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Comparing Nitrate-N Losses through Leaching by Field Measurements and Nitrogen Balance Estimations

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Nitrogen (N) balance method is a valuable tool for estimating N losses. However, this technique could lead to incorrect estimates of the amount of nitrate (NO_3^-N) leaching if processes relevant to N losses are not considered properly. The aim of this study was to compare NO_3^--N leaching losses estimated using an N balance (nonrecovered N, Nne) with data of NO_3^--N leaching losses (Nl). The experiment was made on a Typic Argiudoll soil planted with corn (five growing seasons) under 0, 100, and 200 kg N ha^{-1}. The ceramic soil-water suction samplers were installed (1 m deep). Drainage was estimated by the LEACH-W model. The greatest overestimation with the N balance method occurred for years with annual rainfall below the historical average and at times of high NO_3^--N availability. Future research should focus on investigating mechanisms of N losses relevant under limited water availability.

Keywords Nitrogen, nutrient cycling, water quality

Introduction

The high crop yields achieved in modern agriculture are closely related to high application rates of fertilizers (Stewart, Lawrence, and Van Kauwenbergh 2005). Nitrogen (N) fertilizers are used the most, given the high demand of N by crops and its frequent deficiency. Stewart, Lawrence, and Van Kauwenbergh (2005) examined the effects of nutrient inputs, especially of commercial fertilizers, on crop yields. The authors report that the average percentage of yield attributable to fertilizer generally ranged from about 40 to 60 percent in the USA and England and tended to be much greater in the tropics. Recently calculated budgets for N, phosphorus (P), and potassium (K) indicate that commercial fertilizers make up the majority of nutrient inputs necessary to sustain current crop yields in the USA. Worldwide,

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N fertilizer use reached almost 87 million tons of N by 2011 (IFA, 2013). In Argentina, about 846,000 Mg of N was applied in the farming year 2011–2012 (Fertilizar Asociación Civil 2012), which is almost two to three times more than the amount used in the middle of the 1990s.

Raun and Johnson (1999) reported a global 33 percent recovery efficiency of N in cereal grains. This poor recovery is probably due to a sum of inefficiencies in the production process. In Argentina, the recovery efficiency in wheat and corn has been reported to range from 50 to 60 percent of the N applied (Sainz Rozas et al. 1999; Melaj et al. 2003; Videla et al. 2004; Barbieri, Sainz Rozas, and Echeverría 2008). In well-structured soils without drainage problems, nitrate (NO_3^-) leaching is one of the main mechanisms by which N is lost from the root zone and could potentially contaminate groundwater (Martínez 1995; Costa and Vidal 1998; Costa et al. 2002; Andriulo et al. 2002; Rimski-Korsakov, Rubio, and Lavado 2004; Portela et al. 2006). Groundwater contamination by NO_3^- is a widespread problem in the corn belt of the USA, particularly since the increase in the use of N fertilizers between 1950 and 1980 (Burkart and James 1999).

Information on the effects of tillage systems on N losses by leaching is controversial. In general, conventional tillage (CT) has greater mineralization of soil organic matter (Studdert, Echeverría, and Casanovas 1997) and nitrification than no tillage (NT), resulting in greater losses of N under CT if the period of maximum production of NO_3^- coincides with an excess of water. For instance, Jayasundara et al. (2007), working in imperfectly drained soils, reported that CT increased N loss compared to NT during the fallow period after a corn crop due to a greater residual NO_3^- content in the soil at the time of harvesting. In contrast, NO_3^- leaching from a fertilizer source could be greater in soils under NT if greater levels of N are applied because soils generally have greater moisture content and a greater proportion of biopores. Nissen and Wander (2003), working in Mollisols with a long history of NT and CT and under different moisture regimes, reported that total NO_3^- losses from leaching were similar under both tillage systems, but that under NT more N was lost from the fertilizer and less from the soil because of a greater flow through macropores. In Argentina, Abril et al. (2007) reported that that the application of high N fertilizer doses under NT in wheat crops has the following disadvantages: (a) low fertilizer-N-use efficiency and (b) N losses due to leaching that may contaminate groundwater with nitrates.

