DIVISÃO 3 - USO E MANEJO DO SOLO

Comissão 3.1 - Fertilidade do solo e nutrição de plantas

NITROGEN DYNAMICS IN SOIL MANAGEMENT SYSTEMS. I - FLUX OF INORGANIC NITROGEN (NH_4^+ AND NO_3^-)(1)

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ABSTRACT

In agricultural systems the N-NH_4^+ and N-NO_3^- contents is significantly affected by soil management. This study investigated the dynamics of inorganic nitrogen (N; NH_4^+ and NO_3^-) in an experimental evaluation of soil management systems (SMSs) adopted in 1988 at the experimental station of the ABC Foundation in Ponta Grossa, in the Central South region of the State of Paraná. The objective of this study was to evaluate the changes in N-NH_4^+ and N-NO_3^- flux in the surface layer of a Red Latosol arising from SMSs over a 12-month period. The experiment was arranged in a completely randomized block design in split plots, in three replications. The plots consisted of the following SMSs: 1) conventional tillage (CT); 2) minimum tillage (MT); 3) no-tillage with chisel plow every three years (NT_{CH}); and 4) continuous no-tillage (CNT). To evaluate the dynamics of inorganic N, the subplots represented samplings (11 sampling times, T_1 - T_{11}). The ammonium N (N-NH_4^+) and nitric N (N-NO_3^-) contents were higher in systems with reduced tillage (MT and NT_{CH}) and without tillage (CNT) than in the CT system. In the period from October 2003 to February 2004, the N-NH_4^+ was higher than the N-NO_3^- soil content.

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Conversely, in the period from May 2004 to July 2004, the N-NO_3^- was higher than the N-NH_4^+ content. The greatest fluctuation in the N-NH_4^+ and N-NO_3^- contents occurred in the 0–2.5 cm layer, and the highest peak in the N-NH_4^+ and N-NO_3^- concentrations occurred after the surface application of N. Both N-NH_4^+ and N-NO_3^- were strongly correlated with the soil organic C content, which indicated that these properties vary together in the system.

Index terms: C, N, conservation tillage systems, no-tillage, conventional tillage.

RESUMO: *DINÂMICA DO NITROGÊNIO EM SISTEMAS DE MANEJO DO SOLO. I- FLUXO DO NITROGÊNIO INORGÂNICO (NH_4^+ E NO_3^-)*

Nos sistemas agrícolas o conteúdo de N-NH_4^+ e N-NO_3^- é significativamente afetado pelo manejo do solo. Estudou-se a dinâmica do nitrogênio (N) inorgânico (NH_4^+ e NO_3^-) em experimento com avaliação de sistemas de manejo do solo (SMS) implantado em 1988, na Estação Experimental da Fundação ABC, em Ponta Grossa, região Centro-Sul do Estado do Paraná. Objetivou-se, com este trabalho, avaliar as alterações ocasionadas pelos SMS no fluxo do N-NH_4^+ e N-NO_3^- na camada superficial de um Latossolo Vermelho, em um período de 12 meses. O delineamento experimental utilizado foi o de blocos completos ao acaso, em esquema de parcelas subdivididas com três repetições. As parcelas foram constituídas pelos seguintes SMS: 1) preparo convencional (PC); 2) preparo mínimo (PM); 3) plantio direto com escarificação a cada três anos (PDE); e 4) plantio direto permanente (PDP). Para avaliar a dinâmica do N inorgânico, as subparcelas foram constituídas pelo tempo de coleta (11 tempos de coleta – T_1 a T_{11}). O conteúdo de N amoniacal (N-NH_4^+) e de N nítrico (N-NO_3^-) foi superior nos sistemas com menor mobilização do solo (PM e PDE) e sem mobilização (PDP), em comparação com o PC. No período de outubro de 2003 a fevereiro de 2004, o conteúdo de N-NH_4^+ no solo foi superior ao de N-NO_3^-. Entretanto, no período de maio de 2004 a julho 2004 o conteúdo de N-NO_3^- foi superior. A maior flutuação do conteúdo do N-NH_4^+ e do N-NO_3^- ocorreu na camada de 0–2,5 cm, e o maior pico na concentração N-NH_4^+ e do N-NO_3^- aconteceu depois da aplicação de N em cobertura da cultura do trigo. Tanto o N-NH_4^+ quanto o N-NO_3^- apresentaram elevada correlação com o conteúdo de C-orgânico do solo, indicando que tais atributos variam juntos no sistema.

Termos de indexação: C, N, sistemas conservacionistas, plantio direto, plantio convencional.

