USE OF ACTIVE CROP CANOPY REFLECTANCE SENSOR FOR NITROGEN SUGARCANE FERTILIZATION

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ABSTRACT

Sugarcane response to nitrogen is spatially and temporarily variable, making it difficult to develop models to estimate its demands. In this context, optical sensing has a great potential to evaluate and allow in-season crop nutrition. Experiments have been conducted on plots set over distinct growing conditions and nitrogen rates based on the CropCircle ACS-210 optical sensor (Holland Scientific, Lincoln, NE, USA). Evaluations with the sensor were conducted according to the crop height. The relationship between yield and the vegetation indices $NDVI_{ambar}$ and CI_{ambar} were analyzed, in addition to the chlorophyll content (Minolta SPAD). Due to the variability of situations where sugarcane is cultivated, it was proposed the comparison of a specific algorithm for each situation ("N-ramp") and a general algorithm ("N-rich strip") aiming variable-rate nitrogen recommendation. The ideal period to perform measurements with the optical sensor is when the crop is between 0.4 to 0.7 m height, before that there is not enough biomass, and after that, the sensor signal begins to saturate. Vegetation indices showed high correlation with the final yield, while for the chlorophyll content it did not happen all the time. The specific methodology showed contradictory results, assigning nitrogen in excess at fields that did not responded to nitrogen. The general methodology, working with normalized values, was adequate, since a correct yield estimative is performed by producers, to be introduced in the algorithm. The CI_{ambar} resulted in recommendations two to three times more N than $NDVI_{ambar}$. Long-term studies must be conducted to compare the recommendation methodologies and vegetation indices. The sensor was efficient in determining sugarcane crop N needs, although several changes have to be undertaken on the methodologies of recommendation that have been studied for other crops around the world.

Keywords: Crop canopy sensor, nitrogen recommendations, proximal sensing

INTRODUCTION

Sugarcane (*Saccharum spp.*) is the most important crop for sugar and ethanol production in tropical and subtropical regions, accounting for approximately 80% of the world sugar production and about 35% of ethanol global production (FAO, 2011). Brazil is the main producer with over a third of the world ethanol production (FAO, 2011). It has climate and soil conditions to produce this kind of alternative energy source which appears as the alternative that best meets the requirements of world economies because it is renewable and pollute less than fossil sources. Applying more efficient processes which increase productivity and reduce production costs is essential to the sector development.

Among the inputs nitrogen (N) is one that demands more attention from researchers and farmers. Crops shows variable response due the difficulty in estimating the amount of N mineralized from soil organic matter during the development of crop and high losses by leaching in the soil profile. Cantarella et al. (2007) found that in sugarcane the nitrogen use efficiency (NUE) is less than 40%, lower than most crops cultivated in Brazil, between 50 and 70%. NUE could be increased with the use of methods that estimate the crop response in a particular situation of climate and soil N content during the season, which would allow the N variable rate application (Solari, 2006).

One of these alternative methods is the use of ground-based active crop canopy sensors, a technology widely studied in crops highly domesticated such as wheat (Raun et al., 2002; Berntsen et al., 2006) and corn (Teal et al., 2006; Solari et al., 2008; Kitchen et al., 2010). This kind of sensor has been effective for N fertilization in these and other crops (Ferguson et al., 2011; Vellidis et al., 2011).

However, in crops such as sugarcane, with relatively few scientific studies of its physiology and nutrition, the use of this technique for N recommendation is still a challenge. Brazilian studies with canopy sensors on sugarcane have been conducted. Molin et al. (2010) and Amaral and Molin (2011) tested the canopy sensors GreenSeeker and CropCircle ACS-210 on sugarcane and found significant regressions between N rates and theire NDVI values. Portz et al. (2012) reported that N-Sensor ALS was able to identify the variability of biomass and N uptake on sugarcane.

In USA, Lofton et al. (2012) comparing check plots (no N applied) with reference plots (sufficient N applied) – Response index (RI) – verified good relationship between RI estimated by GreenSeeker canopy sensor and RI at harvest for cane tonnage. It is import to emphasize that results like these are difficult to obtain because the crop stay in the field throughout the year exposed to many events after the evaluation with the canopy sensor that may affect the production.