The main N loss from humid and subhumid regions and from irrigated agriculture is through leaching and denitrification (Fageria and Baligar 2005). The Pampa region in Argentina (30–40° S and 57–66° W) is known as one of the most important grain-producing areas in the world (Satorre and Slafer 1999). The area has a humid to subhumid climate (rainfall ranging from 800 to1000 mm) with water excess that generally occur at the beginning of the growing season and during the fallow period. Wheat, corn, and soybean are the main crops in the region, grown mainly on well-structured Molisolls (Typic Argiudolls, Paleudoles, Typic Hapludoll) without internal drainage problems. Corn is the crop with the greatest potential for leaching losses of N because of its high demand for N, which leads to high N application rates, and because the growing season of corn coincides with the period of high precipitation in the region. Sainz Rozas, Echeverría, and Barbieri (2004), working on soils from the Pampas, estimated that 20 percent of the N applied as fertilizer to corn under NT was not recovered using N balance, and it was assumed to have been lost as NO_3^- leaching.

Although the N balance method is a valuable tool to estimate N losses (Meisenger, Calderon, and Jenkison 2008), the sum of errors incurred when each one of the pools is determined could lead to incorrect estimations of the amount of leached NO_3^-. Furthermore, great care must be taken when interpreting the results and calculating the losses via leaching if all the components of the N balance are not measured. For example, N loss through ammonia volatilization from plants is usually not taken into account when the N balances are formulated, and the losses via this mechanism can become large under water stress (Francis, Schepers, and Vigil 1993).

There are many reports in the literature of component N balances measured for various crops (Giletto and Echeverría 2013; Soltani and Sinclair 2012; Aparicio, Costa, and Zamora 2008; Ju et al. 2006; Sainz Rozas, Echeverría, and Barbieri 2004; Costa et al. 2002; Schuman et al. 1999]. However, studies comparing the leaching of nitrate measured in the field with estimated nitrate leaching from an N balance under contrasting soil water availability conditions have not been reported in the literature. The aim of this study was to estimate the amount of N leached (Nl) using an N balance technique and compare estimated NI with measured NI in the field for five growing seasons.

Materials and Methods

Experimental Site

The field experiment was conducted in an area of 420 m^2, in Balcarce County of the Buenos Aires province in Argentina (37° 49′ 52.44″ S; 58° 18′ 40.18″ W). The soil was classified a Typic Argiudoll (fine, illitic, thermic) of the Mar del Plata series (Mapa de Suelos de República Argentina INTA, 1976). The soil at the site was sampled from four pits located next to the field experiment. Soil characterization is shown in Table 1 and described in detail by Aparicio, Costa, and Zamora (2008). The soil at the site is typical of the Pampa region and of many other humid and subhumid agricultural regions of the world. It is well structured and well drained and contains approximately 3 percent organic carbon at the surface.

Variation in Precipitation During the Study Period

Monthly rainfall figures for the period studied are shown in Table 2. The extent of the study period allowed a temporal variability in rainfall, rendering the study more valuable by enabling data collection under a variety of field conditions. Yearly precipitations for 2004, 2005, and 2006 were lower than the long-term average (1968–97) by 5, 8, and 12 percent, respectively; whereas yearly precipitations in 2002 and 2003 were greater than the long-term average by 62 and 36 percent, respectively.

Treatments, Experiment, Design, and Crop Management

The field experiment started in 1998 and involved first conventional tillage. In the 2000–2001 growing season, the tillage system was changed to no-till. The experiment reported here started after 1 year of no till and spanned five growing seasons (2001–2002, 2001–2003, 2003–2004, 2004–2005, and 2005–2006). Fertilization treatments consisted of three N rates (0, 100, and 200 kg N ha^{-1}) using UAN (32 percent N) as the N source. The application of the fertilizer was carried out by backpack spraying at the time of sowing. Plots were 3.5 m wide by 10 m long and treatments were arranged in completely randomized blocks with four repetitions.

