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Alternatives for Nitrogen Diagnosis for Wheat with Different Yield Potentials in the Humid Pampas of Argentina

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A correct determination of nitrogen (N) fertilization thresholds in wheat that is based on objective yield produces efficient use of this nutrient. Nitrogen fertilization recommendations for traditional wheat require determination of nitrate (NO_3^-)-N availability at 60 cm deep at planting time. However, this methodology is complicated, expensive, and time-consuming; thus, the determination of NO_3^--N level at a lesser depth and at a different time would be desirable. The goals of this work were to determine available N in soil thresholds for traditional and French germplasm wheats and the feasibility of diagnosing N requirements by measuring NO_3^--N at 40 cm deep, at planting or tillering times, in the southeastern Pampas. The experiments were factorial combinations of N rates and fertilization times (planting and tillering) at different sites and years during 2002–2006. Nitrogen fertilization significantly increased grain yield and protein content. French varieties presented greater grain yield (23%), lower protein content (11%), and greater yield per N unit, indicating greater N-use efficiency (NUE) than traditional varieties. A similar relationship was determined between grain yield and available N at both sampling depths. This might be explained by the strong association between NO_3^--N content at 60 and 40 cm deep at both sampling dates. Maximum yield and available N determined at 60 or 40 cm soil deep showed that thresholds were lower for tillering than for planting, regardless of the genotype (152 and 174 kg of available N, respectively). Available N thresholds for 95% of maximum yield were less at 0–40 cm deep than at 0–60 cm deep (10 and 14 kg N ha^{-1} for traditional and French genotypes, respectively). The results of this experiment suggest the possibility of diagnosing N requirements for wheat by measuring NO_3^--N content at 40 cm deep, instead of the usual 60 cm, for both traditional and French genotypes.

Keywords N diagnosis, soil sampling, traditional and French genotype, wheat

Introduction

In the humid southeastern Pampa of Argentina (Figure 1), spring wheat is one of the most important crops, with an average production of 2.5 million Mg over 0.7 million ha (average of the past 5 years). In the past two decades, intensive cropping with conventional

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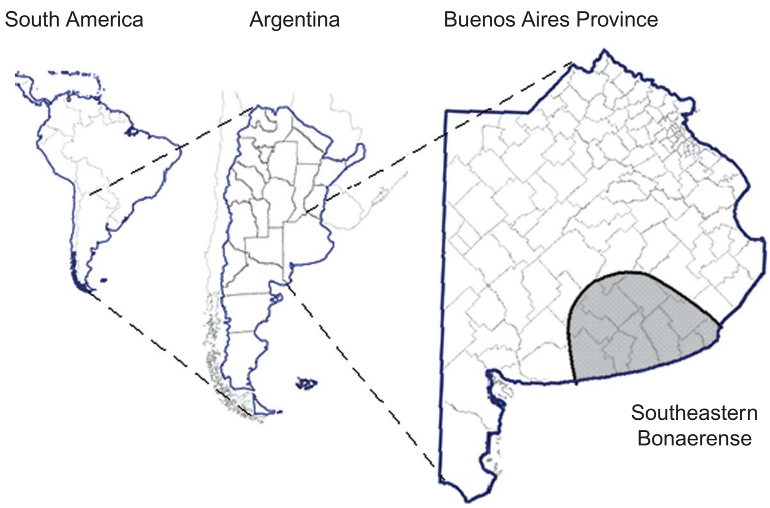

Figure 1. Map of South America indicating Argentina, Buenos Aires Province, and southeastern Buenos Aires (shaded area) (color figure available online).

tillage has led to deterioration of soil physical, biological, and chemical properties. The reduction in soil organic matter has increased soil erosion and exacerbated nitrogen (N) deficiency problems (Studdert and Echeverría 2000). In addition, lower N availability in soil managed with no tillage increases wheat response to N fertilization (Falotico, Studdert, and Echeverría 1999). This area has an average annual rainfall of 870 mm, half of which takes place during the wheat-growing season. The greater proportion of soils are Typic Argiudolls, with loam texture at the surface layer, loam to clay loam at subsurface layers, and sandy loam below 110 cm deep, and Petrocalcic Paleudoll, which presents discontinuous layers of petrocalcic horizon below 0.8 m and greater clay contents at subsurface layers than Typic Argiudolls. More details of weather and soils in that area were described in Barbieri, Sainz Rozas, and Echeverría (2008).

