SOIL AND PLANT NUTRITION - Article

Nitrogen fertilization in top dressing for wheat crop in succession to soybean under a no-till system

Shivelly Los Galetto[1]*, Angelo Rafael Bini[1], Adriano Haliski[1], Danilo Augusto Scharr[1],
Paulo Rogério Borszowskei[2], Eduardo Fávero Caires[3]

1. Universidade Estadual de Ponta Grossa - Agronomia - Ponta Grossa (PR), Brazil.
2. Centro de Ensino Superior dos Campos Gerais - Agronomia - Ponta Grossa (PR), Brazil.
3. Universidade Estadual de Ponta Grossa - Departamento de Ciência do Solo e Engenharia Agrícola - Ponta Grossa (PR), Brazil.

ABSTRACT: Agricultural intensification to improve wheat yield has increased the demand for nitrogen fertilizers. This study aimed to investigate the wheat response in succession to soybean due to application of nitrogen rates and sources in top dressing, as well as to determine the N rates of maximum technical yield (MTY) and maximum economic yield (MEY). A field experiment was carried out in Ponta Grossa, Paraná State, Brazil, on a clayey Typic Hapludox (Oxisol) under a continuous no-till. A randomized block design was used, with 3 replications in a 4 × 3 complete factorial arrangement. The treatments consisted of a control and 3 N rates at 40; 80 and 120 kg·ha^{-1} as calcium nitrate (CN), ammonium sulfate (AS), and urea (UR) in top dressing at tillering of wheat crop. Increasing N rate in top dressing increased plant height, 1,000-grain mass, and grain yield, but it also favored the plant lodging and reduced the hectoliter mass of wheat. The N, P, Ca, and S concentrations in grains increased with N fertilization. MTY would be obtained at 96; 69 and 67 kg N·ha^{-1} in top dressing, respectively, as CN, AS, and UR. Although CN proved to be an effective source of N for application in top dressing, its use was infeasible by the high cost of fertilizer. Both AS and UR showed economic viability, and MEY with these 2 sources would be obtained at a rate of 45 kg N·ha^{-1} in top dressing for wheat yield of 4.0 t·ha^{-1} in succession with soybean.

Key words: *Triticum aestivum* L., nitrogen, calcium nitrate, ammonium sulfate, urea.

*Corresponding author: shivelly@gmail.com

INTRODUCTION

The main wheat producers in order of volume are the United States of America, China, and European Union (USDA 2016). Wheat is the major winter crop grown in Sothern Brazil in succession of corn or soybean (Mori e Ignaczak 2011). The estimated production of wheat in Brazil is around 6.0 million tons, with an average yield of 2.3 t·ha^{-1} (CONAB 2016). Because nitrogen is the nutrient absorbed and exported in the largest amount by the wheat crop, proper management of N fertilization has been one of the most important management practices to increase wheat grain yield and quality (Rossi et al. 2013).

In Southern Brazil, particularly in the states of Rio Grande do Sul and Santa Catarina, N recommendations for the wheat crop have been based on the soil organic matter (SOM) content and the previous crop (corn and soybean) with a grain yield of 2.0 t·ha^{-1} (CQFS and SBCS 2004). It is also recommended adding 20 kg N·ha^{-1} for the wheat grown after soybean and 30 kg N·ha^{-1} for the wheat grown after corn, per additional ton of grain to be produced. The use of SOM content to calculate N rates is based on constant rates of mineralization and release of N. Since factors related to soil, climate, and cropping system interfere with N mineralization, this type of recommendation has not shown great reliability (van Raij 2011). In the Paraná State, the N fertilizer recommendations for the wheat crop have been based solely on previous crop of corn or soybean (RCBPTT 2014).

The development of more productive genotypes requires some adjustments in N fertilization to meet adequate demand of N by plants. When applied at a low rate, N can limit grain yield, whereas excessive N rate can cause plant lodging, making it difficult to harvest and reduce wheat yield (Schwenke et al. 2014). In addition, the use of excessive N rate results in a high risk to the environment, leading to economic and environmental unsustainability of the agricultural system.

