OPTICAL CROP SENSOR FOR VARIABLE-RATE NITROGEN FERTILIZATION IN CORN: II - INDICES OF FERTILIZER EFFICIENCY AND CORN YIELD[1]

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SUMMARY

Generally, in tropical and subtropical agroecosystems, the efficiency of nitrogen (N) fertilization is low, inducing a temporal variability of crop yield, economic losses, and environmental impacts. Variable-rate N fertilization (VRF), based on optical spectrometry crop sensors, could increase the N use efficiency (NUE). The objective of this study was to evaluate the corn grain yield and N fertilization efficiency under VRF determined by an optical sensor in comparison to the traditional single-application N fertilization (TSF). With this purpose, three experiments with no-tillage corn were carried out in the 2008/09 and 2010/11 growing seasons on a Hapludox in South Brazil, in a completely randomized design, at three different sites that were analyzed separately. The following crop properties were evaluated: aboveground dry matter production and quantity of N uptake at corn flowering, grain yield, and vegetation index determined by an N-Sensor® ALS optical sensor. Across the sites, the corn N fertilizer had a positive effect on corn N uptake, resulting in increased corn dry matter and grain yield. However, N fertilization induced lower increases of corn grain yield at site 2, where there was a severe drought during the growing period. The VRF defined by the optical crop sensor increased the apparent N recovery (NRE) and agronomic efficiency of N (NAE) compared to the traditional fertilizer strategy. In the average of sites 1 and 3, which were not affected by

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drought, VRF promoted an increase of 28.0 and 41.3 % in NAE and NRE, respectively. Despite these results, no increases in corn grain yield were observed by the use of VRF compared to TSF.

Index terms: nitrogen, N-Sensor, optical spectrometry, precision farming.

RESUMO: *SENSOR ÓPTICO NA FERTILIZAÇAO NITROGENADA À DOSE VARIÁVEL NO MILHO: II - ÍNDICES DE EFICIÊNCIA DA FERTILIZAÇÃO E PRODUTIVIDADE DE GRÃOS DE MILHO*

Geralmente, em agroecossistemas tropicais e subtropicais, a eficiência da fertilização nitrogenada para culturas agrícolas anuais é baixa, o que promove variabilidade temporal na produtividade das culturas, perdas econômicas e impacto ambiental. A fertilização à dose variada de nitrogênio (VRF) com base em sensores de culturas por espectrometria óptica pode aumentar a eficiência de uso do nitrogênio (NUE). Este estudo teve o objetivo de avaliar a produtividade do milho e a eficiência da VRF prescrita por um sensor óptico, em comparação com a fertilização à dose uniforme de nitrogênio (TSF). Com este propósito, três experimentos com milho sob sistema plantio direto foram conduzidos durante as safras agrícolas 2008/09 e 2010/11 sobre um Latossolo do sul do Brasil. O experimento foi conduzido em delineamento inteiramente casualizado, com cada local sendo analisado isoladamente. Os seguintes atributos foram avaliados: produção de matéria seca, acúmulo de N na biomassa no pleno florescimento do milho, produtividade de grãos de milho e índice de vegetação (VI) medido pelo sensor óptico N-Sensor® ALS. Independentemente do local investigado, a fertilização nitrogenada incrementou a quantidade de N absorvido pelas plantas, resultando em incremento da produção de matéria seca e da produtividade de milho. Os menores incrementos na produtividade de milho foram observados na área 2, que apresentou déficit hídrico em estádio fenológico crítico. A VRF aumentou a eficiência de recuperação aparente de N (NRE) e a eficiência agronômica do uso de NAE pelo milho. Nas áreas 1 e 3, que não foram interferidas pela restrição hídrica, verificaram-se aumentos de 28,0 e 41,3 % na NAE e NRE, respectivamente, promovido pela VRF, em relação à TSF. Apesar desses resultados, não foi verificado aumento de produtividade do milho pelo uso da VRF, em comparação a TSF.

Termos de indexação: nitrogênio, N-Sensor, espectrometria óptica, agricultura de precisão.

INTRODUCTION

The average Brazilian corn grain yield is around 4.2 Mg ha^{-1}, far below the 10 to 15 Mg ha^{-1} recorded in rainfed croplands with intensive use of technology in the main Brazilian agroecoregions (Glat, 2010). According to the projections, the corn grain demand for animal feed will increase by 37 % between 2005-2015 (Brasil, 2007). To attend this demand, corn grain yield should increase by 3.4 % per year in the same period.

Corn grain yield depends on the quality of the crop management, especially nitrogen (N) fertilization. Worldwide, the N fertilization efficiency is low (33 %) (Raun & Johnson, 1999). This situation is aggravated in tropical and subtropical agroecosystems, where N losses can range from 18 to 78 % of the N mineral fertilizer input (Lara Cabezas et al., 1997a; Fontoura & Bayer, 2010; Rojas et al., 2012).

