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REVIEW ARTICLE

A novel approach for determining nitrogen requirement based on a new agronomic principle—sugarcane as a crop model

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Abstract There are growing evidence that nitrogen (N) recommendation based on the expected yield concept developed by Stanford in 1973 lacks in agronomic principles, despite it widespread use worldwide. In Brazil, the main sugarcane producer worldwide, for example, a fixed N factor of 1 kg N per Mg^{-1} of stalk is used. However, literature demonstrates that sugarcane responsiveness to N is much higher in sandy soils rather than in clayey soils, whereas the recommended N is usually higher in clayey soils because of its improved yield potential. We investigated 146 response curves of sugarcane (*Saccharum* spp.) to N to define a better approach for determining N rates instead of using exclusively the expected yield concept. First, we found no correlation between the economically optimal N rate (N_{opt}, kg ha^{-1}) and the yield (Mg ha^{-1}) obtained in N_{opt}. Second, we calculate the N requirement (N_{req}, kg N Mg^{-1} stalk) as the quotient between N_{opt} and the yield, for each response curve. There was a negative correlation between yield at control plot and N_{req}, demonstrating that higher N rates are required to maximize yield in sandy (low yield) sites. The N_{req} was 1.3, 0.9, 0.7 and 0.6 kg N Mg^{-1} stalk for expected yields < 69, 69–84, 84–102, and > 102 Mg ha^{-1}, respectively, differing from the standard 1 kg N Mg^{-1} stalk currently used. The method proposed here is based indirectly on the N-supplying power of the soil and should be tested for other crops to deliver an improved N recommendation system.

Keywords *Saccharum* spp. · Ratoon · Fertilization · Green cane · Sustainability

Introduction

According to the goals set by the Brazilian government at COP-21, ethanol production is expected to reach 54 billion liters in 2030, twice the production in 2018. Under current yields, an additional 945 million tons of sugarcane will need to be produced per season to reach this goal (EPE, 2018). Achieving the goals established at COP-21 will lead to irreversible change in the Brazilian sugar-energy sector and has great potential to replace fossil fuel imports with ethanol to reduce greenhouse gases (GHGs) (Jaiswal et al., 2017).

Expanding production raises concerns about the need to increase fertilizer consumption, which is a major determinant of the sustainability of the

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production process. Globally, biomass production involves high demand for nutrients such as nitrogen (N) and phosphorus (P) (Galloway et al., 2004; Wang et al., 2014). In Brazil, fertilizer consumption increased by 50% between 2005 and 2015 (IPNI, 2016). N is the second most required element for sugarcane, behind only potassium (K) (Cherubin et al., 2018; Otto et al., 2019), but has the greatest effect on the sustainability of bioenergy production (Erisman et al., 2010). Without the use of fertilizers, especially nitrogenous fertilizers, current agricultural production would be drastically reduced (Gruber and Galloway, 2008; Ullah et al., 2020). N fertilization plays a fundamental role in crop yield but negatively impacts the environment by increasing the emissions of GHGs such as nitric oxide (NO) and nitrous oxide (N_2O) (Galloway et al., 2004; Crutzen et al., 2008; Soares et al., 2015; Ullah et al., 2020). N_2O is a potent greenhouse gas with global warming potential 296 times higher than CO_2 per unit of molar mass (Conrad, 1996). In this context, to avoid increased production costs and environmental damage, the expansion of sugarcane production in Brazil must not lead to further intensification of N fertilizer consumption.

In many countries, including Brazil, N fertilizer recommendations for sugarcane are based exclusively on the concept of expected yield (Spironello et al., 1997; Schroeder et al., 2010; Robinson et al., 2011). This occurs not only for sugarcane, but for many other crops cultivated worldwide in which N recommendation is based on the concept developed by Stanford (1973) that basically indicates that higher yields require larger amounts of N-fertilizer. However, several advances have been made in N fertilization recommendations in recent decades. In Australia, Thorburn et al. (2011) proposed the "*N replacement method*" to define the N rate to be applied to sugarcane fields. This method, which takes into account the replacement of N exported by sugarcane (which varies depending on the yield) and a factor associated with losses, significantly reduces the amount of N applied compared to the standard fertilizer recommendation method (Schroeder et al., 2010). However, the practical use of this method by growers in the Australian sugar and energy sector are not available, and an appropriate definition of the N rate remains the major factor limiting increased N use efficiency in sugarcane cultivation (Thorburn et al., 2017).

The contribution of the soil to crop nutrition is another important factor to consider in developing fertilizer recommendations. Several studies have shown that soil, not fertilizer, is the main source of N for sugarcane (Dourado-Neto et al., 2010; Franco et al., 2011; Vieira-Megda et al., 2015). This may explain the low contribution of N fertilizer to the total N accumulated in sugarcane, which varies from 10 to 20% at harvest but can reach more than 50% in the early stages of crop development (Franco et al., 2011). Fertilizer clearly has an important impact at the beginning of the crop cycle, but as sugarcane develops, soil becomes the main N source for the plant. Therefore, recommendations for sugarcane N fertilization must supply N to maximize growth in the initial stages but do not need to replace the total amount extracted by the crop, since the soil supplies the major N demand through soil organic matter (SOM) mineralization. Accordingly, the N rate used in Brazilian sugarcane fields, which ranges from 60 to 100 kg ha^{-1} N, tends to be lower than those applied in other countries, such as 150 to 400 kg ha^{-1} N in India and 100 to 755 kg ha^{-1} N in China (Robinson et al., 2011).