INTRODUCTION

Inadequate management practices are responsible for the degradation of soil organic matter (SOM) and changes in the physical, chemical and biological properties of soil. Moreover, inadequate management practices are also responsible for erosion, environmental pollution and decreased crop production. Since the 1970s, the adoption of conservation soil management systems to minimize these problems has been studied and promoted in Brazil, with a view to improve soil properties and production sustainability by no-tillage (NT) combined with crop rotation for straw production (Holland, 2004).

The agriculture-based conservation systems even have greater a potential of net fixation of atmospheric carbon dioxide (CO_2) than undisturbed natural systems, especially in the most superficial soil layer (Bayer et al., 2006). In addition, these systems, which are not disturbed by soil management, have the possibility of accumulating N. Using this approach, Sá et al. (2001) compared the stocks of C and N in conventional tillage (CT) and NT over 22 years in an experiment in a clayey Red Latosol in the Central South region of the State of Paraná. They observed a C and N gain of 19.0 and 1.90 t ha^{-1}, respectively, at a depth of 0–40 cm, and also found that 81.8 and 74.5 % of the increase in the C and N stocks, respectively, occurred in the 0–10 cm layer. Coupled with reduced soil disturbance, the use of crop sequences that generate increased amounts of crop residue that remain longer on the soil surface also tends to improve the balance of C and N (Vieira et al., 2007; Sá & Lal, 2009). In Latosols in Rio Grande do Sul, Boddey et al. (2010) found an increase in the C and N stocks in NT over CT, down to a depth of 1 m. However, they found the greatest differences in the 0–5 cm layer, indicating that the primary transformation of C and N occurs in the first few centimeters of the soil profile.

The increase of organic matter in the soil profile, considered one of the major N sources in the soil, is beneficial to raise N levels. However, most of this N is not readily available to plants (Urquiaga & Zapata, 2000) because it has to be released in absorbable, inorganic forms (NH_4^+ and NO_3^-). In conservation systems, inorganic N may increase over time to higher values than of total soil N. This fact was observed by Purnomo et al. (2000) and Siqueira Neto (2003), who reported higher NH_4^+ levels in no-tillage systems, especially in the 0–2.5 cm layer, caused by the deposition of crop residue on the soil surface.

Due to the N dynamics in soil, the study of inorganic N flux throughout the year based on several annual samplings is important in understanding this process. Such studies provide valuable information for crop nutrition, and contribute to develop strategies of environmental sustainability.

The aim of this study was to evaluate the changes in $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ flux over a 12-month period in the surface layers of a Red Latosol caused by different soil management systems and to correlate these systems with accumulation in these layers.

MATERIALS AND METHODS

The experiment was conducted at the ABC Foundation Experimental Station, in areas where soil management systems (SMSs) had been adopted as of 1988. The experimental station is located in the municipality of Ponta Grossa, Paraná, situated on the second plateau in the central South region of the State (25°20'S and 50º20'W, 980 m asl).

The climate of the experimental area is characterized as humid subtropical type Cfb (Köppen classification) with cool summers and frost in winter. The average annual rainfall and temperature are 1545 mm and 20 °C, respectively (IAPAR, 1994) (Figure 1). The soil is classified as typical Red Latosol (Embrapa, 2006), and is deep, well-structured and drained, with a clayey texture. The soil was derived from reworked sandstone material from the Furnas formation and shale from the Ponta Grossa formation, dating back to the Devonian Period.

In October 2003, soil samples were collected from the soil layers 0–2.5, 2.5–5 and 5–10 cm to determine soil fertility. The samples were air-dried, homogenized and sieved through 2 mm mesh for subsequent analysis. The following parameters were analyzed as previously described by Embrapa (1997): pH; Ca^{2+}, Mg^{2+} and Al^{3+} (extracted with KCl); H + Al, and K^+ and P (extracted using Mehlich-1) (Table 1).

The experimental design included completely randomized blocks split into split plots in three replications. The plots consisted of the following SMSs: 1) conventional tillage (CT), by subsoiling to a depth of 20 cm followed by two disk harrowings; 2) minimum tillage (MT), by a chisel plow reaching a depth of 30 cm followed by disk harrowing; 3) no tillage with chisel plow (NT_{CH}), consisting of direct planting on crop residues left on the soil surface plus chisel plowing to a depth of 30 cm every three years; and 4) continuous no-tillage (CNT), consisting of continuous direct planting on crop residues left on the soil surface. To evaluate the dynamics of inorganic N, the subplots were represented by sampling times (11 samplings, T_1–T_{11}). Each experimental unit had a size of 8.3 x 25 m and the total area 2500 m^2.