The main causes for the low efficiency of corn N fertilization are: high losses by N-NH_3 volatilization (Lara Cabezas et al., 1997b; Cantarella et al., 2008), N-NO_3^- leaching (Sangoi et al., 2003; Ceretta et al., 2005), lack of synchrony between crop demand and N availability (Amado et al., 2002; Aita & Giacomini, 2008), inter-annual variability in the crop response to N fertilization (Fiorin et al., 2007; Ciampitti & Garcia, 2008), and spatial variability of soil organic matter (SOM) and N mineralization potential (Shahandeh et al., 2005; Gregoret et al., 2006; Solie et al., 1999; Casa et al., 2011; Portz et al., 2012). All these factors influence N fertilization, making an increase in fertilizer use efficiency a complex challenge.

N fertilization recommendations for corn in Southern Brazil are based on the following parameters: soil organic matter (SOM) content, previous crop, and target grain yield, resulting in a TSF for a cropland (Amado et al., 2002; CQFSRS/SC, 2004). However, climatic conditions can affect soil N availability (Bragagnolo et al., 2013), crop residue input (Amado et al., 2002), and corn N use efficiency (NUE) (Melchiori et al., 2005), resulting in temporal variability of the crop N requirements. Consequently, the crops will require adjustments of the N fertilization strategy during the season (Melchiori et al., 2005; Singh et al., 2006).

The use of VRF is based on the spatial variability of the crop nutrition status in the field. Typically, there is a decrease in N fertilizer rate at sites where the cropland is already well nourished and on the other hand N rates are raised where the plants are undernourished. Thus, the N fertilizer efficiency is increased (Raun et al., 2005; Singh et al., 2006; Li et al., 2010), promoting higher economic revenue at a lower environmental impact (Gregoret et al., 2006). When N fertilization rates exceed the crop demand, they can increase the soil N-NO_3^- content and therefore increase the risk of N losses through denitrification (Fernandes & Libardi, 2007; Escobar et al., 2010) or leaching (Sangoi et al., 2003; Ceretta et al., 2005; Fernandes & Libardi, 2007).

The use of real-time crop sensors, by which the plant nutritional status can be indirectly estimated, represents an innovation in N fertilization (Argenta et al., 2003; Raun et al., 2005; Berntsen et al., 2006; Portz et al., 2012). Among the optical sensors commercially available, the Yara N-Sensor® ALS (Yara International ASA) has been used successfully in different crops (Jasper et al., 2009; Portz et al., 2012; Bragagnolo et al., 2013).

Previous studies addressing the efficiency of this sensor show increases in cereal yield from 3 to 13 % over TSF, reduced crop lodging, increase of combine efficiency, improvement in grain protein content, and NUE (Singh et al., 2006). The increase in NUE could promote the reduction of N fertilizer input by 14 % without impairing grain yield. This is a relevant achievement from the economic and environmental point of view (Singh et al., 2006). Apart from fertilization, this optical sensor has been used for objectives such as providing supplementary information for crop yield maps and prescriptions of agrochemical input (Singh et al., 2006).

Research with N fertilization based real-time crop sensors is still emerging in Brazil. The objective of this study was to evaluate the effect of VRF prescribed by an optical sensor in comparison to the traditional single-rate N fertilization (TSF) on corn grain yield and NUE in South Brazil.

MATERIAL AND METHODS

The treatments, experimental design, site locations, soil, and climate characteristics were previously reported in Bragagnolo et al. (2013).

Corn grain yield

Corn grain yield was assessed on the basis of corn cobs collected from 2 m in two rows of corn close to the georeferenced sampling points, where the plant vegetative properties were evaluated (Bragagnolo et al., 2013). Grain yield samples were collected at nine georeferenced points per treatment (distance of 40 m between each plot) at site 1, while at site 2 samples were collected at 12 georeferenced points per treatment (distance of 20 m between each plot), and at site three samples were collected at seven georeferenced points per plot (distance of 40 m between plots). Results were adjusted to a grain moisture content of 13 %.

Nitrogen use efficiency indices

The NUE was calculated by the equations suggested by Dobermann (2005):

$$PFP = Y_N/X_N \qquad (1)$$

where PFP = partial factor productivity (kg kg^{-1} of grain by N input); Y_N = grain yield of a given treatment with N fertilization (kg ha^{-1} of grain); and X_N= quantity of N fertilizer input (kg ha^{-1} of N).

$$NAE = (Y_N - Y_C)/X_N \qquad (2)$$

where NAE = N agronomic efficiency (kg kg^{-1} of grain by N input); Y_N = grain yield in treatment with N fertilization (kg ha^{-1} of grain); Y_C = grain yield in control treatment (without N fertilization) (kg ha^{-1} of grain); and X_N = N fertilization (kg ha^{-1} of N).

For site 1, where the control treatment had received starter N fertilization (27 kg ha^{-1} of N), this value was from the total N fertilization rate (X_N) in the equation.

$$NRE = (NU_N - NU_C)/X_N \qquad (3)$$

where NRE = N apparent recovery efficiency (kg kg^{-1}); NU_N = N uptake in the treatment with N fertilization (kg ha^{-1}); NU_C = N uptake in the control treatment (without N fertilization) (kg ha^{-1}); X_N = N fertilization (kg ha^{-1}).