Urea (UR) is the most produced and used N source in agriculture. However, depending on soil and weather conditions, considerable NH$_3$-N losses by volatilization can occur following UR application on the soil surface (Soares et al. 2012; Schwenke et al. 2014). Wheat in Southern Brazil has been grown in no-till systems. Cover crop residue on the soil surface, which is essential to the no-till success, reduces the contact of the fertilizer with the soil and decreases the conversion of NH$_3$ to NH$_4^+$, favoring NH$_3$ volatilization losses (Prando et al. 2013). The NH$_3$ losses occur due to hydrolysis of UR by urease, producing ammonium carbonate, which readily unfolds in NH$_3$ e CO$_2$ (Tasca et al. 2011). The rate of hydrolysis of UR is influenced by the amount and type of vegetation present in the soil surface, as well as amount of N applied (Espindula et al. 2014).

Because of high cost of N fertilizer for production crop, the use of N sources which promote lower N-NH$_3$ losses by volatilization, as calcium nitrate (CN) or ammonium sulfate (AS), would be a way to increase fertilizer efficiency and maximize wheat yield (Yano et al. 2005; Teixeira Filho et al. 2010; Prando et al. 2013; Schwenke et al. 2014). Since Ca exhibits synergism with N (Franco et al. 2007), using an N source containing Ca could increase the N use efficiency by wheat. However, there is insufficient information on the efficiency and economic viability of using CN in wheat crop. Field studies comparing traditional N sources applied in top dressing in wheat, such as AS and UR, with the use of CN (which contains Ca in its composition), are essential to evaluate the N use efficiency and to define appropriate rates of application by the N sources.

This study reports a field trial that examined the effects of N rates and sources in top dressing at tillering of wheat following soybean in a no-till system on yield and quality of wheat. The objectives were (i) to evaluate grain yield and nutrient concentration in grain of wheat as affected by N rates applied in the forms of CN, AS, and UR; (ii) to determine the N rates of maximum technical yield (MTY) and maximum economic yield (MEY) to obtain high wheat yield.

MATERIAL AND METHODS

The experiment was carried out in Ponta Grossa, Paraná, Brazil (lat 25°03′S; long 50°05′W) on a clayey Typic Hapludox (Oxisol) (Embrapa 2013). According to Köppen-Geiger System (Peel et al. 2007), the climate at the site is classified as a Cfb type (mesothermal, humid, subtropical), with mild summer, frequent frosts during the winter, and no defined dry season. The average altitude is 972 m with average maximum and minimum temperatures of 22 and 13 °C, respectively. The annual precipitation is about 1,550 mm. Before the establishment of the experiment, soil chemical and granulometric analyses of the 0 – 0.20 m depth showed the following results: pH (1:2.5 soil: 0.01 mol·L^{-1} CaCl$_2$ suspension)

of 4.8; total acidity (H + Al) of 70.8 mmol$_c$·dm^{-3}; exchangeable Ca^{2+}, Mg^{2+}, and K$^+$ contents of 33.5; 9.0 and 2.0 mmol$_c$·dm^{-3}, respectively; P (Mehlich-1) of 10.7 mg·dm^{-3}; SO$_4$–S (0.01 mol·L^{-1} calcium phosphate) of 8.3 mg·dm^{-3}; total organic matter of 43.9 g·dm^{-3}; and 490; 122 and 388 g·kg^{-1} of clay, silt, and sand, respectively. The field site had been used for grain cropping under the no-till system during 10 years with predominance of soybean-wheat succession. Only during the 2007 and 2012 winter season, black oat was grown as a cover crop.

A randomized block design was used, with 3 replications in a 4 × 3 complete factorial arrangement. Plot size was 5.0 × 4.0 m, with 23 rows. The treatments consisted of a control and 3 N rates at 40; 80 and 120 kg·ha^{-1} as CN, AS, and UR in top dressing at tillering of wheat crop. The N sources used contained in its composition: CN — 160 g N·kg^{-1} and 136 g Ca·kg^{-1}; AS — 210 g N·kg^{-1} and 220 g S·kg^{-1}; and UR — 440 g N·kg^{-1}. The N rates as CN, AS, and UR were applied manually in a single application on the total area at the soil surface of each plot at 20 days after plant emergence, preceding a rain event of 20 mm.

