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Nitrogen Fertilization of No-Tillage Winter Cereals in the South-Central Region of Paraná, Brazil

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ABSTRACT: High winter cereal yields depend on an adequate supply of nitrogen (N). We developed a system for indicating N rates for wheat and barley in the South-Central region of the state of Paraná, Brazil, using results of 72 field experiments conducted from 2007 to 2012. The N rates recommended for winter cereals were estimated to supply the amounts of N fertilizer needed to obtain increasing yields (<3.5, 3.5-4.5, 4.5-5.5, and >5.5 Mg ha^{-1}) of crops grown after soybean and corn on soils with a variable organic matter content (<40, 40-60, and >60 g dm^{-3}). The apparent mineralization rate of soil N was estimated to be 1 % and the N fertilization efficiency 50 %. The N rates recommended for wheat ranged from 30 to 150 kg ha^{-1} when cultivated after soybean, and from 30 to 170 kg ha^{-1} after corn. The N rates for barley ranged from 30 to 120 kg ha^{-1} when grown after soybean, and from 30 to 130 kg ha^{-1} after corn. These N rates are consistent with those indicated by the Soil Fertility Commission for the states of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016), and also with the rates of maximum economic efficiency estimated in our study. The proposed N rate recommendation system can be used by agricultural technicians and producers to manage N fertilization of wheat and barley in the South-Central region of Paraná, Brazil.

Keywords: *Triticum aestivum*, *Hordeum vulgare* L., N indication, urea.

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INTRODUCTION

Winter cereals grown in rotation with soybean (*Glycine max L.*) or corn (*Zea mays L.*) in the South-Central region of Paraná, Brazil, cover an area of approximately 60,000 ha, cultivated exclusively under no-tillage (Fontoura et al., 2015). Roughly one-half of the acreage produces wheat (*Triticum aestivum* L.) and the other half barley (*Hordeum vulgare L.*), with a mean yield of around 5,000 kg ha^{-1} (Agrária, 2016). However, grain yield in both crops in experimental areas managed by the *Fundação Agrária de Pesquisa Agropecuária* (FAPA) in Guarapuava-PR is as high as 9,000 kg ha^{-1}, which testifies to the high productive potential of these cereals in the region and demonstrates a marked yield difference between experimental sites and farmers' fields.

Grain productivity depends not only on the use of productive varieties, and suitable phytosanitary and weed control measures (Benin et al., 2012), but also on an adequate supply of nutrients (particularly nitrogen N) (De Bona et al., 2016). However, the lack of recommendation systems to facilitate efficient N fertilization in some Brazilian regions has led to poorer cereal responses to N fertilization and lower profitability relative to other crops such as corn. The N rates recommended for wheat in the states of Mato Grosso do Sul and São Paulo are based on grain yield expectations and the preceding crop (Minella, 2015). However, in the states of Rio Grande do Sul and Santa Catarina, the estimated N rates also consider the organic matter content, which is related to the potential of the soil to supply the crops with N (CQFS-RS/SC, 2016).

The South-Central region of Paraná lacks an official N recommendation system for winter cereals. Despite the high technology levels in regional agriculture, the recommended N rates for winter cereals have been based on average N rates established by technicians and producers or on recommendations extrapolated from other regions such as Rio Grande do Sul and Santa Catarina. As with corn (Fontoura and Bayer, 2009), a specific N recommendation system for winter cereals might increase the agronomic efficiency of N fertilizers while minimizing the potential impact of these nutrient inputs on the environment.

In this study, we tested the hypothesis that N rates to be applied aiming to attain crescent grain yields of wheat and barley are also dependent on soil organic matter level and preceding summer crop. Our main objective was to develop an N recommendation system for wheat and barley in the South-Central region of Paraná that considers the preceding crop (soybean or corn), soil organic matter, and expected grain yield by examining the results of 72 field experiments performed from 2007 to 2012 in experimental areas managed by the FAPA.

MATERIAL AND METHODS

Region description

The South-Central region of Paraná is located on the third physiographic plateau of the state (Figure 1), 800 to 1,200 m a.s.l. The soils were derived from basalt and are predominantly Brown Latossol by Brazilian Classification (Fontoura et al., 2015) and clayey Hapludox (Soil Survey Staff, 2014). With regard to soil organic matter (OM), 59 % of the soils of the region managed by the *Cooperativa Agrária Agroindustrial* (Guarapuava, Paraná) contain 41-60 g dm^{-3} of OM, 16 % contain less than 40 g dm^{-3} of OM, and 25 % more than 60 g dm^{-3} of OM (Figure 1).

The climate in the region is humid subtropical (Cfb according to Köppen system), with an average annual rainfall of 1,900 mm well distributed throughout the year, with no dry season; rainfall is lowest in August, coinciding with the period of N fertilizer topdressing on winter cereals. Based on data from the weather stations of the FAPA, monthly rainfall ranges from 145 to 220 mm, except in August, with about 100 mm only. The average annual temperature is 16.8 °C and monthly averages range from 12.6 °C in July to 20.3 °C in January (Figure 1).