The recognition that soil is the main N source for plants has led to continuous improvements in recommendation methods based on soil analysis for different crops. Following the first studies by Stanford and Smith (1972), new methods have been developed or reevaluated for crops such as corn, wheat and rice, especially in temperate regions (e.g., Malone et al., 2010; Gill, 2019; Bavougian et al., 2019). However, these methods have not yet been widely adopted, despite evidence that they increase the accuracy of N recommendation and reduce the possibility of excessive or insufficient N rates (Mulvaney et al., 2006; Franzluebbers, 2018; McDaniel et al., 2020). For sugarcane-cropped soils, Otto et al. (2013) tested the Illinois Soil Nitrogen Test (ISNT) developed by Khan and Mulvaney (2001) and found that the ISNT is an effective approach for categorizing soils as highly, moderately, and unresponsive to N fertilization. However, Mariano et al. (2017) found that the ISNT method was not superior to several other chemical and biological indexes, concluding that all of the analyzed methods were not useful for identifying the optimum N rate for sugarcane. Notably, half of the 21 experiments evaluated by Mariano et al. (2017) were not responsive to N, which may have compromised the accuracy of finding a soil N based approach for determining N rates. More recently, Otto et al. (2020) again assessed the ISNT in sugarcane and confirmed its ability to quantify the capacity of the soil to supply N to plants. However, the results of the ISNT were similar in areas that were responsive and non-responsive to N, demonstrating that calibration is still required.

Boschiero et al. (2019) highlighted the importance of adjusting current N recommendation systems for sugarcane in Brazil based on a study at two sites: one showed a consistent response to N fertilization, while the other did not respond to N in five consecutive seasons (ratoons). Adopting the N recommendation based exclusively on the expected yield concept would lead to overfertilization at the non-responsive site, resulting in unnecessary use of N fertilizer as well as environmental pollution. Similarly, Mariano et al. (2017) reported that 50% of 21 areas assessed did not respond to N. The lack of sugarcane response to N is most related to soil N mineralization, which supplies the crop's demand for N (Otto et al., 2013), as well as the history of use of organic by-products (filter cake and vinasse), which increase the soil's potential to supply N to plants (Otto et al., 2016, 2020).

The variability in the response of sugarcane to N has raised questions about the necessity of increasing N rates in green sugarcane harvest systems. At the beginning of large-scale adoption of mechanized harvesting without burning (green sugarcane), intense immobilization of N fertilizer in the straw decomposition process was expected, which theoretically would increase the responsiveness of sugarcane to N (Robertson and Thorburn, 2007; Cantarella et al., 2007). For this reason, the N rate of 1 kg N Mg^{-1} of stalks usually used in the pre-harvest burnt sugarcane system (Spironello et al., 1997) was empirically replaced with 1.2 kg N Mg $^{-1}$ in green sugarcane systems by most growers in Southeast Brazil. However, the low responsiveness of green cane to N rates in recent studies performed under Brazilian conditions (Otto et al., 2016; Mariano et al., 2017; Boschiero et al., 2019) suggests that N rates may need to be reduced rather than increased for green cane, contrary to what have been pointed under practical sugarcane cultivation.

Because properly calibrated soil analysis methods are not available to end users, an alternative strategy is to propose improvements to the current recommendation system based on expected yields that ultimately derives from the original study of Stanford (1973). Vitti et al. (2007) observed a linear response of green cane yield to N rates in sandy soil. Similarly, Otto et al. (2013) showed that the response of green cane to N was highest in sandy soil. Barth et al. (2020) also observed that sandy soils with low SOM content have high N responsiveness. Taken together, these results suggest that sandy soils with low SOM content ("poor soils") are more responsive to N fertilization and, consequently, require higher N rates than clayey soils with higher levels of SOM ("good soils"). Otto et al. (2016) also revealed that soils presenting low yields in control (unfertilized) plots, what usually occurs in poor soils, presented higher yield gains due to N fertilization compared with good soils.

The logic behind fertilizer recommendation systems based on expected yield, although complex, is to satisfy the plant's demand for N by discounting the amount supplied by the soil (Stanford, 1973; Morris et al., 2018). This system, which is used for a variety of crops in different countries, assumes that a proportionally larger N rate is required as the expected yield increases (Morris et al., 2018). However, its simplicity hides a series of weaknesses, among which its lack of association with any factor of crop responsiveness to N may be the most relevant. In this sense, several authors have already proved that there is no direct relationship between the optimal N rate (expressed in kg ha^{-1}) and yield level (expressed in t ha^{-1}) for cereals (Raun et al., 2011; Morris et al., 2018) and sugarcane (Thorburn et al., 2017, 2018), demonstrating that the use of a fixed N factor is not a viable strategy, whereas it continues to be employed in many countries. In addition, Rodriguez et al. (2019) identified a series of flaws in the study that resulted on the internal N requirement factor proposed by Stanford (1973). In summary, whereas the concept of Stanford (1973) continues to be used for recommending N rates for most crops in many countries, there are increasingly evidences that this recommendation system is not based on solid agronomic principles and should be gradually substituted by more comprehensive N recommendation systems.

In this study, we investigate 146 response curves of sugarcane to N to define a better approach for determining N rates instead of using exclusively the expected yield concept. The rationale behind this goal was based on evidences that sugarcane responsiveness to N is much higher in sandy soils rather than in clayey soils, whereas the recommended N is usually higher in clayey soils because of the improved yield potential of sugarcane cultivated on those soils. The objective of this study was to perform a meta-analysis of sugarcane N response under Brazilian conditions not only to test the relationship between yield and the N rate but also to derive a N recommendation index to improve the current fertilizer recommendation system based exclusively on the expected yield concept.

