Available online at www.sciencedirect.com
ScienceDirect

ELSEVIER

Agriculture, Ecosystems and Environment 119 (2007) 171–176

Agriculture
Ecosystems &
Environment

www.elsevier.com/locate/agee

Effect of wheat crop fertilization on nitrogen dynamics and balance in the Humid Pampas, Argentina

A. Abril [*], D. Baleani, N. Casado-Murillo, L. Noe

Microbiología Agrícola, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, cc 509,
5000 Córdoba, Argentina

Received 31 March 2006; received in revised form 3 July 2006; accepted 10 July 2006
Available online 28 August 2006

Abstract

Water contamination by nitrates has increased international awareness. It is widely accepted that massive fertilizer application is the principal factor responsible for water nitrate contamination. During the last years, Argentina has extraordinarily increased the use of fertilizers, particularly on wheat (*Triticum aestivum* L.). However, few studies have quantified nitrate losses. Here we report N dynamics in soil fractions and N balance in wheat crops in Marcos Juarez, province of Córdoba (Argentina) with the aim of determining nitrate loss and its possible influence on water contamination. Four treatments were studied to evaluate the combined effect of tillage systems and N fertilizer doses on N losses in soil 0–20 cm in depth. The treatments analyzed were: (a) conventional tillage, non-fertilized (CT 0N), (b) no-till and 25 kg N ha^{-1} (NT 25N), (c) no-till and 50 kg N ha^{-1} (NT 50N), and (d) no-till and 140 kg N ha^{-1} (NT 140N). Determinations were: soil total N, NO_3^--N, NH_4^+-N, microbial biomass N, crop residue biomass, crop residue N, and grain N. N balance was calculated as the difference in N fractions between harvest and sowing samples. N balance was negative in all treatments evaluated; the highest N loss (-1075 kg N ha^{-1}) occurred with the highest fertilization rate (140 kg N ha^{-1}). Losses of microbial and soluble N fractions were significant at the end of the crop cycle in all the treatments analyzed (15 and 40%, respectively), probably due to leaching by high precipitations (250 mm). Much of the N lost was soil organic matter N, a fact seldom considered in other N balances. Furthermore, it was observed that neither yield efficiency nor the remaining N increased significantly with the highest fertilization dose (140N). Our data show that high doses of nitrogen fertilizer result in low N utilization efficiency and a high risk of water contamination by nitrates.

Keywords: Nitrate; Microbial biomass N; Water contamination; Fertilization efficiency; Leaching

1. Introduction

Nitrate contamination of surface and ground water due to excessive use of fertilizers is a world-level concern. In the last years, the use of fertilizers has increased drastically worldwide and unexceptionably in Argentina (Vitousek et al., 1997; Galloway et al., 2002). Although the fertilizer rates applied in Argentina are still not as high as in other countries, the application of no-tillage (NT) systems brought about the use of fertilization, with the aim of counteracting the immobilization of nutrients in surface crop residues (Power and Peterson, 1998). However, it has been demonstrated that under NT, a large proportion of fertilizers is lost by leaching and volatilization, and that the longer the period under NT, the lower the amount of fertilizers needed (Power and Peterson, 1998; Alves et al., 1999; Cantero-Martínez et al., 2003; Abril et al., 2005). Wheat is one of the most fertilized crops in Argentina. Because of the importance of this crop per unit cultivated area and the associated economic yield, the use of fertilizers may involve a high risk of environmental contamination.

Although the use of fertilizers in Argentina is massive, few studies have been conducted on requirements and efficiency of fertilization (Costa et al., 2002; Rimski-Korsakov et al., 2004). Most studies analyze the relationship

---

[*] Corresponding author. Tel.: +54 351 4334103; fax: +54 351 4334103.
E-mail address: aabril@agro.uncor.edu (A. Abril).

0167-8809/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2006.07.005

between fertilizer costs and crop yield (Álvarez et al., 2004) but, unlike research works conducted in other parts of the world, they neglect the balance between profitability and risks of water contamination (Cassman et al., 2002; Brye et al., 2003; Karlsson et al., 2003; Garrido-Lestache et al., 2004).

