = 0.001	p < 0.001	p = 0.004
Guinea grass	Control	8.9 ± 0.3	5.1 ± 0.3	72 ± 2	40 ± 1	33 ± 1
Guinea grass	90	9.7 ± 0.4	5.3 ± 0.4	77 ± 1	47 ± 1	30 ± 1
Guinea grass	180	9.4 ± 0.4	5.2 ± 0.4	77 ± 1	46 ± 2	31 ± 1
Guinea grass	270	9.1 ± 0.5	6.2 ± 0.4	77 ± 1	48 ± 2	29 ± 1
Palisade grass	Control	8.6 ± 0.6	5.2 ± 0.4	72 ± 1	39 ± 1	33 ± 1
Palisade grass	90	8.3 ± 0.4	6.1 ± 0.4	76 ± 1	45 ± 1	31 ± 1
Palisade grass	180	7.4 ± 0.5	5.6 ± 0.4	75 ± 1	44 ± 1	31 ± 1
Palisade grass	270	7.1 ± 0.1	8.3 ± 0.6	75 ± 1	44 ± 1	30 ± 1
		p = 0.080	p = 0.139	p = 0.743	p = 0.791	p = 0.970

Different lowercase letters indicate significant differences at the 5% level. MM, CP, NDF, ADF, and HEM: mineral material, crude protein, neutral detergent fiber, acid detergent fiber, and hemicelluloses, respectively.

Table 2. Bromatological quality of forage grass at cutting in Nov. 2018. The error bars represent the SEM (n = 16, 8, and 4 for forage grass, N rate, and forage grass × N rate, respectively).

Forage Grass	**N Rate kg ha^{-1}**	**MM %**	**CP**	**NDF**	**ADF**	**HEM**	**CEL**	**LIG**
Guinea grass	-	10.3 ± 0.2	10.0 ± 0.7	66 ± 1 a	34 ± 1 a	31 ± 1	30 ± 1 a	2.2 ± 0.2
Palisade grass	-	10.4 ± 0.4	9.6 ± 0.6	62 ± 1 b	31 ± 1 b	31 ± 1	27 ± 1 b	1.8 ± 0.2
		p = 0.910	p = 0.809	p = 0.030	p = 0.004	p = 0.631	p = 0.009	p = 0.234
-	Control	10.7 ± 0.4	7.6 ± 0.5 b	64 ± 2	32 ± 1	32 ± 1	27 ± 1	2.02 ± 0.2
-	90	9.9 ± 0.6	11.4 ± 0.9 a	64 ± 2	32 ± 1	31 ± 1	28 ± 1	2.22 ± 0.2
-	180	10.9 ± 0.5	10.3 ± 1.1 a	64 ± 1	33 ± 1	31 ± 1	29 ± 1	1.93 ± 0.2
-	270	9.8 ± 0.4	9.9 ± 0.5 a	64 ± 1	33 ± 1	31 ± 1	29 ± 1	1.98 ± 0.2
		p = 0.151	p = 0.002	p = 0.990	p = 0.529	p = 0.383	p = 0.098	p = 0.728
Guinea grass	Control	10.6 ± 0.5	7.8 ± 0.7	66 ± 2	33 ± 1	33 ± 1	28 ± 1	2.4 ± 0.3
Guinea grass	90	10.4 ± 1.1	10.8 ± 1.6	65 ± 2	34 ± 1	31 ± 1	29 ± 1	2.3 ± 0.3
Guinea grass	180	10.1 ± 0.5	11.3 ± 2.0	64 ± 1	34 ± 1	30 ± 1	30 ± 1	2.1 ± 0.3
Guinea grass	270	10.1 ± 0.5	9.9 ± 0.5	67 ± 1	36 ± 1	31 ± 1	32 ± 1	2.2 ± 0.3
Palisade grass	Control	10.8 ± 0.8	7.4 ± 0.8	60 ± 1	30 ± 1	30 ± 1	26 ± 1	1.7 ± 0.2
Palisade grass	90	9.4 ± 0.3	12.0 ± 1.0	62 ± 3	31 ± 2	31 ± 1	27 ± 1	2.1 ± 0.3
Palisade grass	180	11.6 ± 0.8	9.2 ± 1.0	63 ± 1	31 ± 1	31 ± 1	27 ± 1	1.8 ± 0.3
Palisade grass	270	9.6 ± 0.7	9.9 ± 1.0	61 ± 2	30 ± 1	30 ± 1	27 ± 1	1.8 ± 0.3
		p = 0.148	p = 0.320	p = 0.344	p = 0.489	p = 0.070	p = 0.200	p = 0.826