Wheat (*Triticum aestivum* L.) cv. Supera was sown on June 22, 2014, after the soybean crop at a seeding rate of 58 seeds·m^{-1} and row spacing of 0.17 m. During wheat sowing, 330 kg·ha^{-1} of the 5–25–25 (N–P$_2$O$_5$–K$_2$O) formula were applied. The control of pests, disease, and weeds was carried out according to the needs of the wheat crop, so as to enable adequate development of the plants to achieve the maximum grain yield potential. The air temperature and rainfall historical averages (40 years) as well as those that occurred during the wheat crop development period in 2014 are shown in Figure 1. Throughout the development period

Figure 1. Monthly rainfall and temperature during the development period of the wheat crop in 2014, and 40 years average monthly rainfall and temperature at Ponta Grossa, Southern Brazil.

of the wheat crop, there was no water limitation. Rainfall and temperature data for the duration of the experiment were very close to the historical average of the region.

Samples of wheat flag leaves were collected for foliar analysis diagnosis, in 30 plants of each subplot, during the crop flowering period. The concentrations of N, P, K, Ca, Mg, and S in leaves were determined according to the procedures described by Malavolta et al. (1997).

At physiological maturity of the wheat crop, plant height and percentage of lodged plant were determined according to the methodology described by Prando et al. (2012). Plant height was evaluated in 3 plants of each plot (from the plant base to the apex of the principal stem, excluding the awn). Lodging of the plants was also evaluated by visual estimation of the percentage of plants with slope upper than 45° in a central area of 12 m² of each plot. Soon after, grain was harvested from 7.65 m² (middle of 15 rows × 4 m in length), and grain yield was expressed in 130 g·kg^{-1} moisture content. After harvest, a sample grain was ground, and grain concentrations of N, P, K, Ca, Mg, and S were analyzed according to the procedures described in Malavolta et al. (1997).

The 1,000-grain mass was determined by weighing 2 sub-samples of 500 grains of each plot and the hectoliter mass (HM), by weighing a sample of known volume (250 mL), being the result transformed in standard unit (kg·hL^{-1}).

The partial factor productivity of N (PFP$_N$) was calculated according to Ladha et al. (2005) by the equation:

$$PFP_N \ (kg \cdot kg^{-1}) = G_N / N_A$$

where: G$_N$ is the grain yield by adding a determined N rate (kg·ha^{-1}); N$_A$ is the amount of N (kg·ha^{-1}) applied. For this calculation, it was used the total amount of N applied in wheat crop in both sowing and top dressing.

Data were submitted to analysis of variance and regression methods. The N rates applied were analyzed through regression analyses where the criterion for model selection was the magnitude of the determination coefficients significant at $p < 0.05$. The effects of N sources were compared by the Tukey's test at $p = 0.05$. Statistical analysis was performed by using the computational program Sisvar 5.3. An economic analysis of N fertilization was conducted using global average prices of the products over the last 5 years. The average prices of fertilizers per kg of N, based on Cost, Insurance and Freight (CIF) payment,
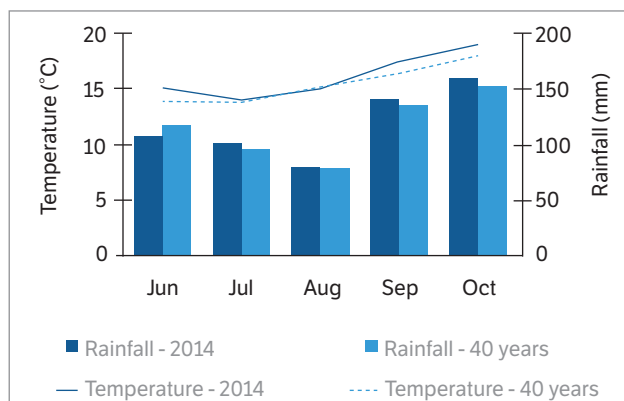
were estimated at $ 3.86 for CN, $ 1.94 for AS, and $ 1.37 for UR. The average price of wheat was estimated at $ 263.00 per ton of grain. Based on average prices of the products, the ratio of unit cost between kg of N and kg of wheat grain was 14.7 for CN, 7.4 for AS, and 5.2 for UR. MTY and MEY of N in top dressing were calculated according to the procedures described by Alvarez (1994).