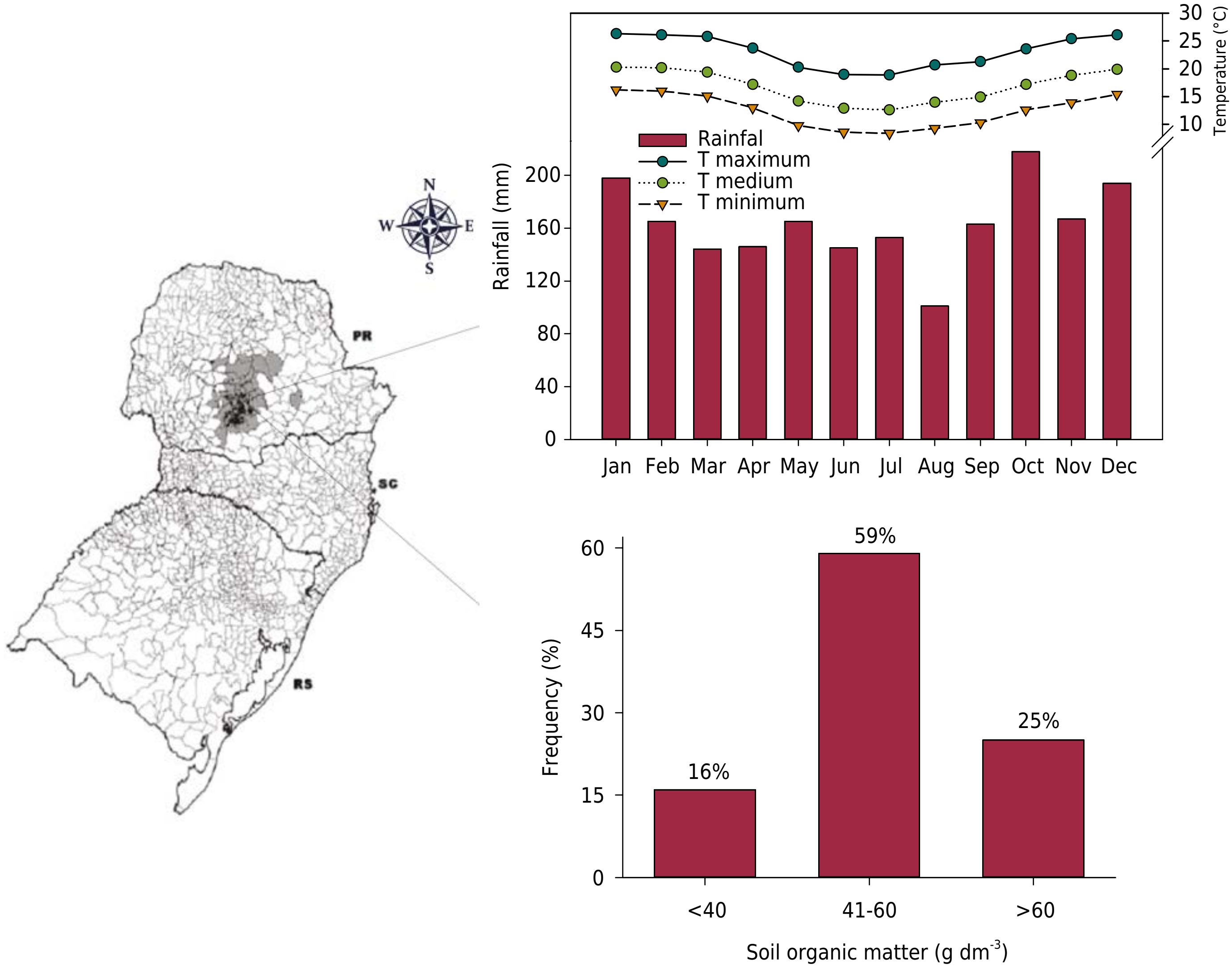

Figure 1. Map of Southern Brazil and South-Central Paraná (in gray), where the experiments of N fertilization of winter cereals were conducted. Monthly rainfall and temperatures (maximum, medium, and minimum), and soil organic matter distribution (Fontoura et al., 2015) are shown.

Experiments

The study was based on results of 72 experiments conducted from 2007 to 2012 by FAPA in areas cultivated under no-tillage for more than 20 years. In total, 52 experiments involved increasing rates of urea-N applied as topdressing to winter cereals cultivated in soybean-corn succession: 22 under wheat (*Triticum aestivum* L.) and 30 under barley (*Hordeum vulgare L.*) (Table 1). Another 20 experiments were conducted in 2008 and 2009, 10 with wheat and 10 with barley, in order to assess the N supply potential of the soils. The experiments were distributed in five sites (Guarapuava, Candói, Pinhão, Murakami, and Teixeira Soares) in the region managed by the *Cooperativa Agrária Agroindustrial*. The tables 2 and 3 show the chemical properties of the soils.

The experiments were arranged in a randomized block design with four replications. The applied N fertilizer consisted of common urea, applied as topdressing between the sprouting and elongation stages, generally corresponding to the stage of 4 to 6 leaves on the main stem (Haun, 1973).

The rates to obtain maximum economic efficiency (MEE) were calculated for those treatments where the response of crop yields to increasing N rates followed a polynomial behavior and were based on the average grain price from 2007 to 2012. The fertilizer : grain price ratio (price of kg of N per price of kg of grain) was 4.362 for wheat and 4.137 for barley [grain yield class I = grain yield × commercial classification (grain >2.5 mm)] (Brasil, 1996).

Table 1. Preceding crops, N rates, and cultivars used in the N fertilization experiments of wheat and barley conducted from 2007 to 2012 in the South-Central region of Paraná, Brazil

Year	Pre-crop	N rates	Cultivars
		kg ha^{-1}	
		Wheat	
2007	Soybean Corn	0, 30, 60, 90, and 120	BRS Guabijú, BRS Guamirim, Quartzo, Safira
2008	Soybean Corn	0, 30, 60, 90, and 120	BRS Guabijú, BRS Guamirim, Quartzo, Safira
2009	Soybean Corn	0, 30, 60, 90, and 120	BRS Guabijú, BRS Tangará, Campeiro, Quartzo
2011	Soybean	0, 30, 60, 90, and 120	Campeiro, TBio Iguaçu, TBio Mestre
2012	Soybean Corn	0, 30, 60, 90, and 120	Campeiro, Tbio Iguaçú, Tbio Mestre
		Barley	
2007	Soybean Corn	0, 20, 40, 60, 80, and 100	BRS Cauê, BRS Elis, BRS Yeda
2008	Soybean Corn	0, 20, 40, 60, 80, and 100	BRS Cauê, BRS Elis, BRS Brau
2009	Soybean Corn	0, 20, 40, 60, 80, and 100	BRS Cauê, BRS Elis, BRS Brau
2011	Soybean	0, 20, 40, 60, 80, and 120	BRS Brau, MN 6021, PFC 2006127
2012	Soybean Corn	0, 20, 40, 60, 80, and 120	BRS Brau, MN 6021, BRS Korbel

Each pre-crop (soybean or corn) and cultivar represented an experiment in combination with the topdressed N fertilizer rate. Fifty-two experiments were carried out; in some years, not all cultivars were assessed with both pre-crops.

Table 2. Chemical properties of the soils where the nitrogen fertilization experiments with winter cereal crops were conducted in the South-Central region of Paraná

Year	Pre-crop	OM	pH($CaCl_2$)	P	K^+	V
		g dm^{-3}		mg dm^{-3}	cmol$_c$ dm^{-3}	%
			Wheat			
2007	Soybean	47	4.8	10.0	0.34	52
	Corn	48	4.8	13.9	0.24	55
2008	Soybean	49	5.0	8.7	0.27	62
	Corn	49	5.4	9.4	0.32	67
2009	Soybean	60	5.5	15.3	0.71	67
	Corn	50	5.1	9.3	0.37	58
2011	Soybean	56	5.0	14.0	0.37	50
2012	Soybean	52	5.1	8.6	0.19	55
	Corn	46	4.9	9.6	0.27	46
			Barley			
2007	Soybean	47	4.8	10.0	0.34	52
	Corn	48	4.9	13.0	0.24	54
2008	Soybean	49	5.1	9.4	0.28	62
2009	Soybean	60	5.5	17.1	0.73	66
	Corn	50	5.1	9.3	0.37	57
2011	Soybean	56	4.9	11.2	0.30	45
2012	Soybean	52	5.1	8.6	0.19	55
	Corn	46	4.9	8.6	0.27	46

OM: soil organic matter (Walkley-Black); P: available phosphorus (Mehlich-1); K^+: exchangeable potassium (Mehlich-1); V: base saturation. Experiments with different wheat and barley cultivars following soybean or corn (Table 1) were conducted each year.