One of the methods for evaluating N losses in agroecosystems is by estimating the balance between N incorporated, N removed by the crop, and residual nitrate (Cassman et al., 2002; Brye et al., 2003; Guarda et al., 2004). Because N is a very versatile and mobile element, a representative balance should include N dynamics relative to depositions (soil N, microbial biomass N, crop residues N, etc.) and physical, chemical, and biological processes involved (atmospheric deposition, biological fixation, leaching, run off, N translocation to the grain, residue mineralization, etc.) (Singh and Singh, 1993; Bauhus and Khanna, 1999; Karlsson et al., 2003). In practice, N balance is estimated considering the most representative parameters, assuming that the remaining ones are negligible or that they barely change over short periods (Brye et al., 2003).

The objective of this work was to analyze N dynamics and balance in wheat crops treated with different fertilization rates in the wheat growing area of the province of Córdoba, Argentina. These studies aimed at determining possible N losses in the system that may produce contamination in the watertable and reservoirs.

2. Materials and methods

The work was conducted in crop fields from farms located in the department of Marcos Juarez, province of Córdoba (32°45′S, 62°10′W), Argentina, during the 2001 wheat crop cycle. The climate in the region is temperate subhumid without water deficit, with a monsoon precipitation regime (annual precipitation between 850 and 1000 mm) (Capitanelli, 1979). Soils (Typic Argiudolls) are slightly acid, deep, rich in organic matter (3%) and well drained (Jarsún et al., 1990). The watertable in the region is shallow (between 2 and 8 m depth) (Vázquez et al., 1979).

We selected five plots managed under different fertilization schemes, representing the common practices in the region. The selected plots were not experimental, but part of the regular management operations of the different farms. In this paper we named each of these management situations a treatment.

The fertilization treatments analyzed were: (a) conventional tillage (mouldboard plow + disk), non-fertilized (CT 0N); (b) no-till fertilized with 25 kg N as diammonium phosphate in a plot with a history of 5 years under NT, with a soybean–wheat annual crop sequence (NT 25N); (c) no-till fertilized with 50 kg N as urea in a plot with a history of 5 years under NT, with soybean–corn rotation and 1 year with soybean–wheat annual sequence (NT 50N); (d) no-till with 140 kg N as urea and monoammonium phosphate in a plot with a history of 5 years under NT, with a soybean–wheat annual sequence (NT 140N).

In all treatments wheat was sowed in May and harvested in late November. The short-cycle wheat variety Klein Don Enrique (Bainotti et al., 2002) was used. Due to limitations imposed by regular operations in private farms, we restricted sampling to a 100-m square (100 m × 100 m area) located in the center of each plot; 10 soil samples (0–20 cm in depth) and surface crop residues (0.25 m^2) were randomly collected from each area in the plot (o directamente from each plot) at sowing and harvest stages. We assumed that this 1-ha sampling area was representative of the whole plot conditions. Shoots were sampled from 10 randomly selected plants in each sampling area at harvest.

Soil samples were air-dried and passed through a 2-mm pore sieve. The following parameters were then determined from the sieved soil samples: (a) total N by Kjeldahl (Forster, 1995), (b) NO_3^--N and NH_4^+-N by potentiometry (Keeney and Nelson, 1982), and (c) microbial biomass N by the fumigation method (Joergensen, 1995).

Samples of crop residues and shoots were weighed, dried at 60 °C (until constant weight) and milled. Total N content in crop residues and grain were determined by Kjeldahl. Yield (12% moisture) was evaluated by each farmer in the field by precision agriculture techniques using GPS. Climate data were obtained from the records of INTA Marcos Juarez Meteorological Station.

The values of each parameter analyzed were transformed to kg ha^{-1}. The following calculations were performed following Guarda et al. (2004): (a) N recovery = (grain N content of non-fertilized treatment − grain N content of fertilized treatment)/fertilizer N content and (b) agronomic

Table 1
Soil and crop residue N fractions at wheat sowing

	CT 0N	NT 25N	NT 50N	NT 140N	*P*
Soil total N (g kg^{-1})	2.21	1.83	2.21	2.41	0.0701
Crop residue N (g kg^{-1})	6.60	7.20	7.80	7.50	0.3317
NO_3^--N (mg kg^{-1})	12.50	12.50	11.67	16.67	0.4144
NH_4^+-N (mg kg^{-1})	48.21	86.64	30.88	68.79	0.2688
Microbial biomass N (mg kg^{-1})	126.51	180.40	166.89	205.63	0.0711
Crop residue biomass (g m^{-2})	96.40 c	978.80 b	1795.60 a	1348.40 b	0.0001

CT 0N: conventional tillage, non-fertilized; NT 25N: no-till, fertilized with 25 kg N ha^{-1}; NT 50N: no-till, fertilized with 50 kg N ha^{-1}; NT 140N: no-till, fertilized with 140 kg N ha^{-1}. The letters indicate significant differences (LSD test, $P < 0.05$).

