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Nitrogen Management Strategies to Improve Yield and Dough Properties in Hard Red Spring Wheat

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ABSTRACT

Nitrogen supply, environment, and cultivar determine yield and dough properties of hard red spring wheat (*Triticum aestivum* L.); however, the effects of broadcasting N fertilizer at heading, a growing practice in regions such as southern Brazil, have not been explored. The objectives of this study were to: (i) compare the current producer practice vs. alternative fertilizer N management strategies and (ii) quantify their interaction with cultivar and their effects on yield and its components and relevant dough properties. Field experiments were conducted using a complete factorial arrangement in a split-plot design of three cultivars (main plots) and five N strategies (subplots) across three environments in southern Brazil. Overall, the current producer practice (all 70 kg N ha^{-1} applied at tillering) was appropriate to the targeted yield (3.5 Mg ha^{-1}); splitting this fertilizer N rate into tillering and heading applications (either 35 kg N ha^{-1} on tillering + 35 kg N ha^{-1} on heading or 45 kg N ha^{-1} on tillering + 25 kg N ha^{-1} on heading) benefited protein concentration but reduced yield. Best N management resulted in the addition of one late-season N application (70 kg N ha^{-1} on tillering + 23 kg N ha^{-1} on heading) positively impacting yield, protein concentration, dough extensibility, and alveogram index. In-season N management is more relevant for grain quality than yield, more importantly if deductions from low protein are projected, or if premiums from increasing protein concentration exist, justifying a late-season fertilizer N application.

Core Ideas

- Dividing a tillering N application into tillering and heading reduced wheat yield.
- Additional late-season N application increased wheat protein concentration and dough quality.
- Late-season N applications are economically unfit unless there is a reward for protein.
- Wheat yield and quality response to N management was similar across cultivars.
- There are opportunities to improve N management for wheat yield and quality in Southern Brazil.

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Wheat is among the most important field crops grown worldwide, with a total production close to 730 Tg originating from more than 220 million ha (FAO, 2016). Together with rice (*Oryza sativa* L.) and maize (*Zea mays* L.), the three commodities account for 89% of the global cereal production (FAO, 2016). For wheat, however, not only production is important, but its quality also represents a significant factor determining the end-use of the grain (Guttieri et al., 2001; López-Bellido et al., 2001; Saint Pierre et al., 2008). Wheat grain quality plays a significant role in grain grading, marketing, and human nutrition (Finney et al., 1987; Johnson and Mattern, 1987; Bly and Woodard, 2003; Baker et al., 2004). In wheat, major quality characteristics determining end-use include flour extraction, dough-handling characteristics (rheological properties), and flour protein concentration and composition (Finney et al., 1987; Johnson and Mattern, 1987; López-Bellido et al., 2001; Saint Pierre et al., 2008). Among the six classes of wheat, hard red spring is typically characterized by greater grain protein concentration and absence of vernalization requirement, the former stimulating (better quality) and the latter allowing (longer season) this class to be widely produced in many growing regions of the world (Gauer et al., 1992; Garrido-Lestache et al., 2005; Chen et al., 2008; Espindula et al., 2010; Farmaha et al., 2015).

Wheat grain protein concentration is influenced by factors such as environmental conditions, cultivar, total N available during the growing season, and N timing and method of application (Rao et al., 1993; López-Bellido et al., 1998; Garrido-Lestache et al., 2004; Chen et al., 2008). Environmental conditions that lead to greater protein concentration are generally not manageable and include those that decrease the allocation of starch to the developing wheat kernel during grain fill, including heat and drought stresses (Dupont and Altenbach, 2003). Among the manageable agronomic practices, N fertilization represents

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Abbreviations: DE, dough extensibility, DT, dough tenacity, TKW, thousand kernel weight.

one of the most important determinants of both grain yield and quality (López-Bellido et al., 1998; Garrido-Lestache et al., 2004, 2005; Otteson et al., 2007; Chen et al., 2008; Dick et al., 2016), and is among the major economic input a wheat enterprise receives, affecting budget profitability (Bly and Woodard, 2003; Baker et al., 2004; Ladha et al., 2005; Foulkes et al., 2009).

Studies evaluating spring wheat grain yield as affected by N rates (ranging from 0–200 kg N ha^{-1}) and documenting linear response curves are not common. Thus, the use of high N rates rarely leads to yield gains (Gauer et al., 1992; Garrido-Lestache et al., 2004; Chen et al., 2008; Espindula et al., 2010; Farmaha et al., 2015), highlighting an opportunity to reduce the environmental N footprint for this crop (Good and Beatty, 2011; Rajkovich et al., 2017). Overall, optimal N rates for hard red spring wheat around 100 kg ha^{-1} were reported in Brazil (Espindula et al., 2010), in the United States (Chen et al., 2008), Canada (Gauer et al., 1992), and in Spain (Garrido-Lestache et al., 2004), to attain yields from 3 (Gauer et al., 1992; Chen et al., 2008) to 5 Mg ha^{-1} (Garrido-Lestache et al., 2004; Espindula et al., 2010). Typically, N rate determination for wheat are performed mechanistically based on expected yield (or yield goal) and N use efficiency (Raun et al., 2017), for an average of 41 kg N ha^{-1} for every 1 Mg ha^{-1} yield goal of hard red spring wheat (Kaiser et al., 2013). Thus, optimal N rates near 100 kg ha^{-1} are likely related to the average environmental yield of the aforementioned environments, ranging between 3.0 and 3.6 Mg ha^{-1} (FAO, 2016).

Nitrogen rates that maximize grain protein concentration, however, are generally greater than those prescribed for maximum grain yield (Gauer et al., 1992; Baker et al., 2004; Garrido-Lestache et al., 2004) and fertilizing for grain yield only can result in suboptimal protein concentration (Goos et al., 1982). One strategy to increase grain protein concentration is to adjust timing of N fertilization to occur near grain development, such as performing a post-flowering foliar N application. Recent studies tested liquid N broadcast during anthesis in U.S. winter wheat and demonstrated the potential to improve protein concentration (Cruppe et al., 2017). However, the profits are questionable because the late-season N application did not increase winter wheat grain yield (Dick et al., 2016). Protein management would only be profitable under greater wheat prices (Dick et al., 2016) or if premiums from increased grain protein are expected (Bly and Woodard, 2003; Baker et al., 2004; Otteson et al., 2007; Farmaha and Sims, 2013). Nitrogen fertilizer broadcast at heading or postanthesis is a growing practice in some hard red spring wheat regions, such as Brazil (De Bona et al., 2016; Silva et al., 2017), aiming to increase grain quality; however, their effects on yield and dough properties have not been evaluated in these regions nor in other important hard red spring wheat producer worldwide, such as Latin America (Vázquez et al., 2012), Canada (Gauer et al., 1992), and northern United States (Westcott et al., 1997; Bly and Woodard, 2003; Chen et al., 2008).

The main objectives of this study were to: (i) quantify the effects of N late management strategies adopted by hard red spring wheat producers and their interaction with wheat cultivars on grain yield and its components and (ii) compare the traditional N recommendation to different N late management strategies on relevant wheat dough properties.

