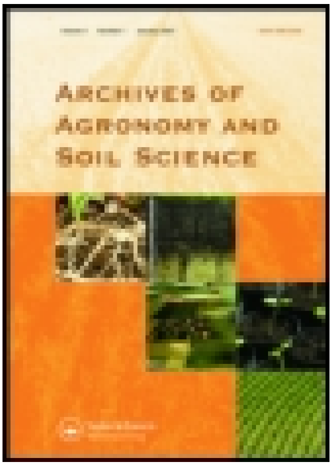

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The Argentinean Pampa is an important grain production region in which nitrogen (N) availability restricts wheat (*Triticum aestivum* L.) yield. We performed 46 experiments in the Semi-arid Pampa for evaluating soil N supplying capacity using a mass balance approach. The information generated was combined with published results from 58 experiments performed in the Humid Pampa. Average rainfall was 50% lower under semi-arid conditions and soils had half of the clay + silt and total N contents than those of humid environments. Wheat yield under humid scenarios doubled the yield attained under semi-arid ones, and N and rainfall use efficiencies were also higher. A model could be fitted with good performance for estimating N-supplying capacity from mineral and organic soil pools (R^2 = 0.53–0.93), absorbed N (R^2 = 0.70) and yield (R^2 = 0.57). This methodology can be used for estimating fertilizer needs under defined climate- and site-specific scenarios. For the average yields, rainfall and soil conditions of the experimental networks, targeted N supply (soil mineral + fertilizer N) was estimated as 160 kg N ha^{-1} in the Humid Pampa and 50 kg N ha^{-1} in the Semi-arid Pampa. Current N rates applied by farmers need to be increased under humid conditions and overfertilization occurs under semi-arid ones.

Keywords: pampean region; wheat; N balance; N use efficiency

Introduction

The Pampas of Argentina have been considered as one of the main wheat (*Triticum aestivum* L.) cropping regions in the world (Satorre & Slafer 1999). Many nitrogen (N) fertilizer recommendation strategies have been developed for the humid portion of the region, but information is scarce in the semi-arid area (Alvarez 2013), despite that N may restrict wheat productivity (Bono et al. 2011), and fertilization is a common practice.

Quantifying soil N availability and crop demand, the balance sheet method offers a conceptual framework for understanding N cycling in agroecosystems (Meisinger 1984; Neeteson 1995). It may be used for determining N rates when yield response functions are unavailable (Vanotti & Bundy 1994) by contrasting soil supplying capacity with crop demand to attain a yield goal (Brye et al. 2003). Fertilizer needs are calculated by the difference between both soil N availability and N crop demand (Neeteson 1995). In the Humid Pampa, the balance sheet methodology had been deeply studied for wheat (Gonzalez Montaner et al. 1997; Alvarez et al. 2004, 2011) and corn (*Zea mays* L.)

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(Sainz Rozas et al. 2004) crops. N mineralization from residue decomposition and organic matter had been assessed and modelled, and losses had been quantified in some cases. Conversely, in the Semi-arid Pampa, only one experiment was performed to estimate soil N-supplying potential by this approach (Bono & Alvarez 2013), and the results cannot be generalized to other sites and production scenarios.

Positive interaction between water and N availability has been described in different agroecosystems (Aulakh & Malhi 2005; Li et al. 2009). As water availability increases, higher N use efficiency may be expected and greater N rates are needed (Fan et al. 2005; Kröbel et al. 2012). In semi-arid environments, fertilizer rate must be carefully adjusted at site level taken into account the interaction between N and water availability to avoid erroneous fertilizer recommendations (Monjardino et al. 2013). In the Pampas, comparisons of N use efficiency as a function of climate scenarios had not been performed yet.

Our objectives were (1) to adjust an N balance methodology to estimate fertilizer recommendations in the Semi-arid Pampa and (2) to compare the efficiency of resources utilization between this region and the Humid Pampa in order to determine if the current farmer's fertilization technology is adequate.