Wheat grain yield in the Argentine Humid Pampas increased after producers increased applied N rates. A gap of at least 3 t ha^{-1}, however, remains between current and potential yield estimated as a function of potential kernel number and kernel mass (Abbate, Andrade, and Culot 1994; Abbate et al. 1997). Much of this gap is related to water availability as consequence of high-frequency droughts late in the growing season. Other factors include fungal diseases and the use of suboptimal N rates (González Montaner, Maddonni, and Di Napoli 1997). Therefore, opportunities exist to increase currently attainable wheat yields.

Currently, the most widespread diagnostic method to determine N fertilization needs in the area is based on the determination of the NO_3^--N content in soil at planting time and at 60 cm deep (González Montaner, Maddonni, and Di Napoli 1997; Calviño, Echeverría, and Redolatti 2002). Barbieri, Echeverría, and Sainz Rozas (2009) reported that the N availability levels (soil + fertilizers) needed for maximum yields when using traditional wheat varieties were 200 and 155 kg N ha^{-1} ($R^2 = 0.38$ and 0.59, respectively) for soil samples (0–60 cm deep) and N applications at the time of planting and tillering, respectively. The lower threshold determined at tillering might be explained by a greater N uptake by the crop (Barbieri, Echeverría, and Sainz Rozas 2009). This greater N-use efficiency (NUE) obtained by fertilizing at tillering might become relevant because of the high value of N in production cost and the reduction of environmental impact by using lower N rates (Barbieri, Sainz Rozas, and Echeverría 2008). Furthermore, in recent years French genotype materials with greater yield potential have been introduced in the area (Calviño, Echeverría, and Redolatti 2002; Barbieri, Echeverría, and Sainz Rozas 2009), which, as they rapidly expand, need adjusted N thresholds for fertilization.

In general, the response of wheat crops to increasing N rates can be described by a quadratic model. However, N levels for maximum yield determined by using quadratic-plateau model are lower than those determined with the quadratic model, regardless of the variety and maximum yield reached. Cerrato and Blackmer (1990) observed that the quadratic model tends to overestimate N requirements and the use of this model determined optimal economical N levels that are too high from an agronomical standpoint. Similar results were obtained in southeastern Buenos Aires for corn (Pagani et al. 2008) and wheat (Barbieri, Echeverría, and Sainz Rozas 2009).

Fertilization recommendation requires determining soil NO_3^--N content up to 60 cm deep because of its mobility through the soil profile (Alvarez, Alvarez, and Steinbach 2001). Even when root development down to 1 m is possible (Jakson et al. 1996), the major proportion of roots are at surface horizons (Barraclough, Weir, and Kuhlmann 1991). In practical terms, sampling at 60 cm soil deep is complicated, expensive, and time-consuming; thus, the determination of the NO_3^--N level at 40 cm deep could be a useful tool to facilitate soil sampling.

The goals of this work were to determine N thresholds in soil for maximum yield and the feasibility of diagnosing N requirements by measuring NO_3^--N content at 40 cm deep at planting or tillering for traditional and French wheat genotypes.

Materials and Methods

The study was carried out during the 2002–2006 growing seasons over a transect of 250 km from east to west in three locations in southeastern Buenos Aires Province, Argentina (Mar del Plata, Balcarce, and Tandil). Some characteristics of the management practices, cultivars, and properties of surface soil at the experimental sites are presented in Table 1.