Table 3. Soil chemical properties in the South-Central region of Paraná where the experiments to determine the apparent N mineralization from soil organic matter were conducted

Experimental site	SOM	pH(H_2O)	P	K^+	V
	g dm^{-3}		mg dm^{-3}	$cmol_c$ dm^{-3}	%
		2008			
Guarapuava	61	5.7	6.6	0.42	62
Candói	59	5.4	4.5	0.33	50
Pinhão	62	5.9	4.9	0.40	71
Teixeira Soares	39	5.9	8.0	0.39	59
		2009			
Candói	50	5.2	2.6	0.20	43
Guarapuava 1	45	6.3	8.6	0.45	84
Guarapuava 2	48	5.5	8.2	0.53	52
Murakami	52	6.0	4.5	0.54	77
Pinhão	44	5.9	4.0	0.65	69
Teixeira Soares	34	5.2	7.0	0.42	43

OM: soil organic matter (Walkley-Black); P: available phosphorus (Mehlich-1); K^+: exchangeable potassium (Mehlich-1); and V: base saturation.

Grain yield expectation ranges and N rates to be applied

Expected yield ranges for wheat and barley were initially established from the overall grain yield for all experiments with increasing N rates. To the overall average, the standard deviation was added and subtracted, with appropriate rounding, adding two extreme values to the range. Thus, the expected yield ranges established for both cereals were <3.5, 3.5-4.5, 4.5-5.5, and >5.5 Mg ha^{-1}.

The mean grain yields of wheat and barley, and the average N rate required to obtain yields within each expectancy range were estimated from the results of the 52 experiments involving application of variable N rates to winter cereals cultivated after soybean or corn. Polynomial equations fitted with average N rates (axis X) and the mean yields (axis Y) estimated for the different expected yield ranges were used to calculate the N rates required to obtain the mean yields for the 3.5-4.5 and 4.5-5.5 Mg ha^{-1} ranges, as well as those for the <3.5 and >5.5 Mg ha^{-1} ranges, leading to yields of 3.0 and 6.0 Mg ha^{-1}, respectively.

Adjusting N rates for soils with different OM levels

The previously estimated N rates correspond to the N recommendations for winter cereals on soils with OM levels from 41 to 60 g dm^{-3}, this range of OM was present in the soils of all 52 experiments (Table 2). These N rates, [N $\text{recommendation}_{(\textit{OM range 41-60 g dm}^{-3})}$] were adjusted for the rates to be applied to soils with OM levels <40 and >60 g dm^{-3}, considering the difference in the amount of mineralized N ($\Delta_{mineralized}$) compared to the soils with OM levels of 40 to 60 g dm^{-3}, and also for the efficiency of urea-N applied in the fertilizer (*Ef aN*), using equations 1 and 2.

$$\text{N recommendation}_{(\textit{OM range <40 g dm}^{-3})} = \text{N rate}_{(\textit{OM range 41-60 g dm}^{-3})} + (\Delta N_{mineralized} \times \frac{1}{\text{Ef aN}}) \qquad \text{Eq. 1}$$

$$\text{N recommendation}_{(\textit{OM range >60 g dm}^{-3})} = \text{N rate}_{(\textit{OM range 41-60 g dm}^{-3})} - (\Delta N_{mineralized} \times \frac{1}{\text{Ef aN}}) \qquad \text{Eq. 2}$$

The difference in mineralized N ($\Delta N_{mineralized}$) between the soils with OM levels in the ranges <40 and >60 g dm^{-3}, and those with levels in the range 41-60 g dm^{-3}, was estimated from the apparent mineralization rate (AMR) of N in the soil according to Fontoura and Bayer (2009). The AMR was based on the results of 20 experiments conducted in areas managed by the *Cooperativa Agrária Agroindustrial* in 2008 and

2009 (Table 3). The experiments involved cultivating wheat and barley in areas where all straw from the preceding crops had been removed from the soil surface. Under these conditions, it was assumed that all N absorbed by winter cereals was mineralized from soil OM and, thus, the apparent N mineralization rate can be calculated by equation 3 (Fontoura and Bayer, 2009).

$$\text{Apparent Mineralization Rate (\%)} = \left(\frac{N\ absorbed}{Soil\ N\ stock}\right) \times 100 \qquad \text{Eq. 3}$$

where: *N absorbed* is the amount of N contained in dry matter (kg ha^{-1}) of the aboveground plant biomass at the milky grain stage; and *Soil N stock* is that of N in the 0.00-0.20 m soil layer (kg ha^{-1}), calculated from the soil N level and bulk density (results not shown). The term "apparent" applies to an indirect method used that may be influenced by possible losses of mineralized N not absorbed by the crop and was, therefore, not considered here. Also, this procedure takes only N contained in aboveground plant biomass into account, measured in 20 plants per plot, but not the N in root biomass.

The apparent N fertilizer efficiency for wheat and barley was estimated according to Mitchell and Tell (1977) (Equation 4):

$$Ef\ aN = \left[\frac{NAPf - NAPwf}{Naf}\right] \times 100 \qquad \text{Eq. 4}$$

where: *Ef aN* is the apparent efficiency of applied N (%); *NAPf* (kg ha^{-1}) is the N amount absorbed by the plants supplied with N fertilizer; *NAPwf* (kg ha^{-1}) is the N amount absorbed by the plants with no N fertilization; and *Naf* (kg ha^{-1}) is the N rate applied via the fertilizer. The cumulative amount of N in aboveground biomass was determined by harvesting 20 plants per plot at the milky grain stage in both crops. The plants were dried and weighed to estimate dry matter yield and ground to determine the N concentration (Tedesco et al., 1995). The term "apparent" efficiency here denotes that the efficiency was assessed by using an indirect method considering the amount of N in the aerial parts of the plant only.

Development and validation of N recommendation system for winter cereals

The previous evaluations and parameters were used to develop a system for calculating the amount of N fertilizer recommended to meet different yield expectations (<3.5, 3.5-4.5, 4.5-5.5, and >5.5 Mg ha^{-1}) of wheat and barley (grain yield class I) grown on soils with different OM levels (<40, 41-60, and >60 g dm^{-3}) under no-tillage after soybean or corn in the South-Central region of Paraná, Brazil.

The proposed system for winter cereals was validated by calculating the significance of the coefficients of the polynomial equations, relating the N rates determined in this work to those recommended by the Fertility Commission of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016) for similar levels of soil OM, the preceding crop (pre-crop) and expected yield. Also, the suitability of the N rates recommended for the South-Central region of Paraná was assessed by the significance of the coefficients of the polynomial regression with the MEE rates calculated from the N fertilization response curves for wheat and barley.

RESULTS AND DISCUSSION

Expected grain yield ranges and N rates to be applied

The grain yields obtained testify to the high potential of soils in the South-Central region of Paraná for growing winter cereals; even without N fertilization, yields exceeded 4.0 Mg ha^{-1} and peaked at 6.0 Mg ha^{-1} (Figure 2). These results reflect advances in the management of these crops and the use of modern varieties with high potential yields (Barraclough et al., 2010; Beche et al., 2014).

The amount of N applied increased linearly with increases in expected grain yield; in the OM range 41-60 g dm^{-3}, applied N ranged from 30 to 143 kg ha^{-1} for wheat (Figure 3a) and 38 to 90 kg ha^{-1} for barley (Figure 3b). The pre-crop also influenced the N requirements of the winter cereals; thus, greater amounts of N were needed after corn than after soybean (Figures 2 and 3). The increased N rate required after corn was probably associated to N immobilization by soil microbiota during decomposition of corn residues, which has a high C/N ratio (Amado et al., 2002; Braz et al., 2006). Also, the amount of required N to reach the same grain yield range was higher in wheat than in barley, which may be a result from a higher crop capacity to remobilize absorbed N (Masclaux-Daubresse et al., 2010).

