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ORIGINAL ARTICLE

Fertilizer dynamics in different tillage and crop rotation systems in a Vertisol in Central Mexico

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Abstract N-fertilization dynamics and agronomic practices on a Vertisol in central Mexico were evaluated under irrigated conditions: (1) wheat-maize rotation with conventional tillage (CT) and burning of residues (W-M/CT/B, regional control); (2) wheat-beans rotation with CT and incorporation of residues into the soil (W-P/CT/I); (3) wheat-maize rotation with CT and incorporation of residues into the soil (W-M/CT/I); (4) maize-beans rotation bi-annual with CT and incorporation of residues into the soil (M-P/CT/Bi); and (5) wheat-maize, no tillage (NT) and residues left on the soil surface as mulch (W-M/NT/S). ^{15}N and acetylene inhibition techniques were used to estimate N fertilizer efficiency and losses ($N_2 + N_2O$). Treatments received 240, 60, and 300 kg N ha^{-1} for spring maize, beans and winter wheat, as ammonium sulphate enriched with 5.468% atoms ^{15}N excess. In the spring summer cycle, the fertilizer N recovery ranged from 27% for W-M/NT/S to 68% for M-P/CT/Bi. From the total N-fertilizer applied, only 3 to 9% remained in soil after harvest (W-M/NT/S and W-M/CT/I being the respective extremes). Unaccounted N-fertilizer ranged between 27 and 69%, the highest losses corresponding to W-M/NT/S treatment. Fertilizer N recovery in wheat varied from 19 to 37% (W-M/NT/S–W-M/CT/B). N-fertilizer remaining in soil was 14 to 24% (W-M/NT/S – W-M/CT/I). N_2 and N_2O emissions were higher in the no tillage system. Emissions ranged from 3 to 28 kg N ha^{-1} for W-P/CT/I and W-M/NT/S, respectively. The best treatments were those in which residues were incorporated resulting in N immobilization in top soil (0–15 cm), small N gas losses, and higher soil organic matter, these treatments were W-P/CT/I, W-M/CT/I.

Keywords N-balance · Nitrous oxide · Maize · Wheat · Beans

Introduction

Cereals are grown on approximately 5 × 10^5 ha of Vertisols in the “El Bajío” region of central Mexico. Since 1960 the cereal-cereal rotation has been practised, wheat or barley is sown in autumn–winter and maize or sorghum in spring-summer, with a

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constant increase in the rate of nitrogen (N) fertilization: from 120 kg N ha^{-1} in 1960 to 350 kg N ha^{-1} in 2007. Vertisols are usually deficient in N due, generally, to low levels of soil organic matter (SOM); thus, N-fertilizer has to be properly managed in order to avoid losses through volatilization, denitrification and leaching (Siers et al. 2001).

Agricultural practices have caused a drastic reduction in the content of SOM, reducing the sustainability of the system; loss of SOM is linked to increased tillage intensity (Petrie et al. 2006; Pikul et al. 2006). Furthermore, in order to avoid overlap between the autumn–winter and spring-summer cycles, crop residues (3.2×10^6 Mg straw $year^{-1}$) are burned or removed from the soil (Núñez et al. 1963; Grageda-Cabrera et al. 2000). On the order hand, in the "Bajío" region there is a water deficit amounting to 850×10^6 m^3 $year^{-1}$, caused by the extraction of 2.7×10^9 m^3 of water and the recharge of only 1.9×10^9 m^3.

Conservation agriculture under irrigated conditions has great potential to reduce erosion, moisture loss, greenhouse gas emissions and consumption, and increase the sequestration of C and SOM. Conservation agriculture technology is currently being transferred to farmers; however, some questions have emerged over the management of straw, crop rotation, water and fertilizers under local conditions, *i.e.* vertisol soils, irrigation and subtropical climate. Identifying the optimum management practices can help to improve the sustainability of agriculture in the region. Given the economic and ecological importance of N-fertilizer, the objective of this study was to evaluate the influence of crop rotation, residue management and tillage systems on the N-fertilizer dynamics.

