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Predicting Field-Apparent Nitrogen Mineralization from Anaerobically Incubated Nitrogen

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The nitrogen (N) released after a 7-d anaerobic incubation (N_{an}) is a good estimator of the size of the soil N mineralizable pool. However, there is a lack of information on how soil properties and climate affect the apparent field N mineralization (N_{min}) of this pool. The objective of our study was to develop and validate a simple model to estimate N_{min} from N_{an} in corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) fields. To this end, we performed 100 field experiments where we measured N_{min}, N_{an}, rainfall, temperature (T_C), soil texture, pH, soil organic matter (SOM), and pre-sowing mineral N concentration ($N_{initial}$). We performed a stepwise analysis to develop a model to predict N_{min} using data from 70 sites, while the rest of the data was saved for model validation. The N_{an} ranged from 16 to 94 mg kg^{-1} while N_{min} ranged from 22 to 232 kg ha^{-1}. There was a strong association between N_{an} and N_{min} within regions with similar climate and edaphic properties. However, we could not fit a single significant model to estimate N_{min} based solely on N_{an} to be used in all regions. By considering other variables besides N_{an}, we developed a model that allowed predicting N_{min} independently from the site [N_{min} = –252 + 12.3(T_C) + 1.37(N_{an}) + 0.27(rainfall)] (R^2 = 0.89, model validation R^2 = 0.83). This model could be useful to adjust N fertilizer recommendations for corn and wheat, reducing the economic and environmental impact of fertilization.

Abbreviations: DOY, day of year; N_0, potentially mineralizable nitrogen; N_{aerial}, nitrogen concentration in plants aerial biomass; N_{an}, anaerobically incubated nitrogen; N_{grain}, nitrogen concentration in grains; $N_{initial}$, soil inorganic nitrogen concentration before sowing in unfertilized plots; N_{min}, apparent nitrogen mineralization; NP, northern Pampas region; NP_{early}, early corn planting date at the northern Pampas region; NP_{late}, late corn planting date at the northern Pampas region; N_{plant}, nitrogen plant uptake in unfertilized plots; $N_{residual}$, soil inorganic nitrogen concentration after harvest in unfertilized plots; N_{roots}, nitrogen concentration in plant roots; PPNT, soil NO_3^-–N content at planting; SP, southern Pampas region; SOM, soil organic matter; T_C, mean temperature from sowing until the end of the crop critical stage; VIF, variable inflation factor.

Core Ideas

- **Study aimed to predict field N mineralization (N_{min}) from anaerobically incubated N (N_{an}).**
- **N_{an} did not predict N_{min} in areas with contrasting edaphic-climatic properties.**
- **N_{min} was predicted by a model including Nan, temperature and rainfall.**

One of the most common methods used to diagnose soil N availability for corn and wheat is based on the determination of soil NO_3^-–N content at planting (PPNT) (Magdoff et al., 1984; Sainz Rozas et al., 2008; Barbieri et al., 2012). However, this method does not account for the N released by mineralization of organic N during the growing season. To improve the estimation of soil N availability for corn and wheat it would be necessary to consider both N sources: initial inorganic N and N mineralized during the growing season.

Many chemical and biological laboratory indexes have been proposed to estimate the soil N mineralization potential (Pansu and Gautheyrou, 2006; Griffin, 2008; Schomberg et al., 2009), but long-term aerobic incubations are often used as a reference method to determine the N mineralization potential (N_o) (Stanford and Smith, 1972). However, these incubations are lengthy and consequently unsuitable as routine methods for N diagnosis. Keeney (1982) proposed using a short-term anaerobic incubation to estimate N_o. This method consists of quantifying the NH_4^+–N released during a 7-d incubation in waterlogged conditions at 40°C. Several authors described a strong association between N_{an} and N_o (Schomberg et

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al., 2009). The N_{an} method has even been described as a good estimator of sulfur (S) mineralization potential (Wyngaard and Cabrera, 2015; Carciochi et al., 2016). Furthermore, it has been reported that N_{an} is more sensitive to changes in management practices and land use than chemical indices like KCl and the Illinois Soil Test Analysis (Bundy and Meisinger, 1994; Genovese et al., 2009).