For site 1, where the control treatment had received starter N fertilization (27 kg ha^{-1} of N), this value was from the total N fertilization rate (X_N) in the equation.

$$NPE = (Y_N - Y_C)/(NU_N - NU_C) \qquad (4)$$

where NPE = N physiological efficiency (kg kg^{-1} of grain by N input); Y_N = grain yield in treatment with N fertilization (kg ha^{-1} of grain); Y_C = grain yield in control treatment (without N fertilization) (kg ha^{-1} of grain); NU_N = N uptake in treatment with N fertilization (kg ha^{-1} of N); NU_C = N uptake in control treatment (without N fertilization) (kg ha^{-1} of N).

The maximum technical efficiency (MTE) for N fertilization was assessed by adjusting mathematical functions between N fertilization rates and the relative grain yield for each site. The maximum economic efficiency (MEE) was assessed based on 90 % of the MTE (Amado & Mielniczuk, 2000).

The results were subjected to analysis of variance and descriptive statistical analysis. The means were compared by the Tukey test ($p<0.05$), followed by polynomial regression analysis by using SISVAR 4.0 statistical software (Ferreira, 2000). The coefficient of variance (CV) of the optical sensor vegetation index (VI) was classified as low (<12 %), medium (12 to 62 %), or high (>62 %), as proposed by Warrick & Nielsen (1980).

RESULTS AND DISCUSSION

Vegetation index and variable N fertilization rate estimated by the real-time crop sensor

The high number of VI readings provided by the optical sensor reinforces the potential of this equipment for the prescription of VRF, promoting real-time information of the crop nutritional status with high spatial resolution, without requiring plant sampling and laboratory analysis (Table 1). The VI measurements covered around 40, 30, and 33 % of the total experimental corn fields at sites 1, 2, and 3, respectively.

The occurrence of infield spatial variability in plant and soil properties is a prerequisite for the success of precision farming techniques (Saraiva et al., 2006; Povh & Gimenez, 2011). Thus, when the spatial crop variability is high, the probability of success with the VRF strategy is greater. The corn VI spatial variability at the phenological stage V8 for the three areas is presented in figure 1. The VI values at site 1 were about 50 % lower than at the other sites (Table 2). Previously, Tremblay et al. (2009) and Soderstrom et al. (2010) also reported different VI values for the same corn phenological stage, according to the site and crop season.

Table 1. Variable nitrogen fertilization rate based on the crop optical sensor applied at the phenological stage V8 of corn

Experiment characteristic	Location		
	Site 1	Site 2	Site 3
Strip width (m)	15	20	18
Strip length (m)	380	260	300
Velocity (km h^{-1})	5	5	5
Number of observations ha^{-1}	254	310	297
Sampled site (%)	40	30	33

Table 2. Statistical parameters of variable-rate fertilization based on the optical sensor at the phenological stage V8 of corn

Statistical parameter	Location					
	Site 1		Site 2		Site 3	
	VI	NF	VI	NF	VI	NF
		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}
Reference	35.5	91.0	69.2	80.0	64.7	70.0
Minimum	27.9	77.0	45.0	61.9	42.4	24.9
Maximum	52.9	104.8	88.5	104.9	78.9	88.6
Mean	35.5	89.9	69.2	79.4	64.7	70.7
Variance	58.9	21.9	70.3	85.9	24.5	23.6
SD	7.6	4.6	8.3	9.2	4.9	4.8
CV (%)	21.4	5.1	12.0	11.6	7.6	6.8

VI: vegetation index; NF: estimated N fertilization rate; SD: standard deviation; CV: coefficient of variation.

In our study, the CV of the VI values ranged between 7 and 21 % (Table 2), while Tremblay et al. (2009) reported CV for VI of 1 to 28 %. According to the classification proposed by Warrick & Nielsen (1980), the CV of VI at sites 1 and 2 were classified as medium, while at site 3 the CV was low. Thus, according to the crop optical sensor, the first two sites had higher spatial corn variability as expressed by standard deviation (SD) and CV values in relation to site 3 (Table 2). These results could have been associated with the climatic conditions at site 3, which were more favorable for corn growth, soil N mineralization, and plant N uptake than at the other sites (Bragagnolo et al., 2013).

The VI were lowest at site 1 (Table 2), at which the pluvial precipitation volume was highest until stage V8 (63.3 % of the total rainfall in the whole corn growing season), followed by days with low luminosity and cool temperature, which probably impaired corn N uptake. Frequent and intense precipitations increase N-NO_3^- leaching (Sangoi et al., 2003; Ceretta et al., 2005) and, as a consequence, reduce soil N availability to plants. Sites 2 and 3 had higher average VI values (Table 2). These results are coherent with the higher SOM content at sites 2 and 3 (3.8 %) in comparison to site 1 (2.8 %) (Bragagnolo et al., 2013).