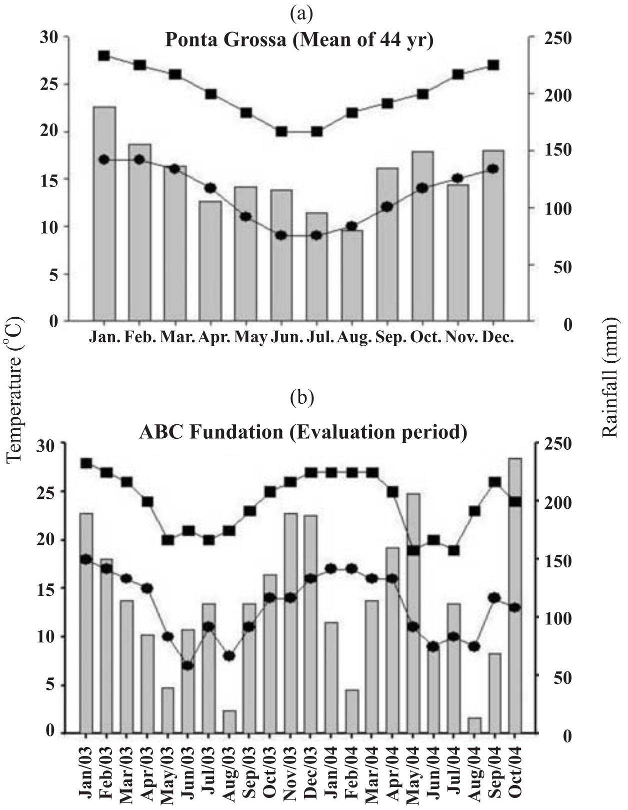

Figure 1. Monthly rainfall distribution (bars) with maximum (■% Tmax) and minimum (●% Tmin) temperatures. Historical data for Ponta Grossa (a) and for the period from January 2003 to October 2004 (b).

Until 1987, the research focus of the experimental station area had been commercial grain production in the conventional tillage system. The initial fertility of the soil was limited, and the soil highly acidic, deficient in exchangeable bases and phosphorus-poor. In the winter of 1988, 4.5 t of dolomitic lime was applied and incorporated by subsoiling and two harrowings prior to the experiment. Black oat was then sown to make the area more homogeneous and form a green cover to implement the SMSs. The history of land use and fertilizer application in the experimental area from 1988 to the 2004 winter growing season are summarized in table 2. To estimate the residue input into the soil by each SMS, the yield of the crops planted during the experiment (soybean in the 2003/2004 and wheat in the 2004 growing seasons) are presented (Table 3).

Table 1. Chemical characterization of soil under different soil management systems (SMSs) before starting the experiment

SMSs(1)	Layer	pH $CaCl_2$	H + Al	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	CEC	P	C	V
	cm		cmol$_c$ dm^{-3}						mg dm^{-3}	g dm^{-3}	%
CNT	0–2.5	5.9	4.8	0.00	5.9	3.1	0.91	14.7	27.2	48.7	66.7
	2.5–5	5.6	6.5	0.07	5.2	2.5	0.55	14.8	17.3	37.3	56.0
	5–10	5.6	6.6	0.07	4.6	2.3	0.40	13.9	20.9	30.0	52.7
NT_{CH}	0–2.5	5.5	5.8	0.00	4.6	2.7	0.80	13.9	14.0	42.3	58.7
	2.5–5	5.3	6.6	0.00	4.6	2.2	0.42	13.8	13.4	39.0	52.7
	5–10	5.2	6.9	0.00	4.2	2.0	0.27	13.3	11.0	35.0	48.7
MT	0–2.5	5.6	5.4	0.00	4.8	2.5	0.74	13.5	9.4	37.0	59.7
	2.5–5	5.5	5.9	0.00	4.8	2.5	0.40	13.5	9.0	33.7	56.7
	5–10	5.4	6.4	0.00	4.7	2.5	0.28	13.8	7.5	27.7	54.0
CT	0–2.5	5.7	5.0	0.00	4.6	2.7	0.80	13.1	8.5	34.3	61.7
	2.5–5	5.6	5.7	0.00	4.4	2.3	0.51	12.9	7.0	33.0	56.3
	5–10	5.4	5.9	0.00	4.2	2.0	0.35	12.5	5.7	31.3	52.0

(1) The following abbreviations are used: CNT, continuous no-tillage; NT_{CH}, no-tillage with chisel plow; MT, minimum tillage; and CT, conventional tillage.