The N_{an} incubation method has been used to improve N fertilizer diagnosis for wheat and corn. Reussi Calvo et al. (2013) and Orcellet et al. (2017) reported that a combined PPNT + N_{an} model better explained wheat and corn yield response to N fertilization, as compared with a simple PPNT model. Along this line, Sainz Rozas et al. (2008) determined that the NO_3^-–N sufficiency threshold determined by PPNT differs depending on soil N_{an}. However, the development of PPNT + N_{an} models for predicting N response for each crop and location requires calibration trials, which are expensive and laborious. An alternative to these models would be to derive the N mineralized in the field during the growing season (kg N ha^{-1}) from N_{an}, and to use the estimated N mineralization as an input in the balance method to predict N availability (Meisinger, 1984).

Although N_{an} can predict N_o measured under controlled conditions, the real N mineralization rate in the field will depend not only on the size of the N mineralizable pool, but on soil properties and climate conditions. Some studies have proposed using a mass balance to estimate N mineralization in the field, considering minimum N losses from the system (Rice and Havlin, 1994; Meisinger, 1984). The mass balance method allows determining the apparent N mineralization (N_{min}) (N mineralization − N losses) as a function of plant N accumulation in unfertilized plots, initial soil mineral N ($N_{initial}$), and final soil mineral N ($N_{residual}$). The main limitation of this method is the long time required for obtaining results. However, the method is still considered a reference method to determine field N mineralization rates (Meisinger et al., 1992).

Previous studies have developed models to predict N_{min} from edaphic and climatic variables. Gonzalez Montaner et al. (1997) developed a model to predict N_{min} during wheat growing season, using soil total organic C content to account for mineralization. Even if some studies observed a relationship between C content and N mineralization potential (Schomberg et al., 2009), this is not always true because the C to N ratio of the soil organic matter (SOM) influences the N release rate per unit of C (Springob and Kirchmann, 2003). Other studies modeled N_{min} using long-term aerobic incubations as predictors (Alvarez and Steinbach, 2011; Egelkraut et al., 2003), which are time-consuming and not suitable for routine analysis. The use of N_{an} in models to predict N_{min} has never been evaluated before.

Previous studies indicate that N_{an} is a good estimator of N mineralization potential (Reussi Calvo et al., 2014b). However, there is a lack of information on how soil properties and climate conditions would affect the field N mineralization rate predicted by N_{an}. The objective of our study was to develop and validate a simple model to estimate N_{min} from N_{an} in corn and wheat fields with contrasting soil properties and climate conditions.

MATERIALS AND METHODS

Field Experiments

One hundred field experiments with three replications per site were conducted in the Argentinean Pampas (30° to 40° S; 57° to 66° W) from 2007 to 2013. The experimental sites were established in two areas with contrasting edaphic properties and climatic conditions: southern Pampas (SP) (Typic Argiudoll; 950 mm mean annual precipitation; 13.5°C mean annual air temperature) and northern Pampas (NP) (Typic Hapludoll/Typic Argiudoll; 975 mm mean annual precipitation; 19.2°C mean annual air temperature). Soils from the SP present a loamy texture and a SOM concentration ranging from 50 to 60 g kg^{-1} in the surface horizon. In contrast, the soils from NP are characterized by a sandy-loam and silty-loam texture, respectively, and a lower SOM concentration (20 to 30 g kg^{-1}) as compared with the SP (Sainz Rozas et al., 2011).

Sixty-one of the experimental sites were sown with corn (35 at NP and 26 at SP) and 39 with wheat (20 at NP and 19 at SP). Each experiment was arranged in a randomized complete block design with three replications. In each block, different N fertilizer rates were evaluated, but only the control treatment (0 kg N ha^{-1}) was used in this study. Each plot was 10 m by 5 m for corn and 10 m by 3 m for wheat.