Different lowercase letters indicate significant differences at the 5% level. MM, CP, NDF, ADF, HEM, CEL, and LIG: mineral material, crude protein, neutral detergent fiber, acid detergent fiber, hemicellulose, cellulose, and lignin, respectively.

3.4. Estimated Meat Production

There was an interaction of the grass species with N rates for the estimated meat production (Figure 4). Overall, the estimated meat production increased with N rates. Guinea grass fertilized with 270 kg ha^{-1} of N resulted in the highest estimated meat production across all treatments and was 1.3-fold higher than when the same N rate was applied to maize intercropped with palisade grass.

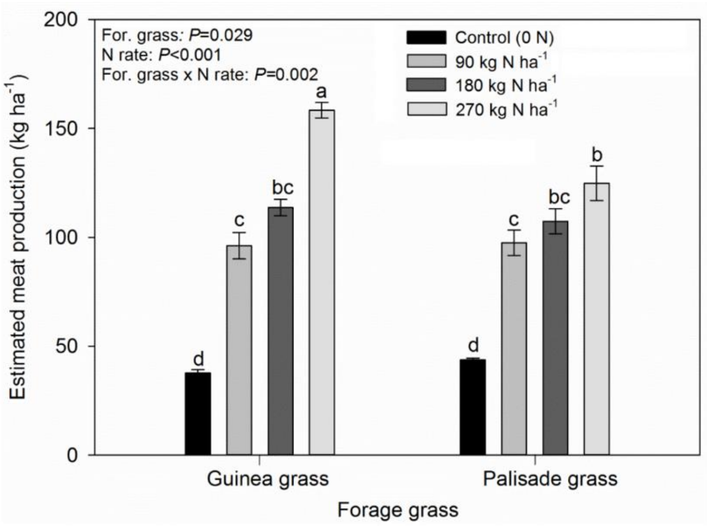

Figure 4. Estimated meat production using the LRNS Cornell model. The error bars represent the SEM (n = 4). Different lowercase letters indicate significant differences at $p \leq 0.05$.

4. Discussion

4.1. Crop Yield and Bromatological Quality at Maize Harvest

The importance of N fertilization for the two forage grasses was remarkable in our field experiment since dry matter yields increased up to threefold following N addition (Figure 2). The N needs for the system are expected to increase in maize–forage grass intercropping. Therefore, N fertilization has been considered a fundamental practice for increasing MGY and FDMY [18,23]. Despite maize response to N fertilization, there was an apparent competition between species when Guinea grass was intercropped, probably due to the vigorous development of Guinea grass, which ended up inhibiting maize growth in intercropping systems [23]. Furthermore, Guinea grass has a high nutritional demand, responding to high N inputs [24], which may have competed with maize for plant nutrients. It has been shown that N deficiency is common in integrated systems [10]. We can infer that N loss was not a problem even with the maximum rate of 240 kg ha^{-1} of N because the response was linear, and no significant loss was found before in a similar experiment [18]. Competition for water may be disregarded since no drought was observed during the maize growing season (Figure 1). There is also plausible evidence that allelopathic suppression due to secondary metabolites of forage grasses could have been a factor inhibiting maize growth, but deleterious effects of Guinea grass on maize growth and yield have not been previously reported. In our study, the grass seeds were planted deeper than maize to delay emergence and minimize competition, but this strategy did not work so well for Guinea grass, which developed vigorously throughout the maize cycle. To mitigate this unwanted effect, the application of post-emergent herbicides has been recommended in sub-rates to suppress initial grass development during the vegetative growth of maize when the crop is more susceptible to competition for light, water, and nutrients. We have attempted to do it, but the applied rate might have been low. We believe that sulfur from ammonium sulfate was not confounding since the gypsum rate was much higher than the amount applied as fertilizer.