Table 2. Historical sequence of winter and summer crops and use of fertilizers as of 1988

Year	Winter crop	Winter fertilization $N\text{-}P_2O_5\text{–}K_2O$	Summer crop	Summer fertilization $N\text{-}P_2O_5\text{–}K_2O$
		kg ha^{-1}		kg ha^{-1}
1988	Black oat	00–00–00	Soybean	00–60–60
1989	Black oat	00–00–00	Soybean	00–60–60
1990	Lupin	00–00–00	Corn(1)	36–72–48
1991	Black oat	00–00–00	Soybean	00–60–60
1992	Wheat	30–60–60	Soybean	00–60–60
1993	Vetch	00–00–00	Corn	30–90–48
1994	White oat	00–00–00	Soybean	00–60–60
1995	Wheat(2)	30–60–60	Soybean	00–60–60
1996	Vetch	00–00–00	Corn	36–72–48
1997	Black oat	00–00–00	Soybean	00–60–60
1998	Wheat	30–60–60	Soybean	00–40–40
1999	Black oat	00–00–00	Corn	30–60–60
2000	White oat	00–00–00	Soybean	0–40–40
2001	Wheat	30–60–60	Soybean	00–40–40
2002	Black oat	00–00–00	Corn	30–60–60
2003	White oat	00–00–00	Soybean	00–40–40
2004	Wheat	24–90–60	Soybean	00–40–40

(1) The value of N for corn refers to applications of 30 to 36 kg ha^{-1} in the sowing furrow and an application of 90 kg ha^{-1} as side dressing between the stages V4 and V6. (2)For wheat, 90 kg ha^{-1} N was used as side dressing.

Table 3. Grain yield of soybean (2003/2004 season) and wheat (2004 season) in the experimental area under continuous no-tillage (CNT), no tillage with chisel plow (NT_{CH}), minimum tillage (MT) and conventional tillage (CT)

Crop	Season	Soil management systems			
		CNT	NT_{CH}	MT	CT
		kg ha^{-1}			
Soybean	2003/2004	3883	3453	3759	3567
Wheat	2004	5453	5553	5241	4879

The study was initiated on residues of white oat (*Avena sativa*; Variety OR3), which were cut and rolling with a knife roller in October 2003. In the same period, the soil in the CT treatment was turned over using subsoiling followed by two disk harrowings, and in the MT treatment chiseling was applied followed by two disk harrowings. Soil sampling began in the last third of October 2003, before sowing soybean.

Soybean (*Glycine max*) cultivar CD-206 was sown at the beginning of November (11/10/2003). The rows were spaced 0.4 m apart and contained approximately 14 plants per meter. In the planting furrow, 160 kg ha^{-1} of 0–25–25 NPK was applied.

In May 2004, before sowing wheat (*Triticum aestivum*), the soil was prepared for the CT and MT treatments, as described above. Wheat variety CD-105 was sown on June 2, 2004 in rows spaced 0.17 m apart, at a sowing density of 140 kg ha^{-1}. The fertilizer (8-30-20 NPK) was applied in the planting furrow at 300 kg ha^{-1}, and N in the form of urea was used as top dressing at 90 kg ha^{-1} N during the full tillering stage for each experimental area.

The accumulation of C and N was determined after soil preparation (October 2003) and after soybean harvest (May 2004). The soil samples were air-dried, homogenized, loosened to break clumps, passed through a 100 mesh sieve and analyzed for total C and N using the dry combustion method (Nelson & Sommers, 1986). The analyses were performed at the Environmental Biogeochemistry laboratory (CENA-USP) in Piracicaba using a LECO CHN-2000 analyzer. The C and N stocks were computed using the following equation:

$$Stocks = (cont. \times Ds \times th)/10$$

where *Stocks* stands for the stock of C and N in the soil at a given depth (t ha^{-1}); *cont.* the total organic carbon (TOC) or total nitrogen (TN) content (g kg^{-1}); *Ds* the average soil density at the depth considered (t m^{-3}); and *th* denotes the thickness (cm) of the layer considered.

To determine mineral N (NH_4^+ and NO_3^-), 11 soil samples were taken from the layers 0–2.5, 2.5–5 and 5–10 cm from October 2003 (immediately after management of white oat) to September 2004. The samples from the layers 0–2.5 and 2.5–5 cm were collected with a spatula, and three subsamples were collected per plot. The samples were then mixed to obtain a composite sample of each of these two layers per plot. From the 5–10 cm layer, the samples were collected with a stainless steel probe (Bravifer®, Piracicaba-SP), with a diameter of 2.0 cm.

Soil samples for determining soil inorganic N (N-NH_4^+ and N-NO_3^-) were prepared the day they had been sampled, immediately upon arrival in the laboratory. The roots were removed from the soil samples, and the inorganic N concentrations determined in soil extracts obtained by extracting inorganic N in a 2 mol L^{-1} KCl solution for 24 h at a solution/soil ratio of 5:1. These extracts were filtered and preserved in closed vials with phenyl mercury acetate to a final concentration of 0.5 mg L^{-1}, to inhibit nitrification (Piccolo et al., 1994). A soil sample (approximately 5 g) was dried at 105 ºC to constant weight (consecutive daily weighing) to determine the gravimetric moisture content.