Table 2
Soil, residue and grain N fractions at wheat harvest time

	CT 0N	NT 25N	NT 50N	NT 140N	P
Soil total N (g kg^{-1})	2.00	1.80	1.90	1.90	0.9352
Crop residue N (g kg^{-1})	5.40	3.30	4.20	5.40	0.0587
NO_3^--N (mg kg^{-1})	4.58 ab	5.67 ab	6.25 a	2.92 b	0.0245
NH_4^+-N (mg kg^{-1})	4.01	5.31	6.50	4.50	0.2313
Microbial biomass N (mg kg^{-1})	34.20	30.35	15.75	26.75	0.1069
Grain N (%)	1.98 b	2.13 a	1.77 c	2.07 ab	0.0004
Crop residue biomass (g m^{-2})	1480 b	1624 b	1808 b	2032 a	0.0049

CT 0N: conventional tillage, non-fertilized; NT 25N: no-till, fertilized with 25 kg N ha^{-1}; NT 50N: no-till, fertilized with 50 kg N ha^{-1}; NT 140N: no-till, fertilized with 140 kg N ha^{-1}. The letters indicate significant differences (LSD test, $P < 0.05$).

efficiency = (yield of fertilized treatment − yield of non-fertilized treatment)/fertilizer N content. N balance was calculated as the difference between N fractions at harvest (soil + crop residue + grain) and N fractions at sowing (soil + crop residue + fertilizer). We assumed that negative values mean N losses of the 0–20 cm soil surface layer, where the amount and dynamics of N is more significant (Daudén and Quílez, 2004). Data were analyzed by ANOVA and LSD test for mean comparison among treatments ($P < 0.05$). A t-test was performed ($P < 0.05$) to determine dynamics of the different N fractions between sowing and harvest samplings in each treatment.