Amaral and Molin (2011) concluded that there are good possibilities of N recommendation for sugarcane based on canopy sensors. Although they emphasize the necessity to prove its effectiveness, both in terms of economic return and non-occurrence of longevity reduction of sugarcane ratoons due to the application of low N rates, as warned out by Vitti et al. (2007).

Bausch and Brodahl (2012) indicate that several vegetation indices are being evaluated and developed to enable N management during the growing season in different crops. However they emphasized that best results have been obtained by comparing the crop in an area of interest (non-fertilized – check plot) and an area which has already received an N rate enough to not limit plants development (reference plot). In this regard, the methodology proposed by Raun et al. (2002), originally for wheat, is one of the most frequently referred. This methodology have as determinant variables the estimation of yield made by prior calibration of the optical sensor, and the crop N response estimated by comparing the area of interest with an area that has received a sufficient N amount (N-rich strip).

Trying to reduce the problem of variability in the short-distances N availability (Raun et al., 2005) and to facilitate the construction of specific fertilization algorithms for each area, other researchers have proposed variations of this technique. One of these variations requires the application of different N rates along a strip in the field, seeking to construct a rate/response curve (Solari et al., 2008; Shaver et al., 2011). Thus, this study has as main objective to compare those two methods of N recommendation based on canopy optical sensor, analyzing their advantages and disadvantages for the sugarcane crop, as well as test two vegetation indices.

MATERIAL AND METHODS

Field sites

Plot experiments were conducted in six commercial sugarcane fields with distinct soil characteristics and cultivated in different periods (table 1), in the central-eastern of Sao Paulo state, Brazil (21° 21' S - 48°04' W). The plots consisted of six sugarcane rows spaced 1.5 m by 15 m long. In all fields, five N rates were applied (0, 50, 100, 150 and 200 kg ha^{-1}) in a randomized block design with four replications. Ammonium nitrate was used as N source on the straw immediately after harvesting.

Table 1. Characteristics of research fields, cropping information and days after harvesting from evaluations. Evaluations 1, 2 and 3 were performed, respectively, when average stem height was around 0.2-0.3 m, 0.4-0.5 m and 0.6-0.7 m.

Field	Variety	Soil texture	Year	Season(1)	Ratoon(2)	Previous harvest	Ev.1	Ev.2 DAH(3)	Ev.3
A1	RB855453	clay	2010	dry	Second	May 2009	74	116	155
A2	RB855453	clay	2010	dry	Fourth	June 2009	67	109	148
A3	CTC2	sandy	2010	wet	Second	Oct. 2009	-	91	105
A4	CTC2	sandy	2010	wet	Third	Oct. 2009	53	84	98
A5	RB855156	clay	2011	dry	Third	May 2010	141	183	-
A6	RB855453	clay	2011	dry	Third	July 2010	-	140	154

[1] dry season between May and August; wet season between September and December
[2] number of harvest performed in the field added by the year of the study
[3] DAH: days after harvest

Canopy reflectance and data collection

Evaluations were performed according to the crop average stem height (0.2-0.3, 0.4-0.5 and 0.6-0.7 m). Plant height was adopted because sugarcane does not have well-defined growth stages; moreover, the number of days after harvest (DAH) is vague information susceptible to variation according to the climatic conditions during the season.

The ground-based active canopy sensor used was the CropCircle ACS-210 (Holland Scientific, Lincoln, NE, USA) which emits modulated light and captures its reflectance in the visible wavelengths (amber - 590 nm) and near infrared (NIR - 880 nm).

The sensor was coupled on a vehicle (Uniport NPK-3000, Máquinas Agrícolas Jacto, Pompéia, SP, Brazil) with enough vertical clearance and maintained at about 1.0 m from the canopy, taking into account the average canopy height. The reflectance values of nearly 400 points collected per plot were averaged to proceed with their subsequent calculation of vegetation indices $NDVI_{amber}$ and CI_{amber}, as Solari et al . (2008).

In addition chlorophyll leaf content was estimated by a portable chlorophyll meter (Minolta SPAD-502) on 20 leaves per plot (top visible dewlap leaf – TVD). One measurement in the middle of one of the leaf blades was performed taking the average of the 20 readings.

Plots were mechanically harvested and the yields were totalized using a truck equipped with load cells.