Material and Methods

Dataset

A search for studies was carried out in the “Web of Science” database using the terms “*Nitrogen*” and “*Sugarcane*” in the title and “*Brazil*” in the address field. Additional searches for scientific articles, thesis, abstracts and other publications were carried out based on the references of the studies identified in the initial search. Only studies that included N response curve assessments with at least three N rates in addition to the control plot (without N) were considered. Whereas occurred rarely, manuscripts presenting only two N rates plus the control were excluded from further analysis. Similar to Thorburn et al. (2018), studies that assessed the N response of the cane plant crop cycle were also excluded in order to prioritize N response curves in ratoon seasons, mainly because sugarcane ratoon represents more than 80% of the area cultivated with sugarcane and has less interaction with the previous soil management on N response as observed in the cane plant cycle. In total, 27 studies were reviewed, including scientific articles, dissertations, thesis, conference papers and technical bulletins (Table 1S). As some studies contained data from more than one experiment or from experiments conducted for consecutive years, it was possible for a study to contain multiple N response curves. Thus, the 27 studies comprised 146 experiments involving N response curves from sugarcane ratoon. To avoid repetition of data, review articles such as Otto et al. (2016) and Mariano et al. (2017), which contemplated several studies whose results had already been published in other articles, were excluded. Unlike Otto et al. (2016), who reviewed 45 experiments of the N response of green sugarcane, in the present study we also included studies with burnt cane, which allowed us to compare the crop responses to N fertilization in these two management systems (burnt and green cane). Therefore, this review is more comprehensive than the one by Otto et al. (2016).

The objective of this meta-analysis was to explore the sugarcane response to N, regardless of fertilization form (superficial or incorporated) or N source (urea, ammonium nitrate or Uan, for example). Similarly, when the original study presented different times of application of the fertilizers, we calculated the average of the times of N application, aiming to represent only the N response curve. In addition, it was also recorded whether in the original study had statistical significance for the N rate factor, being categorized as "yes" or "no". Several studies did not present historical information about the area, such as the use of filter cake or vinasse, as well as previous cultivation with legumes. In these cases, the information was left blank and the use of by-products or legume cultivation was only categorized when this information was explicit in the original work. Several studies did not present the history of the area or the initial soil analysis and in these cases, the data were considered missing. For studies that showed statistical significance (p-value < 0.10), the gain due to N fertilization, the economically optimal N rate (N_{opt}) and the N requirement (N_{req}) were calculated as described below.

Geographic region, variety, N rates, harvest season, soil attributes, soil type, production environment, type of harvest (burnt or green cane), cutting stage (age), month and year of the previous harvest, month and year of the harvest, N application form (superficial or incorporated), N source and yield (t ha^{-1}) were recorded. To improve the representativeness of the dataset, in cases of missing data we made some assumptions. For example, when the clay content was not available in the original study, a clay content of 15% or less was adopted for soils classified as “Neossolo Quartzarênico” and a clay content of $> 35\%$ (clay textural class) was adopted for soils classified as “Nitossolo Vermelho”; we did not distinguish between the clayey and very clayey classes, which were both categorized as clayey (CONAB, 2020). Ribeirão Preto, Piracicaba and São José do Rio Preto were the main regions where the studies were developed (Fig. 1S), and presents historical rainfall mean are 1,362 mm, 1,297 mm and 1,391 mm per year, respectively (INMET, 2021). The studies were published over a period of 25 years, between 1994 and 2019 (Fig. 1S). In more than 80% of the studies, the sugarcane age was second or third harvest, and several varieties representing the main varieties currently cultivated for sugarcane were analyzed (Fig. 1S).

Data analysis

First, the main soil and crop attributes were extracted from the original studies (Fig. 1). For the N response curves that showed statistical significance (*p-value* < 0.10), the yield data as a function of the N rates were adjusted to linear (LN), linear plateau (LP), quadratic (QD), and three-parameter logistic (LM) models. Examples of the models fitted are given in Fig. 2S. Similar to Thorburn et al. (2017), priority was given to fitting linear plateau model, followed by three-parameter logistics and quadratic. Despite that some dataset adjusted to a simple linear regression (Fig. 2S – d), we excluded these experiments from further analysis due to the impossibility to find an economic optimum N rate. When the N response curve was not statistically significant or when no adjustment was significant (*p-value* > 0.10), the experiment was classified as not responsive to N.

Experiments that adjusted to LP, LM and QD, we calculated the economic optimum N rate (N_{opt}) as the N rate at which profitability was the maximum. For LP and LM, the N_{opt} was considered as the minimum rate that achieve the maximum profitability, since the maximum profitability correspond, many times, to a range of N rates. Profitability was calculated from Partial Gross Margin (PGM – Eq. 1) following the procedures described in Thorburn et al. (2017).

$$PGM = Yield * \left(SC_p - HC\right) - N_{rate} * NFp \quad (1)$$

where Yield is the yield at N_{opt}, SC_p is the cane price (US\$ 28.00 Mg^{-1}), HC the harvest costs (UU\$8.00 Mg^{-1}), Nrate is the N fertilizer rate (kg ha^{-1}) and NF_p is the N fertilizer price (US\$1.25 kg N^{-1}). Prices are the mean values practiced in September 2021 with a dollar quotation of R\$5,56 per USD. In this study, "yield at N_{opt}" refers to the yield estimated from the model corresponding to N_{opt}, i.e., the yield obtained with the economic N rate. N_{opt} was calculated instead of the N rate for maximum yield in order to represent the N rate for maximum economic return, which is widely used today (Morris et al., 2018).

