Research Paper

Spectral sensors prove beneficial in determining nitrogen fertilizer needs of *Urochloa brizantha* cv. Xaraés grass in Brazil

Evaluación del beneficio de los sensores espectrales para determinar los requerimientos de nitrógeno en pasturas de Urochloa brizantha *cv. Xaraés en Brasil*

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Abstract

The objective of the present work was to evaluate the use of spectral sensors to determine nitrogen fertilizer requirements for pastures of *Urochloa brizantha* cv. Xaraés in Brazil. The experimental design was a randomized block design with 4 replications of 4 treatments: a control treatment (T_T) without application of N; a reference treatment (T_R) with N applied at a standard predetermined fixed rate (150 kg urea/ha/cycle); a treatment using GreenSeeker^{TM} (T_G) to determine N requirement by the canopy normalized difference vegetation index (NDVI); and a treatment using SPAD 502 (T_S) to determine N requirement by foliar chlorophyll assessment. For treatments involving spectral sensors, N fertilizer was applied at half the rate of that in the reference treatment at the beginning of each cycle and further N was applied only when the nitrogen sufficiency index dropped below 0.85. The sensors used in the work indicated that no additional N fertilizer was required by these pastures above the half rates applied. Applying N at the reduced rates to the pastures was more efficient than the pre-determined fixed rate, as both sensor treatments and the fixed rate treatment produced similar total forage yields, with similar crude protein concentrations. All fertilized pastures supported similar stocking rates, while the sensor treatments used less N fertilizer, i.e. 75 kg urea/ha/cycle less than the reference plot. Longer-term studies to verify these findings are warranted followed by promotion of the technology to farmers to possibly reduce fertilizer application rates, improve profitability and provide environmental benefits.

Keywords: GreenSeeker^{TM}, pasture support capacity, precision agriculture, Spad 502, tropical grasses.

Resumen

El objetivo del trabajo fue evaluar el uso de sensores espectrales para determinar los requerimientos de fertilizantes nitrogenados en pasturas de *Urochloa brizantha* cv. Xaraés, Para el efecto en Leopoldina, Minas Gerais, Brasil, en un diseño experimental de bloques al azar con 4 repeticiones se evaluaron, durante 3 ciclos de rebrote del pasto y subsiguiente pastoreo, los tratamientos: (1) control (T_T) sin aplicación de N; (2) de referencia (T_R) con aplicación de N al inicio de cada ciclo en dosis fija predeterminada estándar (150 kg de urea/ha/ciclo); (3) uso del sensor GreenSeekerTM (T_G) para determinar el requerimiento de N por el índice de vegetación de diferencia normalizada (NDVI); y (4) uso del sensor SPAD 502 (T_S) para determinar el requerimiento de N por evaluación foliar de clorofila. Para los tratamientos con sensores espectrales, el

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fertilizante nitrogenado se aplicó usando la mitad de la tasa del tratamiento de referencia al comienzo de cada ciclo, con aplicación de N adicional solo cuando el índice de suficiencia de nitrógeno era menor que 0.85. Los sensores utilizados mostraron que las pasturas no requerían fertilizante adicional por encima de las tasas medias de N aplicadas. La aplicación de N a las pasturas usando las tasas reducidas fue más eficiente que la tasa fija predeterminada, ya que los tratamientos con sensores y el tratamiento de tasa fija produjeron rendimientos totales de forraje similares, con concentraciones de proteína cruda similares. Todas las pasturas fertilizadas soportaron cargas animal similares, mientras que los tratamientos con sensores demandaron menos fertilizante de N, i.e. 75 kg de urea/ha/ciclo menos que la parcela de referencia. Se justifican estudios a más largo plazo para verificar estos resultados, seguidos de la promoción de la tecnología a los agricultores para posiblemente reducir las tasas de aplicación de fertilizantes, mejorar la rentabilidad y proporcionar beneficios ambientales.

Palabras clave: Agricultura de precisión, capacidad de carga, GreenSeeker™, pastos tropicales, Spad 502.

Introduction

One important characteristic of Brazilian livestock systems is the raising of pasture-fed cattle (Ferraz and Felício 2010), which is regarded as one of the most economical ways to produce beef and milk (Carvalho et al. 2009; Deblitz 2009). In this scenario, factors such as climatic conditions and availability of nutrients in the soil must be considered for the adequate development of the pastures (Fernandes et al. 2015). Farmers must be aware that low availability of nutrients in soils can result in low production and quality of tropical forage (Hare et al. 2015). Determining optimal levels of fertilizer to apply to pastures is critical for maintaining a sustainable business both financially and biologically.

Among the essential nutrients, nitrogen (N) is considered the most important for plant growth and increasing crop yields (Subbarao et al. 2013; Cecato et al. 2014). Nitrogen is present in the amino acids that act in the synthesis of structural and functional proteins (Barbieri et al. 2017), and directly involved within the photosynthetic process due to its participation in the chlorophyll molecule. It also increases tillering and improves the nutritional value of pastures (Marques et al. 2016).

A number of precision farming techniques have been developed to address the spatial variability of nutrients in crop fields more effectively (Hedley 2015). These techniques consist of site-specific management of agricultural crops based on information from each location. Among the techniques of precision agriculture, spectral sensors have been used widely to obtain data which may be related to agronomic characteristics of the crops (Handcock et al. 2016; Wachendorf et al. 2018; Viana et al. 2019).