The amplitude of N fertilization (NF) rates estimated by the optical sensor was lowest at site 1, where the highest NF was 1.4 times higher than the lowest NF (Table 2). The higher amplitude of NF at sites 2 and 3 indicated a greater redistribution of N fertilizer along these plots. The ratio of the highest to the lowest NF at sites 2 and 3 was 1.7 and 3.6, respectively. These results could be explained by the lower VI amplitude (25.0) observed at site 1, in comparison to sites 2 (43.5) and 3 (36.5). Thus, 61 % of the VI measurements at site 1 ranged between 22.6 and 30.6, suggesting low spatial plant variability (Figure 1). Yet at site 1, the corn plants produced least aboveground dry matter and took up least N in V8 of all three experimental sites (Bragagnolo et al., 2013). This result suggests that the N nutrition status of the corn plants at site 1 was homogeneously poor.

Based on the crop nutritional status assessed by VI, the optical sensor estimated the NF rates. For each site, the average VI was used as reference N fertilization rate. Only data of the sites 2 and 3 are shown in Figure 2, due to data storage problems at site 1. There was a linear adjustment between VI and NF rates, therefore for every unit of increase in VI there was a 1 kg ha^{-1} decrease in the estimated NF rate (Figure 2).

N fertilization rates estimated by real-time crop sensor

The NF rates estimated by the optical sensor along the plots with lengths ranging from 260 to 380 m are presented in figure 3. The VRF in this study was

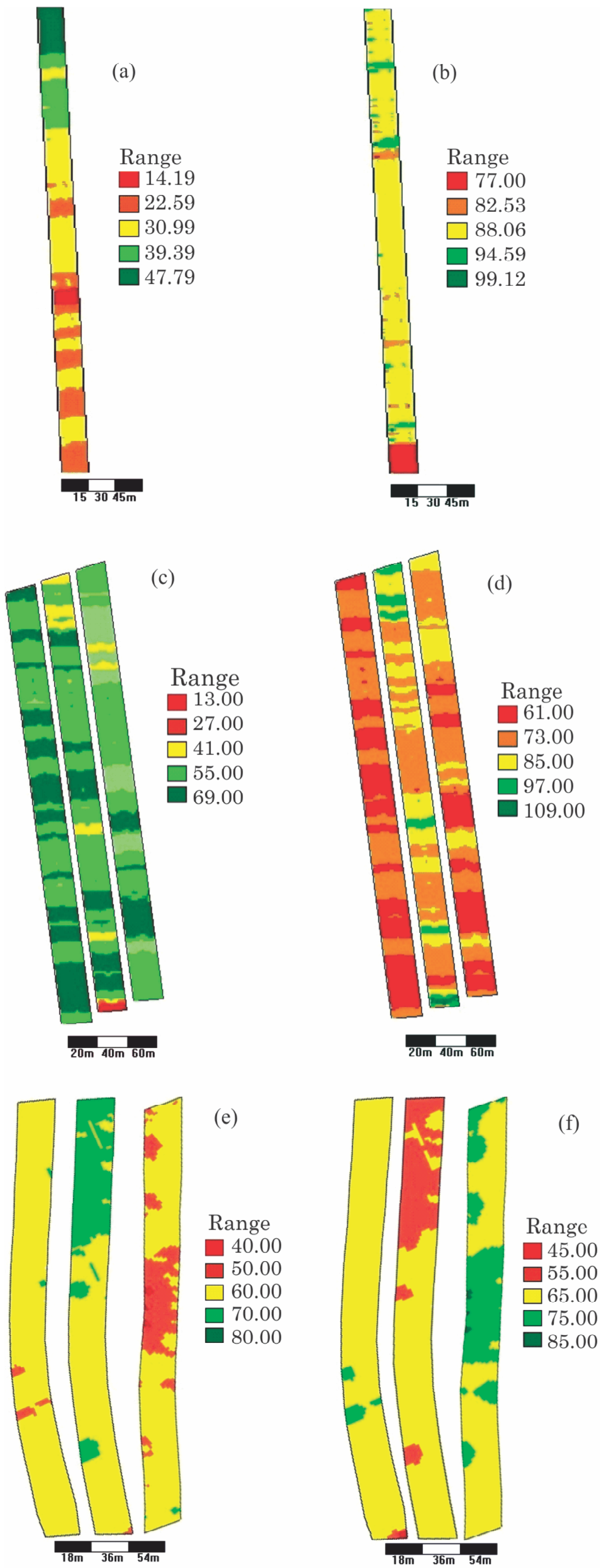

Figure 1. Vegetation index determined by the optical sensor at the phenological stage V8 of corn and the prescription of the variable-rate fertilization at sites 1 (a,b), 2 (c,d) and 3 (e,f).