Materials and methods

Study area

The Argentinean Pampas is a plain of approximately 60 Mha (28°S and 40°S and 57°W and 68°W) with humid and warm-temperate climate (Figure 1). Mean annual rainfall ranges between 500 mm in the West and 1200 mm in the East and mean temperature ranges between 14°C in the South and 23°C in the North. Predominant natural vegetation is grasslands with graminaceous species (Hall et al. 1992). Most common soils are Mollisols formed on loess-like materials, because of the aeolian origin of sediments from Southwest to Northeast and the West–East rainfall gradient, varied from

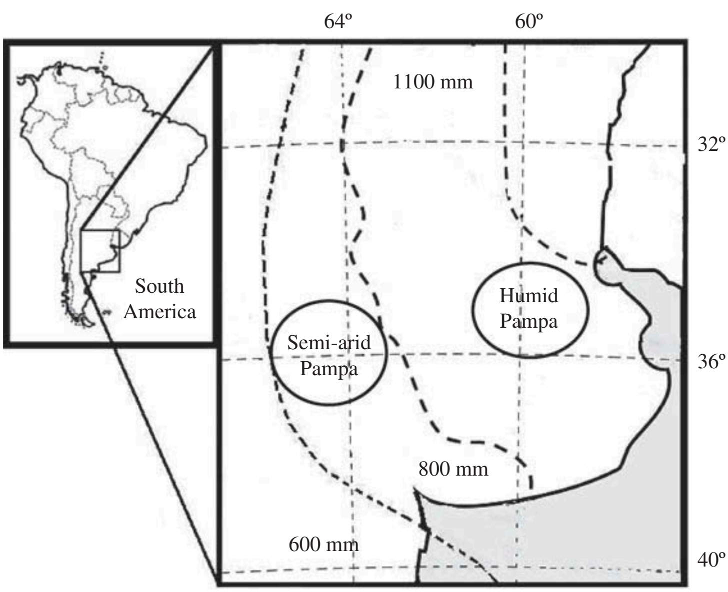

Figure 1. Map of the pampean region showing the two areas of experimentation and isohyets.

fine-textured and deep in the eastern humid portion of the region to sandy-textured and shallow in the semi-arid West (Alvarez & Lavado 1998; Berhongaray et al. 2013). A petrocalcic horizon may be found within the upper 1 m of the soil profile in many sites along the West and South (Teruggi 1957). Soil organic carbon has a strong association with rainfall, but pH values vary usually between 6 and 7 in well-drained soils not following the climate gradient (Alvarez & Lavado 1998; Berhongaray et al. 2013). Only hydromorphic lands present higher pH values (Berhongaray et al. 2013). Acid soils are very uncommon. Above 600 mm of annual rainfall, rain-fed crops are cultivated, being at present approximately 50% of the pampean area under cropping (MinAgri 2014). Wheat accounts for 15% of the total grain production of the region (MinAgri 2014). A widespread utilization of no-till occurred since 1990 joined to the adoption of fertilization as a common practice (MinAgri 2014).

Experimental network

During 2009 and 2011, we performed 46 field experiments in production fields with wheat in the Semi-arid Pampa, concentrated in an area known as Inland Pampa (Hall et al. 1992) (Figure 1). Farms were chosen because they were representative of common production systems in the region. Tillage systems varied from the use of mouldboard plough to no-till, and previous crops were wheat, sunflower (*Helianthus annuus* L.), corn or mixed pastures. At the two-leaf growth stage, two plots of 400 m^2 were delimited in each production field, one fertilized with N and the other used as control treatment. Fields received phosphorus (P) fertilization at sowing when needed, and an N rate of 50 kg ha^{-1} was applied as urea in the fertilized treatment. Soils were sampled, with samples taken at three sites by plot by 20 cm layers to 100 cm depth and pooled by depth layer. Nitrate + ammonium N was determined by steam distillation (Mulvaney 1986), total N with an autoanalyser (LECO Co., St. Joseph, MI, USA), texture by the Bouyuocos method (Gee & Bauder 1986) and bulk density using a steel cylinder (Blake & Hartge 1986). N concentration was transformed to mass data using bulk density data. Surface residue from the previous crop was harvested using four metal squares of 0.25 m^2 by plot. Buried residues to 25 cm depth were sampled with a steel cylinder of 0.02 m^2 at the same sites in which surface residue was harvested. Residue biomass was washed, sieved (2 mm), dried (60°C) and separated from roots by hand before being weighed. At wheat harvest (physiological maturity), soil and residue sampling was repeated. Aboveground wheat biomass and yield were determined at three sites by plot harvesting 2 m^2 in each site. Wheat roots were determined using the same samples used for previous crop residue measurement. N in previous crop residues and wheat biomass was determined by the Kjeldhal method (Bremner 1986) and carbon with the autoanalyser. Aerobic incubations were performed for estimating soil N mineralization potential. Soils were incubated 15 days at 30°C and at water content equivalent to field capacity as described previously (Alvarez et al. 2004). Rainfall was recorded in all the experiments using pluviometers.

