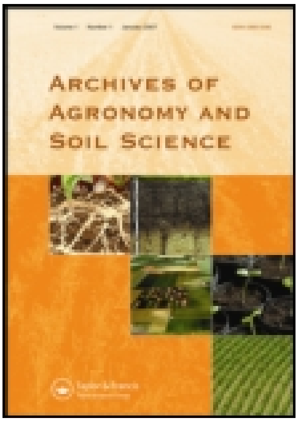

Archives of Agronomy and Soil Science

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gags20

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Version of record first published: 11 Jan 2012.

To cite this article: Alfredo Bono & Roberto Alvarez (2013): Nitrogen mineralization in a coarse soil of the semi-arid Pampas of Argentina, Archives of Agronomy and Soil Science, 59:2, 259-272

To link to this article: http://dx.doi.org/10.1080/03650340.2011.625413

Archives of Agronomy and Soil Science
Vol. 59, No. 2, February 2013, 259–272

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Nitrogen mineralization in a coarse soil of the semi-arid Pampas of Argentina

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(*Received 14 March 2011; final version received 17 September 2011*)

Use of the nitrogen balance sheet method as a fertilization strategy in the semi-arid Pampas of Argentina is restricted because of a lack of available information regarding nitrogen mineralization in its coarse soils. Our objective was to determine nitrogen mineralization during corn (*Zea mays* L.) and following wheat (*Triticum aestivum* L.) growing cycles under contrasting tillage systems in a representative soil of the region. Mineralized nitrogen from decomposing residues was estimated using the litter bag method and mineralization from soil organic matter using a mass balance approach. Soil water content was higher under no-till during the corn growing season and no differences were detected for wheat during this period. Soil temperature was practically not affected by tillage system. Biomass and nitrogen absorption were higher under no-till than under disk till in corn ($p \leq 0.05$), as were nitrogen mineralization from residues and organic matter ($p \leq 0.05$). In wheat, no differences in biomass, nitrogen absorption and mineralization were detected between treatments. Mineralization during crop growing cycles accounted for 44.8–67.5% of the absorbed nitrogen. Differences in nitrogen mineralization between tillage systems resulted from the greater water availability under no-till than under disk till during the summer.

Keywords: nitrogen balance sheet method; nitrogen mineralization; residue decomposition

Introduction

The nitrogen balance sheet method has been widely used for nitrogen fertilizer recommendation in graminaceus crops like corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) (Vanotti and Bundy 1994; Makowski et al. 1999). It also has been a valuable tool for nitrogen flux estimation, which is as difficult to determine as nitrogen mineralization from soil organic matter pools (Salmeron-Miranda et al. 2007). In the Pampean Region of Argentina, the nitrogen balance sheet method allowed the estimation of nitrogen mineralization rates and the design of nitrogen fertilization strategies in fine-textured–rich organic matter soils from the humid portion of the region during corn and wheat growing cycles (Alvarez and Steinbach 2011). In the semi-arid portion of the Pampas, with coarse textured–low organic

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ISSN 0365-0340 print/ISSN 1476-3567 online

http://dx.doi.org/10.1080/03650340.2011.625413
http://www.tandfonline.com

matter soils, there is no available information on nitrogen mineralization from decomposing residues and soil organic matter for applying the nitrogen balance sheet method as a tool for fertilizer recommendation. Farmers apply low nitrogen rates, usually without soil sampling and fertility evaluation. Crop yield improvement may be expected if scientifically sound fertilization recommendation strategies are developed in the region.

The nitrogen balance sheet method may be described by the following equation (Alvarez and Steinbach 2011).

$$Na + Nr = Ns + Nf + Nd + Nm - Nl \tag{1}$$

where: Na = nitrogen absorbed by crop; Nr = residual nitrogen at harvest; Ns = mineral soil nitrogen at sowing; Nf = fertilizer nitrogen rate; Nd = nitrogen mineralized from decomposing residues; Nm = nitrogen mineralized from soil organic matter; and Nl = nitrogen losses by volatilization, denitrification and lixiviation.