MATERIAL AND METHODS

Study Region

Approximately 2 million ha are sown to hard red spring wheat during the spring/winter season in southern Brazil; region that includes the states of Paraná, Santa Catarina, and Rio Grande do Sul. The three states combined represent approximately 90% of total area sown to wheat in Brazil. In the State of Rio Grande do Sul, the total production area with hard red spring wheat is approximately 0.7 million ha, representing 36% of total Brazilian production (CONAB, 2017). Long-term no-tillage system is the most common soil management practice in the region (Casão Junior et al., 2012; de Freitas and Landers, 2014); and typical rotation includes soybean (*Glycine max* L.) or maize as summer crops, and wheat as a fall/winter crop. If wheat is not used in the rotation, black oat (*Avena strigosa* L.), white oat (*Avena sativa* L.), and oilseed radish (*Raphanus sativus* var. *Oleiferus* Metzg) as a cover crop are fall/winter crop alternatives. The Köppen's climate classification in the region is Cfa with hot summer (Alvares et al., 2013), and most wheat fields in the region typically have accentuated slopes (5–20%) with most common soil orders including Oxisols (predominant), Inceptsols, Ultisols, and Alfisols (Soil Survey Staff, 2014).

The traditional N recommendation in this region includes about 20 kg N ha^{-1} at sowing and an additional 60 to 80 kg N ha^{-1} broadcasted between tillering (Feekes growth stage 3; Large, 1954) and stem elongation (Feekes growth stage 7). The final N rate will depend on soil organic matter content, previous crop, and expected yield (Wiethölter, 2011; De Bona et al., 2016; Silva et al., 2017).

Field Experiments

Experiments were conducted at three different sites during the 2013 spring wheat growing season. Locations were near Ajuricaba (Site 1) and near Derrubadas (Sites 2 and 3), in the state of Rio Grande do Sul (Fig. 1). Sites 2 and 3 were close to each other (2 km) but differed regarding previous crop. Site 2 presented a crop rotation with maize followed by oilseed radish as a cover crop and by wheat, while Sites 1 and 3 were preceded with soybean followed by wheat. The three sites have been managed under no-tillage practices for more than 25 yr.

Soil sampling occurred prior to wheat sowing at all sites, and chemical and physical characteristics were analyzed for the 0- to 15-cm depth. The procedures adopted for soil analyses included soil texture (e.g., clay, sand, and silt concentration; Bouyoucos, 1962); soil pH evaluated in a 1:1 soil/water ratio (Shoemaker et al., 1961); organic matter (Walkley and Black, 1934); and extractable P, K, Zn, and Cu measured using Mehlich I procedure (Mehlich, 1953). Additionally, 1.0 mol L^{-1} KCl was used to measure extractable Ca, Mg, and Al (Claessen et al., 1997). The P concentration was determined using colorimetry, K concentration by flame photometry (Nelson et al., 1953) and Al was titrated using NaOH 0.025 mol L^{-1} (Claessen et al., 1997). The B concentration was extracted by hot water, and S ($S\text{-}SO_4$) by $CaHPO_4$ 500 mgPL^{-1} 0.1 mol L^{-1} (Tedesco et al., 1995). The effective cation exchange capacity (ECEC) was calculated using the summation of the exchangeable bases (K, Ca, and Mg) plus Al methodology. Base saturation (V%) was calculated according to CQFS-RS/SC (2004). Total N into soil profile was not

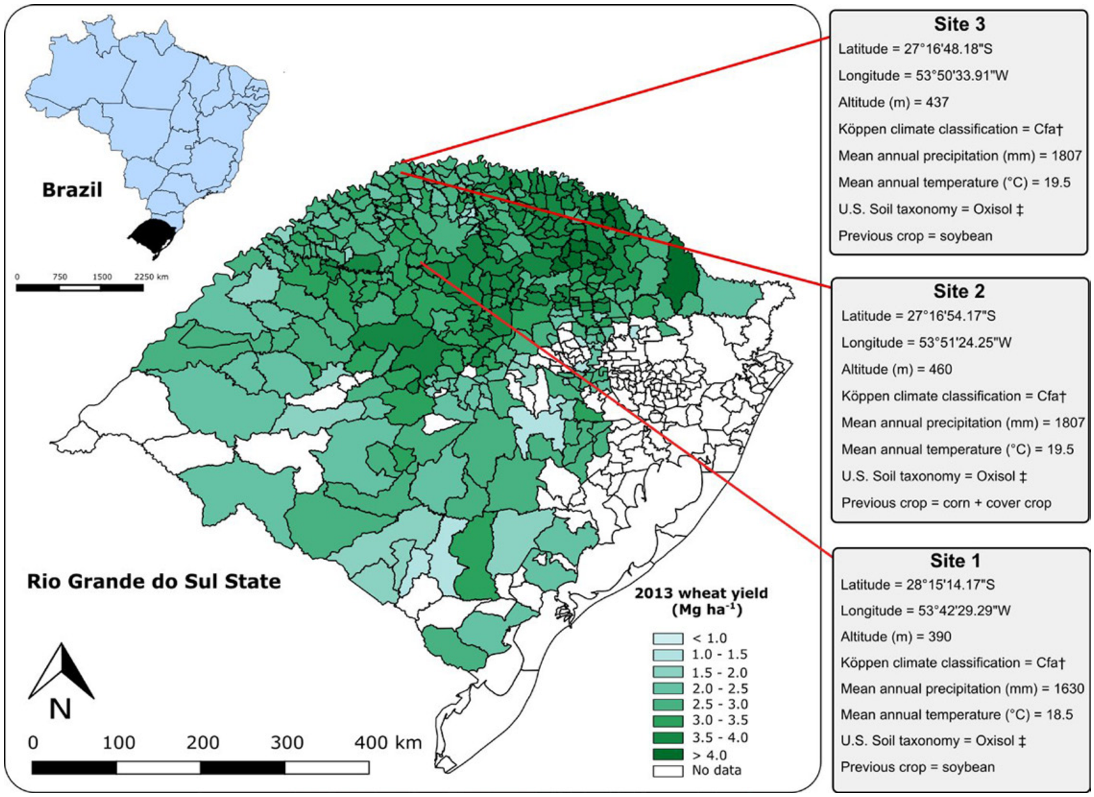

Fig. 1. Location and characterization of experimental Sites 1, 2, and 3 at the state of Rio Grande do Sul, Brazil. The state represents 36% of the total cultivated area with wheat in the country. † Denote Cfa (humid subtropical climate) with hot summer based on Köppen's climate classification (Alvares et al., 2013). ‡ Based on Soil Survey Staff (2014). Note: For understanding of the references to color in this figure legend, the reader is referred to the web version of this article.

measured since it is not considered as a pool source in tropical soils (Socolow, 1999). Due to the high precipitation in the great part of the region (>1600 mm yr^{-1}) (Alvares et al., 2013) there is a low relationship between soil N and available N to the crop. Results of the soil characterization are presented in Table 1.

Experimental Design and Growing Conditions

A two-way factorial treatment structure with three replications was arranged in a split-plot design with main plots arranged in a randomized complete block design and subplots completely randomized within main plot. Three commonly grown wheat cultivars constituted the main plots while five N management strategies constituted the subplots. The selected wheat cultivars (Mirante, Quartzo, and TBIO Itaipu) have a broad area of adaptation, are among the most cultivated cultivars in southern Brazil, and presents different tillering potential (Table 2). The five N management strategies to broadcast application were: (i) 0 kg N ha^{-1} (control), (ii) 70 kg N ha^{-1} on tillering (70T), (iii) 35 kg N ha^{-1} on tillering + 35 kg N ha^{-1} on heading (35T + 35H), (iv) 45 kg N ha^{-1} on tillering + 25 kg N ha^{-1} on heading (45T + 25H), and (v) 70 kg N ha^{-1} on tillering + additional 23 kg N ha^{-1} on heading (70T + 23H). Treatment 70T (ii) reflects the common practice adopted by wheat producers in the region aiming to optimize economic return. The 70T, common practice with all N applied during tillering, was compared to the same rate split between tillering and heading at different ratios (iii: 35T + 35H and iv: 45T + 25H). In addition, late-season N application was also tested to the common practice (v: 70T + 23H) as a potential to improve

Table 1. Selected soil chemical and physical characteristics for the 0- to 15-cm depth at three experimental locations in the State of Rio Grande do Sul, Brazil.