The concentrations of N-NH_4^+ and N-NO_3^- were determined by the automatic system for continuous flow injection analysis (FIA), which was coupled to a digital spectrophotometer (Micronal®; model B342), as previously described by Alves et al. (1994). The N-NH_4^+ and N-NO_3^- soil levels were expressed in kg ha^{-1} with correction according to the density of the different layers. In September 2004, a N-NH_4^+ reading was not collected due to human error. Therefore, only the data up to August 2004 for inorganic N and total soil N-NH_4^+ are presented.

The results were subjected to analysis of variance (ANOVA), and depending on the level of significance, the Student's t-test and one-way ANOVA followed by Least Significant Difference Test (LSD) post hoc analysis was used to compare means at the 5 % significance level ($p < 0.05$) to detect the differences between treatments.

RESULTS AND DISCUSSION

Accumulation of total C and N in the soil

By comparing the accumulation of C and N using the average of two samplings (October 2003 and May 2004), a difference was found between the SMSs. The largest stocks were observed in the treatment with the CNT system (Table 4). The differences between the CNT and other SMSs were observed in the 0–2.5 and 2.5–5 cm soil layers, but the greatest differences were found in the surface layer. The greatest contrast in stocks was between the CNT and CT treatments. The CNT treatment accumulated more C and N than the CT treatment. Accumulations of 3.1 and 2.0 t ha^{-1} of C and 0.31 and 0.19 t ha^{-1} of N were found in the 0–2.5 and 2-5.5 cm layers, respectively, with the CNT treatment. The input of organic material and the lower decomposition rate resulted in increases in the accumulation of C and N in the soil, which was consistent with results reported by Sá et al. (2001), Bayer et al. (2004) and Boddey et al. (2010) who concluded that the introduction of the no-tillage system with an increase in crop residues results in an increase in the soil C content.

Between the growing seasons of October 2003 and May 2004, there was an increase in carbon stocks only in the 0–2.5 and 2.5–5 cm layers in the CNT system, which demonstrated that conservation tillage systems induced higher accumulation of C and N than the CT system (Table 4).

The lower C and N accumulation in the CT treatment to a depth of 5 cm can be explained by the influence of the initial soil tillage on decomposition rates, compared to the other managements with less or no tillage. The higher humification coefficient and lower annual rate of organic matter loss in the soil with the NT treatment, which explain the higher accumulation of C and N in the soil in the NT than the CT treatment were also reported by Lovato et al. (2004). This result indicated that the elimination of soil tilling associated with the imput of high quantities of crop residue is an essential practice in the recovery of degraded soils (Sá & Lal, 2009).

Table 4. Carbon and nitrogen accumulation in the soil layers 0–2.5, 2.5–5 and 5–10 cm as related to different soil management practices in Ponta Grossa (PR), in October 2003 and May 2004

Layer	Month	Soil management system⁽¹⁾ CNT	NT_{CH}	MT	CT	Mean
cm		Carbon ($t\ ha^{-1}$)				
0–2.5	Oct/03	9.6Ab ⁽²⁾	8.8 Aa	8.3 ABa	7.1 Ba	8.5a
	May/04	10.9 Aa	9.1 Ba	8.3 BCa	7.2 Ca	8.9a
	Mean	10.2 A	8.9 AB	8.3 BC	7.1 C	
2. 5–5	Oct/03	9.8Ab	9.3 ABa	9.1 Ba	8.2 Ca	9.1b
	May/04	10.5 Aa	9.7 Ba	9.4 Ba	8.0 Ca	9.4a
	Mean	10.1 A	9.5 B	9.2 B	8.1 C	
5–10	Oct/03	15.6 Aa	15.4 Aa	16.8 Aa	15.5 Aa	15.9 a
	May/04	17.8 ABa	16.0 BCa	18.2 Aa	15.7 Ca	17.0 a
	Mean	16.7 A	15.7 A	17.5 A	15.6 A	
		Nitrogen ($t\ ha^{-1}$)				
0–2.5	Oct/03	0.72 Aa	0.61 ABa	0.55 BCa	0.45 Ca	0.58 a
	May/04	0.76 Aa	0.61 ABa	0.51 BCa	0.41 Ca	0.57 a
	Mean	0.74 A	0.61 B	0.53 BC	0.43 C	
2. 5–5	Oct/03	0.67 Aa	0.64 Aa	0.60 Aa	0.52 Ba	0.61 a
	May/04	0.70 Aa	0.61 Ba	0.59 Ba	0.47 Ca	0.59 a
	Mean	0.68 A	0.63 AB	0.59 B	0.49 C	
5–10	Oct/03	0.99 Aa	1.01 Aa	1.09 Aa	0.98 Aa	1.02 a
	May/04	1.08 ABa	1.00 ABa	1.13 Aa	0.94 Ca	1.04 a
	Mean	1.04 A	1.00 A	1.11 A	0.96 A	