All terms in the balance equation are expressed in kg N ha^{-1} and any one may be calculated if the others are known. Fertilizer recommendation, related to target yield, may be performed by determining soil available mineral nitrogen at sowing and estimating mineralization, losses, residual nitrate and crop nitrogen requirement. Because determination of nitrogen losses from agroecosystems is rather difficult during nitrogen mineralization estimation under filed conditions, the balance methodology may be simplified as follows:

$$(Nd + Nm - Nl) = (Na + Nr) - (Ns + Nf) \tag{2}$$

The term ($Nd + Nm + Nl$) is called apparent nitrogen mineralization and is an estimation of nitrogen mineralized during the crop growing period from residues and organic matter minus nitrogen losses from the agroecosystem (Blankenau et al. 2000, 2002). If independent measurements of nitrogen released during residue decomposition are performed it is also possible to estimate mineralization coefficients for soil organic matter (Alvarez and Steinbach 2011). Once these coefficients have been determined for a specific region and soil type, the balance approach may be used for fertilizer recommendation as a simple methodology based on an estimated target yield and soil sampling before seeding to determine available mineral nitrogen. Our objective was to determine nitrogen mineralization during corn and following wheat growing cycles in a typical soil of the semi-arid Pampas under different tillage systems commonly used in the region.

Materials and methods

Experimental design and sampling

A field experiment was performed at INTA Anguil Experimental Station, located in the Province of La Pampa, Argentina (36°30′S, 63°49′W, 165 masl), which started in 1998. The typical crop rotation of dry land conditions for this region was used. This experiment performed in the semi-arid Pampas, in which the effects of tillage systems on soils and crops are compared, is the only one of its type in the region. Mean annual rainfall (1913–2000) was 664 mm, with great interannual variation (400–1000 mm). Around 75% of total rainfall occurred during spring and summer.

During corn (2001–2002) and wheat (2002) growing seasons, rainfall at the experimental site was 370 and 240 mm, respectively. Mean annual temperature at the site was 16°C. The soil was an Entic Haplustoll (USDA 2003) with an A horizon of 18 cm, a petrocalcic horizon between 80 and 120 cm depth, and a loam texture (clay 94 g kg^{-1}, sand 530 g kg^{-1}). Intensive soil sampling, using a grid design of 1-m depth subdivided into 20-cm layers, was performed prior to installation of the experiment and many chemical and physical soil properties were determined to verify the uniformity of the field. Data were analyzed by mixed models and a clear linear covariate data structure was detected, indicating the unsuitability of common experimental designs because of a lack of independency between possible future plots. Consequently, the field was divided into two main plots and differences for all evaluated soil variables were tested. No significant difference was detected between these two plots and each was assigned to a tillage treatment. This design ensures that all differences at the end of the experiment were due to the treatments applied. Detailed information about variables evaluated before initiation of the experiment and statistical methods of comparison used at the start have been published elsewhere (Bono et al. 2008); some main soil properties are presented in Table 1.

Two tillage systems were tested: no-till, in which weeds were controlled chemically using glyphosate [*N*-(phosphomethyl)glycine]; and disk till, in which soil was tilled using a disk plow to 15–18-cm depth three months prior to crop seeding and then refined by a harrow disk. Each tillage system was applied to one single plot of 3630 m^2. Rotation was as follows: wheat during 1998, sunflower (*Helianthus annus* L.) during 1999/2000, oat (*Avena sativa* L.) + hairy vetch (*Vicia sativa* L.) during 2000, corn during 2001/2002 (70,000 plants ha^{-1}) and wheat during 2002 (1,100,000 plants ha^{-1}). Urea was broadcast for corn and wheat at seeding at rates varying between 43.5 and 50 kg N ha^{-1}. The large plots assigned to each tillage treatment were divided into 18 subplots for sampling in a grid design, of 202 m^2 each. In each subplot, one soil sample was taken with a corer in layers 20 cm to 1 m deep for water content determination and to 0.6 m deep for nitrate analysis at seeding of corn and wheat. Fresh samples were homogenized with a knife and sieved to 2 mm before analysis for nitrates. At harvest, nitrate sampling was repeated for residual nitrogen evaluation.

Aboveground crop biomass was hand-harvested from microplots (10 m^2 each), once by subplot at physiological maturity. Root biomass at crop maturity to 20-cm depth was determined by removing six columns (3000 cm^3 each) by microplot on the row and in the middle of the furrows. Soil was dispersed in water and sieved through

Table 1. Some main soil properties for the no till and disk till plots at the beginning of the experiment.