Crude protein was higher with 270 kg ha^{-1} of N regardless of grass species. The response to N was expected since it is a critical factor in the biochemical processes, a constituent of proteins, chlorophyll, enzymes, coenzymes, and nucleic acids. Despite being considered the least digestible bromatological fraction, represented by the plant cell wall, fiber is fundamental for rumination and the health of the gastrointestinal tract [25]. Bulky foods, i.e., foods containing >18% crude fiber, have low energy density, so their consumption is limited [26]. The higher the ADF content, the lower the digestibility, while the NDF correlated negatively with the consumption of grasses, 40% of ADF and 60% of NDF are assumed to limit digestibility and consumption, respectively [27]. Neutral detergent fiber and ADF were higher following N addition, and even in the absence of N fertilization, the levels of NDF and ADF were higher in our experiment than in those previously reported [27] as limiting consumption. Therefore, such results lead to the inference that this level of forage quality would have resulted in lower consumption and lower digestibility. Similar data were reported before [28], when an increased grass dry matter yield was related with N fertilization, thus accelerating the senescence of the grass, which becomes more fibrous and eventually digestibility is decreased. The amount of biomass produced is associated with the chemical composition of the plant tissue, such as the contents of hemicellulose, cellulose, and lignin [29]. Knowing that N stimulates grass growth, the higher hemicellulose found in treatments without N indicates that fibrous constituents increase with the thickening and lignification of the cellular walls as the plant matures.

4.2. Light Interception and SPAD Index after Maize Harvesting

Light interception has been assumed as the best criterion for determining ideal pasture events during the regrowth of forage species [30,31]. A grass is considered appropriate for grazing when the pasture intercepts 95% of the photosynthetic active radiation. Above 95% of LI grass growth changes, increasing the proportion of the stem and accumulation of dead material [32]. Since maize requires high N amounts, which range from 180 to 200 kg ha^{-1} [33], differences in the growth of forage grasses after maize grain harvest can be insignificant, although Guinea grass has a vigorous development in N-rich systems [18]. This ends up affecting, even if indirectly, the LI by grasses, resulting in no differences between species when cut concomitantly. The linear models fitted to LI data for Guinea grass and palisade grass in this study were very similar for both species. Although not performed here, to obtain a forage response to N after maize harvest it would be advisable to reapply N. As N is part of the chlorophyll molecule, the increase in N fertilization directly affects the SPAD index reading. In addition, more chlorophyll is synthesized under higher N availability [34]. The SPAD index ranged from 22 to 34 in N-unfertilized and fertilized control treatments, respectively. Lavres Júnior et al. [35] evaluated the SPAD index in Guinea grass in two growth periods, and in the second growth period, the average chlorophyll content ranged from 21 to 39 SPAD units, corresponding to the lowest and the highest N rate, respectively. Such a range may be at least partly explained by the variations in the growth rates and the beginning of leaf senescence. Generally, in the second period of grass growth leaf senescence flux is more pronounced than in the first growth [36]. An increase in SPAD units with the highest N rate in palisade grass fertilized with N rates (100, 200, and 300 kg ha^{-1}) has been reported [37,38].

4.3. Dry Matter, Bromatological Quality, and Estimated Meat Production

The FDMY assessed in April and November responded to N fertilization. These results differ from those of Almeida et al. [39], who observed that the residual N applied to maize did not favor palisade grass growth following maize harvest. Our experiment was established in a fallow area under no-till since 2014; thus, the mineralization of organic matter may have made nutrients available to the grasses ensuring the appropriate N supply to the plants. Under reduced luminosity, forage plants change their structure and nutrient concentration [29]. From May to September, the luminosity and temperature are lower in tropical Brazil. There is an ideal N concentration for a certain level of dry matter yield [40]. Under full sunlight, there is higher dry matter production, with more N taken up and translocated to shoots than in shaded plants, where the dry matter accumulated is lower, and N concentration may be higher. This occurs because the plant is not metabolizing all the N taken up and converting it into dry matter. Plants well adapted to shade tend to prioritize reserves for leaf area growth and increase chlorophyll concentration [41]. Shading can decrease the availability of photoassimilates used for secondary cell wall development, contributing to the reduction in fiber content and increasing digestibility [41,42]. This may explain the higher crude protein content in the grass by cutting time (November 2018; Table 2) compared with the crude protein content of grass at maize harvest (April 2018; Table 1). It has also been observed that palisade grass and Guinea grass had higher PB contents in fall, followed by winter, spring, and summer [43]. In addition, crude protein levels were adequate even in the absence of N fertilization (>7%). Crude protein levels <7% in tropical grasses may result in reduced digestion of these grasses due to inadequate N levels for rumen microorganisms (van Soest, 1994). At the final cutting, crude protein was also affected by N fertilization, since N is part of many organic molecules found in plant tissues.