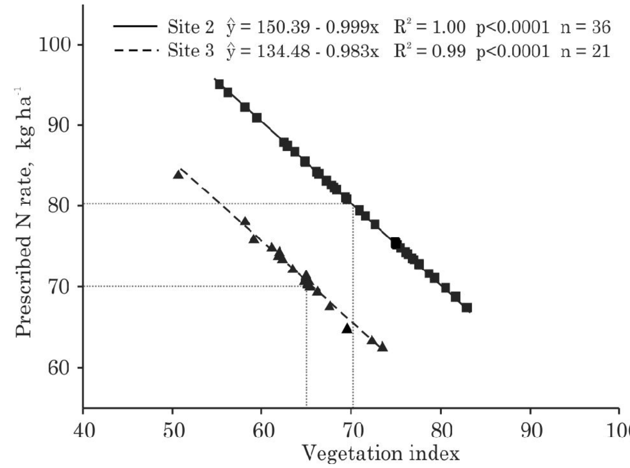

Figure 2. Nitrogen fertilization rate estimated by the optical sensor following the corn vegetation index at the phenological stage V8 for sites 2 and 3.

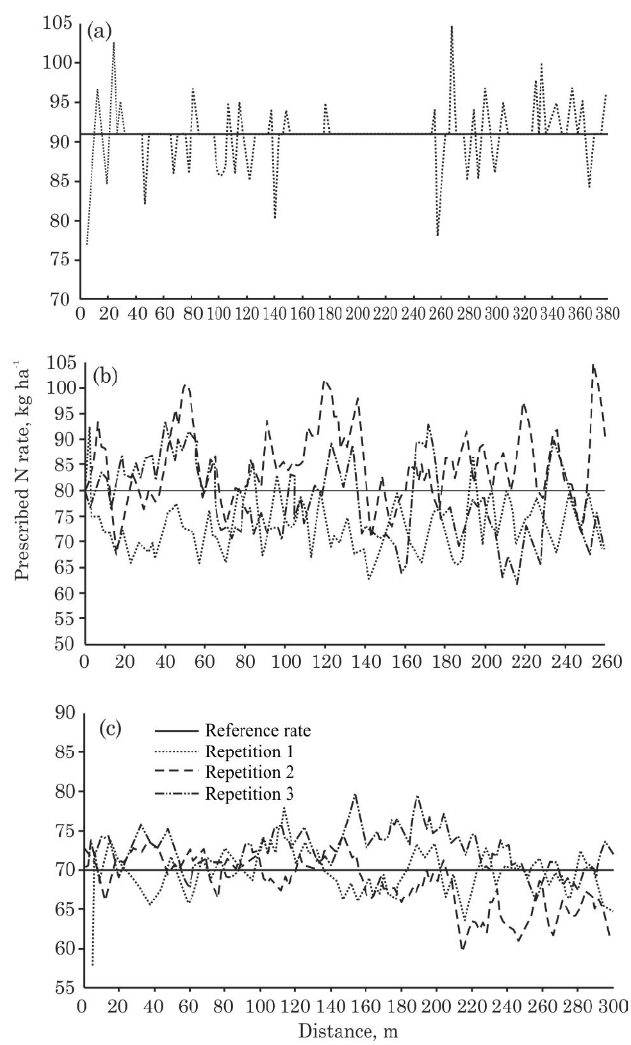

Figure 3. Variable nitrogen fertilization rates estimated by the optical sensor and the reference rate for (a) site 1 (91 kg ha^{-1}), (b) 2 (80 kg ha^{-1}), and (c) 3 (70 kg ha^{-1}).

used only in the second topdressing fertilization (phenological stage V8) when the optical sensor was efficient to capture the corn nutrition status (Bragagnolo et al., 2013). For site 1 (without replication), 70 % of the NF estimated by the optical sensor was coincident with the reference N fertilization rate (91 kg ha^{-1}), while 15.2 and 14.5 % of the NF estimated was lower and higher, respectively. There was a long continuous series (between 170 and 250 m), where the N fertilization rate applied was equal to the reference rate (Figure 3a). This fact was due to a lack of GPS satellite signal reception, when the optical sensor automatically prescribed the reference rate (YARA, 2008).

At site 2, NF was estimated equal to the reference rate on only 7.7 % of the site, while 55.5 and 36.8 % of the remaining NF were below and above the reference rate, respectively. Under severe water stress (Bragagnolo et al., 2013), the spatial variability for VRF was highest at site 2, probably due to differences in soil water storage, since corn N uptake is strongly affected by plant water availability (Amado et al., 2002). The NF prescription at site 3 coincided in 9.7 % with the reference N rate, while 36.9 and 53.4 % of the site had N fertilization rates below and above the reference N rate, respectively.

N fertilization relationships with corn plant nutrition and grain yield

An analysis of the data across the three experimental sites showed a positive correlation between the quantity of corn N uptake at flowering with dry matter production (R^2=0.76; p<0.0001) and grain yield (R^2=0.68; p<0.0001) (Figure 4).