For sugarcane cultivation in Brazil, there is a widely accepted concept called "environment production" that was calibrated considering the yield obtained under field conditions (in consecutive seasons) in different soil orders and textural classes (Prado, 2008). Environment production A shows a historical yield (in the average of five harvests) higher than 100 Mg ha^{-1}, while environment production E has a yield potential lower than 68 Mg ha^{-1}. For a similar weather condition, the factor most important categorizing yield potential was the clay content. In other words, for a similar weather condition, the average yield of sugarcane is higher in clay soils than in sandy soils. In this text, in order to simplify the concept, we will refer to "poor" soil as sandy soils which present lower yield potential (representing the E production environment) and "good" soils as clayey soils that present higher yield potential (representing the A production environment).

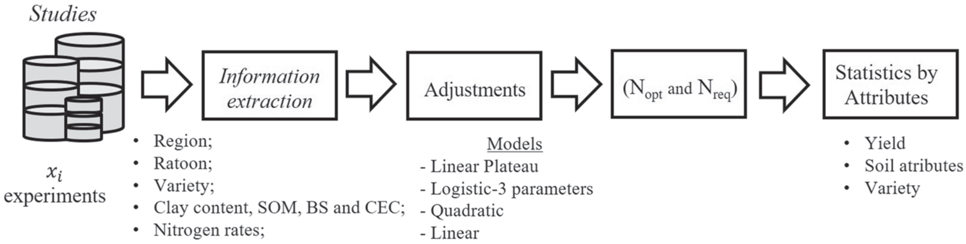

Fig. 1 Data analysis framework applied to the dataset

The main advantage of the recommendation system based on yield expectations is its acceptance by the end user as an intuitive method (Morris et al., 2018). For this reason, in order to develop a recommendation for N that is related to expected yield, we sought to calculate an index that permits a recommendation of N rate based on the expected yield while also incorporating the N supplied by the soil in non-fertilized plots. In the present study, N_{req} was defined for each experiment as the quotient between the N_{opt} for each experiment and the yield obtained at N_{opt} (Eq. 2).

$$N_{req} = \frac{N_{opt}}{Yield} \tag{2}$$

where N_{req} is the N requirement (kg N Mg^{-1}), N_{opt} is the economically optimal N rate (kg N ha^{-1}); and Yield is the yield at N_{opt} (Mg ha^{-1}).

Next, to test our hypothesis that areas with lower yield potential ("poor soils") are more responsive to N, that is, require higher N rates for a given level of yield compared to areas with greater yield potential ("good soils"), we plotted the N_{req} from each experiment as a function of the yield at control plot. We plotted N_{req} *vs* yield at control plot to avoid autocorrelation that would occur in case we plot N_{req} *vs* Yield at N_{opt}. We also followed the rationale of Otto et al. (2016) that showed fields with lower yields in the control plots presenting more responsiveness to N. The gain promoted by N fertilization was calculated as the difference in yield between the control plot (without N) and the yield corresponding to N_{opt}. The gain promoted by N fertilization was calculated in absolute terms (Mg ha^{-1}) and as a percentage (Eq. 3).

$$Yieldgain = \frac{Yield\left(N_{opt}\right) - Yield(Controlplot)}{Yield(Controlplot)} x100 \tag{3}$$

where Yield gain is the yield promoted by N fertilization in t ha^{-1} or %; Yield (N_{opt}) is the yield at N_{opt} in Mg ha^{-1}; and Yield (Control plot) is the yield obtained in the control treatment in Mg ha^{-1}.

The mean values of N_{opt} and N_{req} were categorized according to the following classes of soil attributes and yield at control plot: soil texture (< 150, between 150 and 350, and > 350 g kg^{-1} of clay for sandy, medium, and clayey, respectively), Soil Organic Matter-SOM (< 25 and > 25 g dm^{-3}), Cation Exchange Capacity-CEC (< 40, between 40 and 80, and > 80 $mmol_c$ dm^{-3}), Base Saturation-BS (< 50%, between 50 and 60%, and > 60%) and yield at control plot (< 69, between 69 and 84, between 84 and 102 and > 102 Mg ha^{-1}. Here, yield was classified by quantile division of the dataset. N_{opt} and N_{req} from each class were subjected to analysis of variance, and when the F test was significant (*p-value* < 0.10), the means were compared using the Tukey test. All statistical analyses were performed using the Statistica program (Tibco Software Inc., 2018).

Results

Of the 146 experiments assessed, 98 were responsive to N fertilization, and 48 were not responsive to N, corresponding to 2/3 and 1/3 of the total experiments, respectively. About responsive experiments, 65, 18, 12 and, 3 experiments were adjusted to LP, LN, QD and, LM models, respectively. The yield gain promoted by N fertilization compared with the yield of the control plot (without N) revealed a tendency of increasing production gains as the productivity of the control treatment decreased (Fig. 2). This result shows a weak, but clear tendency (r = -0.48) towards a greater response to N fertilization in areas with lower yields at control plots. However, further analysis did not identify a significant correlation between N_{opt} and yield at N_{opt} (Fig. 3), demonstrating that there is no relationship between the yield of an area and the economically optimal N rate in kg N ha^{-1}. While type of harvest (Fig. 3a) not showed any trend, soil texture (Fig. 3b) presented a weak correlation with N_{opt}, where sandy soils showed greater N demand (N_{opt} = 107.89 kg ha^{-1} in average) than clay soils (N_{opt} = 89.71 kg ha^{-1} in average); both excluding the experiments that presented N_{opt} = zero.