The experimental data covered a wide range of meteorological and soil fertility conditions to consider different productive scenarios. Hence, the data sets represent a wide range of wheat yield responses to N availability. Preventive applications of herbicides and fungicides were done. Treatments at all sites comprised progressive N rate applications as urea (46–0–0) at planting or tillering on traditional and French wheat genotypes. In 2002 and 2003, N rates varied according to the initial soil N-NO_3^- to reach available N levels (soil + fertilizer) of 100, 150, and 200 kg N ha^{-1}. In 2004, a steady 120 kg N ha^{-1} (fertilizer) rate was applied, and in 2005 and 2006 steady N rates of 60 and 120 kg ha^{-1} (fertilizer) were applied. A control treatment (N0) was added at all experimental sites, which consisted of plots 10 m long and 3 m wide. Management practices used in each experimental site were the same as those used by farmers (planting, weed, insect, and fungal disease control). At planting time, experiments were fertilized with P as monoammonium phosphate (11–48–0) at a rate of 22 kg P ha^{-1} and S as calcium sulfate (18.6% S) at a rate of 10 kg S ha^{-1}. Weeds were controlled with applications of metsulforon methyl {methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)]amine]carbonil]amine]sulfonil} benzoate at 6 g a.i. ha^{-1} plus 2,4-D (2,4-dicholoro-phenoxyacetic acid) at 0.5 kg a.i. ha^{-1}. When necessary, insects were controlled by application of deltamethrin {(S)-[cyano (3-phenoxyphenyl) methyl] cis-(4)-3-(2,2-dibromoethenyl)-2,2-dimethylciclop ropanecarboxylate} at 5 g a.i. ha^{-1}.

Table 1
Information describing experimental sites for planting and tillering

Site-year	Year	Site	Genotytpe	Previous crop	OM (g $100g^{-1}$)	pH	P-Bray (mg kg^{-1})
1	2002	Mar del Plata	Traditional and French	Sunflower	5.1	6.2	19.7
2	2002	Balcarce	Traditional and French	Soy	5.7	6.0	14.3
3	2002	Tandil	Traditional and French	Corn	5.3	6.0	20.3
4	2003	Mar del Plata	Traditional and French	Sunflower	5.1	6.2	19.7
5	2003	Tandil	Traditional and French	Corn	5.8	6.0	25.9
6	2004	Balcarce	Traditional	Soy	5.7	6.1	11.0
7	2004	Tandil	Traditional	Corn	6.1	6.2	12.0
8	2004	Mar del Plata	Traditional	Corn	5.6	5.9	13.0
9	2005	Balcarce	Traditional	Sunflower	5.3	6.0	8.2
10	2005	Mar del Plata	French	Soy	5.9	5.6	13.8
11	2006	Mar del Plata	French	Soy	5.2	6.2	19.8
12	2006	Balcarce	French	Corn	5.0	5.8	37.0

OM, organic matter; P-Bray, available P by Bray I method

At each site/year, determinations of N-NO_3^- content at 60 cm deep were carried out through layers of 20 cm at planting and tillering times (Bremner and Keeney 1966). At maturity, the plants were harvested and grain yield was determined by harvesting an area of 9.6 m^2 (8 m long by 1.2 m wide), corrected to 140 g kg^{-1} grain moisture content. Protein content was estimated as N content in grain determined by method A (without salicylic acid modifications) reported by Nelson and Sommers (1973) multiplied by a 5.7 factor.

For both wheat genotypes, the quadratic-plateau model was adjusted to describe yield response as a function of available N. Analyses were performed using Table Curve software (Jandel Scientific, Corte Madera, Calif.). Analysis of variance (grain yield and protein) and simple regression analyses (40 vs 60) were made using GLM and REG procedures, respectively, Coincidence and parallelism tests were used to compare slopes and intercepts used the software Statistical Analysis System (SAS Institute 1985). Treatment means were compared using the least significant different (LSD) mean separation procedure (Steel and Torrie 1980).