Soil attribute	Unit	Site 1†	Site 2‡	Site 3§
Clay	g kg^{-1}	590	610	610
Sand	g kg^{-1}	160	120	170
Silt	g kg^{-1}	250	270	220
Organic matter	g kg^{-1}	31.0	37.0	38.0
pH (water 1:1)	–	6.0	6.4	5.9
P¶	mg dm^{-3}	8.5	7.2	6.5
K¶	mg dm^{-3}	148	84	65
Ca	cmol$_c$ dm^{-3}	9.2	7.5	7.2
Mg	cmol$_c$ dm^{-3}	3.6	2.9	3.6
Al	cmol$_c$ dm^{-3}	0.0	0.0	0.0
Base saturation	%	79.0	86	74
Cation exchange capacity	cmol$_c$ dm^{-3}	16.5	13.7	14.9
S	mg dm^{-3}	4.8	11	9.5
Zn¶	mg dm^{-3}	3.7	4.9	1.1
Cu¶	mg dm^{-3}	7.1	13	3.2
B	mg dm^{-3}	0.3	0.5	0.4

† Ajuricaba, RS, Brazil. Previous crop: Soybean.

‡ Derrubadas, RS, Brazil. Previous crop: Corn followed by cover crop (oilseed radish).

§ Derrubadas, RS, Brazil. Previous crop: Soybean.

¶ Mehlich I.

Table 2. Characteristics of wheat cultivars evaluated at three experimental sites in the State of Rio Grande do Sul, Brazil.

	Cultivar		
Feature	Mirante	Quartzo	TBIO Itaipu
Breeding program	OR Sementes†	OR Sementes	Biotrigo Genetica‡
Tillering potential	Medium	Medium	High
Thousand kernel weight, g	39	36	36
Lodging tolerance	Moderate	Moderate	Moderate
Emergence-heading, days	85	91	87
Emergence-harvest, days	128	140	125

† OR Sementes, Passo Fundo, RS– Brazil. Information available at: http://www.orsementes.com.br/.

‡ Biotrigo Genetica, Passo Fundo, RS– Brazil. Information available at: http://www.biotrigo.com.br/.

both yield and dough properties. The rationale to fertilizer rate (23 kg N ha^{-1}) applied at heading was based on an application of 50 kg ha^{-1} of urea (46% of N), which is the most widespread N source for wheat producers in southern Brazil and a common rate for producers during wheat heading (Silva et al., 2017). The tillering and heading growth stages considered in this study corresponded to Feekes growth stage 3 and 10.1 (Large, 1954). The N fertilizer source used was urea (46–0–0) as this is the most widespread N source for wheat producers in southern Brazil.

The experiments were sown on 5 July (Sites 2 and 3) and 10 July 2013 (Site 1) using a 21-row planter with 17-cm row spacing and with a seeding depth of approximately 4 cm. Experimental units (subplots) were 21-rows wide (3.6 m) and 3.5 m long. Seed density was 3.3 million seed ha^{-1} for all cultivars, following regional recommendations. A total of 20 kg N ha^{-1}, 50 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1} [(8–20–20), (N–P_2O_5–K_2O)] was applied at sowing (6 cm depth) to all plots, following the common practice adopted by wheat producers. Other management factors such as pest and disease control during the growing season were those typically adopted by the producer and recommended for the region. Due to the high incidence of fungal diseases in Brazilian wheat production (Silva et al., 2017), three fungicide applications were performed in all Sites (Fig. 2). The fungicide used was 0.3 L ha^{-1} of azoxistrobine (0.2 kg L^{-1}) (methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) plus ciproconazol (0.08 kg L^{-1}) [(2RS,3RS;2RS,3SR)-2-(4-chlorophenyl)-3-cyclopropyl-1-(1H-1,2,4-triazol-1-yl)butan-2-ol] at a spray volume of 150 L water ha^{-1}.

Measurements and Analysis

Yield and Yield Components

Before harvesting, 30 individual plants were collected per plot to quantify yield components: number of heads per square meter (heads m^{-2}), head length (cm), kernels per head, spikelets per head, and thousand kernel weight (TKW, in g). Immediately after collecting the aforementioned samples, the 15 center rows from each experimental unit were hand-harvested to determine grain yield (Mg ha^{-1}). Three outside rows were excluded both sides of the plot to avoid any possible border effect. Grain weight and moisture were measured on site for each experimental unit and adjusted to 130 g kg^{-1} moisture content.

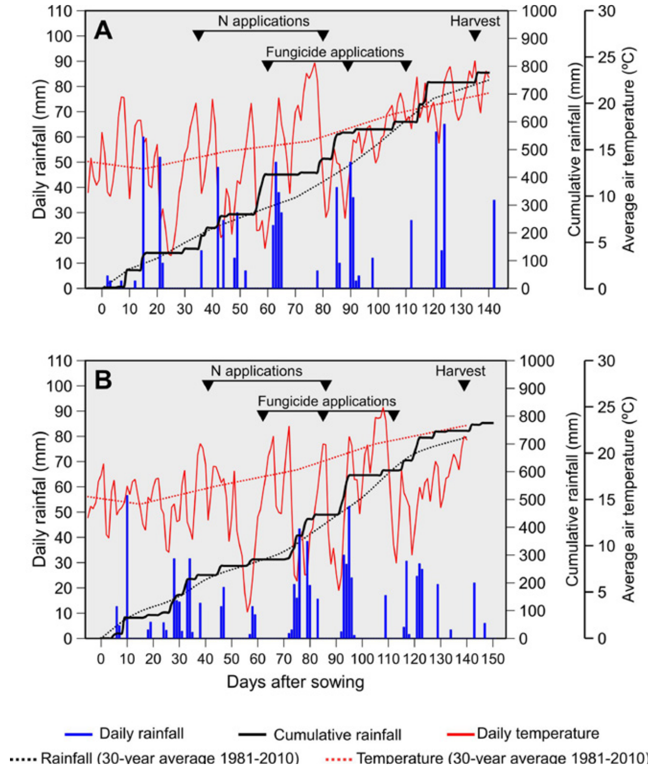

Fig. 2. Daily and cumulative rainfall, and average air temperature registered during the spring wheat growing season at Ajuricaba (Site 1, A) and Derrubadas (Sites 2 and 3, B) during the 2013 growing season. Dotted lines are representing the 30-yr average rainfall (black line) and air temperature (red line). Note: For understanding of the references to color in this figure legend, the reader is referred to the web version of this article.

Dough Properties

Several parameters were measured to quantify the effects of cultivar, N management, and their interaction on dough properties. A Schopper chondrometer (55-10 method) was used to measure grain test weight (weight per unit of volume [kg m^{-3}]) (AACC, 2009). The experimental extraction of flour was expressed in percentage and reported in 140 g kg^{-1} water basis. Grain protein concentration was evaluated by near-infrared reflectance spectroscopy using a Perten DA 7200 (Perten Instruments, Springfield, IL) based on 39-10.01 method (AACC, 2009) and was reported on a 0 g kg^{-1} water basis. The alveogram index (W, in $\times 10^{-4}$ J) was evaluated according to 54-30A method (AACC, 2009) and using a Chopin alveograph (Chopin Technologies, Villeneuve-la-Garenne, France). To quantify the alveogram index, the dough was prepared from flour and water under standard conditions and formed into disc-shaped pieces that were inflated into bubbles. The alveogram index value was calculated by the area under the curve (AACC, 2009), which is proportional to the energy required to break the dough bubble (Garrido-Lestache et al., 2004).