Algorithm for nitrogen recommendation

For comparison purposes simulations with two N recommendation methods and two vegetation indices from the results of plot experiments were performed. The first method, proposed by Raun et al. (2002), requires the estimation of crop yield and its response to N application, based on measurements during the growing season in an N-rich strip. Yield is estimated based on values measured by the sensor. The response index (RI) is obtained dividing the average value measured in the N-rich strip by the value from the area to be fertilized (in this study the treatment with 200 kg ha^{-1} N rate was adopted as N-rich strip). This information allows the estimation of yield to be produced with the specific N application. Knowing the N demands for the production of a specific cane mass and the fertilization efficiency, it is possibly to establish the N content to be applied. Following recommendations of Cantarella et al. (2007), the sugarcane needs about 2 N kg cane t^{-1} with efficiency around 40%.

The second method used by Shaver et al. (2011) in corn, aims to obtain specific algorithm for each situation (rate/response curve), seeking to take into account the crop N response, called here as “N-ramp”. To do this, instead of a single rate, like happens in the N-rich strip, the application of increasing N rates is performed along one or more strips in the field. Then, a wide range of RIs are created by dividing the sensor value of an N applied plot by the sensor value of a plot with no N applied (target area).

Both methods use the term "response index" (RI). However, the first is calculated by dividing the value obtained in the treatment that received the highest

N rate (simulating the N-rich strip) by the other treatments. The second method divide treatments that received N by the treatment without N application. So, the first is mentioned as $RI_{reference}$ and the second as $RI_{algorithm}$.

The results were evaluated by comparison between crop N response, yield data and the N amount recommended by both methods and vegetation indices. Correlations, regression analyzes and means comparison tests were applied by using the statistical software SISVAR (Ferreira, 2011).

RESULTS AND DISCUSSION

Correct moment for response index estimation

Relating the yield $RI_{reference}$ with the three evaluations (table 2) it is possible to observe good capacity of the optical sensor to identify the N response of sugarcane but with better results when the crop is 0.4-0.5 m height. Before this period there is still much interference from the substrate due to the low biomass, resulting in reduction in the ability of the sensor to distinguish variations in plant canopy. After that, some saturation of the sensor signal can happen due to the intense biomass growth, as observed by Portz et al. (2012).

High correlation between $NDVI_{amber}$/CI_{amber} with leaf chlorophyll content (SPAD) was observed on the second evaluation (r = 0643^{**} and 0624^{**}, respectively $NDVI_{amber}$ and CI_{amber}) that demonstrate efficiency of vegetation indices in identifying the amount of chlorophyll on the canopy. On the other hand, the chlorophyll meter was not efficient on more developed plants (0.6-0.7 m) verified by decreased correlation between yield and vegetation indices (r = 0.140^{ns} and 0.165^{ns} for $NDVI_{amber}$ and CI_{amber}).

It should be noted that the evaluation of leaf chlorophyll content by portable meter is still not consolidated in Brazilian sugarcane. Amaral et al. (2010), testing different chlorophyll meters identified variable capacity between equipment in distinguishing N rates on sugarcane, arguing that the problem may be on the leaf and location measured in the plant.

Table 2. RMSE and R^2 between response index ($RI_{reference}$) obtained from vegetation indices ($NDVI_{amber}$ e CI_{amber}) and leaf chlorophyll content (SPAD) by cane tonnage in the three evaluations

	Evaluation 1 (0.2-0.3 m)		Evaluation 2 (0.4-0.5 m)		Evaluation 3 (0.6-0.7 m)	
	R^2	RMSE	R^2	RMSE	R^2	RMSE
$NDVI_{amber}$	0.454^{**}	0.161	0.536^{**}	0.146	0.175^{**}	0.205
CI_{amber}	0.150^{**}	0.200	0.492^{**}	0.153	0.323^{**}	0.176
SPAD	0.012^{ns}	0.218	0.111	0.202	0.006^{ns}	0.227

^{ns} e ** indicate, respectively, linear correlation not significant (p>0.05) and significant at 1% (p<0.01)

Algorithms construction

General algorithm (N-rich strip)

Sugarcane shows a wide yield variation as a function of different climate and soil conditions and varietal characteristics. For this reason, the establishment of generalized models to estimate its production based on measurements with optical sensors is more difficult than like is done in wheat (e.g. Raun et al., 2005) and corn (e.g. Teal et al., 2006). It is not possible to associate the absolute value of yield with vegetation indices and vice versa (*data not showed*).