Minolta's indirect chlorophyll meter, SPAD (Soil-Plant Analyses Development) 502, is an example of such sensors. The SPAD 502 quantitatively evaluates the intensity of the green color in leaves by measuring light transmitted at 650 nm, where light absorption by the chlorophyll molecule occurs, and at 940 nm, where absorption ceases (Nogueira et al. 2018). Intensity of green color in leaves is an indication

of the level of N taken up by the plant. Another example of use of sensors for site-specific N management is the GreenSeeker™. This sensor uses radiation emission diodes at the red (650 nm) and near infrared (770 nm) wavelengths over the vegetation canopy, providing the normalized difference vegetation index (NDVI) (Bredemeier et al. 2013).

The GreenSeeker™ seems to present some advantages when compared with the SPAD 502. Since the GreenSeeker™ is a canopy sensor, it has a wider field of vision and is able to cover a larger area of study, integrating information about the vegetation as a whole (Chapman and Barreto 1997).

The use of spectral sensors in the management of nitrogen fertilizer application has become a promising technique for farmers seeking practical, easily applied and reliable methods for pasture management. Research has shown that measurements with SPAD and the NDVI index correlate with plant nitrogen concentration in tissue and/or yield of various crops, including the osier (Daniel et al. 2016), Japanese cucumber (Pôrto et al. 2014), irrigated rice (Pocojeski et al. 2015), wheat (Theago et al. 2014), potato (Giletto and Echeverría 2016), cotton (Lee et al. 2009), forest species (Ribeiro et al. 2009) and forage (Bravin and Oliveira 2014; Villar et al. 2015; Corrêdo et al. 2019). We designed this study to evaluate the use of spectral sensors for determining desirable levels of nitrogen fertilizer application to *Urochloa brizantha* cv. Xaraés pastures.

Materials and Methods

The study was carried out in an experimental field, located in Leopoldina, Minas Gerais, Brazil (21°28'25" S, 42°43'15" W; 187 masl), during the period April–August 2017. According to the climatic classification of Köppen, the climate type of the region is Aw, tropical humid with dry winters and rainy summers, with average temperature of the coldest month being above 18 °C. Soil chemical properties in the 0–20 cm layer of the experimental area are described in Table 1.

Table 1. Soil chemical properties and nutrients before mineral fertilizer application.

Property	Unit	Block 1	Block 2	Block 3	Block 4
Acidity (pH)	H_2O	6.1	5.8	5.8	6.0
P	mg/dm^3	4.6	5.3	6.8	7.3
K	mg/dm^3	64	37	75	53
Ca^{2+}	$cmol_c/dm^3$	2.3	2.3	2.4	2.1
Mg^{2+}	$cmol_c/dm^3$	1.0	1.0	0.9	0.8
H+Al	$cmol_c/dm^3$	2.6	3.1	3.1	2.5
SB	$cmol_c/dm^3$	3.5	3.4	3.5	3.0
CEC(t)	$cmol_c/dm^3$	3.5	3.4	3.5	3.0
CEC(T)	$cmol_c/dm^3$	6.1	6.5	6.6	5.5
BS	%	57.0	52.0	53.0	55.0

SB = sum of basic cations; CEC(t) = effective cation-exchange capacity; CEC(T) = potential cation-exchange capacity; BS = percent base saturation.

With the exception of N, soil nutrient levels were corrected prior to the implementation of the experiment, based on the recommendation of the 5th approximation (Ribeiro et al. 1999), where each plot received 80 kg P_2O_5/ha (35 kg P/ha) and 100 kg K_2O/ha (83 kg K/ha).

Experimental design and management

The experimental area consisted of 16 plots of 0.175 ha each, where *Urochloa brizantha* cv. Xaraés grass has been cultivated since its establishment in December 2008. The experimental design was a randomized block design, with 4 blocks, each containing 4 plots, i.e. a replicate for each of the 4 treatments: T_T – control plot, without application of nitrogen fertilizer; T_R – reference plot, with application at a fixed rate of 150 kg urea/ha/cycle (~46% N); T_G and T_S – experimental plots, with 75 kg urea/ha applied at the beginning of each cycle and further applications based on measurement of spectral variables by the sensors, i.e. the normalized difference vegetation index (NDVI) determined by the GreenSeeker™ (T_G) and the readings of the portable chlorophyll meter SPAD 502 (T_S).

Before the beginning of the experiment on 3 April the grass was cut with a brushcutter coupled to a tractor to a stubble height of 10 cm above soil level. The study continued for 3 cycles with each cycle including the regrowth period following the exit of animals (cows) from the pasture plus the subsequent grazing period until cows were again removed. As a result of limitations in labor availability, commencement of studies in the 4 blocks was staggered with a delay of 1 week between Blocks 1 and 2, Blocks 2 and 3 etc.