RESULTS AND DISCUSSION

The concentrations of N, P, K, Ca, Mg, and S in leaves (Table 1) as well as the concentrations of N, P, K, and Mg in wheat grain (Table 2) were not significantly influenced ($p > 0.05$) by the interaction effect of rates and sources of N in top dressing. The concentrations of Ca and S in wheat grain were significantly influenced ($p < 0.05$) by the interaction of rates and sources of N (Table 3).

Increasing N rates in top dressing in the wheat crop linearly increased the N, P, Ca, and S concentrations and did not affect the K and Mg concentrations, both in leaves (Table 1) and grain (Tables 2,3). The Ca-leaf concentration was higher with the use of CN and the S-leaf concentration was higher with the use of AS (Table 1). The Ca-grain concentration was also higher with the application of CN at the highest N rate

(120 kg·ha⁻¹) and the S-grain concentration was higher with the application of AS at the highest N rates (80 and

Table 2. Concentrations of N, P, K, and Mg in wheat grain as affected by nitrogen rates and sources applied in top dressing in a no-till system.

Treatments	N	P	K	Mg
N rates in top dressing (kg·ha⁻¹)	g·kg⁻¹			
0	22.4	2.6	5.3	1.0
40	23.3	2.8	5.3	1.1
80	25.1	2.9	5.0	1.1
120	25.3	3.0	5.1	1.1
Effect	L**	L**	ns	ns
CV (%)	5.9	6.0	2.5	4.2
N sources (kg·ha⁻¹)	N	P	K	Mg
	g·kg⁻¹			
Calcium nitrate	23.7	2.9	5.2	1.1
Ammonium sulfate	24.1	2.8	5.2	1.1
Urea	24.3	2.8	5.2	1.1
LSD	2.0	0.4	0.3	0.1
CV (%)	1.3	3.4	0.4	2.7

**p < 0.01. ns = Non-significant; L = Linear effect by regression analysis; CV = Coefficient of variation; LSD = Least significant difference by Tukey's test (p = 0.05).

Table 3. Concentrations of Ca and S in wheat grain as affected by nitrogen rates and sources applied in top dressing in a no-till system.

N rates in top dressing (kg·ha⁻¹)	N sources		
	Calcium nitrate	Ammonium sulfate	Urea
	Ca (g·kg⁻¹)		
0	0.17 a	0.18 a	0.17 a
40	0.21 a	0.20 a	0.24 a
80	0.27 a	0.22 a	0.23 a
120	0.34 a	0.24 b	0.25 b
Effect	L**	L*	L*
CV (%)	25.9	10.6	13.9
N rates in top dressing (kg·ha⁻¹)	S (g·kg⁻¹)		
0	0.92 a	0.93 a	0.93 a
40	1.06 a	1.12 a	1.14 a
80	1.24 b	1.37 a	1.19 b
120	1.21 b	1.33 a	1.16 b
Effect	L**	L**	L**
CV (%)	11.6	14.9	9.3

Table 1. Concentrations of N, P, K, Ca, Mg, and S in wheat leaves as affected by nitrogen rates and sources applied in top dressing in a no-till system.

Treatments	N	P	K	Ca	Mg	S
N rates in top dressing (kg·ha⁻¹)	g·kg⁻¹					
0	42.5	2.4	25.3	3.3	1.8	2.7
40	43.0	2.7	26.2	4.0	2.0	3.0
80	44.2	2.9	25.5	4.9	2.1	3.2
120	46.4	2.8	25.6	4.8	1.9	3.4
Effect	L**	L**	ns	L**	ns	L*
CV (%)	3.4	6.9	1.3	15.3	5.7	8.4
N sources (kg·ha⁻¹)	N	P	K	Ca	Mg	S
	g·kg⁻¹					
Calcium nitrate	43.4	2.7	25.5	4.6	2.0	2.9
Ammonium sulfate	43.5	2.6	26.4	3.9	1.9	3.4
Urea	44.7	2.6	25.5	4.0	1.8	3.0
LSD	3.2	0.2	1.6	0.5	0.2	0.3
CV (%)	1.3	1.8	1.6	7.4	4.3	7.0

**p < 0.01; *p < 0.05. ns = Non-significant; L = Linear effect by regression analysis; CV = Coefficient of variation; LSD = Least significant difference by Tukey's test (p = 0.05).