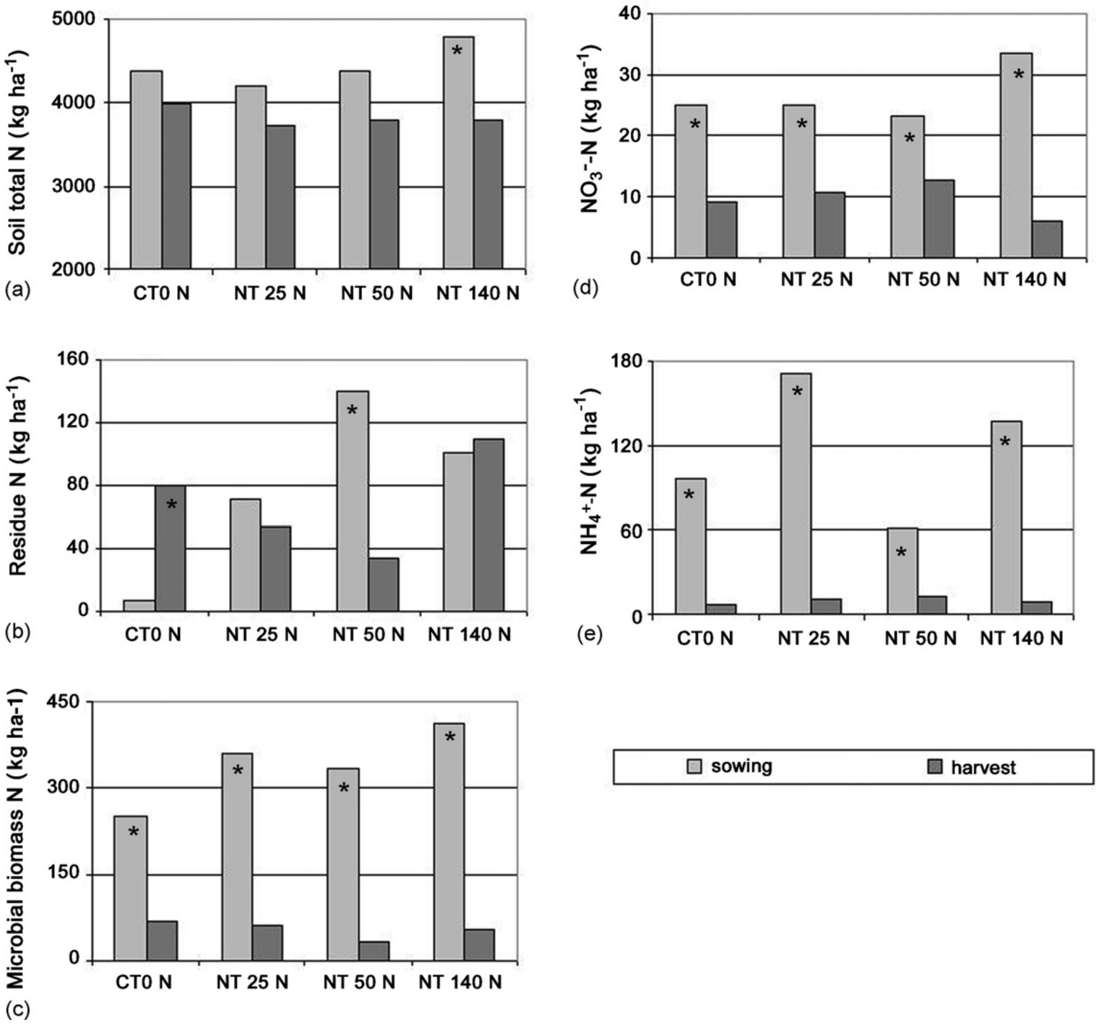

Fig. 1. Dynamics of the soil N fractions between sowing and harvest, corresponding to the different N fertilizer doses analyzed. CT 0N: conventional tillage, non-fertilized; NT 25N: no-till, fertilized with 25 kg N ha^{-1}; NT 50N: no-till, fertilized with 50 kg N ha^{-1}; NT 140N: no-till, fertilized with 140 kg N ha^{-1}. (a) Soil total N; (b) residue N; (c) microbial biomass N; (d) NO_3^--N; (e) NH_4^+-N. *Significant differences between sowing and harvest (t-test, $P < 0.05$).

Table 3
Grain yield of wheat crop (kg ha^{-1}), N recovery index (%), agronomic efficiency (kg kg^{-1}) and N balance (kg ha^{-1}) corresponding to the different fertilization doses analyzed

	CT 0N	NT 25N	NT 50N	NT 140N
Yield (kg ha^{-1})	1800	2000	2500	3000
N recovery index (%)	–	28	17	19
Agronomic efficiency (kg ha^{-1})	–	8.0	14.0	8.6
N balance (kg ha^{-1})	−330	−60	−685	−1075

CT 0N: conventional tillage, non-fertilized; NT 25N: no-till, fertilized with 25 kg N ha^{-1}; NT 50N: no-till, fertilized with 50 kg N ha^{-1}; NT 140N: no-till, fertilized with 140 kg N ha^{-1}

3. Results

At sowing total soil N and its fractions were not significantly. Similarly, N content in crop residues was not significantly different between treatments (Table 1). In contrast, the biomass of crop residues was significantly higher in the NT 50N plot and lower in CT 0N. At harvest, total soil N and its fractions except NO_3 were not significantly different. NO_3 was significantly lower in NT 140N than in the NT 50N. Crop residue nitrogen concentration did not differ among treatments, whereas N concentration in the grain was significantly lower in NT 50N than in the remaining treatments (Table 2). Similar to the biomass of crop residues at sowing (Table 1), the biomass of crop residues at harvest also differed significantly among treatments (Table 2), with the NT 140N plot generating the highest biomass.

The amount of N in the different fractions was significantly lower at harvest in most treatments. Total N in the soil did not vary significantly between harvest and sowing except in NT 140N, being higher at sowing (Fig. 1a). Crop residue N content did not vary in NT 25N or NT 140N, whereas in CT 0N, this parameter was higher at harvest and in NT 50N it was higher at sowing (Fig. 1b). The more labile and soluble soil N fractions (microbial biomass N, NO_3-N and NH_4-N) were significantly higher at sowing than at harvest in all treatments (Fig. 1c–e). Microbial biomass N changes ranged between 68 and 90%. Decreases in NO_3-N ranged between 46 and 82%, whereas NH_4-N changed between 78 and 91%.