Dough tenacity (DT denotes overpressure, in mm) was calculated by the maximum height of the curve, while dough extensibility (DE, in mm) was calculated as the length of the curve until the rupture (Garrido-Lestache et al., 2004; AACC, 2009; EMBRAPA, 2009). The dough balance was calculated as the DT/DE ratio (EMBRAPA, 2009). The falling number test (s), which measures the α-amylase enzyme activity in grains and flour to detect sprout damage (Perten, 1964), was evaluated using the 56-81B method (AACC, 2009) and a Falling Number System (Perten Instruments, Hägersten, Sweden).

Statistical Approach

Treatment effects on the aforementioned independent variables were tested using ANOVA in a generalized linear mixed model procedure (PROC GLIMMIX) in SAS v. 9.3 (SAS Institute, 2016). Analyses were conducted at two hierarchical levels: first, one ANOVA was performed at each site considering N management strategies and wheat cultivars as fixed effects, and replication as random effects. Second, analyses were performed across site considering N management and wheat cultivar as fixed effects, and site and replication nested within the site as random effects. Corrected denominator degrees of freedom were obtained using the Kenward–Roger adjustment. Tukey post-hoc mean comparison test ($\alpha = 0.05$) using the LSMEANS and SLICE options for PROC GLIMMIX in SAS (SAS Institute, Cary, NC) determined whether significant differences between treatments occurred. Linear and nonlinear models for yield, protein, and alveogram index were tested using the lme and nlme procedure in the R program (R Development Core Team, 2013). We then subjected the residuals of the relationships (i) grain yield and grain protein concentration, (ii) grain yield and alveogram index, and (iii) grain protein concentration and alveogram index, to ANOVA to test the effects of N management strategy, cultivar, and their interaction; with the hypothesis that the residuals are statistically similar (Sadras et al., 2003).

RESULTS

Environmental Conditions

The 2013 spring wheat growing season was characterized by favorable weather conditions for wheat grain yield and quality. Cumulative rainfall was 777 mm (climate normal for the region = 750 mm) and 776 mm (climate normal = 725 mm) for Sites 1 and 2 to 3, respectively, while the average growing season temperature was 15.2°C (Site 1) (climate normal = 15.2°C) and 15.4°C (Sites 2 and 3) (climate normal = 17.1°C) (INMET: www.inmet.gov.br) (Fig. 2). After N application at tillering, rainfall events were timely and incorporated the N fertilizer in the root zone, as 62 and 37 mm were documented in the Sites 1 and 2 to 3 in the 10 days following application, respectively. Rainfall events also occurred after N application at heading (Fig. 2), with a total 160 and 270 mm precipitation for Site 1 and Sites 2 to 3 between anthesis and physiological maturity, respectively. Average temperature during the same period was 18.3 (Site 1) and 15.9°C (Sites 2 and 3) (Fig. 2).

Wheat Grain Yield and Yield Components

Statistical analyses revealed no significant interaction between cultivar and N management for yield or its components, neither at the individual site evaluated nor in the analysis performed across site (Table 3). Similarly, there was no significant effect of cultivar in grain yield ($P > 0.05$) in either hierarchical level evaluated (Table 3). However, grain yield was significantly affected by N management strategies at Sites 1 and 3 ($P < 0.001$), but not at Site 2 ($P = 0.869$) (Table 3). At Site 2, wheat was preceded of corn followed by oilseed radish, and the grain yields across N management strategies were: 3.9 (control), 4.1 (70T), 4.0 (35T + 35H), 4.1 (45T + 25H), and 4.2 Mg ha^{-1} (70T + 23H) (Supplemental Table S2). The similar yields measured in Site 2 resulted from statistically similar yield components (Table 3). Site 1 resulted in the lowest average yield among all sites, with greatest yield obtained for treatments 70T + 23H (3.2 Mg ha^{-1}) and 70T (3.0 Mg ha^{-1}), the former also portraying the greatest number of heads m^{-2} and both treatments maximizing kernels per head (Supplemental Table S1). Fertilized treatments were superior ($P < 0.001$) than control for all yield components evaluated in Site 1, indicating that the supplemental N increased heads m^{-2}, head length, spikelets and kernels head^{-1}, and TKW. At Site 3, all fertilized treatments resulted in similar grain yield, but still all treatments being greater than the control ($P < 0.001$) (Supplemental Table S3). Grain test weight, a common parameter determining grain grading and affecting producer's remuneration in Brazil, did not differ among N management for Sites 1 and 2, but was superior in the treatments that received a late N application in Site 3 (Supplemental Table S3).

Across locations, wheat grain yield was similar among all cultivars ($P = 0.39$) (Table 3), with an average grain yield of 3.9, 3.8 and 3.7 Mg ha^{-1} for Mirante, Quartzo, and TBIO Itaipu, respectively (Table 4). The cultivar Mirante, presented a lower number of heads ($P < 0.001$) relative to the other two alternative cultivars (approximately 7% lower than Quartzo and 9% lower than TBIO Itaipu). Nonetheless, Mirante and Quartzo had a greater head length ($P = 0.011$) than TBIO Itaipu, likely compensating in final grain yield (Table 4). Likewise, the number of kernels per head was greater ($P = 0.011$) in the cultivars Mirante and Quartzo than to TBIO Itaipu. Quartzo and TBIO Itaipu resulted in lower TKW as compared to Mirante (9%, $P < 0.001$, Table 4). The current analysis elucidates different mechanisms determining wheat yield as affected by its components and cultivar tillering ability (Table 2). Despite the lower number of heads m^{-2} in a low tillering cultivar, the greater number of grains head^{-1} and TKW likely explain the similar grain yield for Mirante as compared to other cultivars.

Wheat grain yield was affected by N management across sites ($P < 0.001$) (Table 3). As expected, lowest grain yield and yield component parameters were measured in the control treatment (e.g., zero N after sowing, 3.2 Mg ha^{-1}) (Table 4), as all treatments receiving N fertilizer resulted in approximately 20% greater grain yield as compared to control (Fig. 3). Grain yield measured in the traditional N management strategy (70T) did not differ statistically from any of the treatments receiving N fertilizer, including the ones in which the same N rate was split between tillering and heading (e.g., 35T+35H and 45T+25H). A slight increase in grain yield (~5%) occurred for the 70T+23H treatment (higher total N dose) as compared to other fertilized treatments; however, these differences were only statistically greater than 35T + 35H (Fig. 3). The majority of the yield components were also affected by N management strategy (Table 3). The control treatment resulted in the lowest number of heads m^{-2} and shorter head length, while the application of greater N rate at tillering (70T and 70T+23H) promoted a greater number of heads (Table 4, Fig. 3). The split fertilization strategy with the same rate among tillering and heading (35T + 35H) resulted in greater number of kernels per head (6%) and TKW (5%) than the single N application at tillering (70T) (Fig. 3). The number of spikelet per head was not affected by the different N management strategies studied (Table 2).

Table 3. Significance of *F* values for the effect of wheat cultivar (C), N management strategy (N), and their interactions on grain yield, yield components, and dough properties at three experimental locations in the Rio Grande do Sul state, Brazil, during the 2013 spring wheat growing season. Statistical analyses were performed at each individual site and across locations.