⁽¹⁾ CNT: continuous no-tillage; NT_{CH}: no-tillage with chisel plow; MT: minimum tillage; and CT: conventional tillage. ⁽²⁾ The same uppercase letters in rows, which compare soil management systems, and lower case letters in columns, which compare the sampling month, do not differ by the Student's LSD test ($p < 0.1$).

In the 5–10 cm layer, the treatments with SMS did not differ in C and N accumulation (Table 4). Kern & Johnson (1993), Chan et al. (2003) and Bayer et al. (2004) reported similar findings. According to Freixo et al. (2002), this behavior in NT and CT treatments in clayey soils may be explained by the physical protection of organic matter in highly stable microaggregates, which are barely affected by the management.

In the 0–2.5 and 2.5–5 cm soil layers, some conservation tillage systems differed from the CT treatment with higher quantities of C and N in both October 2003 and May 2004 (Table 4). These differences in C and N stocks may be attributed to soil densification because the soil density was increased in the surface layer in the no-tillage systems, as previously reported in the literature (Secco et al., 2005). This effect may have been due to the absence of soil tilling and the establishment of a soil architecture with continuous pores in favor of the physical SOM protection. In this case, the fracturing of aggregates caused by soil tilling is restricted to the planting line, and the exposure of SOM to microbial attack is minimized, which potentially allows for the beneficial effects found with increased soil density in no-tillage systems (Sá et al., 2001).

Concentration of inorganic N

The concentration of inorganic N was higher in the conservation tillage systems (CNT, NT_{CH} and MT) as compared to the CT system in all layers evaluated. However, the differences were only significant for the CNT treatment in the 0–2.5 cm layer. Salinas-Garcia et al. (1997) observed an increase in inorganic N in conservation tillage systems compared to systems with intensive land preparation, which was consistent with the results observed in this study.

During the evaluation period, the inorganic N levels differed across all layers and SMSs. In July 2004, the concentration of inorganic N was highest observed in all layers (Figure 2), which was correlated with fertilizer application in the sowing furrow in June 2004

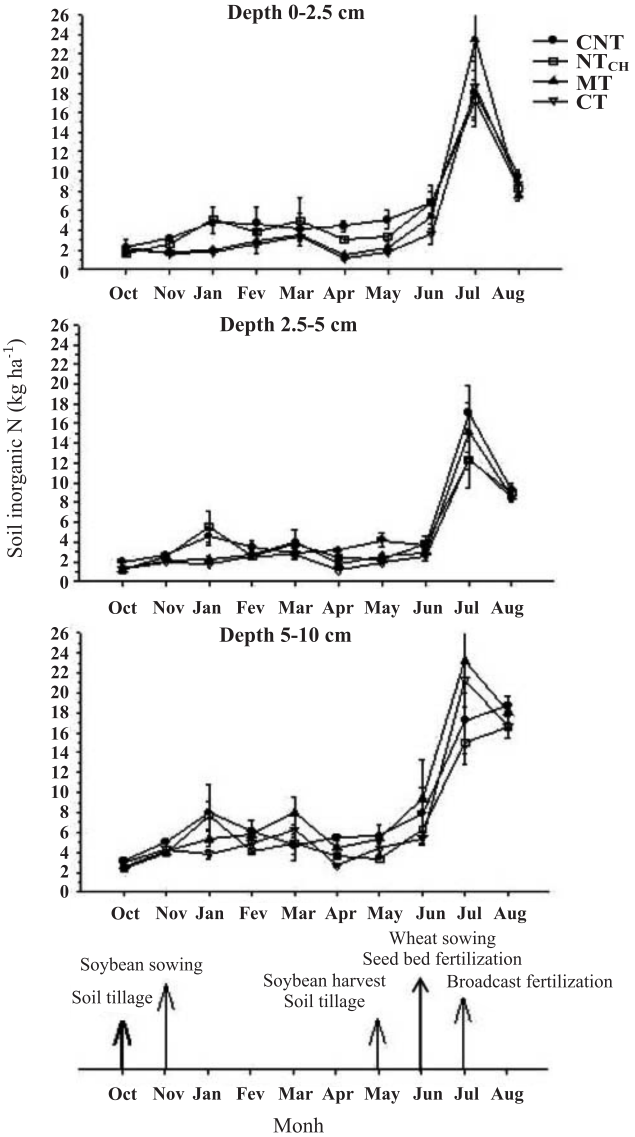

Figure 2. Total inorganic N ($N\text{-}NO_3^- + N\text{-}NH_4^+$) in the 0–2.5, 2.5–5 and 5–10 cm layers under continuous no-tillage (CNT), no-tillage with chisel plow (NT_{CH}), minimum tillage (MT) and conventional tillage (CT) from October 2003 to August 2004. The results represent the mean ± standard error.