Soil parameter	Disk till	No till
Soil bulk density (g cm^{-3})	1.18	1.18
Sand (%)	54.6	51.2
Silt (%)	36.4	39.0
Clay (%)	8.95	9.84
pH in water (1:2.5)	6.07	6.16
Extractable P (Bray, mg kg^{-1})	14.4	15.4
Organic carbon (g kg^{-1})	11.7	12.1

a 0.5-mm mesh to retain roots. Plant material was dried at 60°C and ground for chemical analysis. Root biomass to 100-cm depth was estimated assuming that roots in the 0–20-cm layer accounted for 60% of the biomass in the upper 1 m of the soil profile (Jackson et al. 1996). Rhizodeposition, defined as root-derived nitrogen remaining in the soil at harvest, originated from decomposition of dead roots, exudates and sloughed root cells, and was estimated to be 7% of the nitrogen accumulated in aboveground biomass + roots, assuming it is equal to carbon rhizodeposition (Swinnen et al. 1994; Kisselle et al. 2001). Total nitrogen absorbed by crops was calculated as the sum of nitrogen in the biomass and rhizodeposition, because this latter nitrogen pool was originally mineral soil nitrogen that was absorbed by crops and then excreted into the soil as organic nitrogen.

Decomposition of corn and wheat residues was determined between May 2000 and July 2003 using the litter bag technique (Andrén and Paustian 1987). The initial N concentration of the residues was 0.82–0.84% for both materials and the C/N was ~48. Litter bags of 20 × 20 cm and 4-mm mesh size, containing 50 g dry matter (DM) straw, were installed on the soil surface in the no-till treatment, or buried to 15 cm in the disk till treatment, and left in the field for up to 880 days. The bag mesh size was selected to permit a normal flux of water between residue and soil, and the activity of mesofauna in order to avoid underestimation of decomposition (Tian et al. 1992). At variable time intervals, one bag was taken from each subplot ($n = 18$ by sampling time and tillage treatment) of each plant type, the remaining straw was carefully washed to remove contaminating soil (Potthoff and Loftfield 1998), oven-dried at 60°C and ground.

Total soil organic nitrogen was determined by one sample per subplot in layers of 25 cm to 1 m depth. A corer (244 cm^3) was used for soil bulk density determinations in layers of 5 cm to 1 m depth. Nitrogen mineralization from incubated soil was performed to assess the stability of organic matter in different soil layers. Air-dried soil was ground and sieved through a 2-mm sieve, and 150 g was incubated for 15 days at 30°C with the water content adjusted to field capacity in 400-mL topped flasks.

The initial surface and buried residue mass at seeding of corn and wheat were determined re-collecting one sample by subplot with a iron box (0.15 m wide × 0.30 m long), buried 0.15 m into the soil. The surface residue within the iron box was picked by hand and sampled soil with buried residues were washed, sieved through a 0.5-mm mesh, dried at 60°C and ground.

Measurements

Soil water content was determined gravimetrically, soil nitrates by the chromotropic acid method (West and Ramachandran 1966), and nitrogen in soil and plant material by wet digestion using the Kjeldahl method (Bremner 1996). Soil organic nitrogen was assumed to be equal to total nitrogen because in these coarse soils ammonium nitrogen usually accounts for $<0.5\%$ of total nitrogen. Nitrogen concentration was transformed into mass using soil bulk density data. Ammonium and nitrate nitrogen in incubated flasks were analyzed at the start and at the end of the incubation by steam distillation (Mulvaney 1996). Soil temperature at 10-cm depth was measured in each subplot using standard thermometers covered with caps. All measurements were performed in duplicate.

Modeling residue decomposition and apparent mineralization

The decomposition and nitrogen mineralization kinetics were assessed using a two-compartment model (Trinsoutrot et al. 2000):

$$X_{rem} = X_L(e^{-k_L t}) + X_R \tag{3}$$

where: X_{rem} = remaining DM or nitrogen in decomposing residues (%); X_{L} = labile fraction of dry matter or nitrogen in residue (%); X_{R} = recalcitrant fraction of dry matter or nitrogen in residue (%); $X_{\mathrm{R}} + X_{\mathrm{L}} = 100$; k_{L} = decomposition constant (fraction decomposed by day) and t = time (day).

By fitting the model, DM or residue nitrogen can be partitioned into two pools of contrasting resistance to degradation, and the decomposition constant of the more labile one can also be assessed. Residue nitrogen release estimation during crop growing seasons (*Nd*) was performed by determining residue mass and nitrogen at seeding and estimating nitrogen mineralization by means of models from Equation (3), fitted separately to surface and buried residues. It was assumed that 70% of the estimated nitrogen decrease in the surface residues between seeding and harvest, and 30% from buried residues were released into the soil solution, assuming that the remainder was immobilized in microbial biomass (Parton et al. 1994). Apparent nitrogen mineralization from soil organic matter ($Nm - Nl$) was estimated as the difference between total apparent nitrogen mineralization ($Nd + Nm - Nl$) and residue mineralization (*Nd*).