As N fertilization generally increases the FDMY [44], enhancing the growth, tillering, and leaf production, as well as the expansion of shoots and roots, this may explain why cellulose, NDF, and ADF were higher in Guinea grass compared with palisade grass, since the former is very demanding in N [24]. An FDMY >1.6 Mg ha^{-1} was considered satisfactory to ensure lawn stability and animal production based on the average Brazilian commercial stocking rate, consumption, and herd [45]. However, it depends on the stocking rate and time of year. Our results of FDMY were, on average, >1.6 Mg ha^{-1} under N fertilization, which also influenced the estimated meat production, which increased with the N rate. Indeed, Guinea grass fertilized with 270 kg ha^{-1} of N led to the highest estimated meat production, and as described before, this may also have occurred due to its vigorous growth and high nutrient demand [24].

It should be considered that these results refer to a one-year experiment. However, they are representative of most wet tropical regions with similar rainfall and temperatures.

5. Conclusions

This study proves the potential of ICLSs for meat production in the off-season of humid tropical regions when maize is intercropped with forage grasses. Nitrogen application is paramount in this system since N fertilization positively affects forage growth and nutritional quality, resulting in a higher maize grain yield, higher forage production and quality, and eventually higher estimated meat production. Nitrogen should be applied at higher rates than when maize is grown as a sole crop. Light interception by forage grasses is not affected by N application. Guinea grass resulted in the highest estimate of meat production when fertilized with 270 kg ha^{-1} of N, despite the high NDF, ADF, and cellulose. Further studies on economics and residual N in the soil after years of cultivation could help prove the real benefits of ICLSs for the sustainability of these integrated agricultural systems.

Author Contributions: Conceptualization, C.A.R., E.M. and C.S.G.; methodology, C.S.G., E.M. and B.R.G.; formal analysis, C.S.G. and B.R.G.; resources, C.A.R.; data curation, C.A.R. and E.M.; writing—original draft preparation, C.S.G. and B.R.G.; writing—review and editing, C.A.R. and E.M.; project administration, C.A.R.; funding acquisition, C.A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was undertaken as part of NUCLEUS, a virtual joint center to deliver enhanced N-use efficiency via an integrated soil–plant systems approach for the United Kingdom and Brazil. Funded in Brazil by FAPESP-São Paulo Research Foundation (grant number 2015/50305-8); FAPEG-Goiás Research Foundation (grant number 2015-10267001479); and FAPEMA-Maranhão Research Foundation (grant number RCUK-02771/16); and in the United Kingdom by the Biotechnology and Biological Sciences (Research Council [grant number BB/N013201/1] under the Newton Fund scheme).