and the surface application of 90 kg ha^{-1} of N as urea applied to wheat. Moreover, the soil sampling period conducted nine days after fertilizer application showed that the mineral N was already largely in the form of N-NO_3^-, which was consistent with the high nitrate quantities found in this month (Figure 3). This peak was transient, and the amount of inorganic N significantly decreased one month after N topdressing (August 2004). The reduction in the levels of inorganic N was likely due to the N uptake by wheat in the form of N-NO_3^-, which was observed in the 0–2.5 and 2.5–5 cm layers (Figure 2).

Although not evaluated statistically, the quantities of N-NH_4^+ in the studied layers were generally greater than of N-NO_3^- across all SMSs and all layers from October 2003 to February 2004 (Figure 3). One possible explanation for this result could be that there was a low initial population of nitrogen-fixing bacteria in the soil associated with the addition of white oat crop residues (high C/N ratio) before planting soybean, which may have induced N consumption by the soil microbial biomass. In this case, the nitrification rates decreased, due to the high immobilization and the consequent low supply of N for the nitrification process by the microbial community, as also reported by Robertson & Groffman (2007). This approach was also presented by Heinzmann (1985), who discussed the immobilization of inorganic N in the cellular mass from the microbial biomass and reported lower soil levels of N-NO_3^- in plots with black oat. Moreover, Heinzmann (1985) also reported that the flux of N release into the system is influenced by the presence of crop residues with higher C/N ratios.

In the months from May to July 2004, the quantity of N-NO_3^- tended to be greater than that of N-NH_4^+, compared with the differences in the other months (Figure 3). The increase in inorganic N in the 0–2.5 and 2.5–5 cm layers in all management systems may be associated with the mineralization of soybean plant residues, which increased the N supply for the microbial biomass, thereby accelerating the nitrification process (Robertson & Groffman, 2007). Gonçalves et al. (2000), Amado et al. (2001) and Weber & Mielniczuk (2009) found that the use of legumes in crop rotation increases soil N. This increase may also occur in the mineralization of native soil N, which is an effect known as "priming" (Fried & Broeshart, 1974).

In August 2004, the quantity of N-NH_4^+ was again higher than of N-NO_3^- for all SMSs and in all layers. This behavior in the MT and CT systems may be explained by nitrate absorption by wheat and temporary immobilization of part of the N fertilizer applied in July 2004 by the soil microbial biomass. N release occurred later by mineralization, which raised the N-NH_4^+ level in all management systems in that month (Figure 3).

The N-NO_3^- content in all sampled layers differed significantly among the SMSs. In the 0–2.5 cm layer, the N-NO_3^- content was higher in the CNT and NT_{CH} treatments than the CT treatment (Figure 3). This result indicated that the effects of soil cover on aggregate protection, maintaining soil moisture for a longer period and maintaining the C flux that originated from crop residue decomposition, stimulated