Means followed by the same letter in the line do not differ by Tukey's test (p = 0.05); **p < 0.01; *p < 0.05. L = Linear effect of nitrogen rates applied in top dressing by regression analysis; CV = Coefficient of variation.

120 kg·ha⁻¹) (Table 3). Since the CN had 136 g Ca·kg⁻¹ and the AS had 220 g S kg⁻¹ in its composition, the effect of these sources on Ca and S nutrition certainly has occurred because of larger amount of Ca and S added to the soil. The N sources did not change the N, P, K, and Mg concentrations in leaves (Table 1) and wheat grain (Table 2).

The synergistic effect between N and P is well known, and this effect was observed in our study, since the increase in N rates in top dressing increased the N and P concentrations in leaves (Table 1) and wheat grain (Table 2), certainly due to higher P uptake by plants. The NO_3^- uptake occurs by active process, which requires metabolic energy for transportation from an electrochemical potential gradient, requiring greater amounts of ATP, formed from the P uptake (Bredemeier and Mundstock 2000). Thus, with the supply of N in top dressing in the wheat crop, the plant may have absorbed larger amount of P in order to maintain balance in metabolism (Ruffy 1990). Moreover, the increase in N provided by top dressing fertilization may have favored root growth of wheat plant (Xue et al. 2014). This could be facilitated by the P uptake, since the mobility of this nutrient in the soil is low (Santos et al. 2008). In our study, increasing the N rate in top dressing significantly increased the N and S concentrations in leaves (Table 1) and wheat grain (Table 3), and this effect must have occurred because of the N × S interaction. The synergistic effect between N and S can directly influence the quality of products. Sulfur increases the methionine concentration in the cereal proteins, and N can change the proportion of albumins, globulins, glutenins,

and polaminas (Tea et al. 2005). Salvagiotti et al. (2009) found that S fertilization in the wheat crop improved the N use efficiency by increasing N uptake by plants due to N × S interaction. Anyway, leaf concentrations of P and S in all treatments were in the sufficient range for wheat crop (Bélanger et al. 2011; Steinfurth et al. 2012).

Wheat grain yield was significantly influenced (p < 0.05) by the interaction of rates and sources of N (Figure 2a). For the 3 N sources, wheat grain yield increased with an increase in top-dressed N rates, exhibiting a quadratic response. The N sources only provided significant differences in wheat grain yield when the higher N rates were applied (80 and 120 kg·ha⁻¹). Grain yield was significantly higher with the use of CN and AS than with the use of UR when 80 kg·N ha⁻¹ were applied in top dressing. At 120 kg N·ha⁻¹, grain yield was higher with the application of CN compared with the use of AS and UR.

In our study, wheat was grown in succession to soybean. Leguminous crops provide considerable N residual in the soil due mainly to the smaller C/N relation of straw (about 20:1), and higher rates of decomposition and mineralization of N can be recycled and recovered by the crop in succession (Nunes et al. 2011b). This could explain the decrease in grain yield when the highest N rate was applied (Figure 2a). Although the greater N uptake provides greater protein concentration in the grain, the excess of N often negatively influences HM, impairing the criteria for marketing grain, since the protein content is not a parameter used in Brazil (Nunes et al. 2011a). In other studies, increased supply of N applied in top dressing also increased wheat grain yield according to the quadratic model, with estimated rates from 70 to 126 kg·ha⁻¹ to obtain grain yields ranging from 3,654 to 5,032 kg·ha⁻¹ (Teixeira Filho et al. 2010, 2011; Espindula et al. 2010; Nunes et al. 2011a). In a soil with high residue of N in succession to leguminous crops, Prando et al. (2012) obtained wheat grain yield of 4,347 kg·ha⁻¹, similarly to that achieved in our study.