	Experimental locations								
	Site 1†			Site 2‡			Site 3§		
Parameter	C	N	C×N	C	N	C×N	C	N	C×N
	Yield components								
Number of heads	0.077	<0.001	0.430	0.058	0.720	0.935	0.278	0.113	0.425
Head length	0.075	0.096	0.096	0.001	0.543	0.719	0.002	0.138	0.908
Kernels per head	0.908	0.024	0.879	0.082	0.817	0.892	0.054	0.001	0.329
Spikelet per head	0.016	0.016	0.881	0.242	0.900	0.608	0.025	0.607	0.975
Thousand kernel weight	<0.001	0.003	0.787	0.004	0.037	0.769	0.004	0.005	0.444
Grain yield	0.594	<0.001	0.496	0.526	0.869	0.901	0.187	<0.001	0.384
	Dough properties								
Test weight	<0.001	0.401	0.475	0.038	0.377	0.491	0.211	0.009	0.333
Alveogram index	<0.001	0.042	0.356	0.162	0.337	0.812	0.097	0.001	0.115
Protein	<0.001	<0.001	0.870	0.228	<0.001	0.709	0.950	<0.001	0.140
Flour	0.142	0.289	0.122	0.189	0.492	0.557	0.817	0.437	0.315
Dough extensibility (DE)	0.038	0.162	0.325	0.900	0.191	0.957	0.094	0.126	0.257
Dough tenacity (DT)	0.528	0.881	0.567	0.067	0.985	0.331	0.095	0.045	0.990
DT/DE ratio	0.097	0.251	0.406	0.132	0.670	0.800	0.088	0.523	0.249
Falling number test	0.145	0.099	0.591	0.338	0.193	0.488	0.089	0.608	0.880
Kernel wheat hardness	0.006	0.058	0.701	0.847	<0.001	0.829	0.018	<0.001	0.324

	Across locations		
	C	N	C×N
	Yield component		
Number of heads	<0.001	<0.001	0.839
Head length	0.011	0.016	0.989
Kernels per head	0.010	0.008	0.891
Spikelet per head	<0.001	0.101	0.778
Thousand kernel weight	<0.001	<0.001	0.486
Grain yield	0.397	<0.001	0.651
	Dough property		
Test weight	0.021	0.009	0.737
Alveogram index	0.009	<0.001	0.140
Protein	0.008	<0.001	0.655
Flour	0.555	0.074	0.673
Dough extensibility (DE)	0.117	0.002	0.296
Dough tenacity (DT)	0.360	0.921	0.276
DT/DE ratio	0.428	0.153	0.534
Falling number test	0.069	0.270	0.680
Kernel wheat hardness	0.007	<0.001	0.728

† Ajuricaba, RS, Brazil. Previous crop: Soybean

‡ Derrubadas, RS, Brazil. Previous crop: Corn followed by cover crop (oilseed radish).

§ Derrubadas, RS, Brazil. Previous crop: Soybean

Dough Properties

Similarly to grain yield, there was no significant interaction between cultivar and N management for any of the dough properties evaluated, neither at the individual site level nor at the combined analysis (Table 3). Therefore, only the main effects of N management and cultivar will be discussed. In the individual analysis, N management strategy significantly affected grain protein concentration at all sites, while the effects on the remaining dough properties were site specific (Table 3). At Sites 1 and 3, greater grain protein concentration was documented in treatments that received late-season (i.e., heading) N application (e.g., 35T + 35H, 45T + 25H, and 70T + 23H) as compared to the control or the 70T. Alveogram index was also lower in the control and 70T as compared to the other treatments (Supplemental Tables S1 and S3). At Site 2, grain protein concentration was greater for fertilized treatments relative to the control, despite similar yields among treatments. Thus, increased N rate increased N exportation from the system. Meanwhile, the alveogram index was similar across N management strategies (Supplemental Table S2).

In our analysis performed across locations, there were significant cultivar effect for test weight, alveogram index, protein concentration, falling number, and kernel hardness (Table 3). The cultivar TBIO Itaipu showed better dough properties as reflected by greater test weight, alveogram index, protein concentration, and kernel hardness (Table 5). The alveogram index and protein concentration, which can considerably attribute market value to the commercialized wheat grain, was 21 and

Table 4. Summary of hard red spring wheat yield components among wheat cultivars and N management strategies across three experimental locations in the Rio Grande do Sul state, Brazil, during the 2013 spring wheat growing season. Relevant single degree of freedom orthogonal contrasts are also shown.

Main factor	Description	Yield component					
		NHD†	HDLG	KHD	SPKL	TKW	GY
			cm			g	Mg ha^{-1}
Cultivar	Mirante	488b‡	8.5a	38.2a	15.4b	40.1a	3.9a
	Quartzo	524a	8.6a	38.7a	16.0a	36.9b	3.8a
	TBIO Itaipu	535a	8.1b	35.4b	15.2b	36.1b	3.7a
N management	Control	476 c	8.1b	36.0b	15.3a	36.9bc	3.2c
	70T	534ab	8.5a	36.1b	15.6a	36.7c	4.0ab
	35T+35H	505bc	8.5a	38.4a	15.3a	38.5a	3.8b
	45T+25H	511b	8.4ab	37.7ab	15.5a	38.5a	3.9ab
	70T+23H	556a	8.7a	39.0a	16.0a	37.8ab	4.1a
Orthogonal	Control × N	<0.001	0.002	0.024	0.181	0.009	<0.001
Contrasts	Control × 70 kg N ha^{-1}	0.005	0.011	0.085	0.454	0.010	<0.001
	Control × 93 kg N ha^{-1}	<0.001	<0.001	0.003	0.017	0.050	<0.001
	70 × 93 kg N ha^{-1}	0.005	0.087	0.055	0.029	0.847	0.067
	Traditional × Split	0.09	0.88	0.030	0.313	<0.001	0.031

† NHD, number of heads per square meter; HDLG, head length; KHD, kernels per head; SPKL, spikelet per head; TKW, thousand kernel weight; GY, grain yield.

‡ Values followed by the same letter indicate no statistically significant difference by Tukey's test ($P \leq 0.05$).

4% greater in the cultivar TBIO Itaipu as compared to Mirante and Quartzo. Quartzo also had the lowest test weight as compared to the other cultivars (Table 5). Flour extraction percent across cultivars averaged 54%, with no statistical differences between cultivars. Similar results were also obtained for dough extensibility (DE) (average of 56.5 mm), dough tenacity (DT) (average of 73.1 mm), and DT/DE ratio for the studied cultivars (Table 5). Mean falling number was 498 s, ranging from 479 s (cultivar Mirante) to 525 s (cultivar TBIO Itaipu). The falling number test detects sprout damage based on the α-amylase enzyme activity in grains, once the rate of α-amylase is increased in situations of sprouting kernel (Perten, 1964).

Nitrogen management strategy also significantly affected selected dough properties (Table 5). Across three sites and three cultivars, poor wheat quality was associated with the control treatment; meanwhile, among fertilized treatments, the full N rate applied at tillering (70T) resulted in the lowest alveogram index values and protein concentration, despite high grain yield (Fig. 4). In treatment 70T, grain protein concentration was 4% lower than 45T+25H and 70T+23H, and 6% lower than 35T+35H, suggesting that not only N rate is an important factor determining wheat protein concentration, but also N timing. Among treatments receiving N fertilizer, 35T+35H showed greater protein concentration, however with lower grain yield. The aforementioned treatment (35T+35H) had the greatest rate of N fertilizer applied at heading as compared to all other treatments, suggesting that late-season N fertilizer applications as dry urea have the potential to benefit wheat grain protein concentration, since the precipitation is sufficient to incorporate the product in the root zone shortly after application. Similar results were detected for alveogram index, as heading N applications increased W values. Compared to 70T, an increase of 12, 14, and 17% was obtained for 35T+35H, 45T+25H, and 70T+23H, respectively (Fig. 4). Similarly, kernel hardness was 3% lower in 70T as compared with split N management, while DE increased approximately 18, 18, and 25% for 35T+35H, 45T+25H, and 70T+23H as compared to 70T (Table 5). As documented for