The perception that areas with lower yield in the control plots are more responsive to N, as observed in the present study (Fig. 2) as well as in the predecessor study by Otto et al. (2016), led us to include the yield at N_{opt} obtained at each location in the calculation to identify N_{req}. Excluding the 18 experiments that adjusted to linear regression, the remaining 80 responsive sites showed a wide variation of N_{req}, varying from 0.61 to 1.32 kg N Mg^{-1} (20 to 80 percentile, respectively). The median value (0.87 kg N Mg^{-1}) (Fig. 4) is somewhat different from

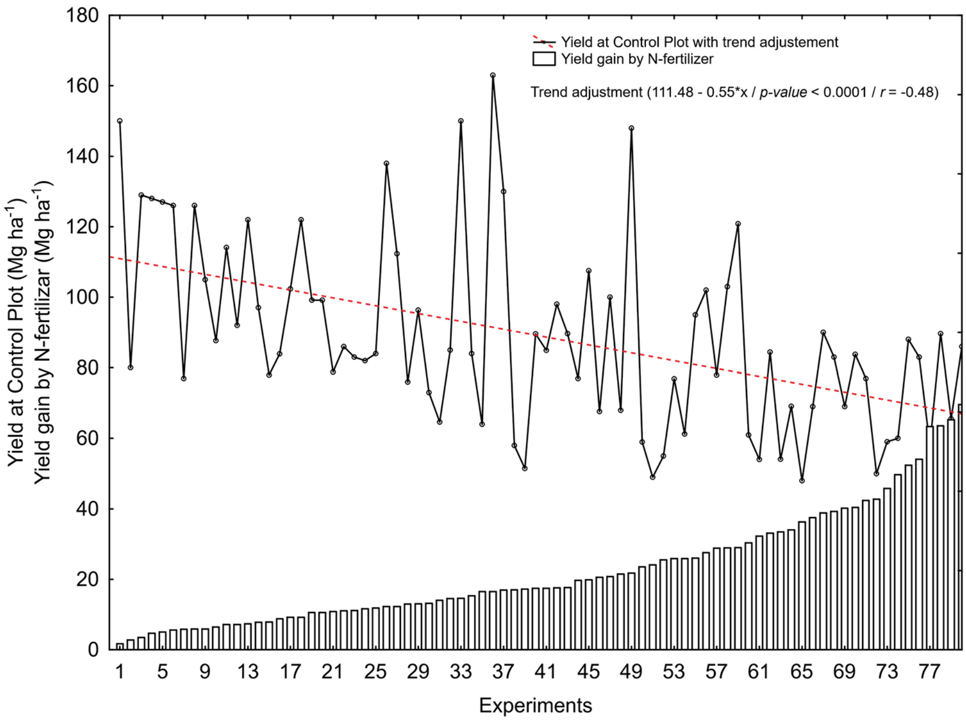

Fig. 2 Yield in the control plots (line plot) vs. yield gain (bat plot) due to N fertilization in the 80 experiments responsive to N fertilization

the factor of 1.0 kg N Mg^{-1} currently recommended for sugarcane production in São Paulo state, the largest producer of sugarcane in Brazil (Spironello et al., 1997).

Even more interesting was the negative correlation between N_{req} and yield at control plot (Fig. 5). This correlation was statistically significant (*p-value* < 0.0001) between the 80 N-responsive experiments. For this analysis, we excluded experiments that were not responsive to N and experiments that adjusted to LN model, as it is not possible to determine economical optimum N rate for such fields. Since there was no differentiation in models created separated by burnt *vs* green cane datasets, indicating similar responsiveness to N in both cases, we decided to create a unique model. The equation defining N_{req} as a function of yield is 2.8889 – 0.032*yield + 0.0001*yield^2 (*p-value* < 0.001).

We calculated the average N_{req} for each class of soil attributes previously selected. The results in Table 1 indicate that N_{req} differs not only among low, medium and high yield levels but also within soil attributes. N_{req} was 1.3, 0.9, 0.7 and 0.6 kg N Mg^{-1} for yields < 69, 69–84, 84–102, and > 102 Mg ha^{-1}, respectively. Despite the lower sensitivity of statistical significance in some cases, N_{req} was 1.3, 1.0 and 0.9 for sandy, medium and clayey soils, respectively. The same trend was observed for the other soil attributes; that is, N_{req} decreased with increasing base saturation (BS), cation exchange capacity (CEC) and SOM (Table 1). All these results indicate that N_{req} decreases as occur an improvement in the soil attributes and the yield of the area.

Discussion

Otto et al. (2016) observed that 24% of analyzed experiments were not responsive to N, somewhat similar to the 34% of non-responsive sites observed in the current study. In the same direction, a recent analysis of green cane reported no response to N in approximately half of the experimental areas (Mariano et al, 2017). Most recent studies have contemplated only areas of green cane due to the current prohibition on burning sugarcane in Brazil. Despite the