Other data sources

The information generated in the Semi-arid Pampa was compared and integrated with results from a field experimental network previously described (Alvarez et al. 2004) performed in the Humid Pampa in an area called Rolling Pampa (Hall et al. 1992) (Figure 1). Briefly, 58 experiments were performed along three growing seasons on representative production fields. Tillage systems varied from the use of mouldboard plough to no-till and previous crops were corn or soybean (*Glycine max* Merr.). In this network, soil mineral N, total N, N mineralization potential, previous crop residue biomass and its N content and wheat aboveground biomass, roots and yield were evaluated by methods similar to those used in the Semi-arid Pampa. Main difference was that soils were sampled in layers of 30 cm. Data of N fertilizer rates currently applied were obtained from RIAN (2014) based on an official field survey in which around 1000 farmers were interviewed. Data on soil mineral N level at wheat seeding were obtained from published survey data from 220 production fields from the two areas studied (Alvarez 2010).

Balance model

We used the following balance model equation for depicting N dynamics in the soil–plant system (Alvarez et al. 2004):

$$\mathrm{N\,crop} = (\mathrm{MNI} - \mathrm{MNF}) + (\mathrm{NRBI} - \mathrm{NRBF})f + (\mathrm{ONI} - \mathrm{ONF} - \mathrm{NL}) \quad (1)$$

where N crop = N absorbed in aboveground and belowground wheat biomass at harvest; MNI = mineral N at initial crop growth stage (soil nitrate and ammonium in the 0–60 cm depth + fertilizer N); MNF = mineral N at final crop growth stage in the 0–60 cm depth; NRBI = N in residue biomass at initial crop growth stage; NRBF = N in residue biomass at final crop growth stage; f = N fraction not incorporated into microbial biomass and released to soil solution for crop utilization, it used an f value of 0.7 for surface residue and 0.3 for buried residue (Parton et al. 1993); ONI = organic N at initial crop growth stage; ONF = organic N at final crop growth stage and NL = N losses from the soil–plant systems by volatilization, denitrification and lixiviation.

The model assumes that N requirement necessary to attain a yield goal is supported by changes in the magnitude of three N pools: the mineral pool, the residue pool and the organic pool, taken into account losses from the system. Changes in the organic N pool between sowing and harvest are very difficult to measure and also N losses are very difficult to be assessed. Consequently, after determining all other equation terms, (ONI – ONF – NL) can be calculated, which represents the difference between net soil N mineralization and losses. This term is similar to the so-called apparent mineralization (Engels & Kuhlmann 1993), differing because N release during previous crop residue decomposition is not included but separately assessed.

Data processing and statistical methods

For comparison of total soil N contents and N mineralization potential between the two experimental networks, in which different sampling depths were used, data were normalized to 30 cm depth in the Semi-arid Pampa. This was performed by fitting a potential model (Berhongaray et al. 2013) to the data generated at the profile level and estimating N contents or mineralization for the 0–30-cm layer using the fitted parameters in each site. The potential model did a good job with $R^2 > 0.95$ in all cases. Partial factor productivity (PFP = ratio between grain production and N supplied) was used as an indicator of mineral N use efficiency of agroecosystems (Cassman et al. 1998). Physiological efficiency (PE = ratio between grain production and N uptake, Ladha et al. 2005) and rainfall use efficiency (RUE = ratio between grain production and rainfall, Sawargaonkar et al. 2013) were also calculated. In all cases, yield was presented as dry matter (0% water). Results from the networks were compared by a two-sample *t*-test. Linear and curvilinear regression methods were used for inspecting the relationships between variables testing significance by the *F*-test ($P = 0.05$). Multiple regression methods were also applied for testing the polynomial model of grade two, in which lineal and curvilinear effects and also interactions between independent variables were included (Alvarez 2009). A stepwise procedure was employed and terms were included in the final model only if they were significant ($P = 0.05$). The autocorrelation between variables was prevented using the variance inflation factor, refusing variables with values over 5 (Neter 1990). Only significant regression models with their R^2 were plotted in figures. The performance of multiple regression models was assessed by plotting observed vs. estimated data testing ordinates and slopes against 0 and 1 with Irene software (Fila et al. 2003). When ordinates and slopes were not different from 0 and 1, respectively, they were dropped from regressions.