Apparent mineralization rate of N from soil organic matter

The apparent mineralization rate (AMR) of soil N at the five studied sites ranged from 1.0 ± 0.17 to 1.5 ± 0.28 % (average 1.19 %) (Figure 4). Therefore, a 1.0 % value was assumed to be appropriate to estimate the differential supply of N ($\Delta N_{mineralized}$) (Equations 1 and 2) in soils with different OM ranges (<40 and >60 g dm^{-3}) because it was the lowest value found over the two years at the five sites. The mineralization rate of N from soil OM depends on the soil type (Fontoura and Bayer, 2009), climatic conditions

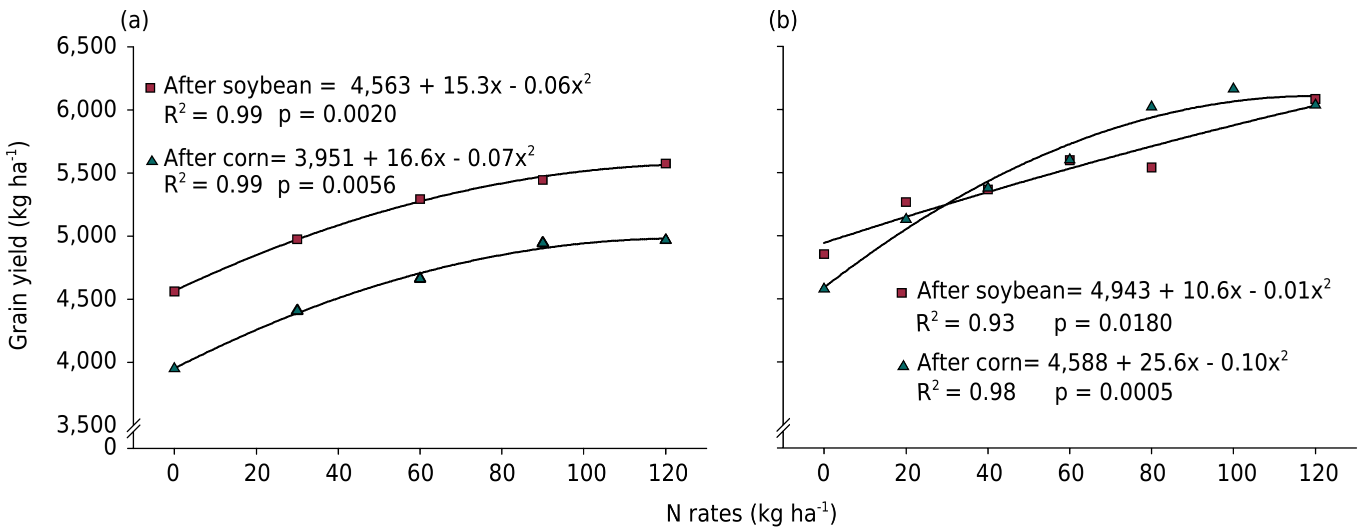

Figure 2. The relationship between grain yield of wheat (a) and barley (b) grown after soybean or corn and supplied with increasing urea-N rates in the South-Central region of Paraná. This relationship was established based on average results from experiments conducted between 2007 and 2012 (22 with wheat and 30 with barley).

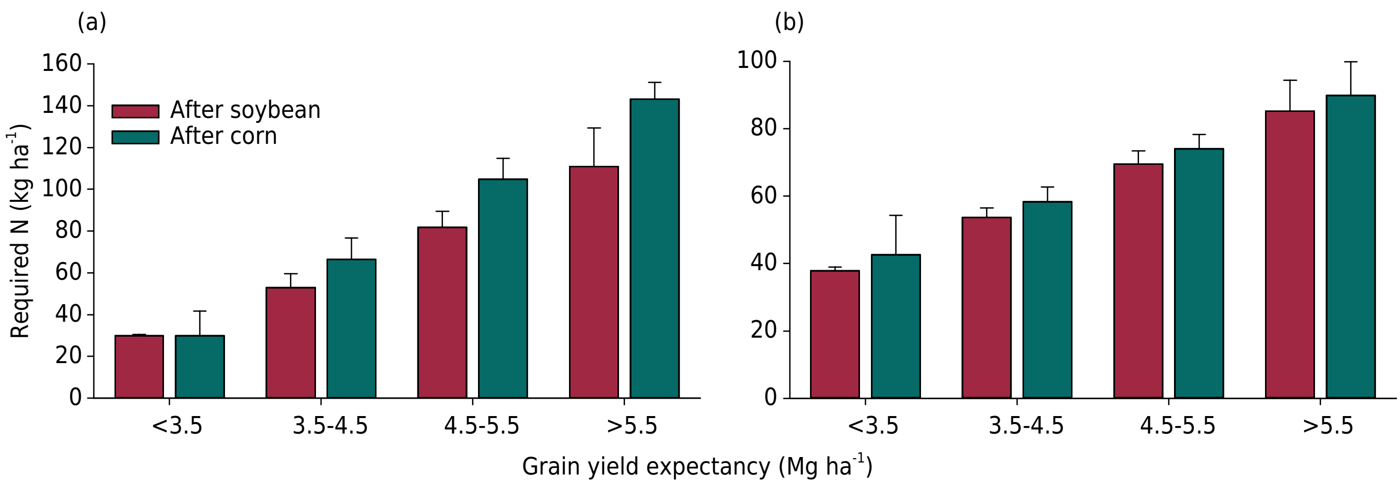

Figure 3. Expected grain yield of wheat (a) and barley (b) and urea-N rates required by the crops for a mean expected yield within the ranges 3.5-4.5 and 4.5-5.5 Mg ha^{-1} and yields of 3.0 and 6.0 Mg ha^{-1} within the expected yield ranges of <3.5 and >5.5 Mg ha^{-1}, respectively, when cultivated after soybean and corn. Vertical bars indicate mean standard deviations.

(Liu et al., 2017), and their seasonal changes. To estimate soil N supply for corn in the same region in the summer, Fontoura and Bayer (2009) used AMR = 3 %, resulting in a three times higher AMR than that estimated here for winter cereals, due to the effect of environmental conditions (temperature, mainly) on N mineralization in soil.

Based on AMR of 1 %, a soil N supply capacity of 35, 50, and 65 kg ha^{-1} was estimated for soils with OM ranges <40, 41-60, and >60 g dm^{-3}, respectively. Thus, soils with OM contents in the ranges <40 and >60 g dm^{-3} delivered 15 kg N ha^{-1} less or more, respectively, compared to soils with OM ranges of 41-60 g dm^{-3}. This difference in N (15 kg ha^{-1}) is equivalent to the value of $\Delta N_{mineralized}$ in equations 2 and 3.