Results and Discussion

Climatic Condition

Water availability did not limit wheat growth and grain yield because the accumulated rainfall during June–December was greater than 380–400 mm at all sites and growing seasons, with the exception of Tandil (2003 and 2004) (Figure 2). At Tandil 2003, however, high yields were obtained because a big proportion of the precipitation took place 60 days before and 10 days after anthesis (Calviño, Echeverría, and Redolatti 2002). At Tandil 2004, water

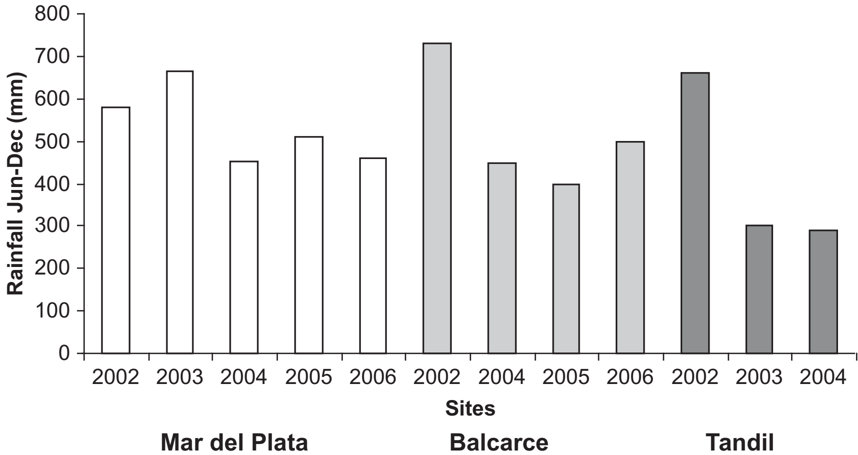

Figure 2. Rainfall during the wheat-growing seasons (June–December) at Mar del Plata, Balcarce, and Tandil.

availability was low since flowering, which decreased wheat yield. In the majority of the site-years, precipitation was high along the first stages of the wheat.

Grain Yield

Grain yield varied from 1600 to 6500 kg ha^{-1} and from 2600 to 8000 kg ha^{-1} for traditional and French genotypes, respectively (Table 2). Average yields by French genotypes were 23% greater than traditional varieties. Similar results were reported by other authors for the same area (Calviño, Echeverría, and Redolatti 2002; Echeverría et al. 2004; Redolatti 2007).

Nitrogen fertilization significantly increased grain yield ($P < 0.05$) at all experiments with the exception of Mar del Plata 2006, where the initial N availability for wheat was high (Table 3). The yield responses to added N (average through years and sites) for greater N rates were 1950 and 2380 kg ha^{-1}, for traditional and French genotypes, respectively (Table 2). The high response to N application indicates severe N deficiency in the evaluated soils (Barbieri, Sainz Rozas, and Echeverría 2008).

French genotypes showed greater yield per unit of available N compared to traditional varieties, indicating NUE differences between genotypes. Nitrogen-use efficiencies for maximum yield were 28 and 40 kg grain per kg available N^{-1} (average of both fertilization dates) for traditional and French genotypes, respectively. The NUE values determined in this experience are similar to those reported by Calviño, Echeverría, and Redolatti (2002) and Redolatti (2007) for the same varieties at southeastern Buenos Aires. Linear coefficient values of equation between grain yield and available N (i.e., kg grain per kg available N^{-1}) were similar regardless of soil depth or sampling date. French genotypes produced greater yield per unit of available N (Figure 3). This difference in NUE would have consequences because traditional varieties contained greater protein concentrations in grain than French genotypes, with 11.9% vs 10.7%, respectively, as averages over years and fertilization dates (Table 2). Differences were greater for control treatments than for those receiving the maximum N rate (Table 2). These results are in agreement with those reported by Fowler (2003), who determined an inverse relationship between grain yield and protein content, even in soils with high N availability. However, for all N rates, a greater average N uptake in grain

Table 2
Yield (kg ha^{-1}) and protein content in grain (%) for traditional and French varieties