Corn (*Zea mays* L.) was sown on 15 October in each growing season; soybean was the crop immediately prior to the start of the experiment (2000–2001 growing season). Calcium triple superphosphate was annually applied to avoid phosphorus deficiency. Weed

Table 1

Thickness, particle-size distribution (clay, silt, and sand), field capacity, permanent wilting point moisture content (33 and 1500 kPa), organic carbon content (OC), apparent density (δa), porosity (φ), hydraulic conductivity at a tension of −30 mm (K_{-30}), cation exchange capacity (CEC), and pH for the main soil horizons at the experimental site

Hz	Thickness (cm)	Clay (%)	Silt (%)	Sand (%)	33 kPa (g 100 grain^{-1})	1500 kPa (g 100 grain^{-1})	OC (g kg^{-1})	Δa (Mg m^{-3})	Φ (%)	K_{-30} (mm h^{-1})	CEC (Cmol$_{+}$kg^{-1})	pH
A	0–30	28	46	27	26.7	15.7	38	1.15	57	18.7	30	5.6
B	30–70	33	40	27	28.1	15.5	15	1.27	52	16.6	26	6.0
C	+ 70	26	45	28	30.0	16.2	5	1.35	49	26.8	28	6.9

Table 2
Monthly rainfall (mm) during the study period

	Rainfall (mm)												
Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
2001	119	119	106	48	69	66	26	118	103	156	198	123	1251
2002	152	71	147	40	197	18	45	100	90	276	169	39	1342
2003	124	90	167	61	69	61	64	49	54	108	142	136	1124
2004	28	97	47	154	9	27	86	125	32	51	70	62	788
2005	67	48	88	4	17	70	51	109	59	60	85	103	760
2006	119	125	21	52	1	79	59	11	45	76	27	113	728
68–97	103	80	77	58	63	46	48	34	46	94	66	113	827

control was carried out by applying atrazine and acetochlor at the time of sowing in each growing season, and glyphosate was used as chemical fallow.

Extracting Soil Solution and Measuring $NO_3{}^-N$ Concentration

A single ceramic soil-water suction sampler was installed 1 m below the surface in each plot. Suction samplers were made of 20-cm-long sections of polyvinyl chloride (PVC) pipe with a diameter of 5 cm. A ceramic cup was cemented to one end, and the opposite end was sealed with a two-hole stopper. Two tubes were placed in the suction sampler through the stopper. One of them was needed to apply vacuum and the other to collect the water sample. To install the suction probe, a vertical hole was drilled with a soil auger that has a diameter similar to that of the probe. To optimize the contact surface between the suction cup and the soil, slurry made with the soil extracted with the auger was put back into the hole before inserting the suction probe. Once the suction sampler was in position, half of the hole was further filled with the slurry. After that, a layer of approximately 3 cm of bentonite was inserted in the hole to avoid the occurrence of preferential flow. The rest of the hole was then filled with the slurry. The tubes from the soil-water suction samplers were maintained at a depth of 30 cm below the soil surface to enable tillage operations. At the end of the plots, the tubes were connected to a manifold where a vacuum pump supplied a suction averaging 45 kPa for 15–20 h. Water samples were collected after a significant rainfall event occurred (usually greater than 30 mm).

Estimating Drained Water Volume

The drained water volume (h) was estimated with the LEACH-W version of the LEACHM (Wagenet and Hutson 1989). The LEACH-W model uses the water model retention model of Campbell (1974) and the Richard's equation to calculate soil water fluxes.

The LEACH-W model was calibrated with soil from the Mar del Plata series by entering soil parameters measured in the experiment (saturated hydraulic conductivity, bulk density, organic matter, water retention curve, texture, and depth of each horizon), irrigation data, and crop variables (phenological stages). Climatic data (potential evapotranspiration and rainfall) was provided by the Balcarce weather station, located 8 km from the test site.

A neutron probe access aluminum tube was installed in each plot, to take volumetric soil moisture (θv) measurements every 100 mm with a Troxler 4301 up to a depth of 1.2 m. Soil water storage (SWS) was calculated as

$$SWS = \sum_{i=1}^{10} \theta_{vi}\ \Delta D_i \tag{1}$$

where ΔD is the thickness of soil layer i (mm).

We compared with the corresponding SWS simulated by LEACH-W model with the purpose of verifying calibration of the model (Aparicio, Costa, and Zamora 2008). Water drainage amounts for the dates corresponding to soil solution samplings were estimated after model calibration.