Statistical methods

Tillage effects on soil temperature and water content were tested using a semi-parametric mixed model by fitting daily measurements using B-splines. Best linear unbiased predictions (BLUP) of daily values of the variables were calculated. The difference between the BLUPs of both tillage systems among sampling dates were tested using the *F*-test. The model used for temperature and water content over time has been described in detail elsewhere (Bono et al. 2008). Pseudoreplication inflates the degrees of freedom increasing the probability of a type I error (Johnson 2006). Consequently, we used spatial covariance matrices to reflect the stochastic association among samples, which in turn affect the degrees of freedom for the tests of differences between no-till and disk till. In doing so, data were analyzed using a one-way model with fixed treatment effects and an anisotropic power covariance structure using PROC MIXED (SAS 1999). Coordinates were the position of the samples in a two-dimensional grid and the degrees of freedom for hypothesis testing were corrected (Kenward and Roger 1997). The model used was:

$$y_{itk} = \sum_{j=1}^{4} B_{ij}^{(tk)}\, b_j + e_{itk} \tag{4}$$

where y_{itk} is the observation from treatment i (1, 2; two tillage treatments), at time t (1, ... , 12; 12 sampling times), from position k (1, ... , 18; 18 subplots by treatment). $B_{ij}^{(tk)}$ is the cubic B-spline coefficient for observation y_{itk}, b_j is the curve parameter, which is actually treated as a random variable and e_{ikt} is the error term. Crop biomass, nitrogen uptake, soil mineral nitrogen and nitrogen mineralization were analyzed using a simplified model in which the t component was dropped. For soil organic nitrogen and mineralization potential analysis a fixed model with a spatial linear covariance structure, and PROC MIXED was used. Effects in the model equation were tillage system, coordinates in the sampling grid and soil depth nested within tillage treatment. The differences between tillage systems at the four soil depths sampled were tested using linear contrasts with degrees of freedom corrected by the procedure suggested by Kenward and Roger (1997). Remaining nitrogen in decomposing residue was fitted to the two-component model using weighted least squares as implemented in PROC NLIN (SAS 1999).

Results

No differences were detected is soil temperature between tillage systems, except at only one sample date (Figure 1). Rainfall during crop growing seasons was close to historic averages of 390 mm for corn and 272 mm for wheat. Soil available water content was $\sim$15% higher in the upper 1 m of the profile under no-till compared with disk till during the corn growing cycle, but significant differences were not detected during wheat cycle (Figure 1). This determined a 30% greater biomass production and yield of corn under no-till (Table 2). Conversely, soil nitrate nitrogen content was greater under disk till than in non-disked soil at corn seeding; no significant differences were detected in wheat (Table 3). Nitrogen absorption was affected by tillage systems only in corn (Table 3). Under no-till, nitrogen absorption was 30% greater than under disk till, a consequence of the greater biomass production.

Residue decomposition was slower when left on the surface in the no-till treatment than when buried in the disk till treatment. After 880 days in the field, nitrogen remaining in residues doubled in surface residues in relation to buried ones (Figure 2). The kinetics of corn and wheat residue decomposition was similar and could be fitted to the same functions. The two-component model described fairly well the evolution of the remaining DM, both surface or buried, and nitrogen in surface residues, but it could not be fitted to nitrogen in buried residues (Table 4). In this case, the remaining nitrogen kinetics were adjusted to a single compartment exponential model. Because dry matter decomposition was faster than nitrogen decomposition, the concentration of nitrogen in residues increased over time (Figure 3). Nitrogen immobilization in residues was not found because the total amount of nitrogen in the remaining residues decreased over the course of the experiment; residues act as a nitrogen source for crops.

Fitted decomposition functions were used to estimate nitrogen mineralization from the residues of previous crops present in soil during corn and wheat growing seasons (Table 5). Residue nitrogen was greater under no-till than disk till at corn seeding (80 vs. 47 kg N ha^{-1}) and wheat seeding (163 vs. 113 kg N ha^{-1}). Significant differences were detected between tillage systems in corn; mineralization was greater under no-till than under disk till. Nevertheless, estimated residue mineralization was small and accounted for only a minor portion of corn nitrogen demand, ranging from 1.5 to 3.0%. During the wheat growing season, mineralization from residues ranged from 5.8 to 12.2% of wheat demand, representing a more significant contribution to crop nitrogen.