The full nitrogen fertilizer dose (150 kg urea/ha) was applied at the beginning of each cycle for reference plots, i.e. when animals were removed, while sensor treatments received only 75 kg urea/ha. Further applications of N fertilizer to sensor treatments were based on the nitrogen sufficiency index (NSI) as proposed by the Potash &

Phosphate Institute (PPI). The Potash & Phosphate Institute published a bulletin (Francis and Piekielek 1999) with guidelines and recommendations for site-specific management of N fertilizer rates. The principle of the PPI methodology is that the plants in the reference plot point to the N absorption potential for a given edaphoclimatic condition (Villar et al. 2015). The NSI is determined based on the readings of given spectral variables, according to Equation 1 (Francis and Piekielek 1999):

$$NSI = \frac{VS_{ps}}{VS_{pr}} \tag{1}$$

where:
NSI is nitrogen sufficiency index;
VS_{ps} is spectral variable in the sensor plots; and
VS_{pr} is spectral variable in the reference plot.

Whenever sensor plots presented NSI below 0.85, 25% of the N fertilizer dose of the reference plot, equivalent to 37.5 kg urea/ha, was applied. The spectral variables were determined based on readings when plants in the reference plot reached 20 and 25 cm in height. To determine the spectral variable for each plot by the chlorophyll meter SPAD 502, readings were performed in the middle third of the newest fully expanded leaf blade of 30 randomly identified plants. The average of readings represented the SPAD value of the plot. The determination of the NDVI spectral variable was performed by GreenSeeker™ (Trimble), where 40 readings were performed randomly throughout the plot with the apparatus positioned at a height of 1.0 m above the canopy. The average of the readings represented the NDVI value of the plot.

Production parameters

Forage yields were determined before grazing when pastures in each plot reached 30 cm in height and after grazing in each grazing cycle. Representative areas of 3 m^2 were selected and sampled using an iron frame of 1 m² at 3 different locations in the plot and weight of fresh forage recorded.

From the cut forage, 300 g subsamples were taken and separated into leaf blade, culm+leaf sheath and dead forage, before being weighed and heated to 65 °C for 72 hours to determine dry matter (DM) percentage for the calculation of forage DM. The growth rate was determined by the difference between amount of forage available when animals were removed from a block and that when they were reintroduced within each cycle divided by the length of the regrowth period, i.e. the amount of forage produced during the regrowth period divided by the length of the regrowth period. The crude protein (CP) concentration in pasture was determined by the Kjeldahl method (Rodrigues et al. 2017) on samples collected prior to the commencement of grazing in each cycle.

After pasture sampling was complete, lactating cows (crossbred Holstein × Zebu) were introduced according to pasture availability. The plots were grazed until the plants reached a mean of 15 cm in height, at which point the cows were removed and the average stocking rate (AU/ha) during each grazing cycle was calculated according to the methodology of Delevatti et al. (2019).

The yield response to fertilizer (Hare at al. 2015), also known as yield efficiency (Abassi et al. 2005), was then calculated, according to Equation 2, for each treatment at the end of each management cycle:

$$\text{Yield response} = \frac{\text{DM}_{\text{fertilized}} - \text{DM}_{\text{control}}}{\text{N}_{\text{app}}} \qquad (2)$$

where:

$\text{DM}_{\text{fertilized}}$ is dry matter yield of the N fertilized plots (T_S, T_G or T_R);

$\text{DM}_{\text{control}}$ is dry matter yield of the control plots (T_T); and

N_{app} is the amount of N applied during the management cycle.

Data on total forage yield, crude protein concentration, growth rate, stocking rate and leaf blade consumption were subjected to analysis of variance. The comparison of means was performed by the Tukey test (P<0.05), using the programming language and environment, R.

Results

Rest periods and weather details

The rest periods, i.e. regrowth periods, for each treatment for the 3 management cycles plus the duration of grazings are shown in Table 2. The length of each growth cycle of Xaraés grass for the different treatments varied according to prevailing weather conditions and whether or not N fertilizer was applied. Fertilized treatments presented similar rest periods in each cycle, while the Control plots required much longer rest periods for forage to reach the desired height. In Cycles 2 and 3, grazing periods were longer in fertilized

treatments than in Control treatments as animals took longer to consume the available forage above 15 cm.

The temperature and rainfall observed during the study are presented in Figure 1. Total rainfall during the period was 74 mm, with the highest rainfall concentration occurring in late May. No rain fell in July-August and mean minimum temperatures fell below 15 °C on numerous occasions during this period.