Quantification of NO_3^--N Losses by Leaching

The amount of NO_3^--N leached below the root zone (*NI*), expressed in units of kg ha^{-1} was estimated as (Moreno et al. 1996)

$$NI = D_J\ C \tag{2}$$

where D_j (mm) is the drainage estimated with LEACH-W, and C (mg L^{-1}) is the NO_3^--N concentration of the soil solution extracted from the porous suction capsule. Estimates of D_j and C were obtained for each of the sampling dates, and the total amount of NO_3^--N lost in the growing season was calculated by adding the values obtained in each sampling. Further details are available in Aparicio, Costa, and Zamora (2008).

Mineral Soil N

To evaluate the initial and final quantities of NO_3^--N in the soil in each growing season, soil samples were taken at presowing and physiological maturity stage at the following depths: 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm. Each sample was a composite of 10 subsamples collected away from the area where the ceramic cup was installed. Determination of NO_3^--N in soil was carried out using colorimetric procedures (Spectrophotometer Beckman DU 65) (Keeney and Nelson 1982). The NO_3^--N content in each soil layer expressed per unit area was calculated using the equation:

$$Nm = (NO_3^- - N)\delta_a h 10^{-1} \tag{3}$$

where *Nm* is the mineral N content (kg ha^{-1}), NO_3^--N is the concentration of NO_3^--N (mg kg^{-1}), δa is the soil apparent density (Mg m^{-3}), and h is the thickness of the layer (cm).

Accumulated N in Crop Biomass

Each growing season, N accumulated in plants was estimated by collecting six plants from each plot. Plants were selected at random during crop physiological maturity and dried in a forced ventilation oven at 60 °C to constant weight. Total N was determined using the micro-Kjeldahl method (Bremner and Mulvaney 1982) and N absorbed by the crop was obtained as product between N concentration and aerial biomass dry weight. At physiological maturity, grain yield was determined at 14 percent moisture content.

Nitrogen Balance in the System

A general N balance in the soil for a crop cycle was defined as (Meisenger 1984):

$$Nf + Na + Nom + Nii = Np + Nr + Ng + Npg + Nl + Ne + Niin + Nif \tag{4}$$

where *Nf* is N provided by the fertilizer (kg N ha^{-1}); *Na* is N provided by biological fixation and/or rain (kg N ha^{-1}); *Nom* is the amount of net organic N mineralized during the growing season (kg N ha^{-1}); *Nii* is initial inorganic N (kg N ha^{-1}); *Np* is N absorbed by biomass area (kg N ha^{-1}); *Nr* is N absorbed by the roots (kg N ha^{-1}); *Ng* is N lost as gases (N_2, N_2O, or NH_3) (kg N ha^{-1}); *Npg* is N lost as NH_3-N from plant; *Nl* is N lost through leaching (kg N ha^{-1}); *Ne* is N lost through erosion (kg N ha^{-1}); *Niin* is the amount of inorganic N immobilized during the growing season (kg N ha^{-1}); and *Nif* is inorganic final N (kg N ha^{-1}).

Estimation of the Components of the Balance

Considering that determinations carried out in Balcarce have shown annual inputs of 3 to 4 kg N ha^{-1} from electrical discharges in the atmosphere (Cecilia Videla, personal communication) and that there is no biological fixation in corn, the component Na in Eq. (4) was not included in computing the N balance.

Estimation of net organic N mineralization was conducted as follows: The difference between gross organic N mineralization and of gross inorganic N immobilization can be defined as net N mineralization (*Nmin*). The value of *Nmin* can be approximated using models which take into account the potentially mineralizable N pool, the rate of potential mineralization, and the effect of the soil moisture and soil temperature on this rate (Echeverría and Bergonzi 1995). In this study, *Nmin* was estimated using the components of the N balance obtained in the nonfertilized treatment as