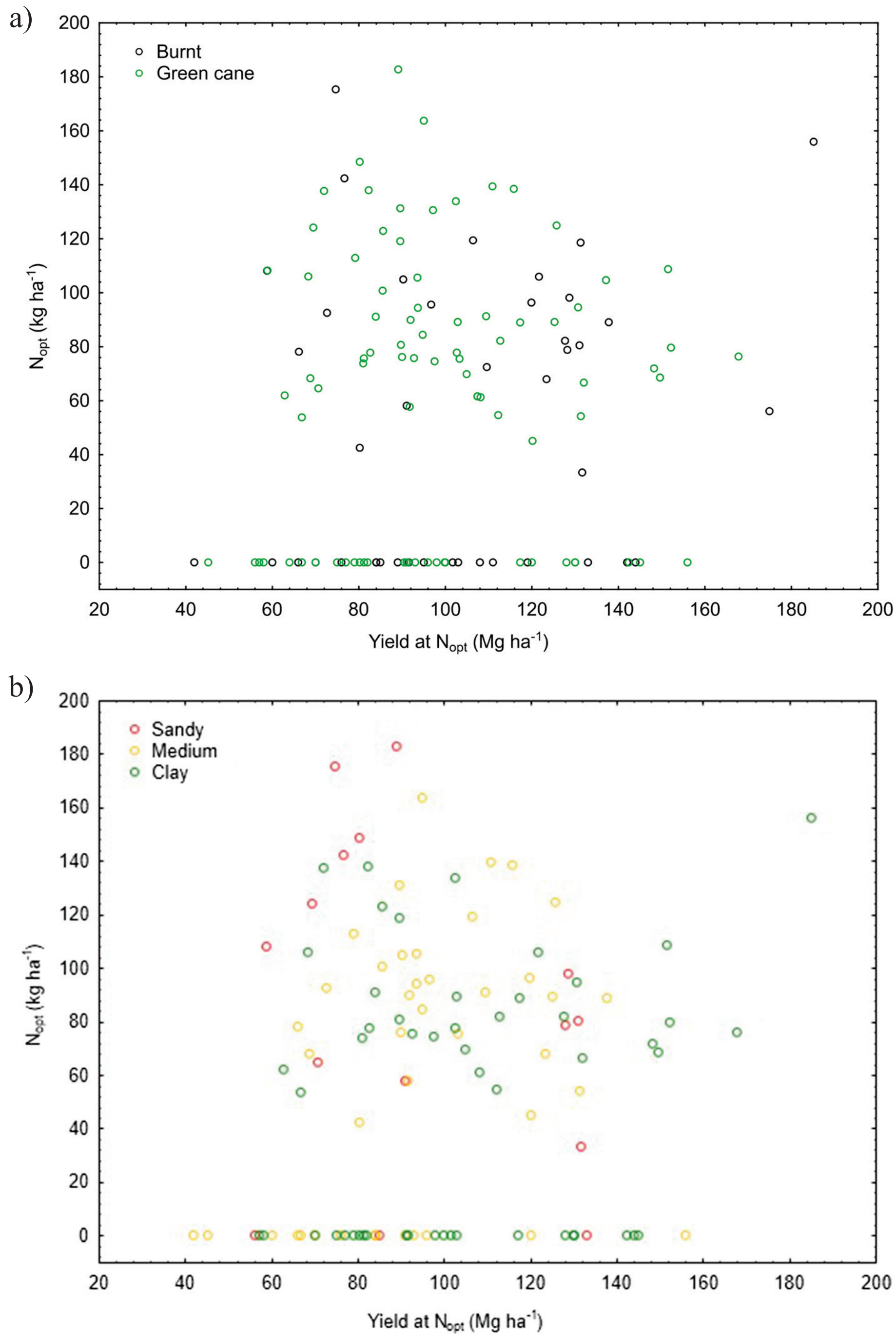

Fig. 3 Dispersion graph of the economically optimal N rate (N_{opt}) as a function of the yield at N_{opt} of each experiment by harvest type (**a**) and soil texture (**b**). No significant correlation was observed for the experiments responsive to N (*p-value* > 0.10)

apparent evidence that green cane cultivation is less responsive to N, in the current study, the pattern of sugarcane responsiveness to N was similar between burnt *vs* green cane, similar to the findings of Meier and Thorburn (2016). However, future studies would continue to evaluate the responsiveness of sugarcane

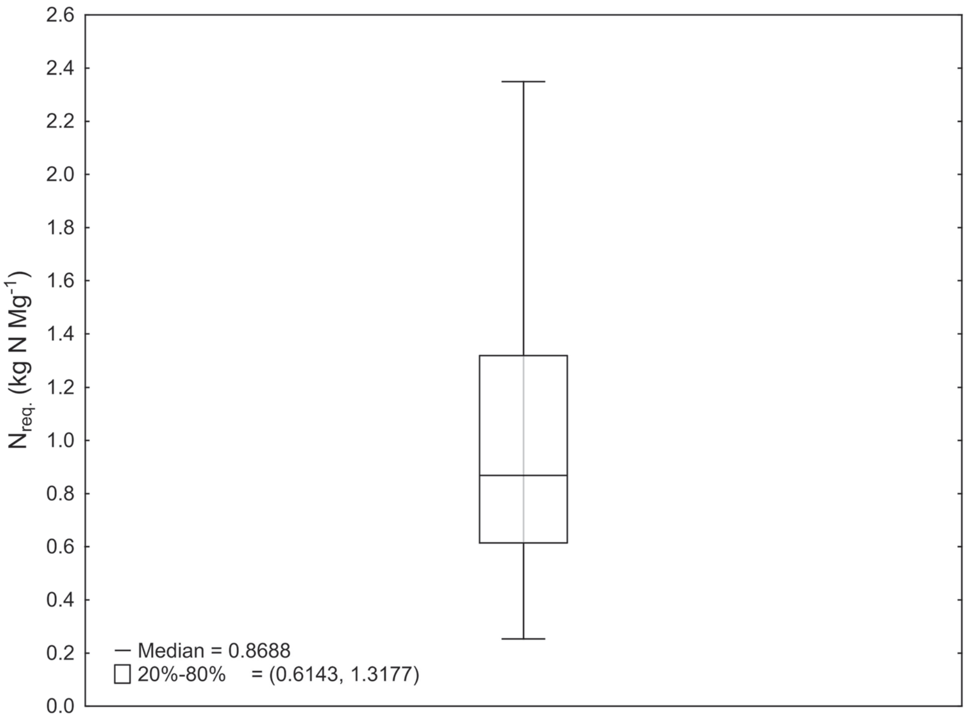

Fig. 4 N requirement ($N_{req.}$) variability of the 80 experiments responsive to N (excluding the experiments adjusted by linear regression)