Results

Differences of soil properties and rainfall were very significantly between the two experimental networks (Table 1). In the Humid Pampa, soils in average doubled fine particles and total N contents than in the Semi-arid Pampa, meanwhile mineral N, potential mineralization capacity and previous crop residue biomass were between three and fourfold greater. The network performed in the Humid Pampa received 50% more rainfall than the one in the Semi-arid Pampa. Only apparent mineralization was greater in the latter area but the difference was small. Total biomass production of wheat, N demand and yield copied the differences in N and water availability between areas (Table 2). Average harvest index was lower under semi-arid conditions than under humid ones, mainly because some very low values were measured in experiments that suffered deep water deficit. Efficiency measures were also significantly higher in the Humid than in the Semi-arid Pampa because of the same reason (Table 2).

Models for estimating the terms of the N balance equation could be fitted with acceptable performance integrating results from the two networks. Changes of the mineral N pool along the growing season could be predicted using the initial mineral N content of the soil (Figure 2(a)), N released during residue decomposition dependent on its total amount of N (Figure 2(b)), and apparent mineralization modelled as a function of soil variables and rainfall using a multiple regression model given in Figure 2(c). The regression of observed vs. the estimated values with this model had ordinates not different from 0 and slopes not different from 1. As total N, potential mineralization and rainfall increased, apparent mineralization also increased. Conversely, it decreased as soils were of finer texture; the level of initial mineral N rise or more residue of previous crop was found at the initiation of the growing season. Wheat yield increased as N absorbed by the crop increased following a curvilinear trend regardless of the pampean area considered (Figure 2(d)).

A three-step model was developed for yield estimation. In the first step, the three terms of the balance model that quantify soil N availability were estimated using soil properties and rainfall using equations given in Figure 2(a)–(c). In the second step, N uptake of crop was calculated by summing these terms (mineral soil N, N from residues, apparent N mineralization), and in the third step, yield was estimated as a function of N crop using the equation given in Figure 2(d). The three-step model had good performance

Table 1. Average soil properties and rainfall of the two wheat experimental networks compared.

Region	C+S ($t\ ha^{-1}$)	TSNI ($t\ ha^{-1}$)	MNLI ($kg\ ha^{-1}$)	MNI ($kg\ ha^{-1}$)	MNI − MNF ($kg\ ha^{-1}$)	RB ($t\ ha^{-1}$)	NRBI (%)	(NRBI − NRBF) f ($kg\ ha^{-1}$)	AM ($kg\ ha^{-1}$)	Rainfall (mm)
Humid	2438 a	6.1 a	167 a	153 a	111 a	9.5 a	1.05 a	17.8 a	38 a	365 a
Semi-arid	1218 b	3.4 b	44 b	78 b	32 b	3.1 b	1.08 a	8.2 b	53 b	244 b

Notes: C + S = clay + silt (0–30 cm).
TSNI = total soil nitrogen at initial growth stage (0–30 cm).
MNLI = mineralized nitrogen in laboratory incubations (0–30 cm).
MNI = mineral nitrogen (soil nitrate + ammonium nitrogen 0–60 cm + fertilizer nitrogen) at initial growth stage.
MNF = mineral nitrogen (soil nitrate + ammonium nitrogen 0–60 cm) at final growth stage.
RB = residue biomass (of previous crop).
NRBI = nitrogen in residue biomass (of previous crop) at initial growth stage.
(NRBI − NRBF)f = nitrogen release during residue decomposition for crop utilization.
AM = apparent mineralization.
Rainfall = between May and November.
Values in a column with different letters indicate significant differences.

Table 2. Average wheat crop performance in the two pampean regions compared.

Region	Yield (t ha^{-1})	YN (%)	AB (t ha^{-1})	ABN (%)	HI	HIN	N crop (kg ha^{-1})	N crop N crop+MNF	PE (kg grain kg^{-1}N)	RUE (kg grain mm^{-1})
Humid	3.75 a	2.23 a	10.7 a	1.21 a	0.36 a	0.68 a	167 a	0.79 a	24.2 a	11.1 a
Semi-arid	1.92 b	2.27 a	6.5 b	1.1 b	0.29 b	0.60 b	93 b	0.66 b	20.5 b	7.9 b

Notes: Yield = yield dry matter.
YN = yield nitrogen.
AB = aboveground biomass.
ABN = aboveground biomass nitrogen.
HI = harvest index.
HIN = harvest index of nitrogen.
N crop = nitrogen in aboveground and belowground organs.
MNF = mineral nitrogen (soil nitrate + ammonium nitrogen 0–60 cm) at final growth stage.
PE = physiological efficiency (yield/N crop).
RUE = rainfall use efficiency (yield/rainfall).
Values in a column with different letters indicate significant differences.