Materials and methods

The experimental site was located at Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP), Celaya, Mexico (20°44′ N, 101°19′ W, 1750 m above sea level). The soil is classified as a Typic Pellustert. It has a $pH_{1:2\,H_2O}$ of 6.7, an organic matter content of 2.24% and a clay texture. The region has an average of 610 mm of rain, mainly between June and August, with a mean annual temperature of 19°C (maximum average of 30°C and minimum average of 10°C).

A long-term study was set up in 2002. The data we report here correspond to the wheat (W, *Triticum aestivum* var. Bárcenas), maize (M, *Zea mays* var. A-791), bean (B, *Phaseolus vulgaris* var. Marcela) crops sown in 2007–2008. Five treatments were laid out in a randomized complete block design with four replications. The treatments were: (1) wheat–maize rotation with conventional tillage (CT) and burning of residues (W-M/CT/B, regional control); (2) wheat-beans rotation with CT and incorporation of residues into the soil (W-P/CT/I); (3) wheat-maize rotation with CT and incorporation of residues into the soil (W-M/CT/I); (4) maize-beans rotation bi-annual, 1 year bean and the next maize, fallow in the autumn–winter cycle with CT and incorporation of residues into the soil (M-P/CT/Bi); and (5) wheat-maize rotation, no tillage (NT) and residues left on the soil surface as mulch (W-M/NT/S).

Each treatment consisted of an area of 300 m^2 (10×30 m). Rows were 0.92 m apart for maize and bean, and 0.28 m apart for wheat. All treatments received 240-40-00, 60-40-00, and 300-80-00 kg $N–P_2O_5–K_2O$ ha^{-1} to spring maize, spring beans and winter wheat, respectively. The N source was ammonium sulphate, the N-fertilizer with the highest efficiency obtained in previous studies (Grageda-Cabrera et al. 2004; Vázquez-Navarro and Peña-Cabriales 1987), and the P source was superphosphate triple of calcium. In all treatments, 1.5×1.5 m microplots were delineated within every plot, on which we applied the same rate of N but with ^{15}N-labelled fertilizer as ammonium sulphate labelled with 5.468 atom % ^{15}N excess. The N-fertilizer was equally split at sowing and 40 days later, all of the P-fertilizer was applied at sowing. The farming practices for sowing, fertilization, irrigation, and pest and weed control were performed following the recommendations of the National Research Institute on Livestock and Agriculture (INIFAP).

Determinations of dry matter production and N accumulation were made at harvest. An area of 16 m^2 was harvested for yield estimates. For the fertilizer-N balance study, plant samples were cut at ground level from an area of 1 m × 1 m for N analysis at harvest from the corresponding ^{15}N-labelled microplot. Roots were disregarded. Fresh weights were recorded, plants chopped into 1- to 2-cm pieces, and a subsample of approximately 300 g taken. Subsamples were oven-dried at 70°C and weighed. Plant material was ground to pass a 0.5-mm sieve and analyzed for total N content by the Kjeldahl method. The $^{15}N/^{14}N$ ratios were determined using an NOI-6e emission spectrometer (Faust et al. 1987). Soil samples were taken with a 4-cm diameter auger at five depths: 0 to 15, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm, then air-dried, ground to pass a 2-mm sieve and thoroughly mixed before subsampling. Total N contents were determined by the modified permanganate-reduced iron Kjeldahl method to include NO_3 and NO_2 (Bremner and Mulvaney 1982). Plant and soil recovery of ^{15}N-labelled fertilizer were calculated following the method described by Zapata (1990).

The closed box method and acetylene inhibition techniques on undisturbed soil cores were used to estimate N loss ($N_2 + N_2O$), with and without enzymatic acetylene inhibition (Vermoesen et al. 1993). The gas samples were taken weekly, in triplicate, from each treatment during each crop cycle. The N_2O was analyzed in a Hewlett Packard gas chromatograph with an electronic ^{63}Ni capture detector and a column of stainless steel Porapack-N, 5 m long and 3.175 mm in diameter, with the following temperatures: injector at 120°C, oven at 100°C, and detector at 120°C. The flow rate of carrier gas was 30 mL min^{-1}.

Gas chromatography results, incubation times, and volume and area of the box used for sampling were utilized to determine the amount of emitted N using the general equation of ideal gases (Vermoesen et al. 1993).