Data Availability Statement: Data will be made available upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Thierfelder, C.; Cheesman, S.; Rusinamhodzi, L. A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Res.* **2012**, *137*, 237–250. [CrossRef]
2. Angelsen, A. Policies for reduced deforestation and their impact on agricultural production. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 19639–19644. [CrossRef] [PubMed]
3. Scopel, E.; Triomphe, B.; Affholder, F.; Da Silva, F.A.M.; Corbeels, M.; Xavier, J.H.V.; Lahmar, R.; Recous, S.; Bernoux, M.; Blanchart, E.; et al. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. *Agron. Sustain. Dev.* **2012**, *33*, 113–130. [CrossRef]
4. Calonego, J.C.; Rosolem, C.A. Estabilidade de agregados do solo após manejo com rotações de culturas e escarificação. *Rev. Bras. Ciência Solo* **2008**, *32*, 1399–1407. [CrossRef]
5. Franzluebbers, A.J.; Stuedemann, J.A. Crop and cattle production responses to tillage and cover crop management in an integrated crop–livestock system in the southeastern USA. *Eur. J. Agron.* **2014**, *57*, 62–70. [CrossRef]
6. Rosolem, C.A.; Ritz, C.; Cantarella, H.; Galdos, M.V.; Hawkesford, M.J.; Whalley, W.R.; Mooney, S.J. Enhanced Plant Rooting and Crop System Management for Improved N Use Efficiency. *Adv. Agron.* **2017**, *146*, 205–239. [CrossRef]
7. Soratto, R.P.; Rosolem, C.A.; Crusciol, C.A.C. *Integração Lavoura-Pecuária-Floresta: Alguns Exemplos No Brasil Centra*, 1st ed.; FEPAF: Botucatu, Brazil, 2011; Volume 01, 110p.
8. Borghi, E.; Crusciol, C.A.C.; Trivelin, P.C.O.; Nascente, A.S.; Costa, C.; Mateus, G.P. Nitrogen fertilization ($^{15}NH_4NO_3$) of palisadegrass and residual effect on subsequent no-tillage corn. *Rev. Bras. Ciência Solo* **2014**, *38*, 1457–1468. [CrossRef]
9. Gazola, B.; Mariano, E.; Andrade, M.G.O.; Costa, V.E.; Rosolem, C.A. Fate of fertilizer N applied to maize intercropped with forage grass and recovery of residual N by soybean in a double cropping system. *Plant Soil* **2023**, *492*, 1–15. [CrossRef]
10. Rosolem, C.A.; Soratto, R.P.; Crusciol, C.A.C. Análise da situação geral. In *Integração Lavoura Pecuária-Floresta: Alguns Exemplos No Brasil Central*; Soratto, R.P., Rosolem, C.A., Crusciol, C.A.C., Eds.; FEPAF: Botucatu, Brazil, 2011; pp. 103–104.
11. Machado, A.O.; Cecato, U.; Mira, R.T.; Pereira, L.A.F.; Damasceno, J.C. Avaliação da composição química e digestibilidade in vitro da matéria seca de cultivares e acessos de *Panicum maximum* Jacq. sob duas alturas de corte. *Rev. Bras. Zootec.* **1998**, *27*, 1057–1063.
12. Leonel, F.d.P.; Pereira, J.C.; Costa, M.G.; Marco, P., Jr.; Lara, L.A.; de Queiroz, A.C. Comportamento produtivo e características nutricionais do capim-braquiária cultivado em consórcio com milho. *Rev. Bras. Zootec.* **2009**, *38*, 177–189. [CrossRef]
13. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; USDA, Natural Resources Conservation Service: Washington, DC, USA, 2014.
14. Gee, G.W.; Bauder, J.W. Particle-size analysis. In *Methods of Soil Analysis*; Klute, A., Ed.; SSSA Book Series, 5.1; SSSA, ASA: Madison, WI, USA, 1986; pp. 383–411.
15. Raij, B.V.; Quaggio, J.A.; Cantarella, H.; Abreu, C.A. Os métodos de análise química do sistema IAC de análise de solo no contexto nacional. In *Análise Química Para Avaliação da Fertilidade de Solos Tropicais*, 2nd ed.; van Raij, B., Andrade, J.C., Cantarella, H., Eds.; IAC: Campinas, Brazil, 2001.
16. Mulvaney, R.L. Nitrogen—Inorganic forms. In *Methods of Soil Analysis*; Sparks, D.L., Ed.; SSSA Book Series, 5; SSSA, ASA: Madison, WI, USA, 1996; pp. 1123–1184.
17. Miranda, K.M.; Espey, M.G.; Wink, D.A. A rapid, simple spectrophotometric method for simultaneous detection of nitrate and nitrite. Nitric oxide. *Biol. Chem.* **2001**, *5*, 62–71. [CrossRef]
18. Rocha, K.F.; Mariano, E.; Grassmann, C.S.; Trivelin, P.C.; Rosolem, C.A. Fate of ^{15}N fertilizer applied to maize in rotation with tropical forage grasses. *Field Crops Res.* **2019**, *238*, 35–44. [CrossRef]
19. Ritchie, S.W.; Hanway, J.J. How a corn plant develops. In *Special Report 48*; Iowa State University of Science and Technology: Ames, IA, USA, 1986.
20. AOAC—Association of Official Analytical Chemists. *Official Methods of Analysis*, 15th ed.; AOAC: Washington, DC, USA, 1990.
21. Van Soest, P.J.; Robertson, J.B.; Lewis, B.A. Symposium: Carbohydrate metodoly, metabolism, and nutritional implications in dairy cattle. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* **1991**, *74*, 3583–3597. [CrossRef]
22. Fox, D.G.; Tedeschi, L.O.; Tylutki, T.P.; Russell, J.B.; Van Amburgh, M.E.; Chase, L.E.; Pell, A.N.; Overton, T.R. The Cornell net carbohydrate and protein system model for evaluating herd nutrition and nutrient excretion. *Anim. Feed. Sci. Technol.* **2004**, *112*, 29–78. [CrossRef]
23. Borghi, E.; Crusciol, C.A.C.; Mateus, G.P.; Nascente, A.S.; Martins, P.O. Intercropping time of corn and palisadegrass or Guinea grass affecting grain yield and forage production. *Crop Sci.* **2013**, *53*, 629–636. [CrossRef]
24. Galindo, F.S.; Buzetti, S.; Teixeira Filho, M.C.M.; Dupas, E.; Ludkiewicz, M.G.Z. Application of different nitrogen doses to increase nitrogen efficiency in Mombasa Guinegrass (*Panicum maximum* cv. Mombasa) at dry and rainy seasons. *Aust. J. Crop Sci* **2017**, *11*, 1657–1664. [CrossRef]
25. Weiss, W.P. Predicitng energy values of feeds. *J. Dairy Sci.* **1993**, *76*, 1802–1811. [CrossRef]
26. Macedo, G.L.M., Jr.; Zanine, A.M.; Borges, I.; Pérez, J.R.O. Qualidade da fibra para a dieta de ruminantes. *Ciência Anim.* **2007**, *17*, 7–17.