Grain yield was higher in NT 140N and lower in CT 0N; grain N recovery was higher in NT 25N. In contrast, agronomic efficiency values were higher in NT 50N (Table 3). N balance was negative in the four treatments analyzed. The amount of N lost in the 0–20 cm soil was highest in NT 140N plot and lowest in NT 25N (Table 3).

4. Discussion

Our results indicate that soil fertility was similar in all treatments in terms of N (both total and respective fractions) before sowing, and that the different fertilization rates produced considerable changes in N dynamics and balance in the soil surface layer. The variation in the amount of crop residue at sowing may be due to differences in the history of each plot, especially the preceding crop and tillage systems. The lower amount of crop residues in CT 0N is expected after conventional tillage, whereas the higher amount of residues in NT 50N could result from the fact that it was the only plot with corn as the preceding crop. It is widely known that corn crop produces a greater amount of residue, which persists in the soil because of its chemical characteristics (Omay et al., 1997; Abril et al., 2005). In plots cultivated on soybean residue with a soybean–wheat 5-year crop sequence, the lower amount of residues would be due to (a) the low amount of residue produced by soybean, and (b) the high decomposition rate of the wheat residue during the rainy season (Karlsson et al., 2003). In contrast, the differences detected in the amount of residues at harvest are directly related to the fertilizer rate applied. The greater amount of residue and grain N observed in the 140N plot is consistent with the effect of the fertilizer N on yield (Brye et al., 2003; Abad et al., 2004).

Grain yield and grain N content values found in our study are lower than values mentioned in the literature worldwide, and also lower than those obtained in the region with Don Enrique wheat cultivar (3500–5000 kg ha^{-1}) (Calviño and Sadras, 2002; Abad et al., 2004; Guarda et al., 2004). These low values could be explained by the fact that 2001 was a relatively dry year for the region, mainly during anthesis (Bainotti et al., 2002). It is well known that water is a limiting factor for productivity in the Pampas region at certain phenological stages of the crop (Calviño and Sadras, 2002; Verón et al., 2004). With lower water deficit, the fertilizer use efficiency may have been higher in all plots evaluated and comparable to records mentioned in the literature (Bainotti et al., 2002; Garrido-Lestache et al., 2004; Guarda et al., 2004).

Guarda et al. (2004) found lower efficiency of N recovery and lower agronomic efficiency with higher fertilization rates. Although Guarda's findings do not agree completely with our results, it is clear from our observations that 140 kg N ha^{-1} does not increase yield agronomic efficiency or fertilizer N recovery rate with respect to plots with lower fertilization rates.

4.1. N dynamics

Our results reveal an important loss in labile and soluble fractions of soil N at the end of the wheat crop cycle in all situations analyzed. The decrease of the inorganic fraction is usually attributed to plant uptake or microbial immobilization. However, it should be considered that plants are dead at harvest, and that microbial biomass detected was scarce, which suggests that the decrease of the inorganic fraction is due to the high precipitations occurred in the last months of the crop cycle (September: 80 mm, October: 106 mm, November: 65 mm). As soils in the region are barely sandy and the watertable is shallow (2–8 m), losses from 0 to 20 cm layer would be indicating probable risks of contamination of the watertable.

It is likely that much of the labile N retained in the microbial biomass at sowing and in the residue of the preceding harvest was mineralized and washed at the end of the wheat crop cycle. Under high fertility conditions, the excess of fertilizer N may have been assimilated by microorganisms that, lacking a similar C source, consume C from soil organic matter (Paul and Clark, 1996; Abril, 2002). This statement is supported by the 41% reduction in soil total N observed in the highest fertilization treatments. When the fertilizer rate is low (25 kg N) a better fertilizer dose-plant demand stability seems to be achieved, since N loss from soil organic matter in these plots was only 3%.

N dynamics in highly fertilized plots can be summarized as follows: (a) at sowing, fertilizer excess that the plant cannot use is assimilated by microbial biomass, which increases in amount and consumes organic matter (b) in winter, with a higher demand by the crop and limiting climatic conditions, a high proportion of microbial biomass dies, (c) in spring, when precipitations begins, a higher fraction of labile N of dead biomass is mineralized, and (d) at harvest, when the plant does not consume N, soluble N fraction is subjected to leaching by abundant precipitations common in the region during this season (Power and Peterson, 1998; Abad et al., 2004).

Thus, one of the main aspects that should be taken into account when planning fertilization is related to synchronization between application dates and physiological requirements of crops. For practical reasons, farmers prefer to apply the fertilizer at sowing, contributing to the N loss dynamic cycle.