Nitrogen uptake at corn flowering ranged from 31.1 to 182.6 kg ha^{-1} in the different treatments and sites investigated, while corn dry matter production ranged from 5,500 to 12,200 kg ha^{-1} and grain yield ranged from 5,403 to 15,564 kg ha^{-1}. Site 2 had the lowest N uptake and corn grain yield due to unfavorable climatic conditions (Bragagnolo et al., 2013). Site 3, which had the most favorable climatic conditions, showed the highest corn N uptake and corn grain yield of the three sites (Figure 4).

The corn grain yields at the experimental sites were similar to yields obtained by farmers who use advanced technology. The average grain yield for sites 1 and 2 (8,053 and 7,745 kg ha^{-1}, respectively) was 96 and 89 % higher, respectively, than the average grain yield in South Brazil (4,100 kg ha^{-1}) in the 2008/09 growing season (CONAB, 2009). The previous results were obtained in spite of a high precipitation volume during the initial stages of corn development (site 1), and a severe drought during the critical corn growth stages (site 2). The average grain yield at site 3 (13,110 kg ha^{-1}) was about three times higher than the average corn grain yield (4,114 kg ha^{-1}) in the 2010/11 season in Southern Brazil (CONAB, 2011). At this location, the high grain yield could be attributed to the good soil fertility, adequate rainfall, luminosity, and cool nights during the corn growth season. Farmers in the same season and region obtained average corn grain yields of 10,000 kg ha^{-1} (Mânica, 2011).

N fertilization had a positive effect on corn grain yields, despite variations among the sites (Figure 5). The grain yields were lowest in the control treatments (without or with limited N fertilization), where grain yields were 57, 65, and 82 % of the highest grain yield recorded at sites 1, 3, and 2, respectively. The highest grain yields achieved in the trials were 15,564 kg ha^{-1} for 210 kg ha^{-1} of N at site 3, 9,403 kg ha^{-1} for 160 kg ha^{-1} of N at site 1, and 8,571 kg ha^{-1} for 140 kg ha^{-1} of N for site 2.

The response in corn grain yield to N fertilization had similar patterns at sites 1 and 3, where there was a linear increment of grain yield in response to NF rates (Figure 5a). Accordingly, the treatments 150VRF and 140VRF (see Table 2, part I) presented increments of 3,870 and 4,656 kg ha^{-1} of grain yield in relation to the control treatment, at sites 1 and 3, respectively, or 31.5 and 33.3 kg kg^{-1} of corn by N input, respectively (Table 3). However, corn grain yield at site 1, in spite of having a high N fertilization rate

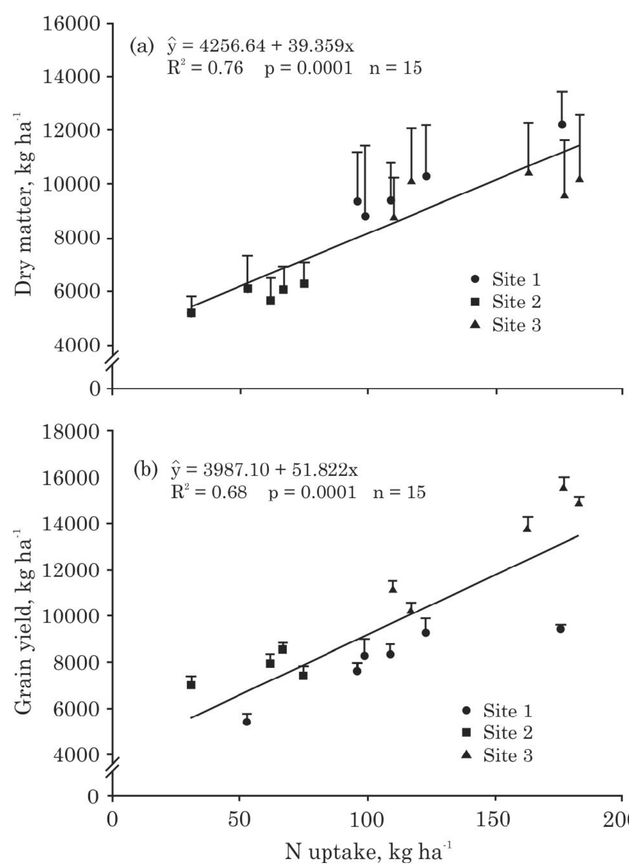

Figure 4. Relationships between corn N uptake at flowering and (a) corn dry matter, and (b) corn grain yield at the three investigated sites under N fertilizer rates.

(140 kg ha^{-1} of N in TSF), was only 81 % of the yield in the control treatment at site 3.

The corn grain yield potential is defined in the early plant growing stages (Cantarella et al., 1993; Fancelli & Dourado Neto, 1996). Thus, even though the corn N demand in the early growing stages is low (Gadioli et al., 2000), a high soil N availability is still required in that period to ensure high corn yields (Binder et al., 2000). The corn N uptake at the phenological stage V8 at site 1 was only 40 % compared to that of site 3 (Bragagnolo et al., 2013). This result may have restricted corn grain yield at site 1. At that site, the nutritional status of corn plants was recovered later and reached 71 % of the amount of N uptake at flowering in relation to site 3. However, corn grain yield at site 1 was only 61 % of that verified at site 3.