Thus, it is proposed a generalized algorithm that works with normalized values for both yield and $NDVI_{amber}$ / CI_{amber} (Fig. 1). Because of the sugarcane planting conditions, often the first growing season (plant cane) does not present N response. In subsequent years, based on previous crop yield, climate and soil conditions producers are able to have reliable average yield estimation for the current season. Attributing the average yield estimation in the model (normalized yield = 100%) it is possible to estimate the expected yield variation across the field based on canopy sensor signal. The vegetation index value taken as reference (normalized NDVI/CI = 100%) is then adopted as the N-rich strip average value. With this yield estimative it is possible to determine the amount of N needed to supply the demand for increased crop yield determined by $RI_{reference}$.

It is possible to verify a wider range of values for CI_{amber}. However, it is not possible to say that it is better estimator of yield because the RMSE and R^2 are comparable to the obtained by $NDVI_{amber}$. Similar results were observed by Solari et al. (2010) working with the same vegetation indices in corn.

Specific algorithm ("N-ramp")

Relationship between canopy sensor and N response was highest in plants with 0.4-0.5 m height (evaluation 2). For this reason, data from this period were used to generate the specific algorithms for each field. Rate/response curves contemplating the results of all experimental units, as achieved by Shaver et al. (2011), were not possible due to the large experimental error inherent at Brazilian commercial fields. For this reason, it was necessary to work with the mean of each treatment to set a reasonable regression model (Fig. 2).

It can be noted, when working with CI_{amber}, that the $RI_{algorithm}$ obtained are higher, showing that CI_{amber} appears to be more sensitive to changes in chlorophyll and biomass than $NDVI_{amber}$. These data corroborate Gitelson et al. (2005) by claiming that this vegetation index is more sensitive than *green* NDVI to identify the chlorophyll present in the plant canopy in crops with moderate to high biomass.

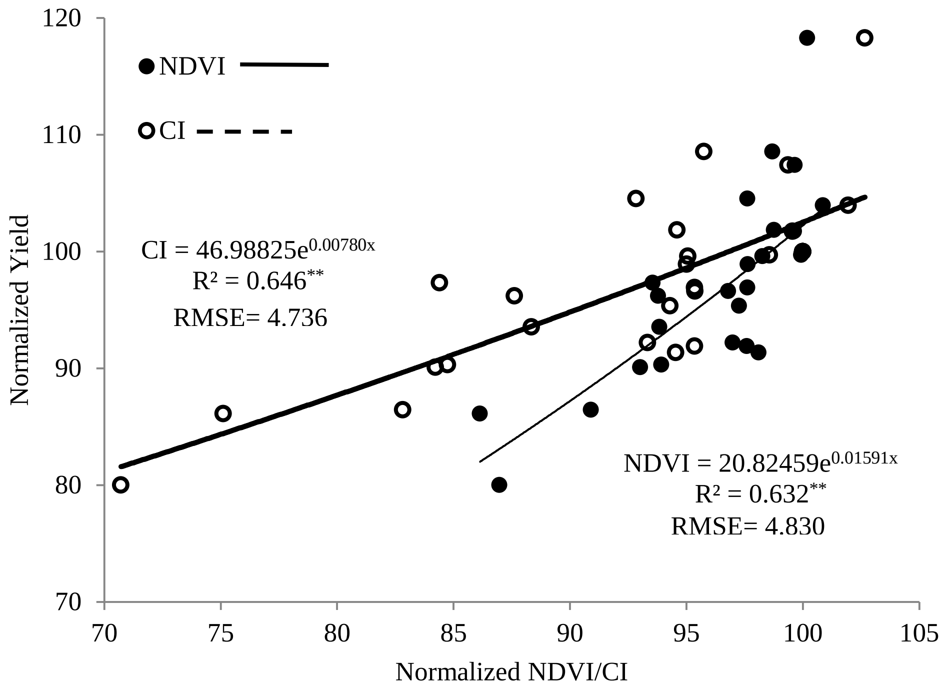

Fig. 1. Generalized algorithm for N-rich strip strategy. Normalized values of $NDVI_{amber}$ and CI_{amber}, where 100% represents the value obtained in the N-rich strip, and normalized yield, where 100% represents the estimated yield for the season

** indicates a significant linear correlation ($p<0.01$)

Regression equations from the rate/response curve were generated (algorithms) for each study site, separately (table 3). These equations were then used for N recommendation, where according a $RI_{algorithm}$ observed (x), a respective N rate was defined (y).