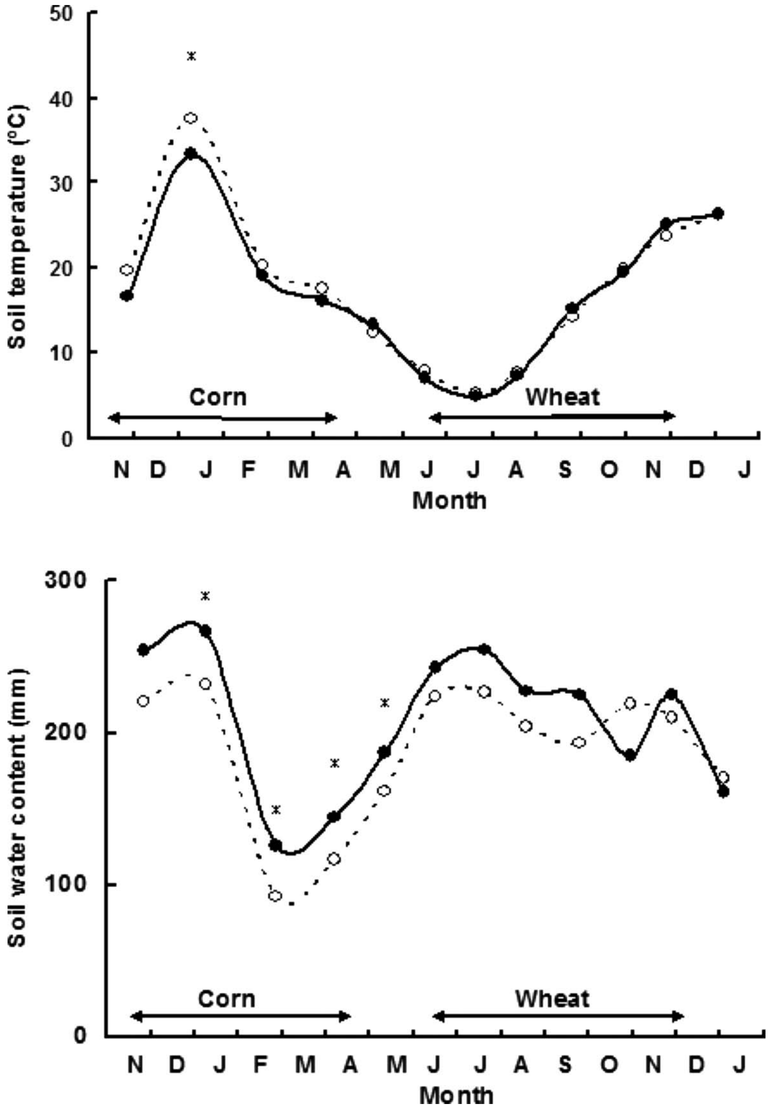

Figure 1. Soil temperature (0-10 cm) and water content (0–100 cm) during corn and wheat growing cycles under no till (●) and disk till (○).

Apparent nitrogen mineralization from organic matter, estimated using the nitrogen balance sheet method, was approximately three times greater during corn than wheat growing season (Table 5). Tillage systems impacted apparent mineralization significantly in corn. Under no-till, mineralization was 75% greater than under disk till. Apparent mineralization from organic matter was the main nitrogen source for crops representing, between 32.7 and 64.5% of the absorbed nitrogen. Nitrogen mineralized from residues was equivalent to 1.5–12.2% of nitrogen absorbed by plants, and both soil organic pools together provide between 44.8 and 67.5% of crop nitrogen requirements (Tables 3 and 5). Taking into account that mineral nitrogen at seeding also came from organic soil pool degradation prior

Table 2. Dry matter biomass and nitrogen in different crop components.

Crop	Tillage system	Straw		Roots and rhizodeposition		Grain	
		Dry matter	Nitrogen	Dry matter	Nitrogen	Dry matter	Nitrogen
		($kg\ ha^{-1}$)					
Corn	Disk till	6290 a	66.7 a	5240 a	58.1 a	6140 a	81.1 a
	No till	8030 b	75.1 b	6670 b	75.0 b	8160 b	117 b
Wheat	Disk till	5330 a	48.4 a	2100 a	7.8 a	2600 a	64.1 a
	No till	5880 b	45.5 a	1990 a	9.2 a	3340 b	66.9 a

Note: Different letters between tillage treatments indicate significant differences at $p = 0.05$.

Table 3. Residue nitrogen allocation, mineral nitrogen availability and nitrogen absorbed by crops under two tillage systems.