4.2. N balance

Our results agree with other works in that N balance is always negative in agricultural soils, being higher with higher fertilizer application rates. For example, it has been reported that losses may reach 50% of the amount of fertilizer applied (Brye et al., 2003; Guarda et al., 2004) and that up to 25% of isotopically labeled N in the fertilizer is not detected in the soil, residue or grain and is considered lost (Power and Peterson, 1998; Schindler and Knighton, 1999). Although many authors do not include organic matter N in balance estimation, assuming that it is a stable parameter, our results indicate that the contribution of this fraction to N dynamics is very important and that it changes with the fertilizer application rate (Karlsson et al., 2003).

Moreover, our results of the N cycle dynamics support the inconvenience of performing N balance in crops considering only residual nitrate (Liu et al., 2003; Abad et al., 2004). Given its high mobility, nitrate is not the most suitable parameter to make an N balance or to evaluate the residual effect of fertilization on a subsequent crop, especially in winter crops in this region. In summer crops, nitrates detected at harvest are probably better indicators of residual N, since they are a result of mineralization activity of the wet season and N accumulation in the dry season.

Another aspect to consider when estimating N balance is the accumulative effect of NT systems on nutrient availability (Alves et al., 1999; Abril et al., 2005). Some authors indicate that, to avoid such error source, studies on N balance in NT should be conducted in the long term (Brye et al., 2003; Cantero-Martínez et al., 2003).

5. Conclusion

Our results show that the application of high N fertilizer doses under no tillage 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.

Acknowledgments

The authors thank Gino Baleani, Bardino Cecci, Jorge Zachía, and Víctor Zachía for allowing us to conduct field work in their cultivated plots. Laboratory analyses were financially supported by Inoculant Production Program. Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba.

References

Abad, A., Lloveras, J., Michelena, A., 2004. Nitrogen fertilization and foliar urea effects on durum wheat yield and quality on residual soil nitrate in irrigated Mediterranean conditions. Field Crop. Res. 87, 257–269.

Abril, A., 2002. La microbiología del suelo: su relación con la agricultura sustentable. In: Sarandon, S.J. (Ed.), Agroecología El Camino hacia una Agricultura Sustentable. Ediciones Científicas Americanas. La Plata, pp. 129–150.

Abril, A., Salas, P., Lovera, E., Kopp, S., Casado-Murillo, N., 2005. Efecto acumulativo de la siembra directa sobre las características del suelo en la región semiárida central de Argentina. Ciencia del Suelo 26, 179–188.

Álvarez, R., Steinbach, H.S., Grigera, S.M., Cartier, E., Obregón, G., Torri, S., García, R., 2004. The balance sheet method as a conceptual framework for nitrogen fertilization of wheat in a Pampean agroecosystem. Agron. J. 96, 1050–1057.

Alves, B., Zotarelli, L., Boddey, R.M., Urquiaga, S., 1999. Ciclaje deN en sistemas de siembra directa y convencional. Biología del Suelo en Siembra Directa. INTA, Asociación Argentina de la Ciencia del Suelo y PROCISUR, Buenos Aires, pp. 1–5.

Bainotti, C.T., Fraschina, J.A., Salines, J.H., Formica, M.B., de Galich, M.T., Nisi, J.E., Galich, A.N., Cuniberti, M., Alberione, E., 2002. Trigo: Actualización. Información para Extensión 71. INTA Marcos Juárez, p. 82.

Bauhus, J., Khanna, P.K., 1999. The significance of microbial biomass in forest soils. In: Rastin, N., Bauhus, J. (Eds.), Going Underground-Ecological Studies in Forest Soils. Research Singnport, Canberra, Australia, pp. 77–110.

Brye, K.R., Norman, J.M., Gower, S.T., Bundy, L.G., 2003. Methodological limitations and N-budget differences among a restored tallgrass prairie and maize agroecosystems. Agric. Ecosyst. Environ. 97, 181–198.

Calviño, P., Sadras, V., 2002. On-farm assessment of constraints to wheat yield in the southeastern Pampas. Field Crop. Res. 74, 1–11.

Cantero-Martínez, C., Angas, P., Lampurlanes, J., 2003. Growth, yield and water productivity of barley (*Hordeum vulgare* L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions of Spain. Field Crop. Res. 84, 341–357.