Corn was sown on the day number of the year (DOY) 288 ± 11 at SP ($n = 26$). At NP, two different corn planting dates were evaluated: early (NP_{early}, DOY 276 ± 5) ($n = 20$) and late (NP_{late}, DOY 342 ± 2) ($n = 15$). This was possible only at NP and not at SP due to the greatest frost-free period in the former region (Cirilo and Andrade, 1994). The seeding rate was 67000 plants ha^{-1} for SP, 80000 plants ha^{-1} for NP_{early}, and 73000 plants ha^{-1} for NP_{late}. Phosphorus (P) and S were applied to all plots (30–40 kg P ha^{-1} and 20–25 kg S ha^{-1}) to avoid deficiencies of these nutrients. Wheat was sown at SP and NP at 250 to 280 plants m^2 seeding rate at DOY 136 ± 30. Phosphorus and S were applied at a 30 kg P ha^{-1} and 20 kg S ha^{-1} rate, respectively. Corn and wheat were managed on a no-tillage system and no irrigation was applied. Weeds were controlled by the application of glyphosate [N-(phosphonomethyl)glycine] at a 1.35 kg a.i. ha^{-1} rate for corn, and metsulfuron-methyl (methyl 2-{[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]oxomethyl]sulfamoyl}benzoic acid) (6 g a.i. ha^{-1}) and 2,4-D (2,4-dichlorophenoxyacetic acid) (0.5 kg a.i. ha^{-1}) for wheat.

Data for cumulative rainfall (mm) and mean air temperature (T_C) measured at a 2 m height were obtained from research meteorological stations located in or near (<10 km) the experimental sites. Both variables were measured from sowing until the end of the crops critical stage (15 d after anthesis). We measured temperature from sowing until R_1 because for NP_{late} we observed large drops in temperature during the last stage of the growing season (from DOY 60), which reduced the mean temperature for the whole season. Consequently, the mean temperature did not fairly represent the temperature during the period of greater mineralization and N plant uptake.

Soil and Plant Analysis

Composite soil samples (20 subsamples) were taken from each plot at a 0- to 20- and 0- to 60-cm depth before sowing, and at a 0- to 60-cm depth after harvest using sharpened stainless steel probes (5.5 cm i.d.). The samples were oven-dried at 30°C and ground to pass a 2-mm sieve. All recognizable plant residues were removed. For soil samples collected from the 0- to 20-cm depth, SOM concentration (Walkley and Black, 1934), texture (Bouyoucos, 1962 as described by Gee and Bauder, 1986), and soil pH (1:2.5 soil/water ratio) were determined. Soil NH_4^+–N + NO_3^-–N concentration (g kg^{-1}) was determined in the 0- to 60-cm deep samples at sowing and after harvest ($N_{initial}$ and $N_{residual}$, respectively) (Bremner and Keeney, 1965; Keeney and Nelson, 1982). These results were expressed in units of kg ha^{-1} using bulk density values estimated as proposed by Hollis et al. (2012). The N_{an} was determined by incubating 10 g of dry and sieved soil (0–20 cm depth) under waterlogged conditions in a stoppered glass test tube (150 mm high by 16 mm diameter) for 7 d at 40°C. The released NH_4^+–N was quantified by steam micro-distillation (Bremner and Keeney, 1965), as proposed by Gianello and Bremner (1986), and the initial soil NH_4^+–N content was subtracted from the NH_4^+–N determined before the incubation. We decided to evaluate N_{an} as a N mineralization estimator because, even though it is relatively time-consuming in comparison to other methods, it is simple, economic, sensitive to changes in management practices (Genovese et al., 2009), highly associated with N_o (Schomberg et al., 2009), and it has been used before as an index to predict plants response to N fertilization (Sainz Rozas et al., 2008; Reussi Calvo et al., 2013; Orcellet et al., 2017).

At physiological maturity, grain yield was determined by hand-harvesting a 10 m^2 or a 1 m^2 area from each corn and wheat plot, respectively. Each plot was harvested separately, resulting in three yield replications per site. Threshing was performed using a stationary machine. Grain yields were corrected to a water content of 140 g kg^{-1}. Total grain N concentration (N_{grain}) was determined by the Dumas method (Jung et al., 2003) using a TruSpec CN analyzer (LECO, 2013) on milled grain samples. Additionally, eight random corn plants from the three central rows or 0.5 m^2 of wheat were cut at ground level in each plot. The plants were then dried at 60°C and milled (without the grains). The total N concentration in the aerial biomass (N_{aerial}) was quantified following the same procedure used for N_{grain}. The total N content in plants (N_{plant}) (N in the aerial biomass + roots + rhizodepositions) was estimated assuming that N in the roots (N_{roots}) is 20% of N_{aerial}, and that rhizodepositions are 6% of N_{aerial} + N_{roots} (Merbach et al., 1999).