				Traditional		French	
Experiment	Year	Site	N rate	Grain yield	Protein	Grain yield	Protein
1	2002	Mar del Plata	0	1637 c	11.4 c	2667 c	7.8 b
			100	3611 b	11.3 b	4547 b	8.7 b
			150	3946 ab	11.5 a	5404 ab	10.4 a
			200	4239 a	12.6 a	6186 a	10.5 a
2	2002	Balcarce	0	3495 b	11.5 c	4236 b	9.0 c
			100	4664 b	11.8 b	6355 a	9.4 bc
			150	5169 a	12.2 a	6253 a	10.2 ab
			200	5161 a	12.9 a	6308 a	10.5 a
3	2002	Tandil	0	2615 c	13.0 c	3290 c	9.6 b
			100	4537 b	13.0 b	4492 b	9.9 b
			150	5197 a	14.1 a	5409 a	10.5 ab
			200	5237 a	14.0 a	5837 a	11.9 a
4	2003	Mar del Plata	0	4093 c	13.3 b	4510 b	8.9 b
			100	5152 b	14.2 a	7660 a	9.6 ab
			150	5924 a	13.8 a	7745 a	10.2 ab
			200	6377 a	15.6 a	8086 a	10.7 a
5	2003	Tandil	0	3535 c	12.2 c	5122 b	8.9 c
			100	4965 b	12.4 b	7258 a	9.4 bc
			150	6106 a	13.5 a	7102 a	10.2 ab
			200	5960 a	14.0 a	7675 a	10.6 a
6	2004	Mar del Plata	0	2830 b	9.3 b	–	–
			120	4376 a	8.7 a	–	–
7	2004	Balcarce	0	4725 b	9.2 b	–	–
			120	5426 a	9.8 a	–	–
8	2004	Tandil	0	2405 b	9.1 b	–	–
			120	4661 a	11.3 a	–	–
9	2005	Balcarce	0	3498 c	9.0 c	–	–
			60	5238 b	9.5 b	–	–
			120	5765 a	10.6 a	–	–
10	2005	Mar del Plata	0	–	–	4418 b	7.6 c
			60	–	–	7118 a	10.0 b
			120	–	–	7783 a	11.3 a
11	2006	Mar del Plata	0	–	–	5530 a	9.9 b
			60	–	–	5986 a	11.1 ab
			120	–	–	5383 c	12.5 a
12	2006	Balcarce	0	–	–	3528 b	10.1 b
			60	–	–	4628 a	11.1 a
			120	–	–	5007 a	13.3

Note. Means followed by the same character are not significantly different from each other based on the LSD test.

Table 3
$N\text{-}NO_3^-$ content (kg ha^{-1}) at 60 and 40 cm deep in traditional and French varieties at planting and tillering

			Depth: 0–60 cm				Depth: 0–40 cm			
			Traditional		French		Traditional		French	
Test	Campaign	Site	Planting	Tillering	Planting	Tillering	Planting	Tillering	Planting	Tillering
1	2002	Mar del Plata	19.2	13.4	21.0	7.9	15.9	10.8	16.0	8.3
2	2002	Balcarce	20.7	44.1	29.1	34.7	15.5	38.0	19.8	37.9
3	2002	Tandil	10.7	28.2	9.2	42.1	8.3	23.2	7.8	25.8
4	2003	Mar del Plata	26.2	52.3	24.3	69.7	25.5	37.0	23.2	44.4
5	2003	Tandil	45.4	28.8	25.1	22.1	39.1	22.8	20.9	17.1
6	2004	Balcarce	67.8	23.1	—	—	56.4	15.8	—	—
7	2004	Tandil	63.6	42.2	—	—	53.0	28.3	—	—
8	2004	Mar del Plata	92.5	26.6	—	—	71.1	18.8	—	—
9	2005	Balcarce	52.2	27.7	—	—	41.7	19.8	—	—
10	2005	Mar del Plata	—	—	35.8	36.5	—	—	32.1	25.5
11	2006	Mar del Plata	—	—	126.0	123.8	—	—	91.0	89.6
12	2006	Balcarce	—	—	39.2	24.9	—	—	33.3	15.8