27. Soest, P.J. *Nutritional Ecology of the Ruminant*, 2nd ed.; Cornell University Press: New York, NY, USA, 1994; 476p.
28. Martuscello, J.A.; Fonseca, D.M.; do Nascimento, D., Jr.; Santos, P.M.; Ribeiro, J.I., Jr.; Cunha, D.N.F.V.; Moreira, L.M. Características morfogênicas e estruturais do capim-xaraés submetido à adubação nitrogenada e desfolhação. *Rev. Bras. Zootec.* **2005**, *34*, 1475–1482. [CrossRef]
29. Carvalho, M.M.; Silva, J.L.O.; Campos, B.A., Jr. Produção de matéria seca e composição mineral da forragem de seis gramíneas tropicais estabelecidas em um sub-bosque de angico vermelho. *Rev. Bras. Zootec.* **1997**, *26*, 213–218.
30. Carnevalli, R.A.; Silva, S.C.; Bueno, A.A.O.; Uebele, M.C.; Bueno, F.O.; Hodgson, J.; Silva, G.N.; Morais, J.P.G. Herbage production and grazing losses in *Panicum maximum* cv. Mombaça under four grazing managements. *Trop. Grassl.* **2006**, *40*, 165–176.
31. Zanini, G.D.; Santos, G.T.; Sbrissia, A.F. Frequencies and intensities of defoliation in Aruana Guineagrass swards: Morphogenetic and structural characteristics. *Rev. Bras. Zootec.* **2012**, *41*, 1848–1857. [CrossRef]
32. Silva, C.C.F.; Bonomo, P.; Pires, A.J.V.; Maranhão, C.M.A.; Patês, N.M.S.; Santos, L.C. Características morfogênicas e estruturais de duas espécies de braquiária adubadas com diferentes doses de nitrogênio. *Rev. Bras. Zootec.* **2009**, *38*, 657–661. [CrossRef]
33. Almeida, R.E.M.; Favarin, J.L.; Otto, R.; Pierozan, C., Jr.; Oliveira, S.M.; Tezotto, T.; Lago, B.C. Effects of nitrogen fertilization on yield components in a corn-palisadegrass intercropping system. *Austr. J. Crop Sci.* **2017**, *11*, 352–359. [CrossRef]
34. Bullock, D.G.; Anderson, D.S. Evaluation of the Minolta SPAD-502 chlorophyll meter for nitrogen management in corn. *J. Plant Nutr.* **1998**, *21*, 741–755. [CrossRef]
35. Lavres, J., Jr.; Santos, J.D.G., Jr.; Monteiro, F.A. Nitrate reductase activity and SPAD readings in leaf tissues of guinea grass submitted to nitrogen and potassium rates. *Rev. Bras. Ciência Solo* **2010**, *34*, 801–809. [CrossRef]
36. Hay, R.K.M.; Walker, A.J. *An Introduction to the Physiology of Crop Yield*; Longman Scientific and Technical: London, UK, 1989; 292p.
37. Costa, K.A.P.; Faquin, V.; Oliveira, I.P.; Araújo, J.L.; Rodrigues, R.B. Doses e fontes de nitrogênio em pastagem de capim-marandu: II—Nutrição nitrogenada da planta. *Rev. Bras. Ciência Solo* **2008**, *32*, 1601–1607. [CrossRef]
38. Costa, N.R.; Andreotti, M.; Gameiro, R.A.; Pariz, C.M.; Buzetti, S.; Lopes, K.S.M. Adubação nitrogenada no consórcio de milho com duas espécies de braquiária em sistema plantio direto. *Pesqui. Agropecuária Bras.* **2012**, *47*, 1038–1047. [CrossRef]
39. Almeida, R.E.M.; Oliveira, S.M.; Lago, B.C.; Junior, C.P.; Trivelin, P.C.O.; Favarin, J.L. Palisadegrass effects on N fertilizer dynamic in intercropping systems with corn. *An. Acad. Bras. Ciências* **2017**, *89*, 1917–1923. [CrossRef]
40. Lemaire, G.; Chartier, M. Relationships between growth dynamics and nitrogen uptake for individual sorghum plants growing at different plant densities. In *Diagnosis of the Nitrogen Status in Crops*; Lemaire, G., Ed.; INRA—Station décophysiologiedes Plantes Fourragères: Paris, France, 1992; pp. 3–43.
41. Soares, A.B.; Sartor, L.R.; Adami, P.F.; Varella, A.C.; Fonseca, L.; Mezzalira, J.C. Influência da luminosidade no comportamento de onze espécies forrageiras perenes de verão. *Rev. Bras. Zootec.* **2009**, *38*, 443–451. [CrossRef]
42. Kephart, K.D.; Buxton, D.R. Forage Quality Responses of C3 and C4 Perennial Grasses to Shade. *Crop Sci.* **1993**, *33*, 831–837. [CrossRef]
43. Gerdes, L.; Werner, J.C.; Colozza, M.T.; Possenti, R.A.; Schammass, E.A. Avaliação de características de valor nutritivo das gramíneas forrageiras marandu, setária e tanzânia nas estações do ano. *R. Bras. Zootecn.* **2000**, *29*, 955–963. [CrossRef]
44. Mazza, L.D.M.; Pôggere, G.C.; Ferraro, F.P.; Ribeiro, C.B.; Cherobim, V.F.; Motta, A.C.V.; De Moraes, A. Adubação nitrogenada na produtividade e composição química do capim-mombaça no primeiro planalto paranaense. *Sci. Agrar.* **2009**, *10*, 257. [CrossRef]
45. Fernandes, J.C.; Buzetti, S.; Dupas, E.; Teixeira Filho, M.C.M.; Andreotti, M. Sources and rates of nitrogen fertilizer used in Mombasa guineagrass in the Brazilian Cerrado region. *Afr. J. Agric. Res.* **2015**, *10*, 2076–2082. [CrossRef]