Apparent efficiency of applied N

The apparent efficiency of N applied to wheat and barley cultivated after soybean or corn ranged from 42 to 56 % (Figure 5). The average apparent efficiency was 52 % and slightly higher for barley and after corn (Figure 5). However, using a single value for the efficiency of N fertilizer applied at the same time of year and under similar climatic conditions to wheat and barley led to an average efficiency of 50 %, which is consistent with reported values (Schirmann et al., 2013; Espindula et al., 2014).

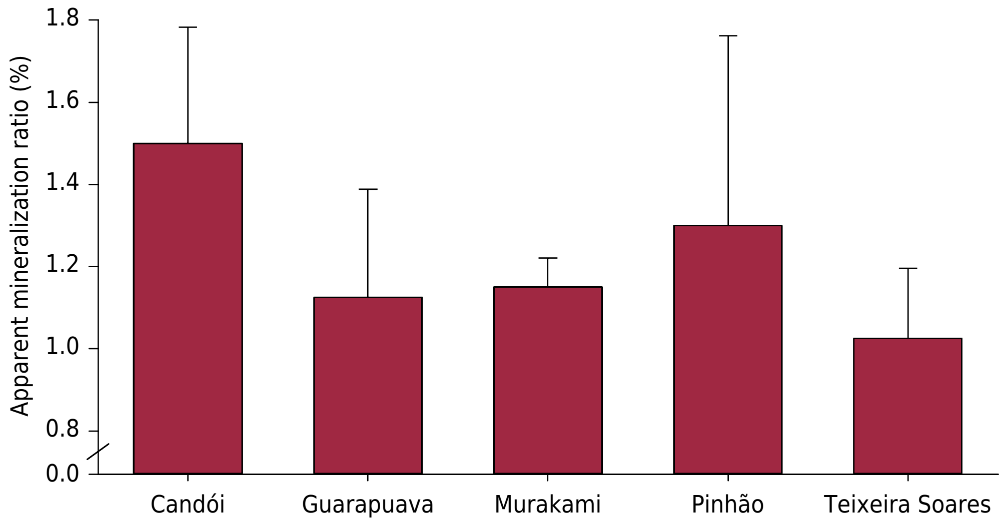

Figure 4. Apparent mineralization ratio of N from soil organic matter at five sites in the South-Central region of Paraná. Vertical bars indicate mean standard errors.

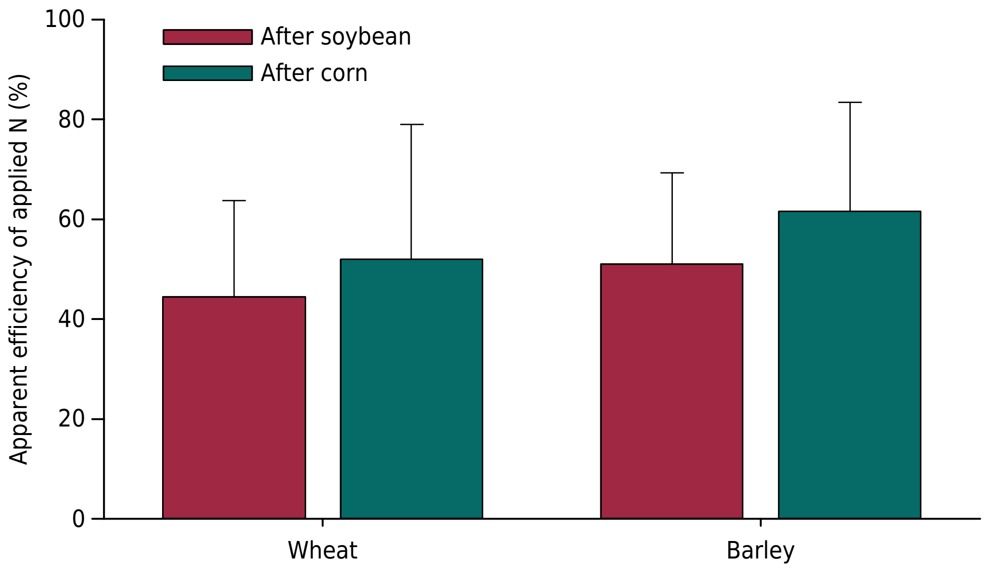

Figure 5. Apparent efficiency of urea-N applied as topdressing to wheat and barley grown after soybean and corn in the South-Central region of Paraná. Vertical bars indicate mean standard errors.

The relatively low efficiency of applied N is a widely known fact, usually associated to heavy volatilization and leaching losses. In response, there have been some regional attempts to control N losses (mainly the volatilization of NH_3) with specific management practices (irrigation, N incorporation) and urease inhibitors (Viero et al., 2014; Viero et al., 2015; Corrêa et al., 2016; Silva et al., 2016). Not only the ability to use applied N is important, but the efficiency in using applied N and converting it into grain yield also plays a central role. Some cultivars may have a low N absorption capacity but a high capacity to convert absorbed N into plant growth - and vice versa (Barraclough et al., 2010; Masclaux-Daubresse et al., 2010).

N rates recommended for wheat and barley

Nitrogen rates recommended for wheat and barley were established for three different soil OM ranges (<40, 41-60, and >60 g dm^{-3}), four expected yield ranges (<3.5, 3.5-4.5, 4.5-5.5, and >5.5 Mg ha^{-1}), and two pre-crops (soybean or corn) (Table 4).

The N rates recommended for wheat grown after soybean and corn ranged from 30 to 150 kg ha^{-1} and 30 to 170 kg ha^{-1} respectively, the lowest rates corresponding to the soils with the highest OM levels (Table 4). In those cases, where SOM was high (>60 g dm^{-3}) and expected grain yield low (<3.5 Mg ha^{-1}), N application was indicated only at sowing (30 kg ha^{-1}). On the other hand, the highest N rates were recommended for high expected grain yield (>5.5 Mg ha^{-1}) and low OM soils. Raising wheat yields above 5.5 Mg ha^{-1} would not only require an adequate N supply, but also the absence of restrictive management and environmental factors limiting crop development (Amado et al., 2002; Benin et al., 2012) such as plant diseases, weed infestation or water deficiency.

Table 4. Indicated urea-N rates for crescent yield expectations of wheat and barley cultivated in soils with different soil organic matter contents and preceding summer crops (corn or soybean) in the South-Central region of Paraná

Pre-Crop/SOM	Expected grain yield			
	Mg ha^{-1}			
	<3.5	3.5-4.5	4.5-5.5	>5.5
	Wheat (2,3)			
After soybean				
<40 g dm^{-3}	50	80	110	150
41-60 g dm^{-3}	30	50	80	120
>60 g dm^{-3}	30	30	50	90
After corn				
<40 g dm^{-3}	70	100	130	170
41-60 g dm^{-3}	40	70	100	140
>60 g dm^{-3}	30	40	70	110
	Barley (2, 3, 4)			
After soybean				
<40 g dm^{-3}	60	80	100	120
41-60 g dm^{-3}	30	50	70	90
>60 g dm^{-3}	30	30	40	60
After corn				
<40 g dm^{-3}	70	90	110	130
41-60 g dm^{-3}	40	60	80	100
>60 g dm^{-3}	30	30	50	70

(1) Soil organic matter in the 0.00-0.20 m layer. (2) Total N rate (kg ha^{-1}). (3) An application of 30 kg ha^{-1} of N is recommended at seeding. (4) Grain yield class 1 (Brasil, 1996).