Capitanelli, R.G., 1979. Clima. In: Vázquez, J.B., Miatello, R.A., Roqué, M.E. (Eds.), Geografía física de la provincia de Córdoba. Editorial Boldt, Buenos Aires, pp. 45–138.

Cassman, K., Dobermann, A., Walters, D., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31, 132–140.

Costa, J.L., Massone, H., Martínez, D., Suero, E.E., Vidal, C.M., Bedmar, F., 2002. Nitrate contamination of a rural aquifer and accumulation in the saturade zone. Agric. Water Manage. 57, 33–47.

Daudén, A., Quílez, D., 2004. Pig slurry mineral fertilization on corn yield and nitrate leaching in a Mediterranean irrigated environment. Eur. J. Agron. 21, 7–19.

Forster, J.C., 1995. Soil nitrogen. In: Alef, K., Nannipieri, P. (Eds.),Methods in Applied soil Microbiology and Biochemistry. Academic Press, London, pp. 79–87.

Galloway, J.N., Cowling, E.B., Seitzinger, S.P., Socolow, R.H., 2002. Reactive nitrogen: too much of a good thing? Ambio 31, 60–63.

Garrido-Lestache, E., López-Bellido, R.J., López-Bellido, L., 2004. Effect of N rate, timing and splitting and N type on bread-making quality in hard red spring wheat under rainfed Mediterranean conditions. Field Crop. Res. 85, 136–213.

Guarda, G., Padovan, S., Delogu, G., 2004. Grain yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels. Eur. J. Agron. 21, 181–192.

Jarsún, B., Gorgas, J., Bosnero, H., Zamora, E., Lovera, E., 1990. Provincia de Córdoba. In: Moscatelli, M. (Ed.), Atlas de suelos de la República Argentina. INTA, pp. 392–512.

Joergensen, R., 1995. The fumigation extraction methods. In: Alef, K., Nannipieri, P. (Eds.), Methods in Applied soil Microbiology and Biochemistry. Academic Press, London, pp. 293–314.

Karlsson, T.L., Andren, O., Katterer, T., Mattsson, L., 2003. Management effects on topsoil carbon and nitrogen in Swedish long-term field experiments-budget calculations with and without humus pool dynamics. Eur. J. Agron. 20, 137–147.

Keeney, D., Nelson, D., 1982. Nitrogen inorganic forms. In: Page, A.L., Miller, R., Keeney, D. (Eds.), Methods of Soil Analysis. Agronomy 9. Am. Soc. Agron. Soil Sci., Madison, WI, pp. 643–698.

Liu, X., Ju, X., Pan, J., Christie, P., 2003. Nitrogen dynamic and budgets in a winter wheat-maize cropping systems in the North China Plain. Field Crop. Res. 83, 111–124.

Omay, A., Rice, C., Maddux, L., Gordon, W., 1997. Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. Soil Sci. Soc. Am. J. 61, 1672–1678.

Paul, E.A., Clark, F.E., 1996. Soil Microbiology and Biochemistry. Academic Press, San Diego, CA.

Power, J.F., Peterson, G.A., 1998. Nitrogen transformations, utilization, and conservation as affected by fallow tillage method. Soil Till. Res. 49, 37–47.

Rimski-Korsakov, H., Rubio, G., Lavado, R.S., 2004. Potential nitrate losses under different agricultural practices in the pampas region, Argentina. Agric. Water Manage. 65, 83–94.

Schindler, F.V., Knighton, R.E., 1999. Fate of fertilizer nitrogen applied to corn as estimated by de isotopic and difference methods. Soil Sci. Soc. Am. J. 63, 1734–1739.

Singh, H., Singh, K., 1993. Effect of residue placement and chemical fertilizer on soil microbial biomass under tropical dryland cultivation. Biol. Fert. Soils 16, 275–281.

Vázquez, J.B., López-Robles, A., Sosa, D.F., Sáez, M.P., 1979. Aguas. In: Vázquez, J.B., Miatello, R.A., Roqué, M.E. (Eds.), Geografía física de la provincia de Córdoba. Editorial Boldt, Buenos Aires, pp. 139–212.

Verón, S.R., Paruelo, J.M., Slafer, G.A., 2004. Interannual variability of wheat yield in the Argentine Pampas during the 20th century. Agric. Ecosyst. Environ. 103, 177–190.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination on earth's ecosystems. Science 277, 494–499.