to N under green cane cultivation, since current evidences suggest that straw preservation might favor the biological N fixation during straw decomposition (Lincoln and Vitousek, 2016) and this might reduce responsiveness to N-fertilizer.

One important question not answered in the current study nor in the study of Thorburn et al. (2018) is how to identify non-responsive sites in a practical way. Otto et al. (2013) separated sugarcane fields in highly responsive, moderately responsive and non-responsive according to the levels of ISNT found in soil samples in the initiation of the experiments. More recently, Otto et al. (2020) found differences in sugarcane responsiveness to N in areas varying in the historical usage of vinasse. In their study, whereas ISNT was correlated to the soil N supplying power, it presented similar contents in the responsive and non-responsive sites. Such evidence reveals that whereas a soil- based test seems the most powerful tool to identify non-responsive sites to N, is still requires further adjustments. In the opposite side, in some cases sugarcane responded linearly to N fertilization. That occurred in 18 areas in the current study, representing 12% of the 146 response curves evaluated. It is not possible to derivate economical optimum return because yield continues to increase above the range of N rates evaluated in the study. The only outcome is that linear response to N can drive farmers to apply above recommended N rates, but this usually not occurs under Brazilian field conditions due to the relatively high prices of N fertilizers that are mostly imported. In addition, linear response to N might occur in very limited sites, and most probably, in sandy soils as in the studies of Vitti et al. (2007) and in one site of Otto et al. (2013).

The datasets assessed by Otto et al. (2016) and in the present study indicate that areas with lower yield in the control plots, with usually occurs in poor soils, are more responsive to N. If this is true for most fields cultivated with sugarcane, the current recommendation criteria for N fertilization based on expected yield using a single fertilization factor for different levels of yield may not only reduce yield in the most restrictive environments (poor soils) but also promote overfertilization at high-yield sites (good soils).

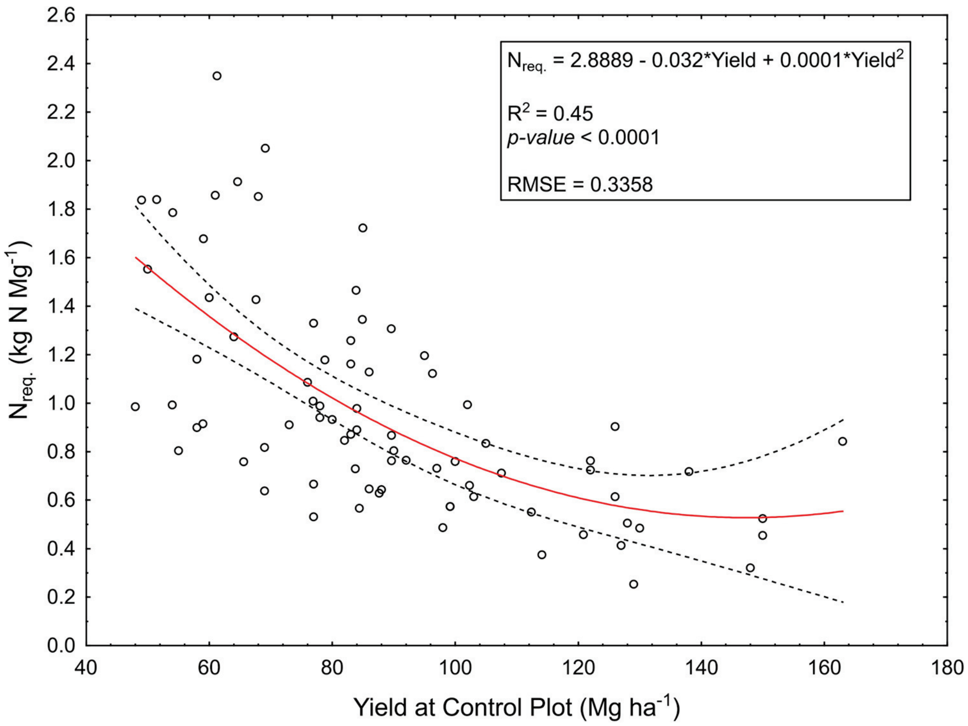

Fig. 5 Quadratic adjustment between yield at control plot (Mg ha^{-1}) and N requirement (N_{req}) for the 80 experiments responsive to N (excluding non-responsive sites and experiments that adjusted do linear regression)

Table 1 N requirement (N_{req}) according to yield at control plot, soil texture, soil organic matter (SOM), base saturation (BS) and cation exchange capacity (CEC) classes