$$N\min = (Np + Nr + Ng + Nl + Nif) - Nii \tag{5}$$

Each variable in Eq. (5) was either measured or obtained from local research under similar conditions. Values of *Niin* reported by Sainz Rozas, Echeverría, and Barbieri (2004) for similar N rates, the same crop sequence, and soil management were used. Values of *Nii* and *Nif* were measured [see Eq. (3) in mineral soil N]. *Np* was determined by aerial biomass sampling (see accumulated N in crop biomass) and *NI* from model output (see quantification of $NO_3{}^{-}$-N losses by leaching). Values of *Nr* were estimated as a proportion of total N uptake in the aerial biomass as 6.6 percent N and 5.3 percent N for the control and fertilized treatments, respectively (Sainz Rozas, Echeverría, and Barbieri 2004; Uhart and Andrade 1996). Losses through volatilization (*Ng*) were taken from García et al. (1999), and losses through denitrification from Sainz Rozas, Echeverría, and Barbieri (2004). Finally, losses caused by erosion (*Ne*) and as NH_3-N (*Npg*) were considered negligible.

Taking all these factors into account, the simplified equation of the N balance to estimate *Nl* with N nonrecovered (*Nne*) was reduced to the following expression:

$$Nne = (Nf + N\min + Nii) - (Np + Nr + Ng + Niin + Nif) \tag{6}$$

The response to the application of N (*Nresp*) was calculated as the difference between grain yields obtained from fertilized and unfertilized (control) treatments. The calculation was performed for each fertilization treatment and growing season.

Statistical Analysis

The Shapiro and Wilk (1965) test was used to providing evidence of normality. Under no evidence of normality, log transformations of the data were made.

Analyses of variance (ANOVA) were performed with SAS version 6.12 software (SAS Institute 1989–1996). The estimated parameters were compared among N rates and cropping seasons as repeated measurement using a mixed linear model (PROC MIXED). The random effect was block and the fixed effects were N rates and cropping seasons. Mean comparisons were evaluated with a significance level of 0.05 using LSMEANS. Simple and multiple linear regressions were utilized for analysis of information.

Results and Discussion

ANOVA of Crop Yield

Grain yield was different by N rate and growing season, but there was no interaction between these two variables. Crop yield increased with N rate (Figure 1a) and the greatest yields were obtained in those growing seasons where the average annual rainfall was above the historical average (Figure 1b; Table 1). Response of corn to N (*Nresp*) was related to the amount of precipitation around the flowering stage, that is, from December to February (PAF) (Calviño, Andrade, and Sadras 2003) and an association between both variables was observed ($Nresp = 0.62 + 0.01^*$ PAF; $r^2 = 0.50$). Nevertheless, once the initial availability of $N\text{-}NO_3^-$ (*Nii*) was included as an independent variable, the r^2 increased ($Nresp = 0.99 + 0.011^*$ PAF—0.0103^* *Nii*; $r^2 = 0.71$). This indicates that *Nresp* is partly conditioned by the initial availability of N, as previously reported (Sainz Rozas et al. 2008; Alvarez and Steinback, 2012).

*ANOVA of N Balance Components (***Nmin, Nii, Nif, Np***, and* **Nl***)*

There was no interaction effect between N and growing season on nitrate *Nii* ($P = 0.3291$). Although *Nii* was significantly affected by growing season ($P < 0.0001$), it was

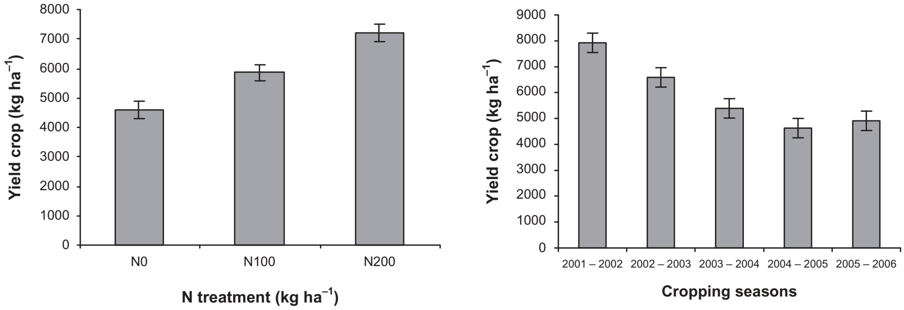

Figure 1. Yield crop in function of (a) N treatment (N0, N100, and N200 in kg ha^{-1}) and (b) cropping seasons. The bars indicate standar error.