The N rates recommended for barley (Table 4) ranged from 30 to 130 kg ha^{-1} and were 10 kg ha^{-1} higher when the crop was grown after corn than after soybean. As an exception, the N rates with both pre-crops were equivalent when barley was cultivated on soils with high OM contents and low grain yield expectations. Increases in the expected grain yield (grain yield class 1) required more N fertilizer: 30 to 60 kg ha^{-1} for the highest expected grain yield (>5.5 Mg ha^{-1}) compared to the <3.5 Mg ha^{-1} range. Whereas soils with low OM levels required greater amounts of applied N, those with high OM contents (>60 g dm^{-3}) and a low expected grain yield (<3.5 Mg ha^{-1}) only demanded N application at sowing (30 kg ha^{-1}).

The N recommendation system for winter cereals in the South-Central region of Paraná (Table 4) followed the same principles underlying that for Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016) and Paraguay (Wendling et al., 2007), and also that for corn in Rio Grande do Sul and Santa Catarina (Amado et al., 2002), and Paraná (Fontoura and Bayer, 2009). In the previous systems, the recommended N rates were higher when the winter cereals were preceded by a grass species - as were our recommendations of N rates after corn. This result may have been a consequence of N immobilization during decomposition of residues with a high C/N ratio or of the increased amounts of N supplied from biomass mineralization of the legume pre-crop (Amado et al., 2002; Braz et al., 2006). Likewise, the amount of N to be applied to soils with a high OM content was small compared to those containing little OM as a result of the high N supply from organic N mineralization in the soil (Liu et al., 2017).

The recommended N rate for both wheat and barley includes the suggestion of an application of 30 kg ha^{-1} at sowing; the remainder should be applied as topdressing between sprouting and elongation (usually with 4-6 leaves on the main stem) (Haun, 1973). Therefore, 30 kg ha^{-1} is the lowest indicated N rate because it can be applied to both cereals. Some cultivar-specific factors of the cereals, such as susceptibility to wind damage and disease, should be considered at the time of N application (Minella, 2015; Cunha et al., 2016). Splitting the N fertilizer rate or using a growth inhibitor can be effective to reduce these risks (Espindula et al., 2010; Teixeira Filho et al., 2010).

Validation of N recommendations for wheat and barley

The N rates recommended for wheat and barley in the South-Central region of Paraná (Table 4) had a significant linear relationship (R^2 = 0.66, p<0.02) with the N rates indicated by the Fertility Commission of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016) (Figure 6). Overall, considering similar SOM levels and yield expectations, the N rates recommended for wheat after soybean in the South-Central region of Paraná were 10-20 kg ha^{-1} higher than those recommended by CQFS-RS/SC (2016). On the other hand, those for wheat after corn were virtually identical.

The N rates recommended for barley sown after soybean on soils with a low OM content and low expected yield in the South-Central region of Paraná are similar to those for the states of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016). For barley after corn, however, the rates recommended by CQFS-RS/SC (2016) were higher whichever the expected yield, but especially (up to 35 kg ha^{-1}) for higher expectations. It should be noted that the N recommendations for barley in the South-Central region of Paraná were based on grain yield class I, whereas those for Rio Grande do Sul and Santa Catarina are based on the total yield of barley grain, which tends to widen the differences.

The increased N rates recommended for barley grown after corn in Rio Grande do Sul and Santa Catarina may have arisen at least partly from the determination procedure, which considers immobilization of N from corn residues twice. In fact, CQFS-RS/SC (2016) considered N immobilization once when indicating an N rate 20 kg ha^{-1} higher after corn than after soybean for a grain yield of 3.0 Mg ha^{-1}, and a second time when indicating a further 10 kg N ha^{-1} after corn than after soybean for each 1.0 Mg ha^{-1} above a yield of 3.0 Mg ha^{-1}. Since this procedure distinguishes the N rate for the baseline yield and that for each 1.0 Mg ha^{-1} additional yield, the effect of N immobilization on N rates is duplicated. This may partly account for the higher rates for the higher yield expectations in Rio Grande do Sul and Santa Catarina compared to our rates for the South-Central region of Paraná. Even though our N rates for wheat are similar to the recommendations of CQFS-RS/SC (2016), considering immobilization twice in the recommendations for Rio Grande do Sul and Santa Catarina is unsustainable because N immobilization is not