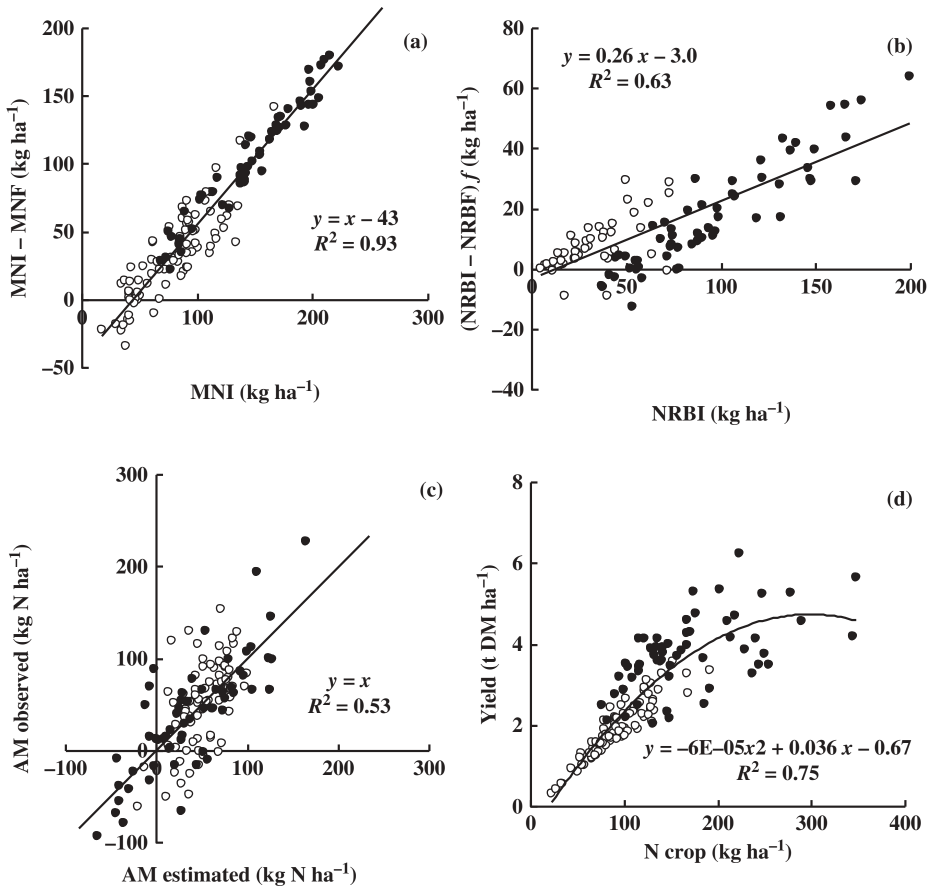

Figure 2. (a) Relationship between mineral soil N + fertilizer N at initial growth stage (MNI) and the change in this pool during the crop growing cycle (MNI − MNF), (MNF = mineral soil N at final growth stage). (b) Relationship between previous crop residue biomass N at initial growth stage (NRBI) and the N released by residue decomposition along the growing cycle (NRBI − NRBF), (NRBF = N in residue biomass at final growth stage). (c) Apparent mineralization of N (AM) observed and estimated by the model: AM = 111 − 1.3 MNI + 0.068 MNI ONI − 0.0022 (C + S) RB + 0.0014 rainfall + 0.00056 rainfall NMLI (ONI: organic N at initial growth stage, C + S: soil clay + silt content, RB: residue biomass, NMLI: N mineralized in laboratory incubation). (d) Relationship between wheat yield and N absorbed in the whole plant (N crop). Black circles: Humid Pampa; white circles: Semi-arid Pampa. Only significant terms were included in the models.

for estimating N crop (Figure 3(a)) and had acceptable performance for estimating yield (Figure 3(b)). Regression of observed vs. estimated values, both for N crop and for yield, had ordinates and slopes not different from 0 and 1, respectively.