Parameter	Class	n[1]	Yield[2]		N_{req}	
			Mg ha^{-1}		kg N Mg^{-1}	
Yield at control plot (Mg ha^{-1})	< 69	32	80.76	d	1.3	a
	69—84	26	107.42	c	0.9	b
	84—102	9	124.52	b	0.7	c
	> 102	13	147.23	a	0.6	c
Soil Texture (% of clay)	< 15	12	95.14	b	1.3	a
	15—45	28	101.30	b	1.0	b
	> 45	31	110.26	a	0.9	b
SOM (g dm^{-3})	< 25	32	89.62	b	1.3	a
	> 25	19	103.66	a	0.9	b
BS (%)	< 50	26	103.62	ab	0.9	ab
	50—60	7	88.69	b	1.3	a
	> 60	27	110.45	a	0.8	b
CEC (mmol$_c$ dm^{-3})	< 40	22	105.27	b	0.9	a
	40—80	24	97.59	b	0.9	a
	> 80	14	119.18	a	0.7	b
Variety	RB72454	12	123.66	a	0.8	bc
	SP813250	12	87.57	b	1.0	b
	SP832847	10	88.20	b	1.7	a

[1]Number of observations
[2]Average yield (at N_{opt}) within the number of observations of each class

Although N fertilization recommendations based on the concept of expected yield have been adopted for more than 50 years throughout the United States and several other regions of the world, the definition of N based on an internal N requirement, mostly derived from empirical calculation and not based in response of crops to N under field conditions, can has serious flaws (Rodriguez et al., 2019). The main advantage of fertilizer recommendation systems based on expected yield is the ease of interpretation, which has facilitated its adoption on a large scale (Morris et al., 2018). Using a single N factor will usually recommend high N rates for high yielding sites and low N rates for low yielding sites. However, as documented here and in the previous study of Otto et al (2016), N responsiveness apparently increases as the yield of the control plot reduces. In other words, data from field trials indicate that larger N rates should be recommended in sandy soils that usually presents limited yield in the control plot, but the expected yield concept will recommend the opposite. Several authors have proved that there is no correlation of the economically optimal N rate with yield (Raun et al., 2011; Morris et al., 2018; Thorburn et al., 2017). Recently, Thorburn et al. (2018) revisited this issue for sugarcane production in Australia and confirmed the absence of a correlation between these parameters, leading the authors to conclude that *"low-yield crops require doses of N as high as high-yield crops*". In the present study, there was also no correlation between yield and N_{opt} (Fig. 3). However, the correlation between N_{req} and yield at control plot observed at the 80 responsive sites indicated a significant reduction of N_{req} at higher yield levels (Fig. 5). The calculation proposed in the present study has not been evaluated previously, and this result is reasonable if we consider that the yield of the control plot (without N) is an indirect indicator of the potential of the soil to supply N to plants (Griffin, 2008). In other words, in areas where the yield is greater, the soil may have a greater capacity to supply N to plants, in addition to nutrients and water.

Many lines of evidence support the hypothesis that poor soils with lower yield potential require higher N rates than good soils (clay soils with higher SOM levels and high yields). First, sandy soils have lower levels of SOM (Brady and Weill, 2008) and less potential to supply nutrients to plants through mineralization (Otto et al., 2013; Griffin, 2008). Second, clay soils normally have greater biological activity (Robertson and Groffman, 2015), which can contribute to a greater supply of N to plants through biological N fixation; this is particularly important for sugarcane, which has the potential to supply part of the demand for N by association with N-fixing microorganisms (Martins et al., 2020). Third, N fertilizer losses through leaching and volatilization tend to be more significant in sandy soils (Ghiberto et al., 2015; Cantarella et al., 2018). All of this evidence supports our hypothesis that sandy soils, due to their lower yield potential, require higher rates of N fertilizer to express maximum yield potential. However, the concept of applying higher N rates in areas with lower yield potential and lower N rates in high-yielding areas contradicts the concept of N fertilization based on productivity expectations introduced by Stanford (1973), which has served as the basis for most systems of recommendation employed globally (Morris et al., 2018; Rodriguez et al., 2019). This concept also contradicts the common sense of practitioners in the sugar-energy sector that soils with greater yield potential are more responsive to fertilization, as they have fewer restrictive factors for development.

The results of this research indicate that calculating N_{req} considering the yield level in the area is a viable strategy not only for increasing productivity in poor soils but also for reducing N fertilizer use and losses in good soils, which naturally have greater potential to supply plants with N. The inclusion of yield at N_{opt} in the calculation of N requirement considers, to some extent, the N-supplying power of the soil and thus improves the internal N requirement method for N recommendation first developed by Stanford (1972).. Since this is the first study to propose the usage of different N factors according to the yield potential of a given site, future studies should compare the method proposed herein with standard methods based exclusively on the expected yield concept. Future studies are also required to improve our understanding of the factors controlling the responsiveness to N, in order to better identify soils that are unresponsive to N.

Conclusion

Despite its widespread adoption for various crops, the N fertilization recommendation method based exclusively on the expected yield concept is not based in a solid agronomic principle. The finding of this study is that sugarcane grown in poor soils, that usually presents low yield potential, requires higher N rates per ton to maximize yield compared to sugarcane grown in good soils, in which yield potential is high.

Multivariate analysis identified variety, yield and base saturation as the factors most influencing N requirement. These results indicate that it is possible to include these parameters to establish an optimal N requirement for sugarcane cultivation, where future studies need to address a model calibration based on these parameters. In this study, N requirement values of 1.3, 0.9, 0.7 and 0.6 kg N Mg^{-1} were obtained for yield levels $<$ 69, 69–84, 84–102, and $>$ 102 Mg ha^{-1}, respectively. Whereas the method proposed herein should be further evaluated in future studies, its adoption showed potential in maximize yields of sugarcane grown in poor soils and reduce overfertilization in good soils, contributing to increased N use efficiency in sugarcane systems.

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Declarations

Conflicts of interest/Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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