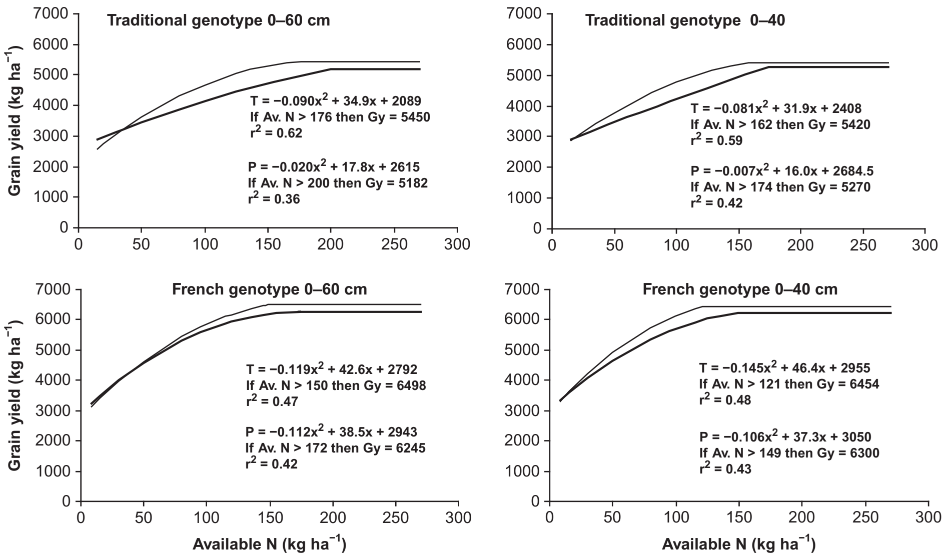

Figure 3. Relationship between wheat grain yield and soil N available at planting (P) or tillering (T) in the southeast of Buenos Aires Province for traditional and French genotypes.

was determined for French genotypes in relation to traditional genotypes (108 and 94 kg N ha^{-1}, respectively; data not shown). These results suggest greater recovery efficiency in French varieties.

In both genotypes, for equal N availability (NO_3^--N content at 0–60 cm deep + fertilizer), N application at tillering produced greater yield than application at planting (Figure 3). A similar behavior for that relationship was observed when NO_3^--N content was determined at 0–40 cm deep (Figure 3). Lower yield related to N application at planting might be explained primarily by the occurrence of greater N loss by leaching and, to a lesser extent, by denitrification (Picone, Videla, and García 1997; Barbieri, Sainz Rozas, and Echeverría 2008). Greater NUE for N applications at tillering compared to planting have been also reported by other authors (Melaj et al. 2003; Videla et al. 2004; López Bellido, López Bellido, and López Bellido 2006; Barbieri, Sainz Rozas, and Echeverría 2008). The greater NUE determined for sampling and fertilization at tillering determined lower available N thresholds to obtain 95% of maximum yield as compared to sampling and fertilization at planting (Figure 3). On the other hand, for both genotypes and sampling depths, the relationships between yield and available N at tillering showed a greater determination coefficient compared to sampling and fertilization at planting, indicating better reliability of this diagnostic method (Figure 3). For both fertilization dates, available N thresholds to 95% of maximum yield were lower for sampling at 40 cm soil deep (Figure 3). Thresholds at 60 cm deep determined in this experience are similar to those reported by Calviño, Echeverría, and Redolatti (2002).

The similar fit determined for grain yield and available N at both depths (Figure 3) is consequence of the high association between NO_3^--N content at 60 and 40 cm deep at both sampling dates (Figure 4). Similar results were reported for the northern area of Buenos Aires Province and the southern area of Santa Fe Province by Alvarez, Alvarez, and Steinbach (2001), who estimated the NO_3^--N content at 60 cm deep using its determination at surface layers. However, in our experiment, adjusted slopes differed between dates ($P < 0.05$), and it therefore is not possible to use only one model to estimate NO_3^--N