Crop	Tillage system	Nitrogen ($kg\ ha^{-1}$)					
		Surface residue N	Buried residue N	Fertilizer N	Nitrate-N (seeding)	Absorbed N in Plant	Residual nitrate-N (harvest)
Corn	Disk till	1.5 a	45.6 a	43.5	89.8 a	206 a	27.9 a
	No till	51.5.a	28.0 a	43.5	68.2 b	267 a	36.6 a
Wheat	Disk till	2.1 a	111.0 a	50.0	51.8 a	120 a	45.7 a
	No till	96.6 b	65.9 a	50.0	47.2 a	122 a	40.2 a

Note: Different letters between tillage treatments indicate significant differences at $p = 0.05$.

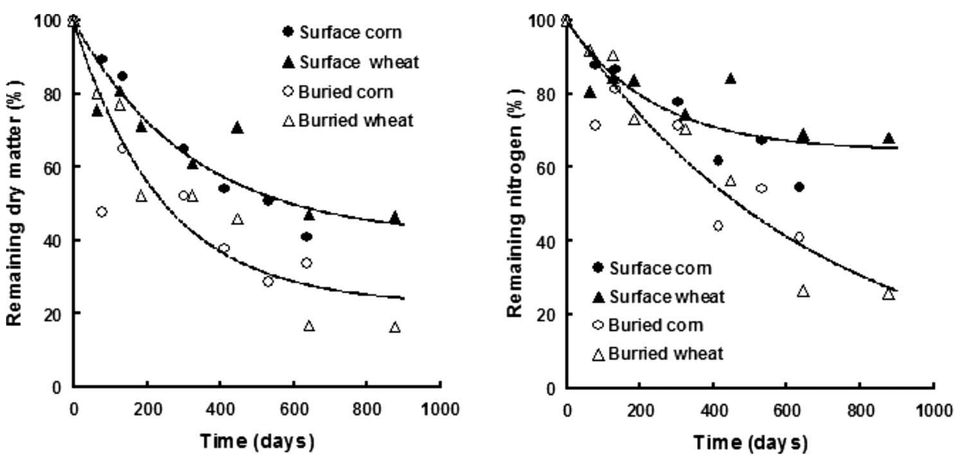

Figure 2. Remaining dry matter and nitrogen in decomposing residues of corn and wheat under two tillage systems. Surface, no till; buried, disc till.

to crop establishment, mineralization of soil organic reservoirs was the main source of nitrogen for crops, with a minor contribution from fertilizers. This latter contribution was equivalent to 14.9–18.5% of total nitrogen availability (initial

Table 4. Parameters and determination coefficients (R^2) of the exponential model fitted to remaining dry matter and residue nitrogen data.

Variable	Residue allocation	Parameters			R^2
		X_R	X_L	k_L	
Dry matter	Buried	22.4	77.6	0.00417	0.840
	Surface	40.7	59.3	0.00313	0.895
Nitrogen	Buried	0	100.0	0.00148	0.898
	Surface	64.3	35.7	0.00423	0.743

Note: X_L, labile fraction of dry matter or nitrogen in residue (%); X_R, recalcitrant fraction of dry matter or nitrogen in residue (%); k_L, decomposition constant (fraction decomposed by day).

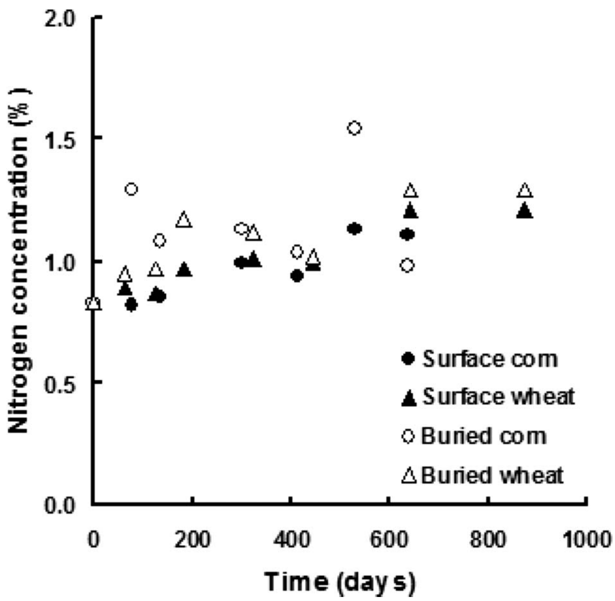

Figure 3. Evolution of the nitrogen concentration of decomposing residues of corn and wheat under two tillage systems.

nitrate + mineralization + fertilizer) for corn and 30.1–32.8% for wheat (Tables 3 and 5).