Modeling Technique and Statistical Analysis

The N_{min} was estimated using the mass balance method (Rice and Havlin, 1994); all forms of N are in units of kg ha^{-1}.

$$N_{min} = N_{plant} + N_{residual} - N_{initial}$$

The normality of data distribution was confirmed by the Shapiro and Wilk (1965) procedure, while the homogeneity of variances was confirmed with the Levene (1960) test. To compare soil variables, yield, N_{grain}, and N_{plant} between regions and planting dates, an ANOVA was performed using the R commander software (R Core Team, 2014). This model considers regions and/or planting dates as fixed effects. Effects were considered statistically significant at $p < 0.05$, and means were compared using Tukey-Kramer test.

To develop the N_{min} predictive model, the data set was randomly partitioned into two sub-sets: 70% for training and 30% for validation. When splitting the data set, each crop, region, and sowing date was proportionally represented in the resulting sub-sets. Simple and multiple linear regressions were performed using the lm procedure (linear model) of the R command software. The stepwise selection method was used to select the best variable combination to explain N_{min} from N_{an}, $N_{initial}$, clay, clay + silt, pH, SOM, T_C, and rainfall. To evaluate the existence of multicollinearity, we calculated the variance inflation factor (VIF), considering a VIF value greater than 5 as an indicator of high multicollinearity (Montgomery and Peck, 1992). Finally, to determine coincidence between regression models, indicator variables (dummy variables) were used at a 5% probability.

The validation data set was also used to evaluate if the resulting model was capable of predicting N_{min} from N_{an} and historical climate data collected from 1980 to 2010 (rainfall and precipitations from sowing until the end of the crops critical stage) for each one of the regions and crops (Bianchi and Cravero, 2010).

RESULTS AND DISCUSSION

The average rainfall amounts from sowing until the end of each crop's critical stage are presented in Table 1. Depending on the crop and studied sites/planting dates, the water demand from sowing until the end of the critical period ranges from 160 to 250 mm (Andrade and Gardiol, 1995; Reussi Calvo and Echeverria, 2006). Therefore, water availability was greater than crop requirement at all sites. The T_C showed differences between areas and planting dates, with greater values at NP_{late} as compared with NP_{early} and SP (Table 1).

The particle size distribution also differed between regions, with a finer texture observed at SP (Table 1). The average SOM content was greater at SP as compared with NP (Table 1). The

Table 1. Anaerobically incubated nitrogen (N_{an}), soil organic matter (SOM), air temperature from sowing until the end of the crops critical stage (T_C), available nitrogen content at a 0- to 60-cm depth at sowing ($N_{initial}$), and apparent mineralized nitrogen (N_{min}) determined in corn and wheat field trials stablished in the Argentinean southern Pampas (SP) and northern Pampas (NP) at two different planting dates for corn: early and late (NP_{early} and NP_{late}, respectively). Values are means ± standard deviation.

Crop	Site	N_{an}	SOM	pH	Clay	Clay + Silt	Rainfall	T_C	$N_{initial}$	N_{min}	Yield†
		mg kg^{-1}	g kg^{-1}		g kg^{-1}		mm	°C	kg ha^{-1}		
Corn	NP_{early}	28 ± 7 b‡	26 ± 7 b	5.9 ± 0.3 c	100 ± 40 b	300 ± 70 b	145 ± 2 d	23 ± 1 b	59 ± 11 b	71 ± 20 b	8820 ± 1902 b
	NP_{late}	29 ± 6 b	29 ± 5 b	6.1 ± 0.2 ab	120 ± 30 b	330 ± 80 b	228 ± 5 b	26 ± 1 a	65 ± 6 b	136 ± 21 a	11888 ± 1629 a
	SP	70 ± 12 a	57 ± 7 a	5.9 ± 0.1 c	200 ± 30 a	480 ± 40 a	192 ± 16 c	19 ± 1 c	73 ± 21 a	86 ± 21 b	8582 ± 1188 b
Wheat	NP	34 ± 9 b	26 ± 2 b	6.2 ± 0.3 a	115 ± 40 b	320 ± 65 b	169 ± 41 cd	14 ± 2 d	61 ± 11 b	30 ± 8 c	2683 ± 615 b
	SP	64 ± 12 a	55 ± 1 a	6.0 ± 0.3 bc	210 ± 40 a	470 ± 60 a	393 ± 58 a	10 ± 1 e	62 ± 13 b	39 ± 20 c	5032 ± 1092 a

† Yield means comparison was performed for each crop separately.

‡ Different letters indicate significant differences between regions, planting dates, and crops as determined by the Tukey-Kramer test (p < 0.05).