Based on regression equations for grain yields (Figure 2a) and unit cost ratio of products (kg of N per kg of wheat grain of 14.7 for CN, 7.4 for AS and 5.2 for UR), MTY and MEY would be reached with rates of 96 and 0.7 kg N·ha⁻¹ as CN; 69 and 45 kg N·ha⁻¹ as AS; and 67 and 45 kg N·ha⁻¹ as UR, respectively. Wheat grain yields at rates of MTY and MEY would be 4,131 and 3,434 kg·ha⁻¹ with CN; 4,182 and 4,082 kg·ha⁻¹ with AS; and 4,015 and
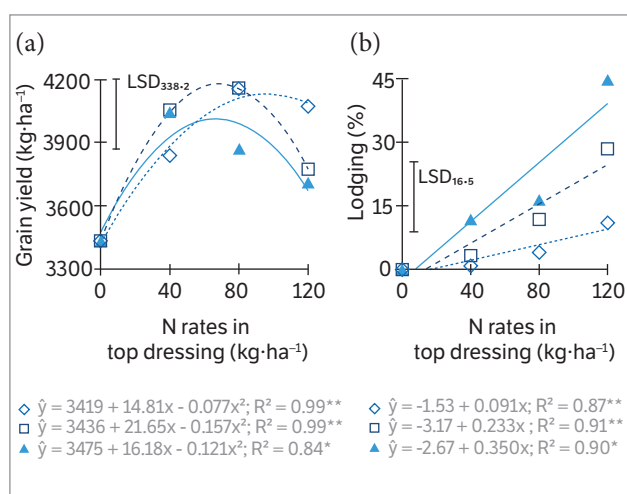

Figure 2. Grain yield (a) and lodging (b) of wheat considering the nitrogen rates and sources in top dressing. **p < 0.01; *p < 0.05. ◇ = Calcium nitrate; □ = Ammonium sulfate; ▲ = Urea; LSD = Least significant difference by Tukey's test (p = 0.05).

3,958 kg·ha^{-1} with UR, respectively. Although CN application have provided an increase in the order of 20% in grain yield, its use has been totally infeasible because of high cost of the fertilizer. Based on average price of wheat of $ 263.00 per ton of grain, the economic return with the use of AS and UR would be $ 85.00 and $ 65.00 per hectare, respectively, with the N application rate of MEY (45 kg·ha^{-1}). Therefore, these 2 sources showed economic viability for application at tillering of wheat following soybean in a no-till system. The MEY rate of N obtained for top-dressed application as AS and UR (45 kg N·ha^{-1}) is in agreement with the current N fertilizer recommendation for wheat crop in the Paraná State, in soil with previous soybean crop (30 – 60 kg N·ha^{-1}) (RCBPTT 2014).

The PFP$_N$ was not significantly influenced (p > 0.05) by the interaction effect of rates and sources of N on top dressing. There was no change in PFP$_N$ with the different N sources. Considering the average amount of N applied by the N sources on wheat crop, the PFP$_N$ varied from 86 to 87 kg·kg^{-1}. Due to the law of diminishing returns, wheat yield gains decreased with increasing N fertilizer rates. The PFP$_N$ decreased from 208 kg·kg^{-1} with N application only at sowing (16.5 kg N·ha^{-1}) to 70; 42; and 28 kg·kg^{-1} with the application of 16.5 kg N·ha^{-1} at sowing more 40; 80 and 120 kg N·ha^{-1} in top dressing, respectively. Since the average global value of the PFP$_N$ for the wheat crop is 44.5 kg·kg^{-1} (Ladha et al. 2005), the PFP$_N$ value obtained in our study was higher than the world average value with N application at a rate of 56.5 kg N·ha^{-1} (16.5 kg·ha^{-1} at sowing and 40 kg·ha^{-1} in top dressing) and remained very close to the world average value with N application at 96.5 kg·ha^{-1} (16.5 kg·ha^{-1} at sowing and 80 kg·ha^{-1} in top dressing).