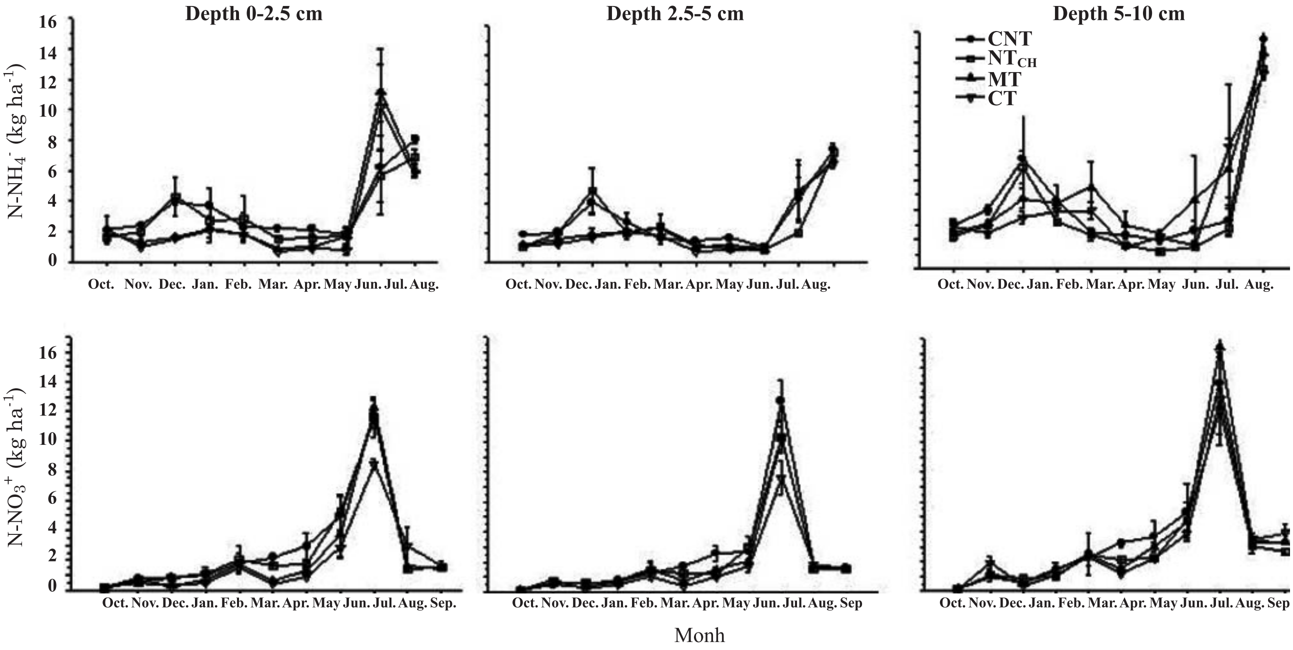

Figure 3. Levels of N-NO_3^- and N-NH_4^+ in the 0–2.5, 2.5–5 and 5–10 cm layers under continuous no-tillage (CNT), no-tillage with chisel plow (NT_{CH}), minimum tillage (MT) and conventional tillage (CT) from October 2003 to August 2004. The results represent the mean ± standard error.

and increased the activity of nitrifying bacteria. Conversely, in the 2.5–5 cm layer, all conservation tillage systems significantly differed from the CT treatment. In addition to the above arguments, the contribution of the root system in this case may have had additional effects in the conservation treatments. There was also a higher $N\text{-}NO_3^-$ content in the CNT treatment in the spring (April and May 2004) despite lower temperatures and less precipitation (Figure 1). In July, a higher $N\text{-}NO_3^-$ content in the 0–2.5 and 2.5–5 cm layers was found in the CNT than the CT treatment (Figure 3).

In January 2004, the $N\text{-}NH_4^+$ content was higher in the 0–2.5 and 2.5–5 cm layers in the CNT and NT_{CH} than the MT and CT treatments. In contrast, in July 2004, the management systems under MT and CT differed from CNT and NT_{CH} with greater quantities of $N\text{-}NH_4^+$ in the 0–2.5 and 5–10 cm layers (Figure 3). This contrasting behavior may have had the following reasons: a) in the summer, rainfall and temperatures were higher (Figure 1), resulting in a higher mineralization rate even in the systems without soil tillage and the maintenance of crop residues on the soil surface; and b) in the winter, there was less rainfall and lower temperatures (Figure 1), which stimulated increased mineralization in the systems in which the residues were mixed with the soil and were in contact with decomposing agents.

In addition, the higher quantity of $N\text{-}NO_3^-$ found in the management systems with minimal or no soil tillage may be attributed to the maintenance and permanence of N in the NT systems, as confirmed by the higher N content found in the CNT than the CT treatment in this study (Table 4). The results reported by Dick et al. (1991) in systems under NT for over 25 years signify that N accumulation in the surface layers is mainly due to the return and maintenance of crop residues on the surface and not the tilling of the soil. In contrast, CT exposes the crop residues to a more intense microbial attack, which accelerates the decomposition of organic material (Souza & Melo, 2000). Similarly, the rapid decomposition of organic matter may explain the higher quantities of ammonium in the MT and CT than the CNT treatment in July 2004.

CONCLUSIONS

1. Compared to the conventional tillage system, the significant increase in total organic C and total N contents in the surface layers under conservation tillage systems was due to the elimination of soil tillage and the consequent maintenance of crop residue on the surface.

2. The processes of inorganic N transformation were closely related to the soil surface layer and the presence of crop residues on the surface.

3. In the surface soil layer, the $N\text{-}NO_3^-$ content was higher in the conservation tillage than the conventional tillage system.

4. The lowest $N\text{-}NO_3^-$ level in systems without soil tillage was observed shortly after the management of white oat (*Avena sativa*).

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