Table 2. Person correlation coefficient (*r*) matrix for the relationship between climate and edaphic variables: clay content, clay + silt content, anaerobically incubated N (N_{an}), soil inorganic N content at sowing ($N_{initial}$), field apparent N mineralization (N_{min}), pH, air temperature from sowing until the end of the crop critical stage (T_c), rainfall during the crops critical stage, and soil organic matter (SOM).

	Clay	Clay + Lime	N_{an}	$N_{initial}$	N_{min}	pH	Rainfall	SOM
Clay + Lime	0.83*							
N_{an}	0.62*	0.39*						
$N_{initial}$	0.02	−0.05	0.10					
N_{min}	−0.44*	−0.50*	−0.12	0.04				
pH	0.26	0.36*	0.06	−0.09	0.03			
Rainfall	0.14	−0.08	0.25	−0.06	−0.21	0.00		
SOM	0.28	−0.12	0.73*	0.32*	0.06	−0.20	0.36*	
T_c	−0.67*	−0.56*	−0.55*	0.04	0.78*	−0.09	−0.59*	−0.33*

* Significant at $p < 0.05$.

difference in SOM levels between NP and SP were associated with differences in soil texture, temperature, and precipitation between regions (Table 2). In addition, the larger history of intensive agriculture using aggressive tillage systems at NP contributed to a negative soil C balance in this region (Sainz Rozas et al., 2011).

The measured N_{an} values were within the range described by other authors (Sainz Rozas et al., 2008; Reussi Calvo et al., 2013, 2014a; Studdert et al., 2015) (Table 1), and were greater at SP than at NP. We determined a significant but moderate correlation between N_{an} and SOM ($r = 0.73$) (Table 2). This trend can be a consequence of the different lability of the SOM in each region, which results in changes in SOM content not necessarily implying a proportional change in the N mineralization potential (Sharifi et al., 2007).

Grain yield varied between regions and/or planting dates for both corn and wheat (Table 1), and these differences were associated with differences in N_{min} (Fig. 1a), and not with $N_{initial}$ (Fig. 1b). Models to predict grain yield from N_{min} did not differ between sites/planting dates for each crop. We also evaluated a linear multiple model to predict grain yield from both $N_{initial}$ and N_{min} (data not shown). However, the inclusion of $N_{initial}$ to the model did not improve its predictive capacity neither for corn ($p = 0.21$) nor wheat ($p = 0.11$). The poor association between $N_{initial}$ and grain yield is common in humid areas, where the magnitude of soil N mineralization during the growing season and $N_{initial}$ leaching losses after soil sampling are significant (Hergert, 1987; Melaj et al., 2003; Barbieri et al., 2008). Along this line, Sainz Rozas et al. (2008) reported that $N_{initial}$ explained only 37% of the relative corn yield variability, while Reussi Calvo et al. (2013) observed that $N_{initial}$ explained 24% of wheat yield variability in the Pampas region.

The average $N_{min,}$ resulting from the mass balance, ranged between 22 and 232 kg ha^{-1} (Table 1). These results are similar to those described by Echeverría and Bergonzi (1995). The N_{min} at NP_{early} was alike that at SP, with an average N_{min} of 74.5 kg ha^{-1} (Table 1). At NP_{late}, N_{min} was almost twice that in SP and NP_{early} (Table 1). The trend we observed for N_{min} ($NP_{late} > NP_{early} = SP$) (Table 1) was different to that observed for N_{an} ($SP > N_{Plate} = NP_{early}$) (Table 1). This difference between N_{min} and N_{an} demonstrates that a greater N mineralization potential (as estimated by N_{an}) does not necessarily imply a greater field N mineralization rate. The greater T_C and rainfall, and the lower clay and silt content at NP could have resulted in a faster mineralization of the labile organic N pool at NP, compensating for the smaller size of this pool as compared with SP.