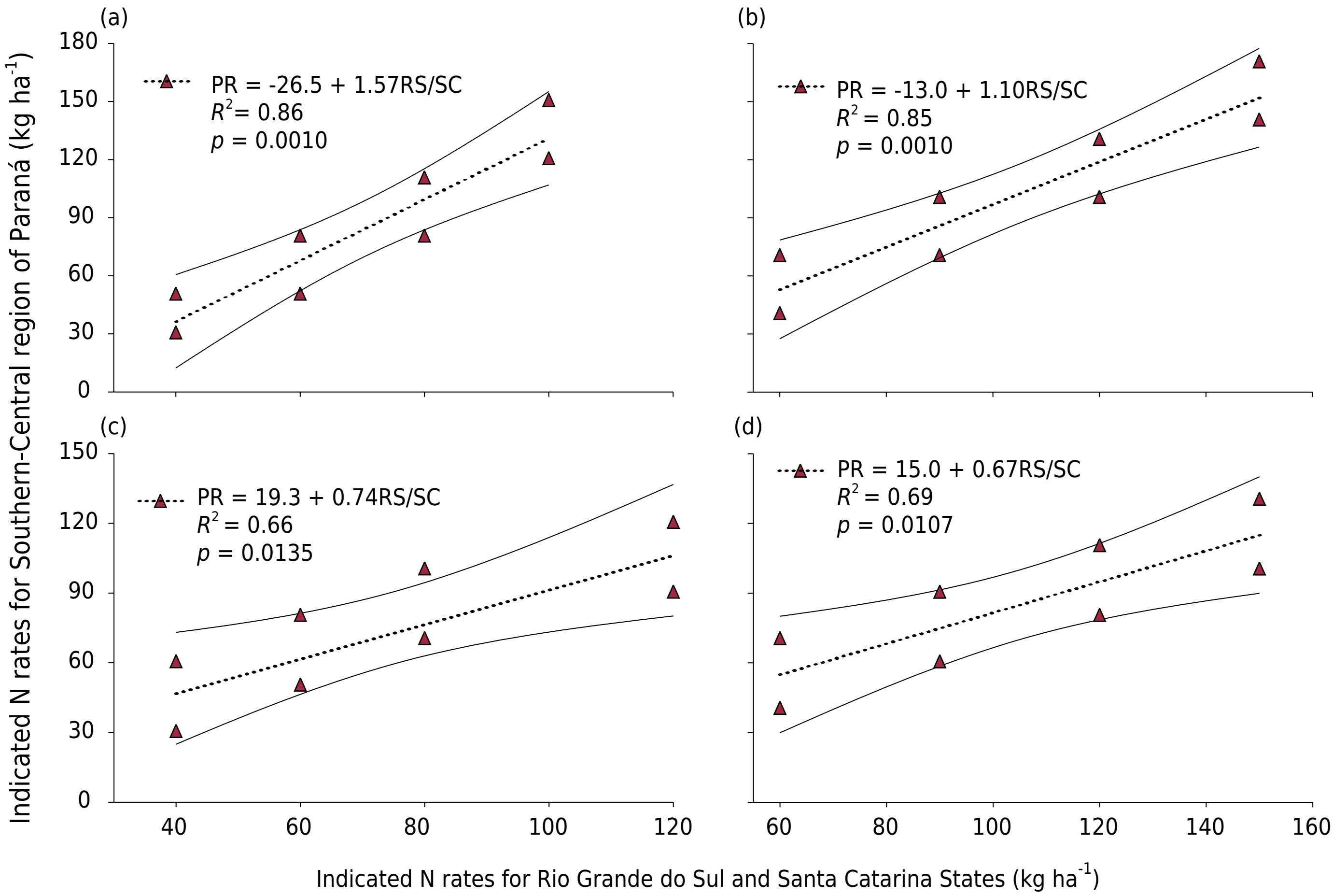

Figure 6. Relationship of indicated urea-N rates for wheat after soybean (a) and after corn (b) and barley after soybean (c) and after corn (d) in Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016), to the proposed N rates for the South-Central region Paraná. Dotted lines represent linear regression curves and solid lines 95 % of the confidence interval.

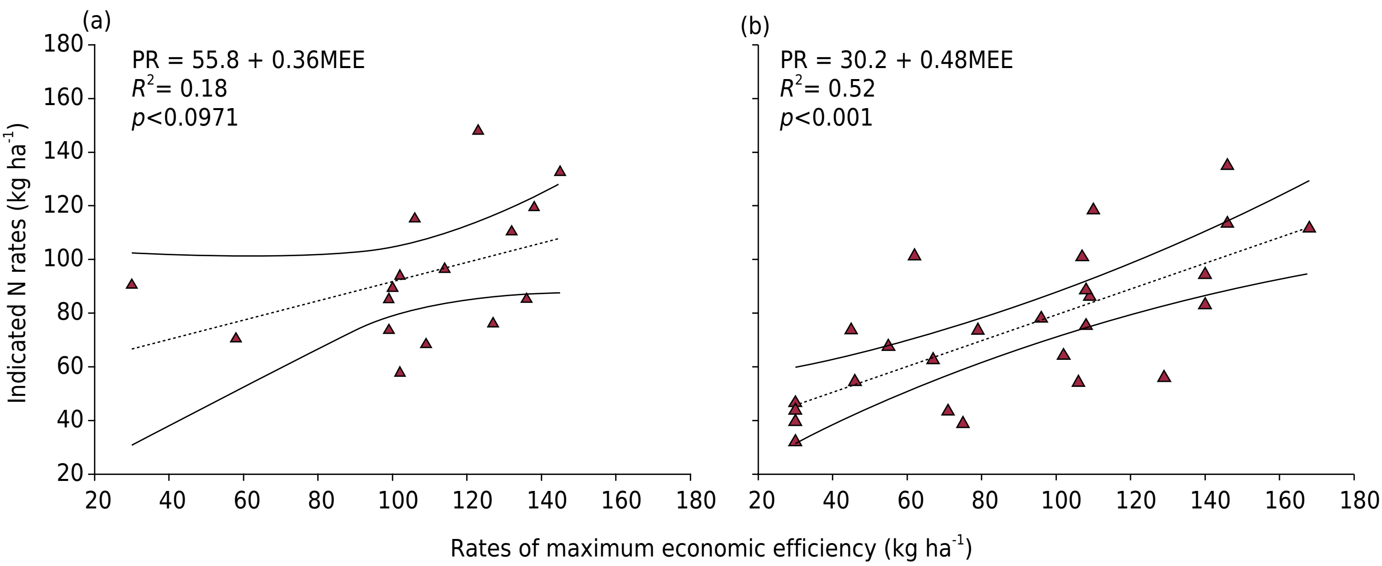

Figure 7. Relationship of maximum economic efficiency rates and urea-N rates indicated for wheat (a) and barley (b) in the South-Central region of Paraná. Dotted lines represent linear regression curves and solid lines 95 % of the confidence interval.

related to the expected crop yield. Therefore, the recommendations for these two states should be revised to determine a single differential N rate for the baseline yield of barley or wheat after soybean or corn, and further amounts of N for each 1 Mg ha^{-1} additional yield, irrespective of the pre-crop.

The recommended N rates were validated by correlation with the estimated MEE rates for wheat and barley (Figure 7). The N rates recommended and MME rates were related with acceptable significance ($p<0.0971$ for wheat and $p<0.0001$ for barley), irrespective of soil OM content and expected yield.

The average MEE rate for wheat cultivated after soybean and corn was 91 and 105 kg ha^{-1}, respectively (Table 5), corresponding to grain yield expectations in the range from 4.5 to 5.5 Mg ha^{-1}. These MEE rates differ by less than 12 % from the N rates recommended (Table 4) for the same expected yield range and soil OM content (41-60 g dm^{-3}). The

Table 5. Fitted equation of grain yield for wheat grown after soybean and corn according to the applied urea-N rate (kg ha^{-1}), maximum economic efficiency (MEE) rate, and respectively yields

Year/Cultivar	Equation(1)	R^2	p	MEE(2)	
				Rate(3)	Yield
	After corn				
2007					
Safira	$y = 3{,}421 + 17.347x - 0.0612x^2$	0.91	0.0861	106	4,572
2008					
Safira	$y = 4{,}024 + 27.336x - 0.0994x^2$	0.98	0.0128	115	5,853
2009					
BRS Guamirim	$y = 4{,}519 - 1.075x + 0.0157x^2$	0.13	0.8675	120	4,616
2012					
Campeiro	$y = 3{,}330 + 15.517x - 0.0705x^2$	0.86	0.1354	79	4,116
Mean				105	4,789
	After soybean				
2007					
BRS Guabiju	$y = 4{,}424 + 8.646x - 0.0763x^2$	0.73	0.2711	28	4,610
BRS Guamirim	$y = 4{,}537 + 7.508x - 0.0061x^2$	0.87	0.1258	120	5,350
Quartzo	$y = 4{,}702 + 12.959x - 0.0611x^2$	0.94	0.0622	70	5,310
Safira	$y = 4{,}446 + 9.745x - 0.0138x^2$	0.94	0.0534	120	5,417
2008					
BRS Guabiju	$y = 4{,}175 + 9.117x - 0.0149x^2$	0.99	0.0043	120	5,054
BRS Guamirim	$y = 5{,}529 + 15.017x - 0.0701x^2$	0.94	0.0574	76	6,265
Quartzo	$y = 4{,}878 + 19.330x - 0.0733x^2$	0.97	0.0300	102	6,087
Safira	$y = 4{,}275 + 28.366x - 0.1627x^2$	0.98	0.0133	74	5,474
2009					
BRS Guamirim	$y = 3{,}951 + 13.463x - 0.0468x^2$	0.99	0.0070	97	4,817
BRS Tangará	$y = 4{,}187 + 23.679x - 0.1406x^2$	0.93	0.0664	69	5,151
Campeiro	$y = 4{,}395 + 23.589x - 0.1144x^2$	0.95	0.0540	84	5,569
Quartzo	$y = 4{,}045 + 14.441x - 0.0363x^2$	0.94	0.0530	128	5,255
2011					
Campeiro	$y = 5{,}804 + 31.608x - 0.1465x^2$	0.94	0.0554	93	7,476
Tbio Iguaçú	$y = 4{,}094 + 38.736x - 0.1593x^2$	0.98	0.0179	108	6,419
Tbio Mestre	$y = 6{,}524 + 0.793x + 0.0373x^2$	0.36	0.6378	-	-
2012					
Campeiro	$y = 3{,}837 + 3.997x - 0.0018x^2$	0.51	0.4841	-	-
Tbio Iguaçú	$y = 3{,}916 - 6.078x + 0.0626x^2$	0.69	0.3114	-	-
Tbio Mestre	$y = 3{,}787 + 5.383x - 0.0071x^2$	0.97	0.0246	72	4,138
Mean				91	5,493