For site 2, treatment 140VRF had a corn grain yield increase of 1,540 kg ha^{-1} in relation to the control treatment, or 11 kg corn per 1 kg of N applied. This result should be analyzed, taking into account that the phenological stages with higher water demand are the periods of corn anthesis and milky grain stage. During these crop stages, evapotranspiration (ETP) is high and can range from 5.3 to 6.6 mm day^{-1} (Matzenauer et al., 1995; Kang et al., 2003). However, water supply after anthesis at sites 1 and 2 was close to 4.7 and 0.3 mm day^{-1}, respectively, indicating a severe hydric restriction at site 2. Site 3 had an appropriate amount of water (6.3 mm day^{-1}) in the same period.

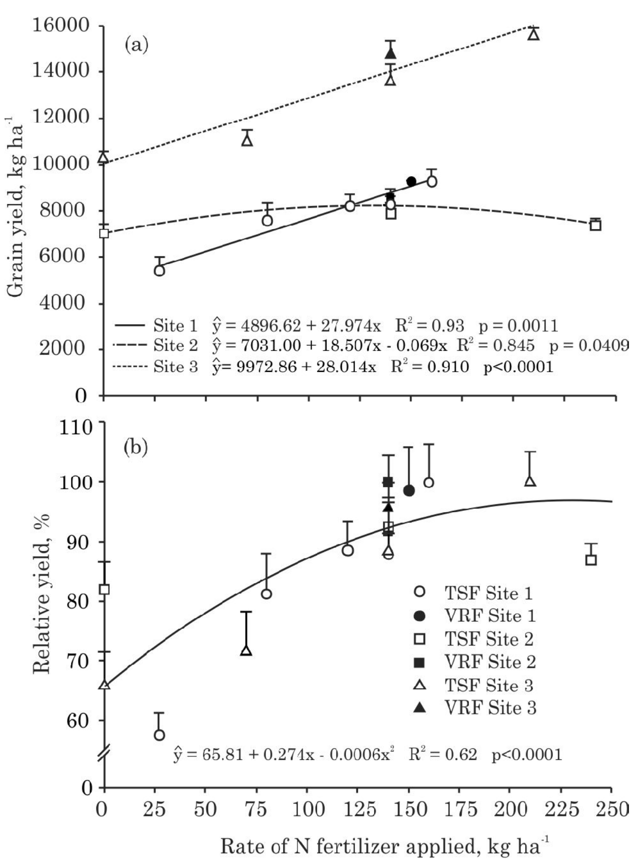

Figure 5. Relationships between N fertilization rates and (a) corn grain yield, and (b) relative corn grain yield at the three investigated sites.

The average MTE of the three investigated sites was 228 kg ha^{-1} of N, while the maximum economic efficiency (MEE) was 125 kg ha^{-1} of N (Figure 5b). Therefore, the NF rate selected to assess the VRF (140 kg ha^{-1} of N) was close to the MEE. Across the sites investigated, the corn grain yield was slightly higher in the optical sensor-based VRF treatments than when fertilization was based on the equations adjusted for TSF (Figure 5b). This result suggests that VRF was an efficient strategy for achieving higher yields with the same NF rate, although statistically there was no difference. Singh et al. (2006) reported that the use of optical sensors allows the maintenance of the grain yield level while reducing the NF rate. Furthermore, in our study the VRF treatments resulted in grain yields similar to those of the highest yield treatments achieved in each site (Figure 5a).

Based on the equations adjusted for grain yield as a function of NF rate, the corn yield of 9,093 kg ha^{-1} at site 1 was estimated for a NF rate of 150 kg ha^{-1} of N under TSF (Figure 5a). This calculation allowed the comparison of TSF and VRF at the same NF rate, showing that VRF increased corn grain yield by 2.0 % (180 kg ha^{-1}). The technical problems with the above-mentioned loss of the GPS signal probably contributed to the lower increase in corn yield than expected. However, at site 2 the same comparison showed that VRF increased corn grain yield by 8.05 % (639 kg ha^{-1}) in relation to TSF. This result was obtained in spite of the adverse climatic conditions registered at this site. The increase in corn grain yield promoted by VRF was coherent with the high redistribution of NF rate in this site (Figure 3). At site 3, VRF increases in corn grain yield by 8.32 % (1,144 kg ha^{-1}) were observed, in relation to TSF. On average, at the three investigated sites, the optical sensor-based VRF increased the corn grain yield by 6.12 % (654 kg ha^{-1}) in relation to TSF, yet this difference was not statistically significant (Table 3).

Previous comparisons of VRF and TSF showed wheat grain yield increases of 0.8 to 1.7 % and protein content increases of 2.4 to 5.1 % (Jørgensen & Jørgensen, 2001, 2007; Mayfield & Trengove, 2009). Raun et al. (2005) also observed slight increases in corn grain yield using another optical sensor (Greenseeker®) in relation to TSF, but with no statistical difference.