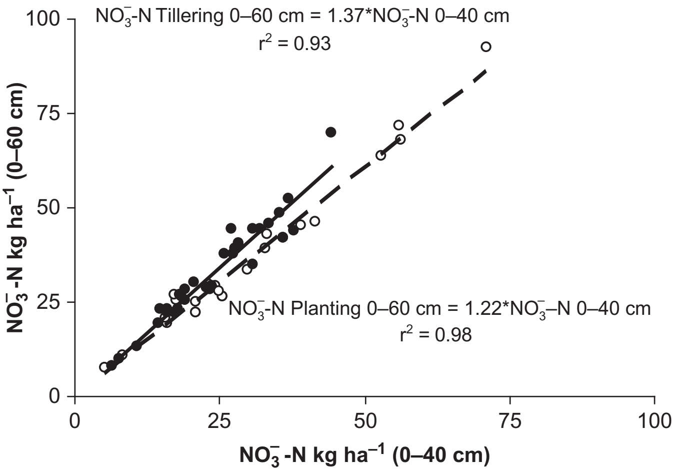

Figure 4. Relationships between nitrate content ($N\text{-}NO_3^-$) 60 and 40 cm deep in N0 treatments.

content at 60 cm deep based on NO_3^--N content at 40 cm deep (Figure 4). At planting, the NO_3^--N content at 0–40 cm deep represented 94% of the content determined at 0–60 cm deep, while at tillering it represented 89%. These results point to a shift in the NO_3^--N content in soil depth between planting and tillering, which may be explained by the high occurrence of excess water during the initial growing stages (Calviño and Sadras 2002; Reussi Calvo and Echeverría 2006), causing nitrate movement (Barbieri, Sainz Rozas, and Echeverría 2008).

The results obtained show that for both genotypes, the N-requirement diagnosis by soil analysis is more accurate and the N threshold is lower for soil sampling performed at tillering, which can be explained by the occurrence of excess water during the initial growing stages of the crop, a frequent situation at southeastern Buenos Aires (Calviño and Sadras 2002; Reussi Calvo and Echeverría 2006). Barbieri, Sainz Rozas, and Echeverría (2008) estimated, using a CERES-wheat simulation model, that NO_3^--N loss by leaching process ranged from 12 to 62 kg N ha^{-1} and only 7 to 16 kg N ha^{-1} for fertilization at planting and tillering, respectively, emphasizing the importance of NO_3^--N leaching.

Available N thresholds for both varieties determined for 95% of maximum yield, fertilization date, and sampling depth are shown in Table 4. French genotypes presented lower available N values regardless of the sampling depth, even when these varieties yielded more than traditional varieties (Table 4). As averages of sampling dates and soil depths, French genotypes presented an N threshold of 30 kg ha^{-1} lower and around 1000 kg ha^{-1} greater yield compared to traditional genotypes. These results manifest, once again, greater NUE by French genotypes, suggesting different fertilization management according to the genotype used. As to sampling depth, thresholds of available N determined for 0- to 40-cm deep were less than 0–60 cm by 10 and 14 kg N ha^{-1} for traditional and French genotypes, respectively (Table 4).

The results of this experiment allow us to conclude that it is possible to diagnose N requirements for wheat crops based on genotype, fertilization date, and sampling depth. As a consequence, it is feasible to take soil samples from the first 40 cm deep, instead of the traditional 60 cm deep. On the other hand, the predictive capacity of the methodology was greater and soil available N thresholds lower when sampling and fertilization

Table 4
Nitrogen fertilization thresholds (kg N ha^{-1}) in soil (0–60 and 0–40 cm deep) at planting and tillering to reach 95% maximum yield (values between parentheses) for traditional and French genotypes of wheat

Threshold	Traditional varieties	French varieties
Planting threshold (95% grain yield)		
0–60 cm	170 (4924)	119 (5935)
0–40 cm	155 (5008)	115 (5923)
Tillering threshold (95% grain yield)		
0–60 cm	136 (5176)	119 (6171)
0–40 cm	129 (5153)	99 (6132)

were done at tillering time. The adoption of N diagnostic methodologies based on soil sampling at a lower depth, along with the lower available N thresholds determined for soil samplings and N applications at tillering, will enable a more rational use of N fertilizers, reducing the environmental impact of their application and thus contributing to improve the sustainability of productive systems.

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