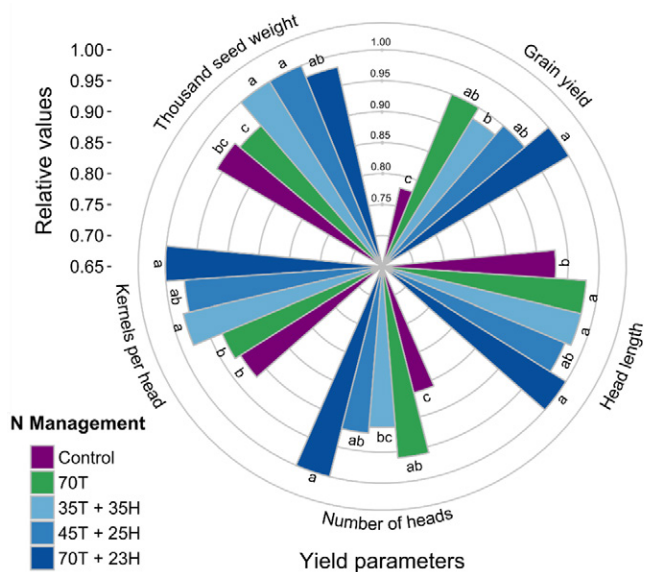

Fig. 3. Hard red spring wheat grain yield and yield components (relative values) as affected by N management strategy across locations and cultivars. Circular rings denote the scale of relative values. Values followed by the same letter indicate no statistically significant difference by Tukey's test ($P \leq 0.05$) between N management strategy for each parameter. Note: For understanding of the references to color in this figure legend, the reader is referred to the web version of this article.

cultivars, the P, DT/DE ratio, and falling number were not affected by N management strategy (Table 3).

DISCUSSION

Spring Wheat Yield Response to Nitrogen Management Strategy

Recent studies conducted with winter wheat indicated that above an optimal rate, late-season N applications rarely influence grain yield (Garrido-Lestache et al., 2004; Blandino et al., 2015; Dick et al., 2016; Cruppe et al., 2017). Similarly, current results with spring wheat demonstrated that the strategy of

Table 5. Hard red spring wheat dough properties as affected by wheat cultivars and N management strategies across three experimental locations in the Rio Grande do Sul state, Brazil, during the 2013 spring wheat growing season. Relevant single degree of freedom orthogonal contrasts are also shown.

	Cultivar		
Dough property	Mirante	Quartzo	TBIO Itaipu
Test weight, kg hL^{-1}	79.7a†	78.3b	79.3a
Alveogram index (W, ´ 10^{-4} J)	149.5b	146.9b	179.0a
Protein, %	11.5b	11.9b	12.2a
Flour, %	54.4	54.1	53.4
Dough extensibility (DE, mm)	51.5	54.8	63.1
Dough tenacity (DT, mm)	75.6	70.1	73.6
DT/DE ratio	1.6	1.4	1.4
Falling number test (s)	479	491	525
Kernel wheat hardness	69.2b	70.4ab	71.9a

	N management				
	Control	70T	35T+35H	45T+25H	70T+23H
Test weight, kg hL^{-1}	78.5c	78.8bc	79.7a	79.1abc	79.4ab
Alveogram index (W, ´ 10^{-4} J)	138.7b	144.7b	165.4a	168.2a	175.4a
Protein, %	11.1c	11.6b	12.3a	12.1a	12.2a
Flour, %	53.3b	53.6b	55.1a	54.2ab	53.8ab
Dough extensibility (DE, mm)	47.4c	51.1bc	60.1ab	60.1ab	63.7a
Dough tenacity (DT, mm)	73.3	71.6	73.1	72.9	74.7
DT/DE ratio	1.77	1.61	1.44	1.34	1.38
Falling number test (s)	482	501	511	503	493
Kernel wheat hardness	67.8c	69.7b	71.6a	71.3a	72.3a

	Orthogonal contrasts				
	Control × N	Control × 70 kg N ha^{-1}	Control × 93 kg N ha^{-1}	70 × 93 kg N ha^{-1}	Traditional × Split
Test weight, kg hL^{-1}	0.012	0.025	0.01	0.429	0.041
Alveogram index (W, ´ 10^{-4} J)	<0.001	0.002	<0.001	0.016	0.002
Protein, %	<0.001	<0.001	<0.001	<0.074	<0.001
Flour, %	0.095	0.069	0.041	0.405	0.067
Dough extensibility (DE, mm)	0.002	0.011	<0.001	0.077	0.026
Dough tenacity (DT, mm)	0.939	0.781	0.660	0.415	0.628
DT/DE ratio	0.036	0.057	0.048	0.603	0.185
Falling number test (s)	0.064	0.039	0.423	0.273	0.615
Kernel wheat hardness	<0.001	<0.001	<0.001	0.006	0.002

†Values followed by the same letter indicate no statistically significant difference by Tukey's test ($P \leq 0.05$).

split N application, as well as an additional rate of 23 kg N ha^{-1} applied on late season, did not improve grain yield (Fig. 3). For this treatment yield improvement was primarily driven by number of heads, a function of increased number of tillers. Genetic potential and environmental conditions determine the number of tillers per plant (Peterson et al., 1982; Longnecker et al., 1993; Mundstock and Bredemeier, 2002; Dick et al., 2016), however the amount of N available early in the season is an important factor affecting tiller number and, consequently, increase the potential number of heads m^{-2} (Longnecker et al., 1993; Mundstock and Bredemeier, 2002). An appropriate N availability at the beginning of growing season benefits production and survival of new tillers (Longnecker et al., 1993). Thus, taking into account the environmental conditions, the application of 35 kg N ha^{-1} at tillering was not enough to increased yields across sites, despite the application of 35 kg N ha^{-1} at heading.

Delaying N application to near stem elongation could also benefit grain yield (Longnecker et al., 1993; Mundstock and Bredemeier, 2002; Garrido-Lestache et al., 2004), although available N at this stage would not affect the number of tillers formed but could improve tiller survival (Davidson and Chevalier, 1990; Shah et al., 1994). Available N ensures the synchronism between main stem and tiller development (e.g., a similar increase of dry mass), allowing for a greater number of heads per plant (Davidson and Chevalier, 1990; Longnecker et al., 1993; Shah et al., 1994). This response explains the proportional reduction on grain yield from lower N rates on early stages observed in our study. Greater yield losses in treatments receiving less N during early stages were likely not observed due to increased number of kernels per head (e.g., the lower number of heads resulted in greater number of kernels per head) and TKW (Fig. 3); the latter probably a function of the N rates applied at heading, which increased grain protein concentration (Fig. 4).

Differential effect of N management on grain yield across sites are likely related to the crop rotation system used in that experimental site, where corn was followed by oilseed radish as cover crop, which was terminated immediately prior to wheat sowing. Other studies indicated that oilseed radish has a great mineralization rate as well as the ability to cycle N (Jackson et al., 1993; Ngouajio and Mutch, 2002; Aita and Giacomini, 2003; Kristensen and Thorup-Kristensen, 2004). Thus, the presence of this cover crop (Site 2) and its N credits released into the production system (Ngouajio and Mutch, 2002; Aita and Giacomini, 2003) likely reduced the amplitude in the differences between the control and fertilized treatments (Supplemental Table 2). While these results are derived from a single site, could indicate that for a potential yield close to 3.5 Mg ha^{--1}, there is a lower probability of N response in sites where wheat is sown after that cover crop, and the needs to re-evaluate N recommendations in these systems exist.