Table 3

N balance in the soil system corn by N treatment for the growing seasons 2001–2002, 2002–2003, 2003–2004, 2004–2005, and 2005–2006

Growing	Available N (kg ha^{-1})			Determined components of N balance (kg ha^{-1})						
season	*Nf*	*Nmin*	*Nii*	*Np*	*Nr*[a]	*Ng*[a]	*Niin*	*Nl*	*Nif*	*Nne*
2001–2002	0	122	61	115	8	5		30	25	30
2001–2002	100	122	51	199	11	13	12	62	26	12
2001–2002	200	122	48	253	13	14	9	68	53	27
2002–2003	0	128	111	134	9	5		52	39	52
2002–2003	100	128	73	155	8	13	12	59	39	74
2002–2003	200	128	89	227	12	14	9	78	71	84
2003–2004	0	75	30	67	4	5		3	26	3
2003–2004	100	75	34	87	5	13	12	18	31	62
2003–2004	200	75	40	151	8	14	9	41	38	95
2004–2005	0	54	19	56	4	5		0	8	0
2004–2005	100	54	23	61	3	13	12	1	3	84
2004–2005	200	54	34	98	5	14	9	2	14	147
2005–2006	0	91	26	96	6	5		0	10	0
2005–2006	100	91	27	113	6	13	12	0	16	60
2005–2006	200	91	34	143	8	14	9	0	29	123

[a]N estimated using the data reported by Sainz Rozas, Echeverría, and Barbieri (2004). In *Ng* a 1% loss through volatilization was also considered (García et al. 1999).

N from fertilizer; Nmin: organic mineral N; Nii: inorganic initial N; Np: N absorbed by biomass area; Nr: N absorbed by roots; Ng: N lost as gases (N_2, N_2O, NH_3); Nl: N lost through leaching; Ne: N lost through erosion; Nif: final inorganic N.

independent of N rate ($P = 0.3604$) (Table 3). There was no interaction effect between N rate and growing season on nitrate *Nif* ($P = 0.3881$) either, but *Nif* was significantly affected by N rate ($P < 0.0001$), with greater accumulation in treatment 200 N compared to 0 N and 100 N. Also, *Nif* differed among growing seasons ($P < 0.0001$) (Table 3). Increases in *Nif* in response to the application of high N rates has been reported by other authors (Zhu and Fox 2003; Jayasundara et al. 2007; Meisenger, Calderon, and Jenkison 2008). Moreover, Sainz Rozas, Echeverría, and Barbieri (2004), working with similar N rates, time of fertilizer application, and type of soil, did not detect increases in the concentration of *Nif*, which could be attributed to the greater plant N uptake determined by these authors.

In this work, the *Nif* of 200 N treatment was superior compared to the other treatments and would indicate that the 200 N rate exceeded the crop uptake N capacity. Pagani et al. (2008) proposed thresholds of available N (soil + fertilizer) at planting of 160 to 170 kg N ha^{-1} to achieve a 95 percent maximum yield. In our study, these values were in general achieved with a rate of 100 kg N ha^{-1} (Table 3), and this rate did not increase *Nif*. Nevertheless, when initial available N was greater than 200 kg N ha^{-1}, *Nif* increased exponentially (Figure 2), which increases the risk of N losses during the fallow period. There was no link between *Nii* and *Nif* of the previous crop, with positive (net mineralization during the fallow period) and negative (losses during the fallow period) differences being recorded over the duration of the experiment (Table 3).