The mass of soil organic nitrogen was stratified to 1-m depth under both tillage systems. Soil nitrogen content was 13% higher in the 0–25-cm layer under no-till, but the difference with disk till was not significant (Figure 4). Soil nitrogen mineralization potential, assessed in laboratory incubations, showed a stratification pattern with depth similar to that with organic nitrogen (Figure 4). Results had a great variability, and no significant differences were detected between tillage systems. The upper soil layers had greater nitrogen mineralization capacity than deeper layers; but intense mineralization also occurred up to 1-m depth. Organic matter mineralization coefficients were estimated as ratio between apparent nitrogen mineralization from organic matter and total soil nitrogen in the upper one meter of the profile (Table 5). These coefficients were significantly different between tillage systems only for corn.

Table 5. Nitrogen mineralization from decomposing residues and soil organic matter during the growing cycles of corn and wheat.

Crop	Tillage system	Mineralized nitrogen: From residues (kg ha^{-1})	From organic matter (kg ha^{-1})	From organic matter (%)
Corn	Disk till	3.1 a	98.6 a	1.24 a
	No till	8.0 a	172.3 b	2.09 b
Wheat	Disk till	7.0 a	57.2 a	0.73 a
	No till	14.9 a	39.7 a	0.48 a

Note: The percentage of nitrogen in organic matter mineralized was calculated as the nitrogen mineralized estimate using the balance approach related to organic nitrogen in the upper 1 m of the profile. Different letters between tillage treatments indicate significant differences at $p = 0.05$.

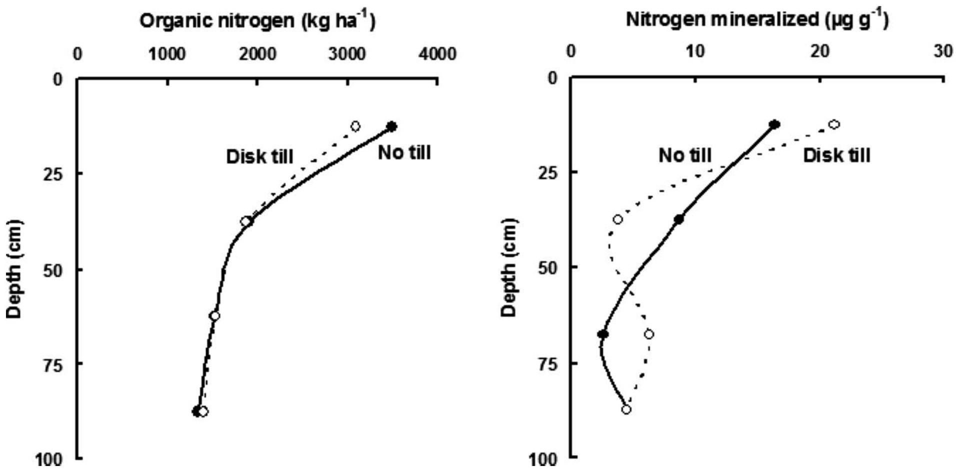

Figure 4. Distribution of organic nitrogen at depth and nitrogen mineralized during laboratory incubations from samples taken at different soil depths under two tillage systems. No significant differences were detected between tillage systems.

Discussion

Mineral nitrogen content at seeding was greater under disk till. This may be a consequence of the greater temperature of tilled soil in one sampling time but, mainly, of the disruption of aggregates produced by tillage, exposing organic matter to microbial attack, which results in an increase in the organic nitrogen mineralization (Davies et al. 2001) and faster residue decomposition (Drinkwater et al. 2000). As in other cropping regions in the world, greater nitrate contents are usually found in tilled soils than under no-till in the Pampas (Alvarez and Steinbach 2009).

The greater biomass production of corn under no-till observed in the semi-arid environment of our experiment, induced by a greater water availability, results in greater nitrogen absorption by plant, despite the lower initial soil mineral nitrogen level under this treatment. This may be explained by the fact that water availability is the main plant productivity control in arid and semi-arid environments of the Pampas (Veron et al. 2002). Also nutrient availability and mass transport could be increased as the consequence of greater water content under no-till (Olson and Kurtz 1982).

Nitrogen mineralization was about double for buried residues compared with the effect of residues left on surface in the semi-arid Pampas; this was also observed in other regions (Lupwayi et al. 2006). Decomposition is commonly faster for buried material, as observed in this experiment, because the water content of residue is generally greater when buried than when on the soil surface (López Sanchez et al. 2003), and contact between the residue and soil is also better when buried than at the surface, allowing a faster microbial colonization (Henriksen and Breland 1999).