Across sites, the traditional N strategy (70T) was suitable to maximize grain yield. Several studies documented no additional response of spring wheat to N beyond an optimal rate (Gauer et al., 1992; Garrido-Lestache et al., 2004; Otteson et al., 2007; Chen et al., 2008; Espindula et al., 2010), which could vary according to environmental conditions (López-Bellido et al., 1998; Garrido-Lestache et al., 2004; Ma et al., 2004; Zebarth et al., 2007; Barraclough et al., 2010; Godfrey et al., 2010; Farmaha et al., 2015). In Canada, positive response was not obtained for rates higher than 120 kg N ha^{-1} (Gauer et al., 1992). Meanwhile, in studies performed under rainfed Mediterranean conditions, optimum grain yield occurred at an overall N rate of 100 kg N ha^{-1} for hard red spring wheat cultivars (Garrido-Lestache et al., 2004). Similarly, in experiments performed in Montana, U.S. researchers tested the effects of split N application (total rate of 101 kg ha^{-1}), and also concluded that yield was not significantly affected (Chen et al., 2008), suggesting that all N should be applied early in the growing season (e.g., seeding). These studies, however, were conducted in dryer growing environments where N is less exposed to losses such as leaching or denitrification (Zhang and Raun, 2006), and thus timing of N application might not be as important. In Brazil, where growing season precipitation usually exceeds 700 mm, few studies exploring wheat response to rate of N fertilization demonstrated that maximum yields were reached at approximately 100 kg N ha^{-1} (Espindula et al., 2010; Teixeira Filho et al., 2012; De Bona et al., 2016), but there have been little efforts in elucidating the optimal N timing. The N fertilizer rates suggested across all studies mentioned above are similar to the traditional rate applied by producers in southern Brazil (i.e., ~20 kg N ha^{-1} applied in the sowing plus ~70 kg N ha^{-1} applied on tillering) (Silva et al., 2017), and lower optimal N rates should be expected in lower yielding environments (<2 Mg ha^{-1}).

Since similar yields are expected between early (sowing + tillering) and split/late (sowing + tillering + heading) applications (Chen et al., 2008), wheat producers should adopt strategies that do not raise the production cost. Within this context, the traditional N management (i.e., ~20 kg ha^{-1} sowing plus 70 kg ha^{-1} on tillering) proved to be a solid strategy. Finally, the lack of significant interaction between wheat cultivar and N management strategy has been previously reported in other hard red spring wheat growing regions in the United States (Farmaha et al., 2015), and suggests that cultivar differences (when existing) were not sufficient as to present different N management strategies.

Late Nitrogen Application Effects on Dough Properties

Late N applications increased grain protein concentration while having no effect on wheat grain yield (Fig. 4). Several studies reported that the optimal rate to maximize yield is not the same to maximize protein (Goos et al., 1982; Gauer et al., 1992; Bly and Woodard, 2003; Baker et al., 2004; Boehm et al., 2004; Dick et al., 2016). The current study presented similar

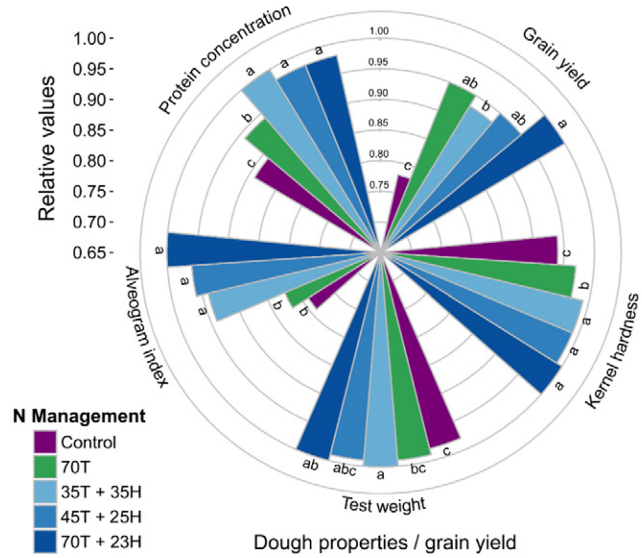

Fig. 4. Hard red spring wheat dough properties (relative values) as affected by N management strategy across locations and cultivars. Grain yield response was included for a practical comparison. Circular rings denote the scale relative values. Values followed by the same letter indicate no statistically significant difference by Tukey's test ($P \leq 0.05$) between N management for each parameter. Note: For understanding of the references to color in this figure legend, the reader is referred to the web version of this article.

outcomes; however, adding to the literature in that using the same N rate but split applied between tillering and heading (e.g., 35T+35H, 45T+25H), grain protein concentration could be increased (Fig. 4). Studies performed in South Dakota reported that late N foliar applications (boot and postpollination stages) also increased the protein of 9 out of 12 site-years (Bly and Woodard, 2003). These result are connected with the content of gliadins and glutenins, the two main proteins of the gluten fraction of wheat seeds (Johansson et al., 2001; Saint Pierre et al., 2008; Dong et al., 2009). The gliadins are responsible for the dough extensibility, while the glutenins confer viscosity and elasticity (Dong et al., 2009). The increase on N supply is significantly correlated with the increase in all protein components containing gliadins and glutenins; increasing the total protein concentration (Johansson et al., 2001). In addition, the current study also documented benefits of late season N application on DE (dough extensibility, function of gliadins content) (Supplemental Tables S1, S2, and S3), which appears to be more sensitive to N management than DT(dough tenacity, function of glutenin content) (Garrido-Lestache et al., 2004; Dong et al., 2009). Previous studies have suggested similar response among environments (Garrido-Lestache et al., 2004). Greater increase in DE as compared to indicate a reduction on DT/DE ratio with late season N application, thus improving dough balance (Garrido-Lestache et al., 2004).

The decision to apply late-season N or to split the common rate in early and late applications needs to be carefully evaluated, once the former could result in less net returns (Dick et al., 2016) and the latter might penalize yields. Following this rationale, the additional N management (70T+23H) could be a reasonable economic decision to be made during the growing season in case premiums from increasing grain protein concentration are expected (Bly and Woodard, 2003; Baker et al., 2004). On the other hand, splitting the usual rate between