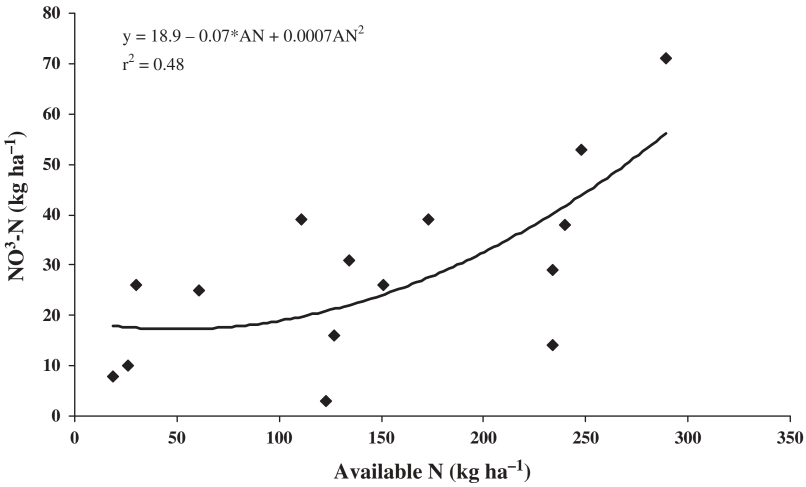

Figure 2. Relationship between available N in the soil (NO_3^--N at depth of 0–100 cm + fertilizer) at the time of planting and the residual NO_3^--N (*Nif*) at soil depth of 0–100 cm at harvest.

There was no interaction effect between nitrogen and growing season on *Np* ($P = 0.1685$), but *Np* was different by N rate ($P < 0.0001$) and by growing season ($P < 0.0001$) (Table 3). Soil available N (AN), defined as soil NO_3^--N content plus fertilizer N at planting, was linearly related to *Np* ($Np = 60.5 + 0.48^*$ AN; $r^2 = 0.50$). The slope of this relationship indicates that AN recovery efficiency by the crop was similar to those reported by other authors for similar rates and time of N application in continuous corn systems (Sainz Rozas, Echeverría, and Barbieri 2004; Stevens, Hoeftb, and Mulvaney 2005).

There was an interaction effect between N and growing season on *Nl* ($P = 0.018$), with *Nl* being significantly affected by N rate ($P < 0.0001$) and growing season ($P < 0.0001$) (Figure 3). The precipitation amounts during the initial crop stages (October

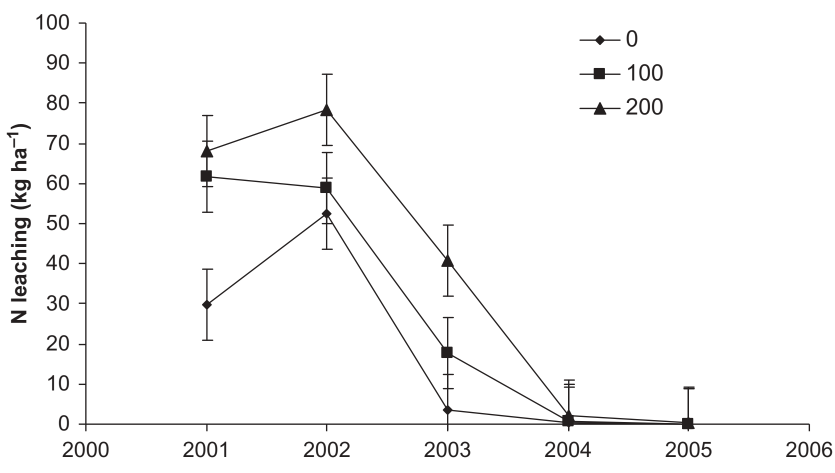

Figure 3. N leaching at 1 m by growing season and *Ntrat*. The bars indicate standar error.

Table 4
Multiple regression model to predict the NO_3^- losses through leaching as a function of the rainfall in October and November (rainfall O–N) and the available N (NO_3^-N soil + fertilizer) at planting (AN)

Dependent variable	Independent variable	Value of paramater	Standard error	*P* value	r^2 partial	r^2 adjusted
Losses through leaching	Ordered	−41.2	7.52	0.001		
	Rainfall O–N	0.173	0.024	0.001	0.82	0.90
	AN[a]	0.097	0.03	0.001	0.08	

[a]Variables chosen according to stepwise criteria.

and November) and AN were positively correlated with *Nl*, with 82 percent of the variability in *Nl* explained by the first variable (Table 4). For wetter growing seasons, values of Nl determined in this experiment were greater than those reported by Walters and Malzer (1990) and Jemison, Jabro, and Fox (1994) for similar N rates and for corn crops growing on sandy and silty loam under conventional tillage. These authors reported leaching losses, mainly at the beginning of the growing season, ranging from 18 to 54 kg N ha^{-1}. On the other hand, *Nl* measured in our experiment were similar to those reported by Sainz Rozas, Echeverría, and Barbieri (2004), for irrigated corn under no tillage and fertilized at planting.