We determined a strong association between N_{an} and N_{min} for each area (r^2 ranging from 0.58 to 0.83) (Fig. 2). The slope of the resulting models (increase in N_{min} per N_{an} unit) was

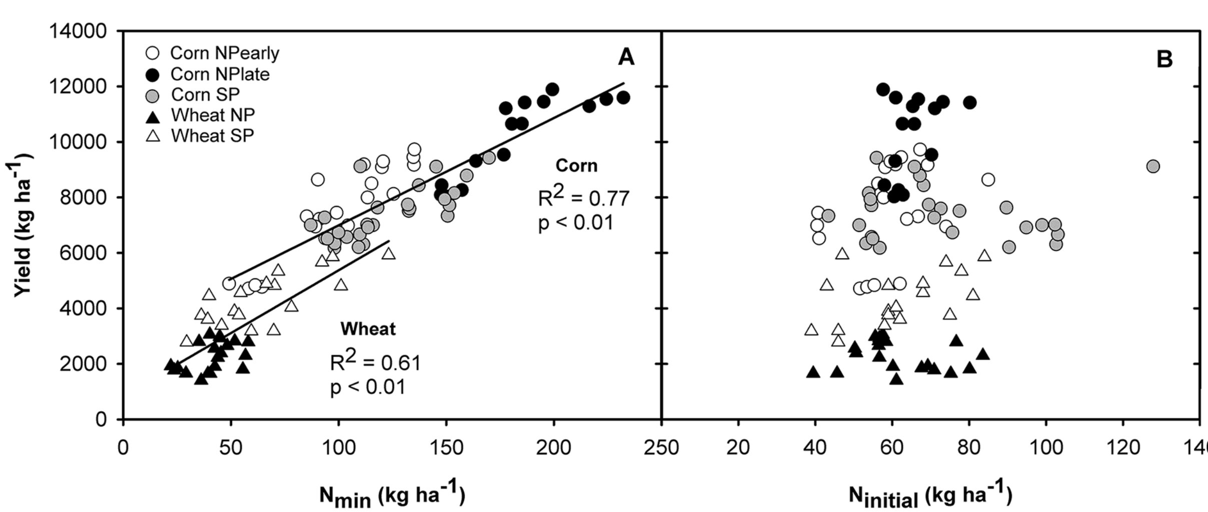

Fig. 1. Relationship between corn or wheat grain yield and (A) apparent nitrogen mineralized during the growing season (N_{min}) or (B) soil inorganic nitrogen content at sowing ($N_{initial}$) (0–60 cm) (*n* = 100).

greater at NP (early and late sowing dates) than at SP ($p \leq 0.05$; Fig. 2). As stated before, this difference can be a consequence of the lower temperature and the greater clay content at SP. Our results indicate that N_{an} is a good indicator of N_{min} but a single N_{an} model cannot be used to predict N_{min} when edaphic or climatic properties at growing sites are contrasting. For example, a value of N_{an} of 30 mg kg^{-1} represents an N_{min} value of 190 kg ha^{-1} for corn during the growing season at NP_{late}, but a N_{min} value of only 100 kg ha^{-1} at NP_{early}. Consequently, even though the association between N_{an} and N_{min} was strong for each region separately, we could not fit a single significant model to estimate N_{min} based solely on N_{an} to be used in all regions.

To account for the effect of edaphic and climatic differences on N mineralization, we performed a stepwise analysis to predict N_{min} from N_{an}, T_C, rainfall, lime + clay, clay, SOM, $N_{initial}$, and pH (Table 1). This selection allowed to create a single model to predict N_{min} at all crops, regions, and planting dates from three variables: N_{an}, T_C, and rainfall (Table 3). This model explained 89% of N_{min} variability, with a greater partial contribution from T_C. The VIF was 1.4, 2.0, and 1.2 for N_{an}, T_C, and rainfall, indicating that multicollinearity is not significant enough to justify the exclusion of one of the predictors from the model. The model was validated using and independent set of data ($n = 30$) (Fig. 3), resulting in an R^2 of 0.83. The intercept of observed vs. estimated data was no different from 1, while the intercept was no different from 0.

We used the predicted N_{min} values to estimate grain yield (Fig. 4). The relationship between the predicted N_{min} and wheat yield ($R^2 = 0.505$) was significant but lower than the one observed between wheat yield and the measured N_{min} ($R^2 = 0.61$) (Fig. 1). Along the same line, the relationship between the predicted N_{min} and corn yield ($R^2 = 0.50$) was significant but lower than the one determined in Fig. 1 ($R^2 = 0.77$).