A model could be fitted that accounts for approximately 50% of PFP variability of mineral N at the initiation of wheat cycle (Figure 4(a)). The model showed that PFP is greater in the Humid Pampa than in the Semi-arid Pampa as a consequence of higher rainfall (Figure 4(b)). PE and RUE were greater in the Humid Pampa than in the Semi-arid Pampa (Table 2). As rainfall increased, the fraction of N absorbed by wheat related to total

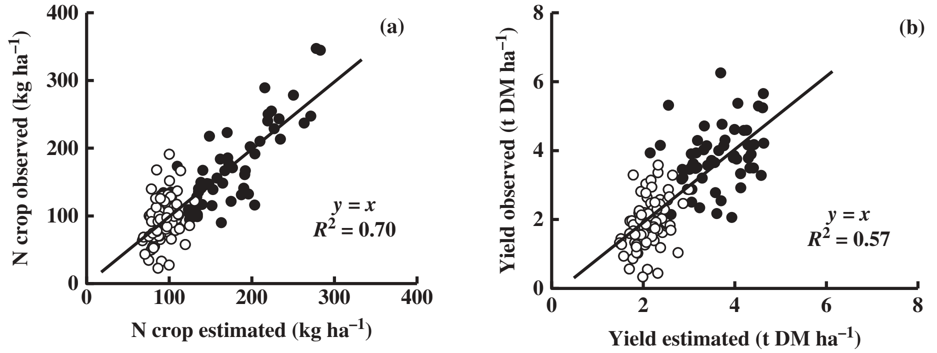

Figure 3. Performance of the N balance method for estimating N absorption by wheat (N crop) (a) and yield (b). Black circles: Humid Pampa; white circles: Semi-arid Pampa. Only significant terms were included in the models.

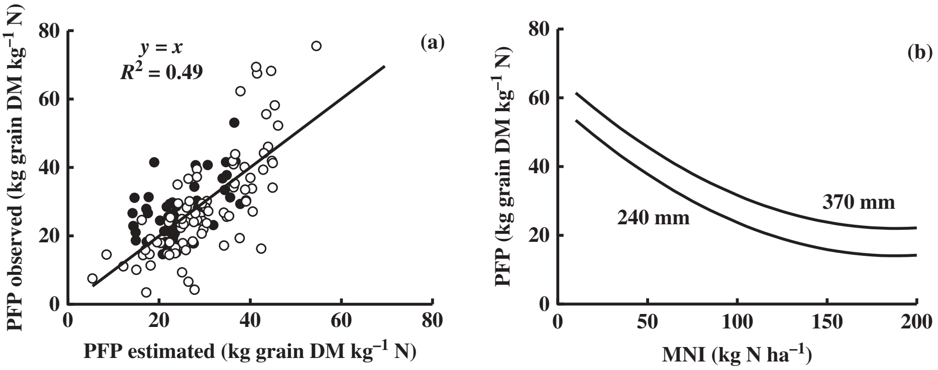

Figure 4. (a) Partial factor productivity (PFP) of mineral N at the initiation of wheat growing cycle (MNI) observed vs. estimated by the model: PFP = 22 − 0.47 MNI + 0.0012 MNI^2 + 0.21 rainfall − 0.00024 rainfall^2. (b) PFP as a function of different combinations of MNI and rainfall. Rainfall scenarios are representative of the Humid and Semi-arid Pampa. Black circles: Humid Pampa; white circles: Semi-arid Pampa. Only significant terms were included in the models.

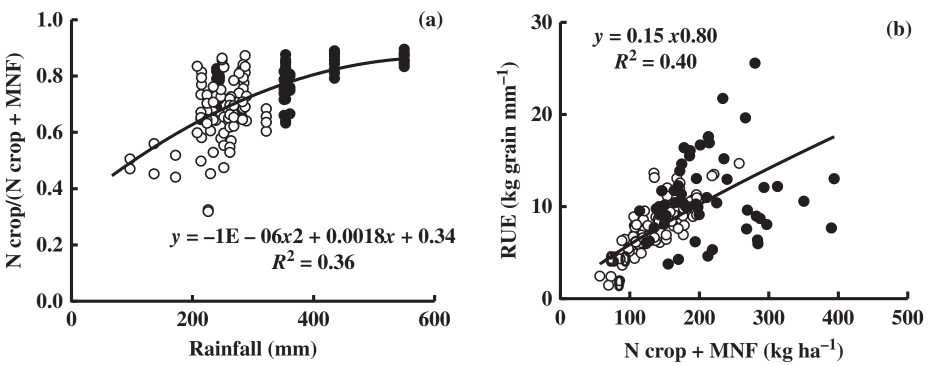

Figure 5. (a) Efficiency of N absorption by wheat as a function of total N available for the crop (N crop: N absorbed in the whole plant, MNF: soil mineral N content at final growth stage). (b) Rainfall use efficiency (RUE) as a function of available N for the crop. Black circles: Humid Pampa; white circles: Semi-arid Pampa.