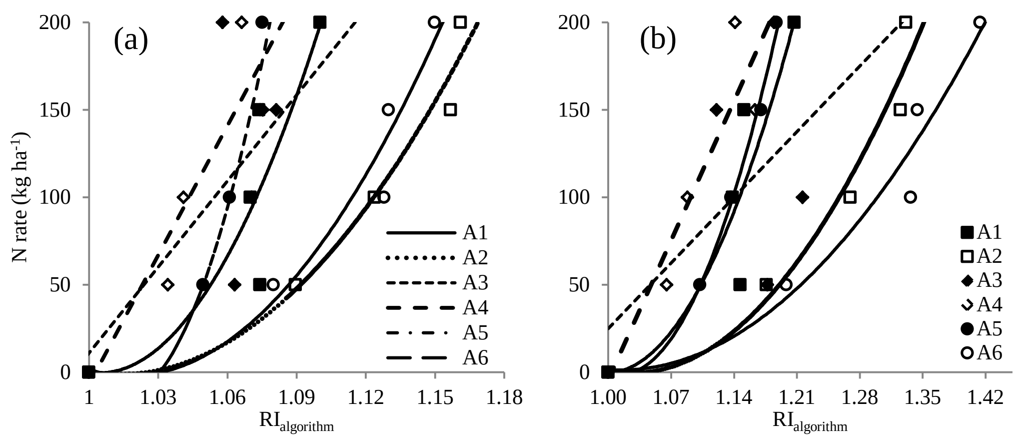

Fig. 2. Rate/response curves generated in the six experimental sites based on $RI_{algorithm}$ measured by the canopy sensor: (a) $NDVI_{amber}$; (b) CI_{amber}

Table 3. Algorithms derived from the regression of rate/response curves obtained in the six experimental sites based on $RI_{algorithm}$, with R^2 and P value of the regression

Field	Equation	R^2	P
Normalized Difference Vegetation Index - $NDVI_{amber}$			
A1	$y = 21795.22x^2 - 43794.18x + 21999.15$	0.791	0.123
A2	$y = 8352.31x^2 - 16928.62x + 8576.79$	0.968	0.178
A3	$y = 1639.58x - 1628.68$	0.447	0.002
A4	$y = 1900.58x^2 - 1479.36x - 426.82$	0.858	0.195
A5	$y = 53333.15x^2 - 108297.66x + 54964.58$	0.959	0.007
A6	$y = 11025.03x^2 - 22445.06x + 11421.65$	0.945	0.001
Chlorophyll Index - CI_{ambar}			
A1	$y = 4643.10x^2 - 9278.76x + 4635.53$	0.817	0.141
A2	$y = 1927.28x^2 - 3966.21x + 2040.36$	0.954	0.202
A3	$y = 535.99x - 510.97$	0.336	0.074
A4	$y = 1137.86x - 1142.14$	0.867	0.001
A5	$y = 6538.59x^2 - 13263.77x + 6725.41$	0.996	0.045
A6	$y = 1204.51x^2 - 2440.72x + 1237.74$	0.955	0.005

Nitrogen recommendation

The amount of N recommended for each experimental fields by both methods and vegetation indices varied significantly ($p < 0.05$), despite of the high variation of results achieved into the same treatments that difficult statistically significant differences. It probably happened because the experiments were installed in commercial fields susceptible to high variability at small distances, such as soil fertility and compaction, as like crop failures which tend to increase with the number of ratoons and are an important noise in reflectance readings with the optical sensor. Vellidis et al. (2011) indicated that when variability in crop status is caused by factors others than N availability, the prescription of N variable rate is much more difficult.

General algorithm ("N-rich strip")

N-rich strip methodology resulted in significantly less N recommended than the N-ramp method. There is similarity between the behavior of Yield $RI_{response}$ and the amount of N recommended in topdressing by the general algorithm.

There is good consistency in results represented by the equivalence of the recommended N rate for the treatment that did not receive N and treatment that received 50 kg ha^{-1}. Adding the treatment rate of 50 kg ha^{-1} plus N in topdressing, the total rate become similar to that recommended only in topdressing to the treatment without N.