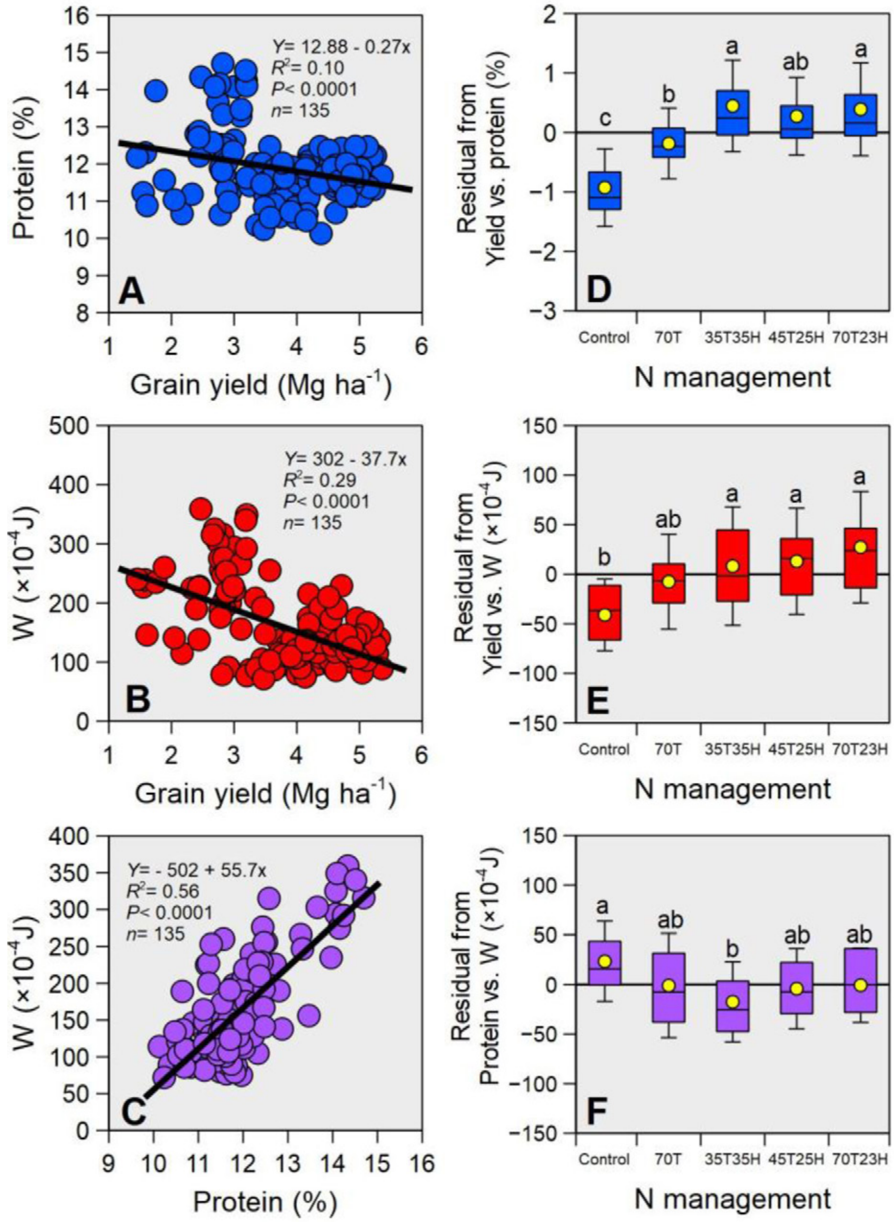

Fig. 5. Relationship between (Panel A) wheat grain yield and grain protein concentration; (Panel B) grain yield and alveogram index (W); and (Panel C) grain protein concentration and W across all evaluated sites. Box plots in Panels D, E, and F represents the residual from the yield vs. protein, yield vs. W, and protein vs. W relationships as affected by N management strategy. Box extends around the quartile second and third (percentiles 25–75), yellow circles represents the mean, and whiskers represent standard deviation around the mean. Residual boxes followed by the same letter indicates no statistically significant difference by Tukey's test ($P \leq 0.05$).

tillering and heading could represent a risk for wheat producers in regions where premiums for increased protein rarely occur, with the potential to reduce grain yield. A later N fertilization enhances grain protein concentration rather than yield (Sowers et al., 1994), since by anthesis ~75 to 80% of N has been uptake by wheat (Harper et al., 1987) and the majority of yield components have already been determined at that time (Peterson et al., 1982; Longnecker et al., 1993; Mundstock and Bredemeier, 2002). Thus, although later applications (i.e., at Feekes growth stage 10.1) may increase total N uptake, they have limited potential to affect yield (Borghi et al., 1997). Instead, the most likely consequences of late-applied N are increased protein concentration, kernel hardness, and TKW (Fig. 4). The benefits to increase grain protein concentration by N applications close to anthesis were documented in studies with durum wheat (Ottman et al., 2000) and winter wheat (Dick et al., 2016; Cruppe et al., 2017)

The negative relationship between grain yield and protein documented across N management ($P < 0.001$) (Fig. 5A) may be attributed to different factors. It might be partially explained by the dilution effect (Bly and Woodard, 2003; Garrido-Lestache et al., 2004; Lollato and Edwards, 2015), thus decreasing grain protein concentration (Dupont and Altenbach, 2003). Alternatively, low protein concentration in high yielding environments could be related to sufficient N to maximize grain yield but insufficient to maximize greater protein concentration (Goos et al., 1982; Bly and Woodard, 2003). Analysis of the residuals of the relationship between grain yield and grain protein concentration revealed that negative residuals occurred for the control, neutral residuals occurred for the 70T, and neutral to positive residuals were accounted for by treatments that received late-N application (Fig. 5D). These results indicate that late N applications could minimize the dilution effect for protein under high grain yield.

Treatments that received late-N application also had improved alveogram index across locations (Fig. 4), implying a greater dough strength. Additionally, there was a negative relationship between grain yield and alveogram index (Fig. 5B). The residual analysis from the relationship between grain yield and alveogram index revealed a similar pattern of that documented for grain protein concentration (Fig. 5E). Positive residual values resulted from treatments that received late-season N applications. Greater values of alveogram index resulting from higher N rates were previously reported in studies conducted in southern Spain (López-Bellido et al., 1998; Garrido-Lestache et al., 2004). Since protein and alveogram index have similar response to N (López-Bellido et al., 1998), a similar response would be expected. In our study, protein and alveogram index showed a significant positive relationship ($P < 0.001$, $R^2 = 0.56$), indicating greater dough strength with greater protein concentration (Fig. 5C). Interestingly, the treatments receiving largest N rate at heading (35T + 35H) resulted in lower residual in the analysis from grain protein concentration and alveogram index as compared to the control (Fig. 5F), indicating that late-season N applications increased grain protein concentration to a greater extent than alveogram index (Silva et al., 2017).

Finally, our results portray an opportunity to fine-tune the N management recommendations. Since until now little information is available about the N applications at heading for hard red spring wheat, the findings for our study should contribute to future N management in regions of the world with similar soil and weather conditions as our study (i.e., high precipitation), such as South America, or irrigated fields in the North of the United States (Westcott et al., 1997) and some parts of Canada. Results indicated that N fertilizer timing is nearly as important as the amount applied to some quality characteristics (i.e., protein, alveogram index) (McNeal et al., 1963). As reported by previous studies in other parts of the world, N recommendations need to consider production goal: grain yield, dough properties (Bly and Woodard, 2003), or both. The N management strategy to be selected has a direct impact on farmers' profitability and represent an important factor potentially reducing the environmental N footprint (Good and Beatty, 2011).

CONCLUSIONS

To our knowledge, this is the first assessment of a set of hard red spring wheat dough property parameters, as well as grain yield, as affected by N management strategy and cultivar in southern Brazil. Our results show that the decision to select the most adequate N application strategy during the growing season is related to the environment and the production goal. If production goal is final yield with no reward for protein concentration, the current N management adopted in southern Brazil (i.e., ~20 kg N ha^{-1} applied during the sowing plus ~70 kg N ha^{-1} applied on tillering) should be suitable in most situations with similar soil and weather conditions than our study. If the production goal includes both grain yield and quality, an additional N application during heading seemed to be the best strategy, increasing grain protein concentration, alveogram index, and dough extensibility. However, late-season N applications increased grain protein concentration more than alveogram index; thus, indicating that grain protein concentration might not be the best indicator of baking quality. Our results also indicated that the split application of the traditional rate, resulting in low rates on early season (tillering), are detrimental to grain yield due to the reduction on number of heads m^{-2}, but benefits protein concentration. Finally, from an economic standpoint, the decision to apply additional late-season N should take into consideration projected deductions from low protein and/or alternatively premiums from increasing protein concentration.

SUPPLEMENTAL MATERIAL

Table S1. Spring wheat yield components and dough properties as affected by wheat cultivars and N management strategies in the Site 1 (Ajuricaba, RS, Brazil) during the 2013 spring wheat growing season. Relevant single degree of freedom orthogonal contrasts are also shown.

Table S2. Spring wheat yield components and dough properties as affected by wheat cultivars and N management strategies in the Site 2 (Derrubadas, RS, Brazil) during the 2013 spring wheat growing season. Relevant single degree of freedom orthogonal contrasts are also shown.

Table S3. Spring wheat yield components and dough properties as affected by wheat cultivars and N management strategies in the Site 3 (Derrubadas, RS, Brazil) during the 2013 spring wheat growing season. Relevant single degree of freedom orthogonal contrasts are also shown.

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