Spectral index during growth cycles of Xaraés grass

Data for the NDVI and SPAD variables and the mean of the NSI variation are shown in Figure 2. The 3 cycles of crop management presented NSI values constantly above 0.85 for treatments where N fertilizer was applied and below 0.85 for the Control, which received no N fertilizer. During each cycle, none of the sensor treatment plots received additional fertilizer after the application of 75 kg urea/ha at the beginning of the cycle, i.e. they received 75 kg urea/ha/cycle less than the reference plots.
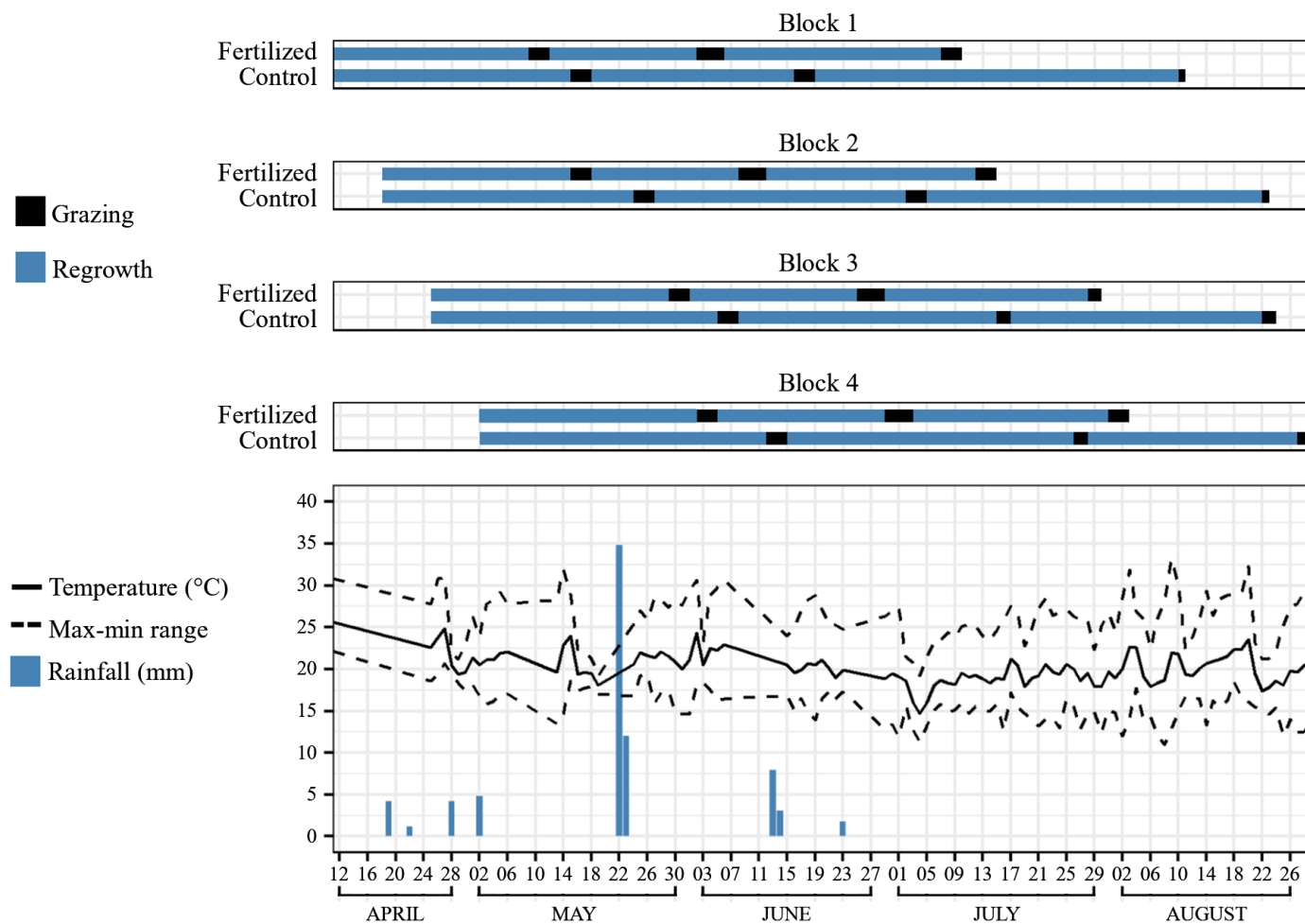
Pasture growth and quality

The average presentation yields of the different components of Xaraés grass for each treatment and for the 3 management cycles when the cows entered the pasture are presented in Table 3. During the experimental period, the availability of total forage and leaf blades in both reference plots and sensor plots were similar (P>0.05). Total forage available for the Control treatment was inferior to that of N-fertilized treatments during all cycles but differences were significant (P<0.05) only in Cycles 2 and 3. The amounts of leaf blade available were higher in fertilized treatments than in Controls in all cycles but differences were significant only in Cycles 1 and 2.

These differences understate the value of fertilizer as the Control treatment took longer to reach the necessary height for grazing so data for Controls represent a longer period than those for the N-fertilized treatments. To obtain a more valid comparison between treatments, their respective daily pasture growth rates, plus stocking rates and leaf blade consumptions are presented in Table 4. Growth rates of total forage during Cycle 2 and leaf blades during both Cycles 2 and 3 were significantly higher (P<0.05) for the fertilized than for the Control treatments. Only during Cycle 2 did the T_G treatment present growth rate of leaf blades significantly inferior to the growth rate of T_S. However, T_G growth rate was still similar to the T_R treatment and superior to the Control. As yield data were not collected when pastures reached 15 cm height and the study officially commenced following the initial cut on 3 April, growth rates for Cycle 1 are not presented in Table 4.

Table 2. Average length (days) of the 3 cycles (regrowth and grazing) of Xaraés grass.

Treatment	Cycle 1		Cycle 2		Cycle 3	
	Regrowth	Grazing	Regrowth	Grazing	Regrowth	Grazing
T_T	38	3	38	2.5	46	2.5
T_R	30	3	23	4	30	4
T_G	31	3	23	4	30	4
T_S	30	3	23	4	30	4

T_T = Control; T_R = Reference; T_G = GreenSeeker™ sensor; T_S = SPAD 502 sensor.

Figure 1. Length of regrowth and grazing periods and the climatic variables observed during the 3 management cycles.