N efficiency indices under different fertilizer strategies

The corn N use efficiency (NUE) can be assessed by several indices, e.g., productivity partial factor (PFP), N agronomic efficiency (NAE), N recovery efficiency (NRE), and N physiological efficiency (NPE) (Dobermann, 2005). These indices are presented in

Table 3. Nitrogen use efficiency according to nitrogen fertilization rates and fertilization at the three sites

Site/treatment(1)	Corn plant-technical property		Efficiency index			
	Grain yield	N uptake(2)	PFP	NAE	NRE	NPE
	kg ha^{-1}		kg kg^{-1}			
Site 1						
27TSF	5403 d	53 c	200	-	-	-
80TSF	7639 c	96 c	95	42	0.82	51
120TSF	8336 bc	109 b	69	31	0.60	52
140TSF	8265 bc	99 b	59	25	0.41	62
150VRF	9273 ab	123 b	62	31	0.57	55
160TSF	9403 a	176 a	58	30	0.92	32
Mean	8053	109	71	32	0.66	50
Site 2						
Control	7031c	31 c	-	-	-	-
140TSF	7932 ab	62 b	57	6	0.22	13
140VRF	8571 a	67 b	61	11	0.25	43
240TSF	7445 bc	75 a	31	2	0.21	20
Mean	7745	57	60	6	0.23	25
Site 3						
Control	10231 c	117 c	-	-	-	-
70TSF	11125 c	110 c	159	*	*	*
140TSF	13743 b	163 b	98	25	0.32	71
140VRF	14887 ab	183 a	106	33	0.46	76
210TSF	15564 a	177 ab	74	25	0.42	88
Mean	13110	153	117	27	0.40	78

(1) For the treatments, see Part I; (2) N uptake at flowering. TSF: single N fertilization rate; VRF: variable N fertilization rate based on the optical sensor; PFP: grain yield partial factor; NAE: agronomic efficiency of N; NRE: N recovery efficiency; NPE: physiological N uptake efficiency; *: missing data.

table 3. The average PFP for sites 1 and 3 was higher than 70 kg kg^{-1}. This value was suggested by Dobermann (2005) as critical for agricultural systems with good N management efficiency. The VRF showed an increase in PFP of 5.0, 7.0, and 8.2 % at sites 1, 2 and 3, respectively, in relation to traditional TSF.

The VRF treatments had NAE 24.0 and 32.0 % higher than TSF treatments at sites 1 and 3, respectively. Site 2 had an increment of 8.3 % by the use of VRF. A previous study with corn NF of 140 kg N ha^{-1} showed NAE values ranging from 16 to 26 kg kg^{-1} (Melchiori et al., 2005). Dobermann (2005) reported that NAE values generally ranged from 10 to 30 kg kg^{-1}, and values above 30 kg kg^{-1} represent well-managed agricultural systems. Thus, VRF promoted NAE values of 31 and 33 kg kg^{-1} at sites 1 and 3, respectively, indicating characteristics of an efficient N fertilization management.

The generally expected NRE values are between 0.3 and 0.5 kg kg^{-1}, and those of well-managed N fertilization systems between 0.5 and 0.8 kg kg^{-1} (Dobermann, 2005). The average NRE at site 1 was 0.66 kg kg^{-1}, indicating good efficiency of N fertilization, while site 3 had an intermediary (0.44 kg kg^{-1}) and site 2 a low value (0.23 kg kg^{-1}). The high NRE at site 1 was probably associated with the low aboveground dry matter production and N uptake until the phenological stage V8 of corn (Bragagnolo et al., 2013), which increases the probability of response to N topdressing. At site 1, VRF increased NRE by 39.0 % in relation to TSF. On the other hand, at site 3, the VRF increased NRE by 43.7 %. For the NPE index, values between 30 and 60 kg kg^{-1} are generally reported, however in well-managed N fertilization systems, values should be higher than 60 kg kg^{-1} (Dobermann, 2005). The treatments 140TSF at sites 1 and treatments 140TSF, 140VRF, and 210TSF at site 3 were classified as well-managed systems, according to the critical values proposed by Dobermann (2005).

The use of the real-time crop sensor for the prescription of NF was a promising technique with regard to corn grain yield and NUE, especially when the climatic conditions were favorable to plant growth. Future research should evaluate larger sites than those investigated in this study, ensuring higher spatial variability. The combination of real-time crop sensors with new N fertilizer sources, which allow the reduction of N losses, should also be investigated as complementary strategies to improve NUE.

CONCLUSIONS

1. At all investigated sites, the corn N uptake, dry matter production, and grain yield increased in response to N fertilization. However, lower increases in corn grain yield associated to N fertilization were noted at site 2, due to the severe drought observed during the corn growing period.

2. The N use efficiency assessed by different indices showed an improvement by the use of optical sensor-based variable fertilization rates in relation to the single-rate fertilization traditionally used by farmers.

3. Variable-rate fertilization, which improved the corn plant nutrition status (N uptake) did not increase corn grain yield in relation to single rate fertilization.

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