From the variables selected by the stepwise model, T_C and water content (estimated by rainfall) are environmental factors well known to regulate soil N release (Quemada and Cabrera, 1997). Gonzalez Montaner et al. (1997) developed a model to predict wheat yield in soils with similar C to N ratio that used soil organic C to estimate N mineralization potential. The fact that SOM was not included in our model is probably a consequence of SOM not considering the different lability of the organic fraction, which is accounted for by N_{an}. Other authors observed that the N mineralization rate was also affected by $N_{initial}$ due to negative or positive priming effects (Gonzalez Montaner et

Table 3. Coefficients from a model to predict apparent N mineralization during corn and wheat growing seasons from STEPWISE selected variables: mean air temperature from sowing until the end of the crops critical stage (T_C), anaerobically incubated N (N_{an}), and rainfall ($n = 70$).

	PV†	p-value	Partial R^2	R^2
Model	–252	<0.01	–	0.89
T_C	12.3	<0.01	0.60	–
N_{an}	1.37	<0.01	0.17	–
Rainfall	0.27	<0.01	0.12	–

† PV, parameter value.

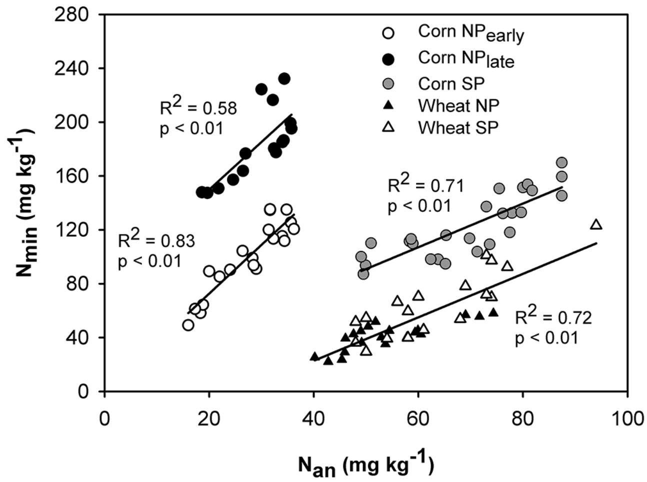

Fig. 2. Relationship between anaerobically incubated nitrogen (N_{an}) (0–20 cm) and apparent N mineralization (N_{min}) determined in corn and wheat trials stablished in the Argentinean southern Pampas (SP) and northern Pampas (NP) at two different planting dates for corn: early and late (NP_{early} and NP_{late}, respectively) ($n = 100$).

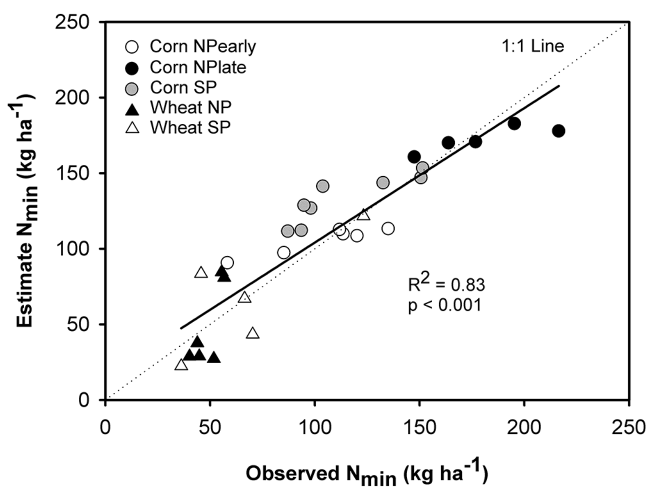

Fig. 3. Validation of a model to estimate apparent N mineralization (N_{min}) from soil and climate variables (anaerobically incubated N, temperature, and rainfall) ($n = 30$).

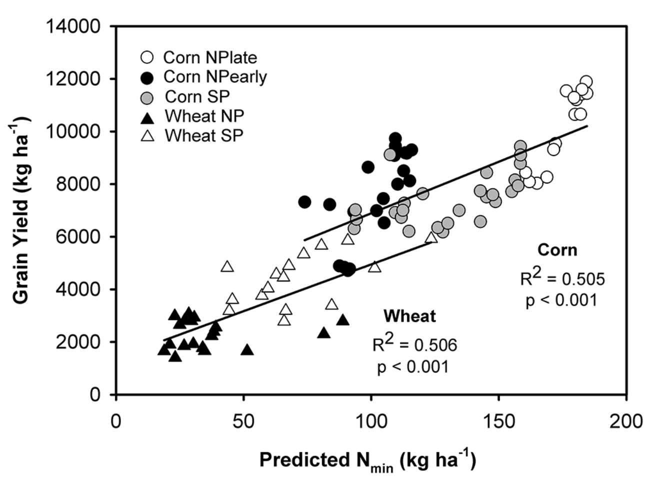

Fig. 4. Relationship between corn or wheat grain yield and the apparent nitrogen mineralized during the growing season estimated by a linear model including edaphic and climatic variables ($n = 100$).