The average stocking rates for treatments that received N fertilizer in the 3 crop management cycles (Table 4) were not significantly different (P>0.05), while stocking rates on the Control plots were significantly lower than on fertilized treatments in all management cycles (P<0.05). The difference in favor of the fertilized treatments increased in Cycles 2 and 3.

The estimated crude protein (CP) concentrations in available forage pre-grazing for each treatment in the 3 crop management cycles are presented in Table 5. All treatments receiving N fertilizer had higher CP percentages in forage than the Control treatment, but differences were significant only for Cycles 2 and 3. Despite differences in amounts of N applied to the various fertilized treatments, CP% did not differ between fertilized treatments (P>0.05), although the reference treatment always presented higher absolute values. While CP% in N treatments remained constant over the 3 cycles, CP% in the Control treatment declined from Cycle 1 to Cycle 3.
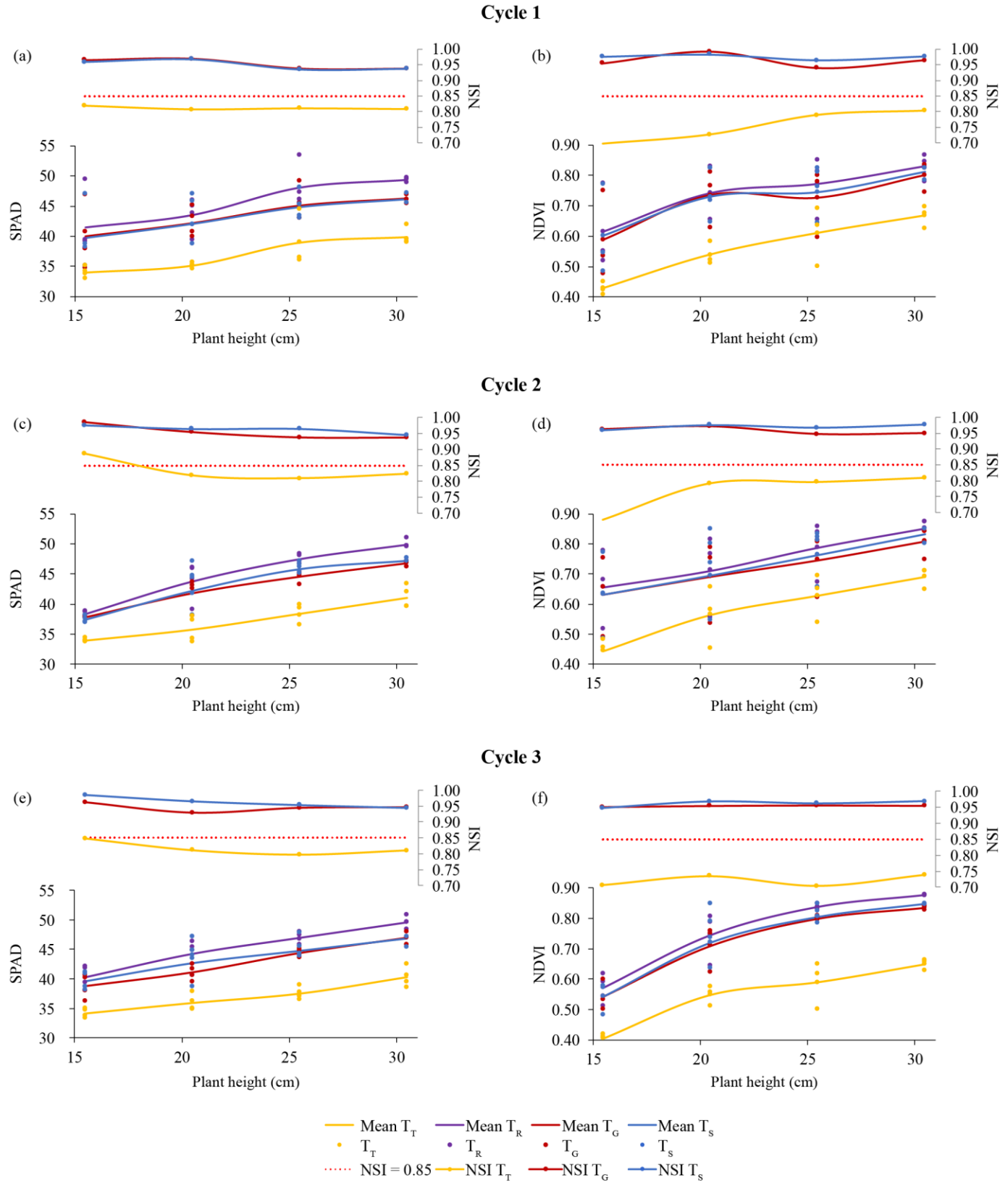
Figure 2. Spectral variables (NDVI and SPAD) and the mean of the Nitrogen Sufficiency Index (NSI) variation based on the GreenSeeker^{TM} and SPAD 502 measurements for each treatment during the regrowth period for the 3 management cycles of Xaraés grass. T_T = Control; T_R = Reference; T_G = GreenSeeker^{TM} sensor; and T_S = SPAD 502 sensor.

Table 3. Presentation yields of the different components of Xaraés grass for each treatment and cycle when the cows entered the pasture – mean per evaluation.