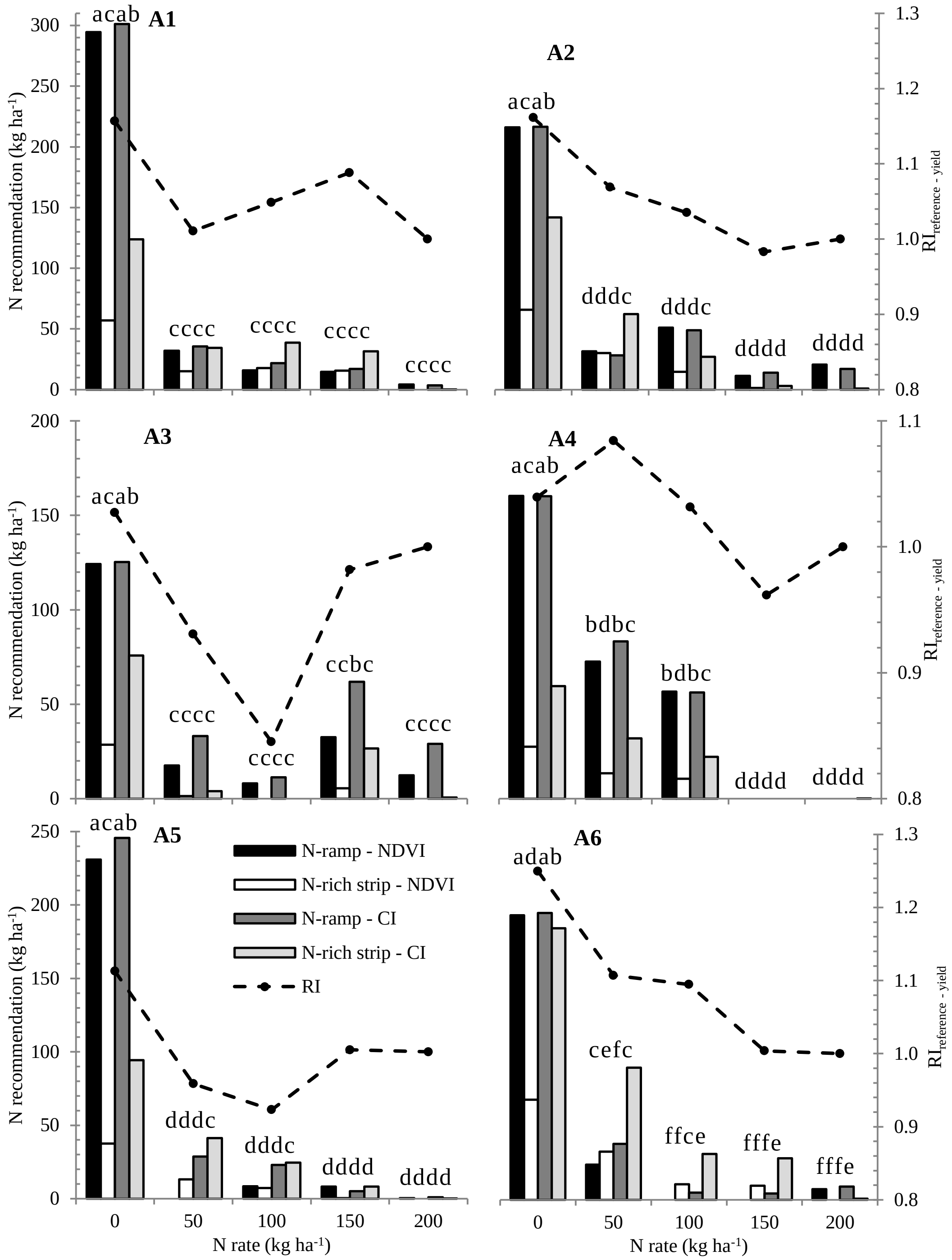

Fig. 3. Amount of N recommended by two methods (N-ramp and N-rich strip) in the six experimental sites based on two vegetation indices ($NDVI_{amber}$ and CI_{amber}) in each treatment; the broken line shows the behavior of the yield response index ($RI_{reference - yield}$) according to the N rates applied as treatments; it is important to pay attention to the differences in scales of the y axes

Different letters indicate difference between the treatments means by Scott-Knott test at 5%

Otherwise, for treatments that received application of 200 kg N ha^{-1}, generally were recommended some N amount. This fact may have occurred because a portion of the N applied could have been lost by leaching or immobilized by straw deposited on soil surface. Nevertheless, rates lower than 20 kg ha^{-1} are irrelevant within sugarcane productive system and would not be applied.