The data were statistically analyzed following standard ANOVA procedures and the significance of differences between mean values was determined at $P \leq 0.05$ by the LSD test (SAS Institute 1990).

Calculations were made to estimate the economical significance of the N-fertilizer losses under the different treatments. The cost of kg of N-fertilizer (USD$ 0.92) was used as reference. The results were expressed in USD$ lost per ha.

Results and discussion

Yield

Results for dry matter production are presented in Table 1. In the spring-summer cycle of 2007–2008 there were significant differences ($P \leq 0.05$) between tillage treatments. Although differences in residue management practices were not significant, the highest yields were obtained when residues were incorporated or burned. This was contrary to expectations as N is reported to be immobilized by the C present in the residues (Green et al. 1995). However, it is possible that this immobilized N was gradually released. Yields were similar to those of the regional control (W-M/CT/B). Similar reports have been made by Clapp et al. (2005) and Pikul Jr et al. (2005b).

The tillage system affected grain yield and dry-matter production; the W-M/CT/B and W-M/CT/I treatments resulted in a higher dry matter production than did W-M/NT/S. The yield losses reported in NT systems were associated with deficient crop uptake of N in wet soils (Olk et al. 2006). In beans, M-P/CT/BI resulted in a higher dry matter production than W-P/CT/I.

Total yield of wheat was higher when grown after beans (Table 1). The lowest yield occurred when wheat was sown after maize and NT. The

Table 1 Effect of tillage system and crop rotation on dry matter yield of maize (M), bean (P), and wheat (W), crop cycle 2007–2008

Treatment	Straw (Mg ha^{-1})			Grain (Mg ha^{-1})			Total (Mg ha^{-1})		
	M	P	W	M	P	W	M	P	W
W-M/CT/B	20.7 a[a]		12.7 a	14.6 a		8.6 a	35.3 a		21.3 b
W-P/CT/I		1.8 b	12.8 a		1.8 b	8.8 a		3.6 b	21.9 a
W-M/CT/I	18.6 a		12.2 b	14.4 a		8.7 a	33.1 a		20.9 b
M-P/CT/Bi		2.6 a			2.6 a			5.2 a	
W-M/NT/S	13. 4 b		11.8 c	10.5 b		7.8 b	23.9 b		19. 6 c

[a] Means within a column followed by same letter are not significantly different (LSD test; $P \leq 0.05$)

performance of the wheat was slightly improved when maize residues were incorporated or burned.

The cereal-legume rotations in vertisols have been shown to considerably increase crop yield of subsequent cereals, as well as increasing the efficiency of N-fertilizer uptake (Siers et al. 2001; Wilhelm and Wortmann 2004). Storage of organic C in soil is an important component of soil fertility, but also plays a role as a mechanism to help reduce carbon dioxide concentration in the atmosphere (Franzluebbers 2004; Reicosky 2001).

Total N and N derived from fertilizer (Ndff)

Results of N content in straw and grain are presented in Table 2. Significant differences ($P \leq 0.05$) were observed between treatments. The NT treatments significantly decreased the accumulation of N in the all crops.

There were highly significant differences ($P \leq 0.05$) with respect to Ndff values among tillage treatments (Table 3). The averages for Ndff in maize were 142, 99 and 66 kg Nddf ha^{-1} for W-M/CT/I, W-M/CT/B, and W-M/NT/S, respectively. In beans, a larger Ndff value was observed with M-P/CT/Bi.

Surprisingly, the efficiency of N-fertilizer use in W-M/CT/I was high (59%) compared to W-M/NT/S (27%). Worldwide applied N use efficiency (NUE) is about 33% (Huggins and Pan 2003). The low recovery of the high N rate (240 kg N ha^{-1}) in W-M/NT/S resulted in a residual N amount in the soil of 144 kg N ha^{-1}, constituting an environmental pollution risk.