Parameter	T_T	T_R	T_G	T_S	P-value[1]	CV (%)
Cycle 1						
Total forage (kg DM/ha)	1,982	2,405	2,352	2,451	0.15	12.3
Leaf blade (kg DM/ha)	1,279b[2]	1,661a	1,596ab	1,737a	0.01	9.5
Culm (kg DM/ha)	578	604	618	544	0.84	20.6
Dead forage (kg DM/ha)	133	140	131	173	0.90	61.6
Cycle 2						
Total forage (kg DM/ha)	1,993b	2,725ab	2,635ab	3,069a	0.01	13.0
Leaf blade (kg DM/ha)	1,038b	1,708a	1,595a	1,918a	0.00	11.5
Culm (kg DM/ha)	771	767	821	902	0.74	29.2
Dead forage (kg DM/ha)	166	194	116	243	0.34	58.9
Cycle 3						
Total forage (kg DM/ha)	2,045b	2,759ab	2,969a	2,793ab	0.04	14.9
Leaf blade (kg DM/ha)	1,427	1,759	1,854	1,714	0.15	14.4
Culm (kg DM/ha)	491	899	969	979	0.09	32.2
Dead forage (kg DM/ha)	122	85	91	71	0.29	38,9

[1]Probability values by the F test of the analysis of variance. [2]Means followed by the same letter on the same line do not differ by the Tukey test (P>0.05), while means with different letters are significantly different (P<0.05). T_T = Control; T_R = Reference; T_G = GreenSeeker[TM] sensor; T_S = SPAD 502 sensor.

Table 4. Growth rates of the various components of Xaraés grass, stocking rate and leaf blade consumption for each treatment at the end of the 3 management cycles (mean per evaluation).

Parameter	T_T	T_R	T_G	T_S	P-value[1]	CV (%)
Cycle 1						
Stocking rate (AU/ha)	2.3b	3.5a	3.4a	3.3a	0.00	8.7
Leaf blade consumption (kg DM/ha)	792	949	922	1179	0.09	19.5
Cycle 2						
Total forage (kg DM/ha/d)	20.7b[2]	51.9a	56.6a	78.0a	0.00	25.9
Leaf blade (kg DM/ha/d)	15.0c	44.6ab	40.8b	61.1a	0.00	21.3
Culm (kg DM/ha/d)	7.0	6.2	17.3	16.8	0.26	80.8
Stocking rate (AU/ha)	2.1b	6.1a	5.7a	5.6a	0.00	14.1
Leaf blade consumption (kg DM/ha)	329b	931a	825ab	1,159a	0.00	28.0
Cycle 3						
Total forage (kg DM/ha/d)	9.7	23.6	29.0	26.8	0.10	46.7
Leaf blade (kg DM/ha/d)	12.9b	32.7a	33.9a	32.7a	0.00	23.9
Culm (kg DM/ha/d)	~0	~0	1.6	3.3	0.44	>100.0
Stocking rate (AU/ha)	1.5b	4.3a	4.1a	4.1a	0.00	7.3
Leaf blade consumption (kg DM/ha)	908	703	944	742	0.48	30.5

[1]Probability values by the F test of the analysis of variance. [2]Means followed by the same letter on the same line do not differ from each other by the Tukey test (P>0.05), while means followed by different letters are significantly different (P<0.05). T_T = Control; T_R = Reference; T_G = GreenSeeker[TM] sensor; T_S = SPAD 502 sensor.

Table 5. Crude protein concentration (% DM) in forage pre-grazing for each treatment in the 3 crop management cycles.

Management cycle	T_T	T_R	T_G	T_S	P-value[1]	CV (%)
Cycle 1	9.2	13.4	11.4	11.9	0.09	19.0
Cycle 2	8.0b[2]	13.6a	12.4a	12.0a	0.00	11.6
Cycle 3	6.5b	13.4a	11.6a	11.7a	0.00	11.5

[1]Probability values by the F test of the analysis of variance. [2]Means followed by the same letter on the same line do not differ by the Tukey test (P>0.05), while means followed by different letters are different (P<0.05). T_T = Control; T_R = Reference; T_G = GreenSeeker[TM] sensor; T_S = SPAD 502 sensor.

The yield responses to nitrogen fertilizer (kg DM/kg N applied) for all management cycles are presented in Table 6. As growth data were not available for Cycle 1, we based our calculations for Cycle 1 on the differences in presentation yields of forage when cows entered the pastures for grazing and the amounts of N applied (Table 3). We considered this approach was valid because the pastures received equal treatment prior to the commencement of the study and any differences between treatments at commencement of grazing were a function of the N applied. Yield response values were higher for the Sensor treatments (T_G and T_S) than for the reference treatment (T_R), although they were not statistically different for Cycles 1 and 3.

Table 6. Yield response to fertilizer (kg DM above Control/kg total N applied) for each treatment during the regrowth period for each management cycle.

Cycle	T_R	T_G	T_S
1	6.1	10.7	13.6
2	5.5c[1]	14.2b	27.9a
3	6.7	13.4	10.6

[1]Means followed by the same letter on the same line do not differ from each other by the Tukey test (P>0.05), while means with different letters are different (P<0.05). T_R = Reference; T_G = GreenSeeker™ sensor; T_S = SPAD 502 sensor.