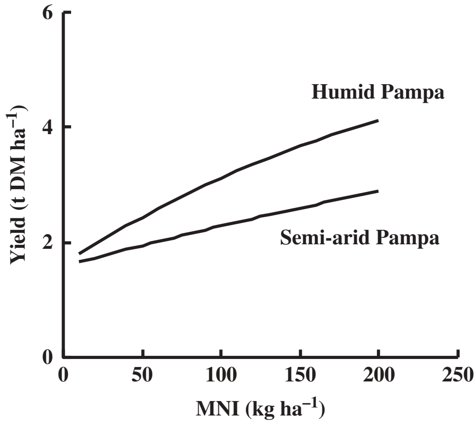

Figure 6. Wheat yield estimated with the balance model for two areas of the Pampas. Corresponding average climate and soil scenarios were used for each area (MNI: soil nitrate + ammonium N content at sowing + fertilizer N rate).

N available (N crop + MNF) increased too (Figure 5(a)). RUE was also associated to total N availability increasing in sites where more N was available (Figure 5(b)).

The three-step model was used for estimating wheat yield under average soil and rainfall conditions of the pampean areas studied as a function of mineral N content in soil (Figure 6). In the Humid Pampa, greater yields would be attained than in the Semi-arid Pampa because of the higher soil N mineralization potential and rainfall. Using site-specific soil properties as texture and total soil N and an average rainfall, the model can be used for estimating a targeted N supply for soils in the Semi-arid Pampa, where other N recommendation methodologies are not available. N rate would be calculated by the difference between the targeted N supply to attain a yield goal and soil mineral N content at sowing. The contribution of some independent variables needed to calculate the model, which are difficult to measure under farm conditions as residue biomass or soil N mineralization potential, was not significant in the final estimations and average values can be used. Maximum bias was introduced in N rate recommendations by using this simplification rounds 10 kg N ha^{-1}, computed as the difference between true N rate for the soil condition and the rate calculated using average values of these two variables.

Current N rates applied by farmers are approximately 62 kg N ha^{-1} in the Humid Pampa and 48 kg N ha^{-1} in the Semi-arid Pampa. Our balance model estimated a targeted N supply of 160 kg N ha^{-1} in the former area and 50 kg N ha^{-1} in the latter one to attain the average yields of the experimental networks. Taking into account average mineral N content usually found in soils at wheat seeding (50 kg N ha^{-1} in both regions), N fertilizer rates would be nearly 100 kg N ha^{-1} in the Humid Pampa and 0 kg N ha^{-1} in the Semi-arid Pampa. Consequently, the model indicated that common fertilization rate used is lower than needed in humid environments but overfertilization exists in semi-arid ones.

Discussion

Soil and climate properties of the pampean areas studied were very contrasting, generating a broad range of wheat yield data and resources use efficiency. For most of the variables used in regression models, one order of magnitude or more was achieved between the minimum and maximum values determined. As a consequence, the N balance model fitted might be a suitable tool for fertilizer rate estimation under many production scenarios. Some of the effects described by the model were known and already shown in the Humid Pampa (Alvarez et al. 2004; Alvarez & Steinbach 2011). The integration of data from semi-arid environments to this previously generated information showed that main controlling factors of N dynamics are the same along the environmental gradient of the Pampas.

The mineral N pool accounted for 66% of N crop in humid environments but only 34% in semi-arid ones, because of the lower N fertilizer rates applied. N-supplying capacity of the mineral N pool could be very well predicted using initial mineral N levels. At wheat harvest, an average of 43 kg N ha^{-1} was found in the soil both in the Semi-arid and in the Humid Pampas. This residual N is mineralized after wheat cessation of absorption in the flowering stage (Alvarez et al. 2004) and shows N limitation under the environments studied because it did not rise with initial soil mineral N content. As N availability gets higher than crop demand, residual N increases (Schlegel et al. 1996), but this trend was not observed in the Pampas. In some soils of the Semi-arid Pampa, which had very low mineral N levels at the initiation of the wheat cycle, the mineral pool seemed to act as a sink and not as a source for N because residual N was greater that initial N. This occurs only in plots of the control treatment.