Yield estimation performed as shown in Fig. 1 reached an average error of 3.1%, validating its effectiveness. Thus, the knowledge about yield potential in each field plus the knowledge of crop N response enabled for N-rich strip provides a good identification of crop N demand (Raun et al., 2010).

In this way, the greatest difficulty would be to install N-rich strips in the correct places over the years. Holland and Schepers (2011) indicate that N-rich strips must be installed each season at a different location in order to not change soil fertility conditions of the area taken as reference. Bausch and Brodahl (2012) found to be problematic to work with average values from this strips, due to spatial variability in N availability. The identification of correct location to N-rich strips will be investigated in the next steps of our research.

Specific algorithm ("N-ramp")

It is noted that for the N-ramp methodology, even with low N crop yield response ($RI_{reference} \approx 1.0$), high N rates are recommended in the treatment that had not received N after harvest (fields A1, A3 and A5).

Another problem was observed making rate/response curves in fields that showed inconsistent treatments response (N rates after harvest). For example, field A3 showed a poor adjust of the equation (R^2 = 0.45) even working with average values within treatments. When it happens, high errors in the N rate applied are expected.

On the other hand, one of the great positive points of this strategy is to take into account the crop N response in specific field and climatic situation. However, for an accurate N rate recommendation is also necessary to know the crop yield potential, which is independent of crop N response (Raun et al., 2010). Therefore, assuming a field with low yield (50 t ha^{-1}) but high N response (RI = 1.5), the demand for N estimated by N-ramp could reach 300 kg N ha^{-1} (e.g. field A6). It would result in less than 100 kg of cane yielded for each 1 kg of N applied, while the desired is 1 kg of N per 1000 kg of cane (Cantarella et al., 2007). So, the NUE would be very low for a good economic return.

Just as the N-rich strip methodology, N-ramp requires installation of one or more strip tests across the field with the aggravation of being mandatory the application of different N rates, which is even more problematic. One solution to these difficulties is the use of another methodology like the virtual reference strip concept (Holland and Schepers, 2011). This possibility will be studied along larger areas in the next steps of our research.

Vegetation indices

We verified similar behaviors for both vegetation indices ($NDVI_{amber}$ and CI_{amber}) but with different magnitudes. This similarity was expected because indexes were calculated from the same wavelengths (590 and 880 nm). Though, we can see that invariably the CI_{amber} recommends two to three times more N.

Looking to the field with greater N response (field A6), when $NDVI_{amber}$ was used we are able to see N rates of 70 and 30 kg ha^{-1} respectively for treatments without N and 50 kg ha^{-1} of N application. Using CI_{amber} N rates would be increased to 185 and 90 kg ha^{-1} respectively. Analyzing the situation of field A6, with yield increasing around 25% ($RI_{reference}$ = 1.25), 50 kg ha^{-1} of N would be necessary. Therefore, the low rate recommended by $NDVI_{amber}$ would satisfy the crop demand.

However, this great fertilizer reduction has to be carefully observed. Cantarella et al. (2007) argue that studies with N performed in field conditions often do not reach statistical significance due to the large experimental error, but when data are analyzed in groups of experiments, important response to this element were observed. Vitti et al. (2007) warns that when N application is insufficient, the effects can appear in the following seasons with reduction in sugarcane crop longevity. For this reason, experiments with N application using the different vegetation indices have to be conducted for consecutive seasons in the same place to get a reliable result on the effectiveness of strategies adopted.

CONCLUSIONS

Good correlation was observed between the vegetation indices ($NDVI_{amber}$ and CI_{amber}) and the final yield, especially when average plant height was between 0.4-0.5 m. The specific methodology for each field (N-ramp) showed several difficulties and N rates recommendation were not coherent within crop response, especially in treatments that had not received N immediately after harvest. The general methodology (N-rich strip) while working with normalized values presented satisfactory amount of N recommended and great accuracy in yield potential estimation. About vegetation indices, CI_{amber} apparently proved to be more sensible than $NDVI_{amber}$ in identifying the sugarcane N response, but recommending about two to three times more N.

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