Discussion

Despite its short duration, this study has shown the benefits of using sensors to determine the need for N fertilizer applications to *U. brizantha* cv. Xaraés pastures during the April–August period in the Southeast region of Brazil. Application of N according to readings made with the sensors produced as much forage with similar CP% as applying N at a set rate at pre-determined intervals, and resulted in a saving of 75 kg urea/ha/cycle. Since fertilizer costs are substantial this would result in significant savings to a farmer.

The absence of statistical differences between the 3 N fertilizer treatments confirms the benefits to be gained from the use of precision tools for determining N fertilizer requirements for Xaraés grass pastures rather than applying fertilizer at fixed rates at set times. The sensor treatments used half the amount of fertilizer applied to the fixed rate treatment, but produced similar amounts of total forage and leaf blade, allowing similar stocking rates on all fertilized treatments. Therefore, using this technology to apply N at variable rates in areas with spatial variability could contribute to higher efficiency of nitrogen use. Additionally, using this methodology would lead to a reduction in application of N in locations where the

productive potential is high and plants are well supplied with N. In those cases, there would be no response to higher doses of nitrogen, and forage production would not suffer (Bredemeier et al. 2013).

The positive results of using the NSI methodology were made possible by the spectral responses evaluated in this experiment. For instance, the NDVI values presented a similar response in the 3 management cycles, tending to increase as the canopy height increased. Increases in NDVI values were expected, since the biomass of the plots increased with the development of the pasture. In addition, there was little difference in the amplitude of NDVI curves between treatments receiving nitrogen fertilizer. This explains why, in situations where available nitrogen levels are high, the maximum potential of the photosynthetic system is reached and the surplus of nitrogen is stored as other reserve compounds (Argenta et al. 2001; Amaral and Molin 2014). In this context, the value of using sensors is enhanced because, besides detecting plots which are deficient in nutrients, it is also possible to infer when fertilizer application exceeds the needs of the pasture, i.e. over-fertilizing. Over-fertilizing leads to an increase in nitrogen losses and a decrease in the efficiency of nutrient use by the plants.

Saturation in sensors that work with NDVI may occur when a high leaf area index is reached, where the linear relationship will no longer apply between sensor measurements and parameters such as biomass increase (Tremblay et al. 2009; Tian et al. 2016). NDVI saturation did not occur during the first 2 cycles since grazing began when height of the pasture reached 30 cm, corresponding to 95% light interception by the leaf canopy of Xaraés grass. This light interception condition prevents the crop canopy from reaching very dense levels, avoiding auto-shading and senescence of the lower leaves, which represents forage loss. There was only a small tendency for NDVI saturation during Cycle 3. This may be a response to cattle grazing and trampling on pasture, which helped cover small regions were soil had been exposed after the drastic cut at the beginning of the experiment.

We also observed a tendency for the SPAD index to increase with growth of the pasture. Supporting evidence for this increase was provided by Cancellier et al. (2013), who evaluated the dynamics of chlorophyll indices resulting from the application of N fertilizer to upland rice genotypes in the municipality of Gurupi, Tocantins, Brazil. The authors concluded that the younger leaves at the top caused an increase in the readings, which were carried out on the last fully expanded leaf of the plant.

As a consequence of the drastic initial brushcut, the rest period for the first growth cycle (30 days for the treatments with N applied) was the same as for the third

cycle, when not only the days were shorter but also total precipitation and average temperatures were lower. There are limited studies on the benefits or setbacks from cutting tropical pastures too close to ground level, but Santos and Fonseca (2016) suggest that cutting pasture short to eliminate material of low acceptance to animals could compromise the speed of regrowth. One must remember that pasture had to regrow from 10 cm after the initial cut to the 30 cm target for Cycle 1, while regrowth in Cycles 2 and 3 was from 15 cm to 30 cm.

The higher forage yields in the second crop management cycle may have been a response to the timing of the rainfall, which occurred mostly at the beginning of the cycle (Figure 1). Another contributing factor could be the fact that defoliation of pasture during the study was carried out by animals and was not as severe or as rapid as defoliation by the brushcutter, so the residual pasture was in a more favorable condition to regenerate.

Only in Cycle 1 has the Control treatment yielded total forage values approaching those of the fertilized treatments. Before the implementation of the experiment, the area was fertilized every 60 days with N, according to the farmer's own criteria, for the maintenance of forage supply for cattle so there may have been residual N in all plots when the study commenced. However, the lack of N fertilizer application on the Control treatment during the study would have resulted in the depletion of N stocks in the soil and caused a reduction in green leaf color (Figure 2) and a decrease in forage yield when compared with the fertilized treatments (Table 3). Leaf blade production on the Control treatment was also statistically similar to those of fertilized treatments during Cycle 3. This may be only a reflection of significantly lower leaf blade consumption in the Control plots during Cycle 2, resulting in high leaf availability at the commencement of grazing in Cycle 3 (Table 4). In Cycle 3, there were clear signs of N deficiency in the Control pasture, including leaf chlorosis, the appearance of smaller leaves and growth restrictions that reflected the extended duration of the crop cycle (Table 2).