Residue dry matter decomposition could be fitted to the two-component model. Microorganisms use initially soluble carbohydrates and easily degradable compounds, like starch, as carbon and energy sources, and when these compounds are exhausted, resistant compounds, mainly cellulose and lignin, are degraded (Trinsoutrot et al. 2000). Nitrogen dynamics seem to follow a different trend in some cases because buried residue nitrogen decomposition kinetics adjusted to a first-order decaying model, which may be a consequence of the small size of the recalcitrant nitrogen pool.

Despite an initial low nitrogen concentration of $\sim$0.82–0.84% of corn and wheat residues, nitrogen mineralization was only observed from residues, but decomposition proceeds at a slow rate. Almost 60% of the initial nitrogen residue was still not liberated after $\sim$2.5 years at the soil surface; for the buried residues this value was 35%. When the nitrogen concentration is $>$2%, mineralization predominates and with lower concentrations, net immobilization occurs (Seneviratne 2000; Trinsoutrot et al. 2000), but this threshold is very variable (Kumar and Goh 2003). In our case, the lack of a nitrogen immobilization phase, even with low nitrogen concentrations in the residues, may be ascribed to low decomposition rate induced by water conditions, which restricts the development of microbial biomass and its effect as sink for nitrogen (Parton et al. 1994).

In the semi-arid environment of our experiment, slow decomposition rate results in greater residue accumulation under no-till than in disk till, especially before corn seeding, and to greater mineralization of nitrogen during the crop growing cycle. Despite this difference, residues from previous crop were not an important source of nitrogen for corn and wheat. The use of nitrogen residue may be greater when it is buried by tillage under scenarios of equal initial soil residue mass (Beare et al. 2002), but the quantity of nitrogen mineralized is a function of residue mass and nitrogen concentration (Alvarez and Steinbach 2011). As residue mass or nitrogen concentration increase; more nitrogen is mineralized. Nitrogen fluxes from residues to the environment in temperate regions under extensive agriculture may vary between 14 to 40 kg N ha^{-1} (Gentry et al. 2001; N'Dayegamiye and Tran 2001), and supply from 20 to 40% of crop nitrogen requirements (Bergensen et al. 2000; Hood et al. 2000), a greater proportion than that observed in the semi-arid Pampas.

In Pampean agroecosystems, temperature is a strong regulator of soil organic matter mineralization under humid and semi-arid environments (Alvarez et al. 2011). This implies that greater nitrogen mineralization rates may be expected during corn growing season than wheat growing season as observed in the present experiment.

Nitrate nitrogen content was higher under disk till at seeding time of corn and mineralization lower than under no-till. Under field conditions, apparent nitrogen mineralization decreased when initial mineral nitrogen was greater (Alvarez and Steinbach 2011). This is the consequence of not only possible repression of mineralization (Sierra 1992), but also greater immobilization and, perhaps, greater losses (Blankenau et al. 2000, 2002). Because corn biomass production was greater under no-till, due to water and nutrient availability, a second reason for the greater mineralization produced in this treatment may be an increase in crop demand, which led to nitrate depletion and incentivized mineralization in relation to disked soil, analogous to Steinbach et al. (2004). In wheat, small differences in nitrate level and water content between tillage systems led to no significant difference in mineralization between treatments.

The great mineralization observed in our experiment seems to be related to the coarse texture of soils; because fine particles protect organic matter from microbial attack (Parton et al. 1994). In experiments performed in the humid portion of the region, on fine-textured soils, with a strong clayey B horizon, and organic matter content double that of our soil, nitrogen mineralization was of similar magnitude to that reported here, for both corn and wheat (Alvarez and Steinbach 2011). In the soil of the semi-arid Pampa, $\sim$40% of total nitrogen was mineralized below 25 cm depth. Conversely, in soils of the humid Pampa, only 15% of total mineralization is produced below the upper 30 cm of the profile (Alvarez 2006). Because mineralization is controlled by both the amount of nitrogen in organic pools (Barrett and Burke 2000) and soil texture (Delin and Linden 2002), coarser soils may mineralize more nitrogen at depth because of a lower protection of organic matter by fine particles. A compensation effect of texture by organic matter content on nitrogen mineralization exists.

Conclusion

In coarse soils of the semi-arid Pampa, mineralization is an important source of nitrogen for crops. Nitrogen release by subsurface layers to 1-m depth is significant and must be considered for fertilizer recommendation using the nitrogen balance sheet method. The tillage system affects mineralization because of its effect on soil water content. Under no-till management more intense nitrogen mineralization may be expected than under tillage, particularly for summer crops.

Acknowledgements

This research was partially supported by grants from the University of Buenos Aires (G004 and G033), CONICET (PIP 02050 and PIP 02608) and FONCYT (PID-BID 37164-49).

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