The plant lodging of wheat was significantly influenced (p < 0.05) by the interaction of rates and sources of N (Figure 2b). Increasing the N rates in top dressing increased linearly the percentage of lodged plants for the 3 N sources studied. However, with the application of the higher N rate (120 kg·ha^{-1}), the plant lodging was significantly lower with the use of CN compared to UR. When the AS was applied, the percentage of lodged plants was not significantly different from treatments with CN and UR. The plant lodging was 11; 28 and 45% with the use of CN, AS, and UR, respectively, at 120 kg N·ha^{-1}. Since the leaf Ca concentration was higher with the use of CN (Table 1), these results should be related to the increase in Ca uptake by wheat crop resulting from

the application of CN to the soil. With the application of 120 kg N·ha^{-1} in the form of CN, there was an addition of 102 kg Ca·ha^{-1}. Calcium in the form of pectate is the main constituent of the middle lamella and provides resistance to cell wall, participating in the biosynthesis of lignin (Hepler 2005). The increase in lignin in wheat stems promotes greater resistance to lodging, suggesting that lignin increases the physical strength of the internodes (Peng et al. 2014). Similar response related to the use of AS and UR on plant lodging of wheat was also observed by Teixeira Filho et al. (2010) and Prando et al. (2013).

In several studies, it is reported evidence of the influence of plant lodging on wheat grain yield (Espindula et al. 2010; Melero et al. 2013; Prando et al. 2012; Teixeira Filho et al. 2010, 2011; Zagonel and Fernandes 2007). However, in our study, there was no significant correlation between the wheat grain yield and plant lodging (r = 0.18^{ns}). Lodged plants can harm the grain filling due to the greater difficulty of the vascular tissue in the translocation of assimilates and nutrients to the grains (Berry et al. 2004). Berry e Spink (2012) evaluated the lodging effect on wheat grain yield due to the induction of different degrees of inclination. The authors concluded that plants with 45° inclination caused up to 18% of losses on grain yield, while, with 80° slope, losses on grain yield reached up to 54%. In addition, the decrease in wheat grain yield due to the plant lodging has been usually more pronounced in the mechanized harvest, in which the fallen plants would not be harvested (Peng et al. 2014). In our study, the absence of a significant correlation between wheat grain yield and plant lodging could occur because the harvest was manual, i.e. all the plants were harvested and threshed, including those which were lodged.

The wheat plant height was not significantly influenced (p > 0.05) by the interaction effect of rates and sources of N in top dressing. However, considering the treatment means, there was main effect of both rates and sources of N on plant height (Figures 3a,b). The N rates applied in top dressing at tillering of wheat crop linearly increased plant height (Figure 3a). In other studies, it was also observed linear increase in wheat plant height with the increment of N rates (Espindula et al. 2010; Pietro-Souza et al. 2013). Because the plant lodging of wheat is caused by excessive vegetative growth, which results in taller plants, thinner stems and susceptible to tipping (Peng et al. 2014), the greater plant height due to the increase in N rates in top dressing certainly contributed to increase the percentage of plants lodged (Melero et al. →

2013; Nunes et al. 2011a). In addition, adequate rainfall in the grain filling stage (Figure 1) may have accentuated this effect (Berry and Spink 2012). However, compared to the use of AS and UR, the application of CN provided plants with greater height (Figure 3b) and, at the same time, lower percentage of plants lodged (Figure 2b) at the highest N rate (120 kg·ha^{-1}), probably due to the presence of Ca in its composition. Calcium is directly associated with meristematic growth of plant cells responsible for the extension of the stem, in addition to stimulation of the mitotic division of these cells (Hepler 2005).

The HM (Figure 3b) and the 1,000-grain mass (Figure 3c) of wheat were not significantly influenced (p > 0.05) by the interaction effect of rates and sources of N in top dressing. The HM decreased linearly with the increase in N rates, at a rate of 0.041 kg·hL^{-1} per kg of N applied in top dressing (Figure 3b). The N sources did not cause significant changes in wheat HM. In several studies involving the application of N rates in the wheat crop, there was also a linear reduction in HM by using N rates of up to 120 kg·ha^{-1} (Cazetta et al. 2008; Prando et al. 2013) or 200 kg·ha^{-1} (Trindade et al.