Consideration of individual parameters in isolation represents only part of the true differences between treatments. An important factor was the difference in the lengths of time to complete each cycle by the various treatments, i.e. fertilized versus Control. Table 3 and Figure 1 show clearly that not only did fertilized treatments produce more forage than the Control in each cycle, but also they did it in a much shorter time. A nitrogen deficiency was the most likely reason for the increase in length of regrowth periods and lower DM yields in the Control treatment.

Since *Urochloa brizantha* is a tropical species, variation in climatic factors could have contributed to the drop in productivity with time in the Control treatment. Tropical forage species have optimal growth within a temperature range of 25–35 °C and their growth is reduced at lower temperatures, ceasing at temperatures between 10 and 15 °C (Dantas et al. 2016). Minimum temperatures were below 15 ºC on only a few occasions, but more frequently during the third management cycle of the experiment. This could result in thermal limitation to the growth of pastures.

Total forage yield depends on factors including genetic composition of the species, availability of soil nutrients and climatic factors such as temperature, luminosity, soil moisture, etc. In the work carried out by Galzerano et al. (2011), the authors evaluated Xaraés grass during the wet season in the region of Jaboticabal, São Paulo, Brazil, using 95% interception of photosynthetically active radiation by the sward as a management criterion and applying 100 kg N/ha. The total forage yield obtained was 149 kg/ha/d, which was similar to the 118–138 kg/ha/d found in Cycle 2 for treatments that received N fertilizer, even though the current study was conducted in the dry season, when the climate was much less favorable for the growth of tropical forages.

Yields of leaf blade tended to exceed those of culm and dead forage in all 3 management cycles, which is a function of pasture being managed at lower heights and high grazing intensity, favoring greater control of stem elongation (Euclides et al. 2009; Carloto et al. 2011). The higher presence of leaf blades relative to culm and dead forage positively affects animal performance, as leaf has higher nutritional value than the other structures (Castro et al. 2013).

Euclides et al. (2009) evaluated animal production and its relationship with the characteristics of *Urochloa brizantha* cvv. Marandu, Xaraés and Piatã, in Campo Grande, Mato Grosso do Sul, Brazil. Mean stocking rates for Xaraés were 3.8 AU/ha in the wet season and 1.4 AU/ha during the dry season, which were generally lower than stocking rates obtained in our study. While many factors impact on stocking rates of pastures, e.g. age of the stand, soil fertility, climatic conditions, etc., those authors applied only 50 kg N/ha in November-December of each year, so there was probably insufficient N available to meet demands of the sward to produce higher forage yields.

In pastures of Marandu grass fertilized with 1,000 kg/ha/yr (20:05:20, N:P:K) and managed with 30 days rest in Valença, Rio de Janeiro, Brazil, Fukumoto et al. (2010) obtained an average stocking rate of 5 AU/ha in the period from January to June 2005. Similar stocking

rate data were obtained in Cycle 2 in our study for the treatments that received N fertilizer, confirming that the application rates determined by the sensors were consistent with the actual needs of the crop.

It is interesting that crude protein concentration in available forage during Cycle 1 did not differ significantly between treatments, although absolute values were higher in fertilized treatments. One possible explanation for the lack of differences is the history of fertilizer application to the area. Before the experiment commenced, the area received nitrogen fertilizer every 60 days in an endeavor to maintain the forage supply for cattle. Residual N in the soil may have boosted CP% in the forage produced in the Control treatment. However, as the study advanced, CP% declined in the Control while it was maintained in the N treatments despite much higher forage yields in these treatments, which should have produced a dilution effect.

The lack of any significant difference in CP values between reference and sensor treatments in Cycles 2 and 3 suggests that there was a possible N loss in the reference treatment that received N fertilizer at a higher fixed rate. The key to optimizing the relationship between crop yield, profit and the preservation of the environment is to achieve a better synchrony between amount of N applied and the demands for N by the grass. Minimizing the environmental impact caused by the excessive use of nutrients is crucial for production systems worldwide if sustainable situations are to be maintained (Shanahan et al. 2008).

The optimization of available N levels in soil is crucial for plants to photosynthesize efficiently, increasing yield and reducing production costs (He et al. 2016). Many studies have shown that increasing doses of N applied can result in increased DM yields (Cecato et al. 2014; Hare et al. 2015; Delevatti et al. 2019), but yield responses can decline at higher N rates (Hare et al. 2015). Delevatti et al. (2019) argued that many countries have been overusing N fertilizer, resulting in harmful impacts on the environment, such as increased greenhouse gas emissions, increased nutrient levels in water runoff and loss of biodiversity. Efficient management of pasture is essential worldwide, as it enhances production while conserving land and resources (Delevatti et al. 2019). Our findings have shown that the use of spectral sensors could be a mechanism for managing pastures in a sustainable manner, by optimizing fertilizer use in individual situations and reducing negative impacts on the environment.

Conclusion

The GreenSeeker™ and SPAD 502 sensors used in this work were efficient in determining the need to apply N fertilizer to *Urochloa brizantha* cv. Xaraés. After 3 grazing cycles, applying N fertilizer at a lower rate determined by readings taken with sensors was more efficient than applying N at a fixed rate at preset intervals. Longer-term studies to confirm these findings seem warranted followed by promotion of this technology to make pasture production more cost-efficient with associated environmental benefits.

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(Note of the editors: All hyperlinks were verified 7 April 2020.)

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