Nitrogen mineralization *Nmin* estimated from the unfertilized plots ranged from 54 to 128 kg N ha^{-1} (Table 3) and it is lower than the reported (96 to 145 kg N ha^{-1}) by Sainz Rozas, Echeverría, and Barbieri (2004) for soils with lower soil organic-matter content and similar management practices (tillage and crop sequence). These authors used the laboratory methodology proposed by Echeverria et al. (1994) with soil disturbed sample and the field experiment carried out without water limitation, factors that could have increased *Nmin* (Rice and Havlin 1994).

Estimation of **Nl** *using the Simplified N Balance*

There was no interaction effect between N and growing season on *Nne* ($p = 0.0867$). Although *Nne* was significantly affected by *Nrate* ($P = 0.0001$), it was not affected by growing season ($P = 0.0595$). For the growing seasons 2001–2002 and 2002–2003, average values of *Nne* and *Nl* for N rates of 100 and 200 kg N ha^{-1} were 43 and 55 kg N ha^{-1}, and 60.5 and 73 kg N ha^{-1}, respectively. For the drier than historical average growing seasons (2003–2004, 2004–2005, and 2005–2006), average values of *Nne* and *Nl* for N rates of 100 and 200 kg N ha^{-1} were 69 and 122 kg N ha^{-1} 6.3 and 14.3 kg N ha^{-1}, respectively. In addition, a relationship was determined between *Nne* and precipitation amount during the growing season (PP) and AN (*Nii* + N fertilizer) ($Nne = 58.8–0.098^*\ PP + 0.41^*\ AN$; $r^2 = 0.65$). This indicates that overestimation was greater for drier than average growing seasons (Table 1) and when drainage was negligible. These results suggest that existence of other mechanisms of N loss not measured in this work that became much more relevant when water availability decreased.

In soils under no-tillage and corn monoculture, the amount of N fertilizer that was still in organic form at the end of the growing season was reported to vary between 24 and

65 kg N ha^{-1} (Kitur et al. 1984; Jokela and Randall 1997; Stevens, Hoeftb, and Mulvaney 2005), which is greater than the values found in this investigation (*Niin*, Table 3). However, for the same region and for similar tillage system, Divito et al. (2011) reported that particulate organic N and potential *Nmin* in the surface layer (0–20 cm) were not changed by N fertilization. These authors mentioned that application of N enhances soil organic N turnover and, as a consequence, reduces the size organic N pool. Therefore, the process of immobilization could explain only a small part of *Nne* attributed to *Nl*, mainly for drier growing seasons.

On the other hand, Francis, Schepers, and Vigil (1993) reported that losses through volatilization of NH_3 from plants increase when N concentration in corn plant is high and under water stress conditions, factors which increase the concentration of ammonia in the apoplast and therefore of NH_3-N losses from the leaves. These authors reported losses of fertilizer N, which varied from 7 to 35 kg N ha^{-1}, according to the N application rate, which explained the 52 to 73 percent of *Nne* determined using ^{15} N. Therefore, this loss mechanism could also lead to an overestimation of the Nl when it is estimated with the *Nne*. Caution must be taken when linking values of *Nne* to *Nl* in simplified N balances.

Conclusions

Measured and estimated components of a nitrogen balance over five growing seasons encompassing contrasting soil water availabilities are discussed in this work. The conditions analyzed are representative of regions in the world growing corn on well-structured soils of the Mollisol order.

Numerous studies have measured nitrate leaching or estimated it through nonrecovered N, but few researchers have compared measured and estimated values of nitrate leaching. Results of this investigation suggest that *Nl* had a low contribution to nonrecovered N in dry growing seasons. Furthermore, the N balance overestimates nitrate leaching (Table 3), particularly in dry years and under high N availability. Future research should focus on investigating mechanisms of N losses relevant under limited water availability.

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