In beans, a larger Ndff value was observed with M-P/CT/BI, than with W-P/CT/I. Efficiency of N use was greater in the cereal-legume rotation compared with cereal-cereal rotation because less N was applied. Efficient use of N, by using rotations, can

Table 2 Effect of tillage system and crop rotation on N yield of maize (M), bean (P), and wheat (W), crop cycle 2007–2008

Treatment	Straw (kg N ha^{-1})			Grain (kg N ha^{-1})			Tota (kg N ha^{-1})l		
	M	P	W	M	P	W	M	P	W
W-M/CT/B	94.4 a[a]		73.2 a	249.6 a		189.6 c	344.0 a		262.7 b
W-P/CT/I		22.5 b	64.5 b		57.0 b	217.7 a		79.5 b	282.2 a
W-M/CT/I	100.1 a		61.4 b	249.0 a		199.8 b	349.1 a		261.2 b
M-P/CT/Bi		29.6 a			84.8 a			114.4 a	
W-M/NT/S	69.1 b		63.0 b	165.3 b		164.8 d	234.4 b		227.8 c

[a] Means within a column followed by same letter are not significantly different (LSD test; $P \leq 0.05$)

Table 3 Effect of tillage system and crop rotation on the N-fertilizer uptake by maize (M) and bean (P) at final harvest, spring-summer cycle 2007

Treatment	Straw (Ndff[a] (kg ha^{-1}))		Grain (Ndff[a] (kg ha^{-1}))		Total (Ndff[a] (kg ha^{-1}))		Fertilizer N recovery (%)	
	M[b]	P[b]	M	P	M	P	M	P
W-M/CT/B	33.0 b[c]		66.0 b		99.0 b		41.2 b	
W-P/CT/I		7.0 b		16.7 b		23.7 b		39.5 b
W-M/CT/I	43.8 a		98.0 a		141.8 a		59.1 a	
M-P/CT/Bi		12.2 a		28.4 a		40.6 a		67.6 a
W-M/NT/S	21.8 c		44.0 c		65.8 c		27.4 c	

[a] Ndff = N derived from fertilizer

[b] Maize fertilized with 240 kg N ha^{-1} and bean fertilized with 60 kg N ha^{-1} as ammonium sulphate enriched with 5.468 atoms % ^{15}N excess

[c] Means within a column followed by same letter were not significantly different (LSD test; $P \leq 0.05$)

minimize potential contamination (Pikul et al. 2005a; Wilhelm and Wortmann 2004).

The values of Nddf in wheat were lower than those observed in the spring-summer crops (Table 4) and showed significant differences between treatments. The Nddf values varied from 57 to 113 kg N ha^{-1} for W-M/NT/S and W-M/CT/B, respectively. The efficiency levels of the Nddf uptake in W-M/CT/B and W-M/CT/I were the highest, with N-fertilizer recovery efficiency of 36%; whereas in W-M/NT/S it was 19%.

Fertilizer-N balance

Values for Ndff residual in the soil at harvest for the spring-summer cycle are given in Table 5. N-fertilizer load in soil profile (0–120 cm) varied considerably between treatments. Approximately 9% of the

Table 4 Effect of tillage system and crop rotation on the fertilizer-N uptake in wheat at final harvest, autumn–winter cycle, 2007–2008

Treatment	Straw (Ndff[a] (kg ha^{-1}))	Grain (Ndff[a] (kg ha^{-1}))	Total (Ndff[a] (kg ha^{-1}))	Fertilizer N recovery (%)
W-M[b]/CT/B	32.9 a[c]	79.8 ab	112.7 a	36.7
W-P[b]/CT/I	25.7 b	77.9 b	103.7 c	34.6
W-M/CT/I	25.0 b	83.0 a	107.9 b	36.0
M-P/CT/Bi				
W-M/NT/S	16.0 c	41.2 c	57.2 d	19.1

[a] Ndff = N derived from fertilizer

[b] Maize fertilized with 240 kg N ha^{-1} and bean fertilized with 60 kg N ha^{-1} as ammonium sulphate enriched with 5.468 atoms % ^{15}N excess

[c] Means within a column followed by same letter were not significantly different (LSD test; $P \leq 0.05$)

Table 5 Nitrogen derived from fertilizer in the soil profile at final harvest, spring-summer cycle 2007