(1) Only for experiments with a quadratic yield response to N fertilization. (2) Maximum economic efficiency (kg ha^{-1}). (3) Fertilizer to grain price ratio (price of the kg of N per price of the kg of wheat grain) = 4.362 (2007 to 2012 average). R^2: coefficient of determination; p: significance level.

MEE rate for barley grown after soybean and corn was 55 and 76 kg ha^{-1}, respectively (Table 6). These rates are 21 and 24 % lower than the N rates recommended for barley grown on soil with soil OM content in the same range (41-60 g dm^{-3}) and grain yields in the ranges 4.5-5.5 and >5.5 Mg ha^{-1}, respectively.

Table 6. Fitted equation of grain yield for barley grown after soybean and corn according to the applied urea-N rate (kg ha^{-1}), maximum economic efficiency (MEE) rate, and respective yields

Year/Cultivar	Equation[1]	R^2	p	MEE[2]	
				Rate[3]	Yield
After corn					
2007					
BRS Cauê	$y = 4,300 + 12.110x - 0.0361x^2$	0.95	0.0096	100	5,150
BRS Elis	$y = 4,231 + 7.536x - 0.068x^2$	0.75	0.1213	25	4,377
BRS Yeda	$y = 4,601 + 6.964x - 0.0959x^2$	0.38	0.4906	15	4,684
2008					
BRS Cauê	$y = 4,753 + 30.563x - 0.1139x^2$	0.97	0.0038	100	6,670
BRS Elis	$y = 5,883 + 7.047x - 0.0449x^2$	0.16	0.7610	32	6,063
BRS Brau	$y = 5,259 + 18.344x - 0.0514x^2$	0.97	0.0050	100	6,579
2009					
BRS Cauê	$y = 4,316 - 19.055x + 0.0638x^2$	0.73	0.1411	-	-
BRS Elis	$y = 4,538 - 26.468x + 0.1551x^2$	0.86	0.0519	-	-
BRS Brau	$y = 4,999 - 2.873x - 0.0789x^2$	0.63	0.2257	-	-
2011					
BRS Brau	$y = 5,699 + 31.146x - 0.1165x^2$	0.85	0.0567	116	7,744
MN 6021	$y = 2,868 + 47.626x - 0.1976x^2$	0.97	0.0050	110	5,716
PFC 2006127	$y = 5,544 + 30.127x - 0.162x^2$	0.85	0.0549	80	6,917
2012					
BRS Brau	$y = 3,686 + 23.465x - 0.1237x^2$	0.95	0.0110	78	4,764
MN 6021	$y = 4,445 + 17.729x - 0.0862x^2$	0.81	0.0830	79	5,308
BRS Korbel	$y = 4,790 + 28.410x - 0.1573x^2$	0.94	0.0157	77	6,045
Mean				76	5,835
After soybean					
2007					
BRS Cauê	$y = 4,551 + 14.542x - 0.0686x^2$	0.89	0.0347	76	5,260
BRS Elis	$y = 4,216 + 17.981x - 0.1142x^2$	0.65	0.2067	45	4,786
BRS Yeda	$y = 4,396 + 0.905x - 0.0839x^2$	0.75	0.1219	30	4,348
2008					
BRS Cauê	$y = 5,283 + 23.250x - 0.2604x^2$	0.88	0.0435	37	5,787
BRS Elis	$y = 6,045 - 11.513x + 0.0182x^2$	0.58	0.2713	100	5,076
BRS Brau	$y = 5,821 + 22.417x - 0.1852x^2$	0.86	0.0538	49	6,475
2009					
BRS Cauê	$y = 3,720 + 7.353x - 0.0028x^2$	0.71	0.1573	-	-
BRS Elis	$y = 4,060 + 21.718x - 0.2163x^2$	0.90	0.0333	41	4,587
BRS Brau	$y = 3,606 + 26.573x - 0.2472x^2$	0.72	0.1494	45	4,301
2011					
BRS Brau	$y = 6,046 + 30.923x + 0.172x^2$	0.78	0.1030	78	7,411
MN 6021	$y = 4,688 + 35.481x - 0.2606x^2$	0.70	0.1629	72	5,885
PFC 2006127	$y = 6,155 + 13.891x - 0.0743^2$	0.49	0.3560	66	6,748
2012					
BRS Brau	$y = 4,610 + 1.0053x + 0.0285x^2$	0.84	0.0626	-	-
MN 6021	$y = 4,308 + 17.333x - 0.0664x^2$	0.89	0.0365	-	-
BRS Korbel	$y = 5,205 + 5.168x - 0.0328x^2$	0.24	0.6622	16	5,279
Mean				55	5,495

[1] Only for experiments with a quadratic yield response to N fertilization. [2] Maximum economic efficiency (kg ha^{-1}). [3] Fertilizer to grain price ratio (price of the kg of N per price of the kg of barley grain) = 4.137 (2007 to 2012 average). R^2: coefficient of determination; p: significance level.

In view of the complexity of the factors (e.g., soil OM content and fertility, crop variety and management, and climatic conditions) potentially affecting the N response or demand, the N rates recommended for the South-Central region of Paraná (Table 4) are quite similar to those recommended by CQFS-RS/SC (2016) and the MME N rates similar to those indicated for the studied region, and can therefore be used as reference in the management of N fertilization of winter cereals by regional producers and agricultural technicians.

CONCLUSIONS

We established the N fertilizer rates for wheat and barley in the South-Central region of Paraná, Southern Brazil. The indicated N rates (30-170 kg ha^{-1} for wheat and 10-130 kg ha^{-1} for barley) are generally consistent with those for Rio Grande do Sul and Santa Catarina, and also with the estimated N rates needed to obtain the maximum economic efficiency. The N rates increased for crescent grain yields expectation, low soil organic matter levels, and when the preceding summer crop was corn. The proposed recommendation can be used as N fertilization references for winter wheat and barley by regional producers and agricultural technicians.

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