2006; Teixeira Filho et al. 2010). In these studies, the lowest HM with increasing N rate was attributed to the increase in the number of ears or grains per area, which may cause an increase in the competition by assimilates, compromising grain quality. However, in our study, there was no such effect because the 1,000-grain mass of wheat was raised with the application of N rates, exhibiting a quadratic response (Figure 3c). Based on the regression equation obtained, the maximum 1,000-grain mass (38 g) would be reached with the rate of 70 kg N·ha^{-1} in top dressing. Thus, a reduction in HM because of increased number of ears or grains per area would be expected only in higher N rates. Relating the 2 parameters, the HM and the 1,000-grain mass, it appears that there is no relationship between them, i.e. the higher HM does not always correspond to the greater 1,000-grain mass, a fact confirmed in the study carried out by Smanhotto et al. (2006). According to these authors, each cultivar has distinct grain size and, consequently, different mass. The HM is divided by the mass of a known volume; regardless of the grain size, the volume is constant, while the 1,000-grain mass does not involve volume, but only mass. In our study, it is more likely that the reduction in HM with increasing N rates occurred due to the higher plant lodging. Lodged plants generate ears in a more humid environment, leading to an increase in germination or rot grain and decrease in HM (Zagonel and Fernandes 2007). Regarding N sources, the use of CN provided greater 1,000-grain mass than the application of AS and UR (Figure 3c), possibly due to the effects of CN on lower percentage of lodged plants (Figure 2b), which may have facilitated the grain filling (Berry et al. 2004).

CN = Calcium nitrate
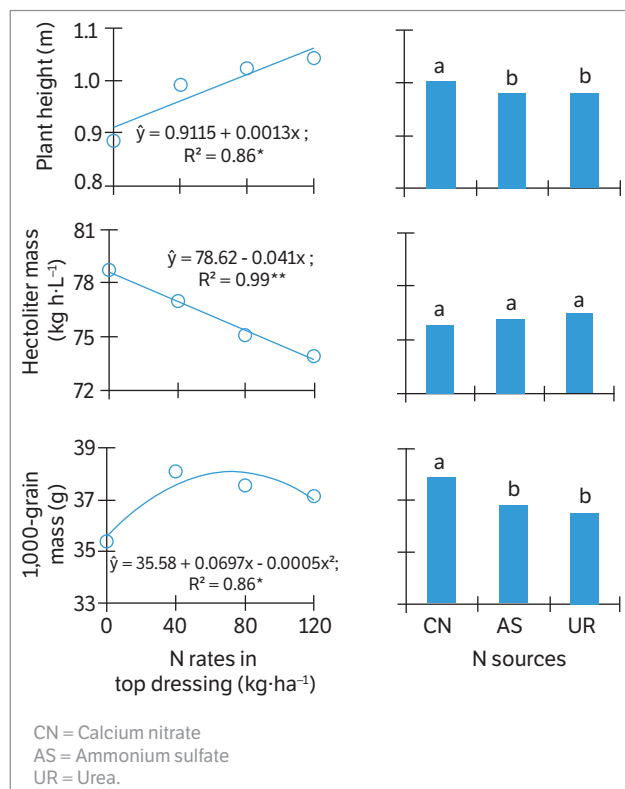AS = Ammonium sulfate
UR = Urea.

Figure 3. Plant height (a), hectoliter mass (b), and 1,000-grain mass (c) of wheat considering the nitrogen rates and sources in top dressing. **p < 0.01; *p < 0.05. Means followed by the same letter do not differ by Tukey's test (p = 0.05).

CONCLUSION

Calcium nitrate is an efficient source for supplying N to wheat grown in succession to soybean, but its use is unfeasible by the high cost of the fertilizer. Ammonium sulfate and urea are economically viable N sources for application in top dressing in wheat following soybean.

The maximum technical yield to the wheat crop following soybean in a no-till system is achieved with the application of 96 kg N·ha^{-1} as CN, 69 kg N·ha^{-1} as AS, and 67 kg N·ha^{-1} as UR.

A rate of 45 kg N·ha^{-1} as AS or UR in top dressing to no-till wheat following soybean provides the maximum economic yield to obtain grain yield of 4.0 t·ha^{-1}.

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