Soil layer (cm)	Tillage treatment				
	W-M/CT/B (Ndff[a] kg ha^{-1})	W-P/CT/I (Ndff[a] kg ha^{-1})	W-M/CT/I (Ndff[a] kg ha^{-1})	M-P/CT/Bi (Ndff[a] kg ha^{-1})	W-M/NT/S (Ndff[a] kg ha^{-1})
0–15	5.5	1.3	12.2	1.1	2.4
15–30	2.4	1.0	8.7	1.0	2.2
30–60	1.7	0.8	0.8	0.6	1.5
60–90	1.2	0.3	0.2	0.2	1.2
90–120	0.8	0.2	0.1	0.2	0.8
Total (Ndff kg ha^{-1})					
M[b]	11.6 b[c]		22.0 a		8.1 c
P[b]		3.6 a		3.1 a	
Total (%Ndff)					
M	4.8 b		9.2 a		3.4 c
P		5.9 ns[d]		5.2 ns	

[a] Ndff = N derived from fertilizer

[b] Maize fertiized with 240 kg N ha^{-1} and bean fertilized with 60 kg N ha^{-1} as ammonium sulphate enriched with 5.468 atoms % ^{15}N excess

[c] Means within a row followed by same letter are not significantly different (LSD test; $P \leq 0.05$)

[d] No significative at $P \leq 0.05$

N-fertilizer applied to W-M/CT/I were found in the 30 cm topsoil, whereas only 3% remained in the other treatments. When residues were incorporated, a considerable amount of N-fertilizer was immobilized in the upper soil layer, probably due to heterotrophic microorganisms and a high availability of C. This treatment may minimize N loss and improve the SOM content (Clapp et al. 2005; Pikul Jr et al. 2005b). The amounts of N-fertilizer at 30 to 120 cm soil depth were similar for all treatments (approximately 3 kg N ha^{-1}).

Using the amounts of N-fertilizer recovered in the plant and remaining in the soil profile, a total N balance was established for the spring season (Table 6). The N-fertilizer recovered in the plant-soil system ranged between 31 and 73%. Between 27 and 69% of the applied N could not be accounted for and presumably was lost as gaseous forms by

Table 6 Fertilizer-N balance, spring-summer cycle 2007

Treatment	Recovered by the crop		Residual in the soil		Total accounted		Total non-accounted	
	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
W-M/CT/B	28.8	99.0	4.8	11.6	46.1	110.6	53.9	129.4
W-P/CT/I	29.8	23.7	5.9	3.6	45.5	27.3	54.5	32.7
W-M/CT/I	40.6	141.8	9.2	22.0	68.2	163.8	31.8	76.2
M-P/CT/Bi	35.5	40.6	5.2	3.1	72.8	43.7	27.2	16.3
W-M/NT/S	28.1	65.8	3.4	8.1	30.8	73.9	69.2	166.1

Table 7 Nitrogen derived from fertilizer in the soil profile at final harvest, autumn–winter cycle, 2007–2008

Soil layer (cm)	Tillage treatment				
	W-M/CT/B (Ndff[a] kg ha^{-1})	W-P/CT/I (Ndff[a] kg ha^{-1})	W-M/CT/I (Ndff[a] kg ha^{-1})	M-P/CT/Bi (Ndff[a] kg ha^{-1})	W-M/NT/S (Ndff[a] kg ha^{-1})
0–15	17.0	41.8	59.5		25.0
15–30	26.2	14.2	6.0		12.8
30–60	10.5	2.4	3.2		2.7
60–90	3.5	2.8	3.1		1.4
90–120	2.4	0.7	0.8		0.3
Total (Ndff kg ha^{-1})	59.6 bc[b]	61.9 b	72.6 a		42.2 c
Total (%Ndff)	19.9 bc	20.6 b	24.2 a		14.1 c

[a] Ndff = N derived from fertilizer

[b] Means within a row followed by same letter are not significantly different (LSD test; $P \leq 0.05$)

Table 8 Fertilizer-N balance, autumn–winter cycle, 2007–2008

Treatment	Recovered by the crop		Residual in the soil		Total accounted		Total non-accounted	
	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
W-M/CT/B	37.6	112.7	19.9	59.6	57.4	172.3	42.6	127.7
W-P/CT/I	34.6	103.7	20.6	61.9	58.8	176.3	41.2	123.7
W-M/CT/I	36.0	107.9	24.2	72.6	60.2	180.5	39.8	119.5
M-P/CT/Bi								
W-M/NT/S	19.1	57.2	14.1	42.2	33.1	99.4	66.9	200.6

denitrification, nitrification and volatilization; a similar observations has been reported for sugar cane (Isa et al. 2005).