Decomposing residue released N in approximately 88% of the sites with immobilization detected in few cases. As the amount of N released is dependent on the amount of N in residue biomass (biomass × N concentration), in the Semi-arid Pampa, this source of N was smaller than in the Humid Pampa because of the lower productivity and mass of residues found in the soils of the area. This N source provides on average only 10% of wheat uptake. Mean N concentration in residues was approximately 1% (equivalent to a C/N of 40) but runs from 0.5% (C/N of 80) to 1.9% (approximately C/N of 20). Immobilization occurs in 13 cases with N concentration ranging from 0.5% to 1% and low mass of residues present in the soil. The dynamics of the N immobilization–mineralization process is regulated by residue N concentration with a net release of N when the C/N is below 20–40, being immobilization the most common above this rank (Janssen 1996; Seneviratne 2000; Kumar & Goh 2003). In our experiments, the C/N of the residues was greater than the threshold indicated in many cases, nevertheless mineralization prevailed.

Apparent mineralization resulted in the most important N source for wheat in the Semi-arid Pampa, accounting for 57% of N crop, but only 23% of the N absorbed by the wheat came from this pool in the Humid Pampa. The effects of the controlling factors on apparent mineralization were previously described in the Humid Pampa and discussed in depth (Alvarez & Steinbach 2011), and these effects also regulated mineralization under semi-arid conditions. The difference between the two areas can be the consequence of the very contrasting initial mineral N levels of the soils, because usually apparent mineralization decreases as mineral N gets greater (Gonzalez Montaner et al. 1997). This can be the consequence of inhibition of gross mineralization due to a feedback process caused by high mineral N (Carpenter-Boggs et al. 2000) or an increased immobilization of N in microbial biomass and organic pools or to greater N losses from the soil–plant system which can result in low or even negative values for apparent mineralization when mineral N is high (Ma et al. 1999; Blankenau et al. 2000).

PFP of mineral N was greater in the Humid Pampa than in the Semi-arid Pampa because of higher water availability. A meta-analysis of worldwide data showed that PFP of fertilizer N in wheat is 44 kg grain kg^{-1} N, taking into account mainly experiments performed in experimental stations (Ladha et al. 2005). In the Pampas, performing experiments in farmers' fields, PFP of mineral N ranged from 4 to 76 kg grain kg^{-1} N, with an average of 28 kg grain kg^{-1} N. It decreased as mineral N increased. Taking into account average rainfall scenarios, PFP, estimated by a regression model, was 12–57% greater in humid environments than in semi-arid ones, the relative difference getting higher as more N was available to the crop. Wheat plants used N with similar efficiencies when N availability was seriously restricted, but when mineral N level was very high, its use was much more efficient in humid scenarios.

A curvilinear function was fitted between absorbed N and yield. The relationship between both variables was close to linear till around 150 kg N crop ha^{-1}, tending to a plateau thereafter. As the curvilinear model had a negative ordinate, this determined that PE was very low for low-yield sites of the Semi-arid Pampa, increases as N crop increased and drops again in the high-yielding sites of the Humid Pampa. Wheat yield is commonly a curvilinear function of N uptake (van keulen & stol 1991; Makowski et al. 1999) because as available N rises nutrient concentration in the plant rises too and the harvested index decreases, making the crop less efficient in producing grain (Alvarez et al. 2004; Barneix 2007). The low PE measured in very low-yielding sites of the Semi-arid Pampa was the consequence of deep drought conditions under which the crop absorbed N during the vegetative phase, but grain formation was strongly affected. Uptake of N, calculated as the ratio N crop/(N crop + MNF), was higher in the Humid Pampa apparently because higher water availability led to greater root growth and N absorption (Campbell et al. 1977). At the same time, plants were more efficient in transforming absorbed N into grain in this area. Many experiments had shown greater water use efficiency under higher N availability conditions (Li et al. 2009; Kröbel et al. 2012; Sawargaonkar et al. 2013). Our results from the Pampas show similar results, with greater RUE in the humid portion of the region than under semi-arid environments.

Conclusion

Our balanced model showed when using average yields attained in the two experimental networks as yield goals, that N rates currently applied by farmers were higher than needed in the Semi-arid Pampa but lower in the Humid Pampa. Special care must be taken with these results in the former area. In high-yielding sites of the Semi-arid Pampa, the balance model estimated N rates from 20 to 100 kg N ha^{-1} for attainable yields, depending on targeted yield and soil mineral N availability. Similarly, in semi-arid Australia using the APSIM model, it has been calculated that farmers applied N fertilizer rates lower than those which would produce best economic returns in high yielding soils (15 vs. 60 kg N ha^{-1}) (Monjardino et al. 2013). Rather than recommending N rates based on regional average soil characteristics, the balance model developed is suitable for estimating N needs taking into account soil properties and historical average wheat yield at the site scale.

Disclosure statement

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