al., 1997; Blankenau et al., 2000; Alvarez and Steinbach, 2011). However, in our study $N_{initial}$ did not significantly contribute to the model, as observed by Campbell and Paul (1978).

We also evaluated if the model was capable of predicting N_{min} using regional historical climate data (Bianchi and Cravero, 2010) as input (Fig. 5). The estimated N_{min} values were positively correlated with the observed ones ($R^2 = 0.74$), but the model tended to overestimate N_{min} during corn growing season for NP_{early}. This overestimation was caused by the greater historical rainfall (300 mm) as compared with the one observed during the experiment (145 mm).

Previous studies have aimed to predict field apparent N mineralization from edaphic and climatic variables. Delphin (2000) could not satisfactorily predict N_{min} from long-term incubation experiments without leaching, and explained the result based on the lack of reliability of their field data. The regression model suggested by Gonzalez Montaner et al. (1997) to predict N_{min} from soil organic carbon, $N_{initial}$ and temperature is simple, but its determination coefficient was low ($R^2 = 0.50$). Alvarez and Steinbach (2011) obtained suitable N_{min} predictions from regression and artificial neural networks ($R^2 > 0.68$). However, these authors used 17-d aerobic incubations to account for the soil N mineralization potential. This type of incubation is laborious and time-consuming, and therefore unsuitable for soil testing labs. In contrast to previous published models to predict N_{min}, the positive aspects of our proposed model are: (i) it requires a simple edaphic analysis (N_{an}) as input, (ii) it was developed and validated using a big data set ($n = 100$), resulting in a significant determination coefficient ($R^2 = 0.89$), (iii) and it proved to be a suitable indicator of N_{min} for two crops, wheat and corn.

The N_{min} values derived from the model could be used to determine the N fertilizer rate by the balance sheet method (Meisinger, 1984). The balance sheet method considers yield goal and N requirement as estimates of N demand, while it estimates soil N supply from soil mineral N, residue decomposition, and soil organic matter N mineralization. When N supply does not meet crops N demand, the application of N fertilizers is recommended to compensate the imbalance. The N_{min} values derived from our model can be used as an input in the balance sheet method, allowing a better estimation of field N mineralization and N supply.

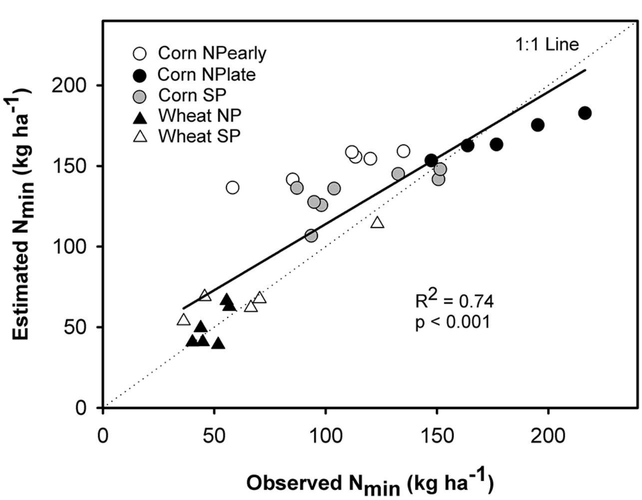

Fig. 5. Validation of a model to estimate apparent N mineralization (N_{min}) from historical climate data (average for 30 yr) ($n = 30$).

CONCLUSIONS

For two crops, corn and wheat, growing in regions with contrasting climate and soil properties, we developed and validated a model based on N_{an}, temperature, and precipitations to estimate N_{min}. This model would allow estimating N mineralization during a crop's growing season independently from the crop and region, using a simple soil testing analysis (N_{an}), and historical mean temperature and rainfall data. The estimation of N_{min} resulting from this model could be useful to adjust N fertilizer recommendations for corn and wheat, reducing the economic and environmental impact of fertilization.

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