In the autumn–winter season, the fraction of N-fertilizer remaining in the soil profile was higher than that observed in the summer season (Table 7), due probably to the fact, as reported by Liu et al. (2007), that low temperatures reduce the nitrifying and denitrifying activities involved in N-oxides emissions.

There were significant differences among treatments in the autumn–winter season. Approximately 24% of N-fertilizer applied to W-M/CT/I was found in the 30 cm topsoil. The same differences were observed between treatments as those for the spring season. The N-fertilizer recovered in the plant-soil system varied between 33 to 60% for W-M/NT/S and W-M/CT/I, respectively (Table 8).

The small amounts of N-fertilizer in the lower soil layers in both cycles showed that little N loss was due to leaching. Sainju et al. (2006) found that sustainable management practices such as conservation tillage increase SOM and reduce N leaching. In other soils, NO_3^- has been detected below 120 cm depth, when amounts of more than 84 kg N ha^{-1} are applied (Halvorson et al. 2004). Many researchers have shown that water infiltration occurs at a faster rate under NT than CT because of surface cover and development of macropores, as in vertisols, and loss of N could be increased by leaching (Dudal and Eswaran 1988; Waddell and Weil 2006). It was observed here that in treatments where residues were incorporated into the soil, the losses of N from leaching and in gaseous forms were smaller than in the control or where NT was applied.

Emissions of N_2 and N_2O

By integrating the weekly emissions, the total amount of N emitted during each crop cycle was calculated (Table 9). Emission rates varied according to the cycle, tillage system and crop rotation. The addition of N-fertilizer caused a higher emission of N_2 and N_2O, as shown previously in the studies of Grageda-Cabrera et al. 2004; Halvorson et al. 2004; Liu et al. 2005, 2007; and Miller et al. 2008. However Halvorson et al. (2004) did not detect any differences of N_2O fluxes by tillage treatment.

Irregular patterns of N_2 and N_2O production were observed. The highest emissions occurred after the application of N-fertilizer and when soil moisture and temperature were highest; also, the largest molar fraction emitted was N_2O. Changes of season and soil conditions (*e.g.* moisture and temperature) explained the emission patterns of N_2O and NO as well as their emission ratios under different tillage systems and in

Table 9 Total production of N_2 and N_2O in the maize, bean and wheat crop cycle 2007–2008

Treatment	N_2O (kg N ha^{-1} cycle^{-1})	N_2(kg N ha^{-1} cycle^{-1})	Total(kg N ha^{-1} cycle^{-1})	Molar fraction N_2O/$N_2O + N_2$
W-M/CT/B				
Maize	3.6 ± 0.45[a]	17.4 ± 3.98	21.0	0.17
Wheat	6.1 ± 0.75	13.5 ± 0.99	19.6	0.31
W-P/CT/I				
Bean	0.5 ± 0.06	2.5 ± 0.58	3.0	0.17
Wheat	5.7 ± 0.47	9.9 ± 1.00	15.6	0.37
W-M/CT/I				
Maize	2.1 ± 0.42	11.9 ± 3.45	14.0	0.15
Wheat	3.5 ± 0.19	10.2 ± 0.76	13.7	0.26
M-P/CT/Bi				
Maize	4.3 ± 0.68	15.3 ± 4.00	19.6	0.22
Bean				
W-M/NT/S				
Maize	6.0 ± 0.96	22.3 ± 3.84	28.3	0.21
Wheat	9.1 ± 1.10	15.0 ± 1.31	24.1	0.38

different years (Jabro et al. 2006; Liu et al. 2005; van Beek et al. 2009). Highest N_2O emissions were reported when high rates of nitrification and denitrification occurred simultaneously. Above the "optimum water content", denitrification will become the dominant process, resulting in increased N_2O production with increasing soil water content, and as the soil becomes more anaerobic, emissions of N_2 will increase while N_2O emission will decrease (Scheer et al. 2009).

In both cycles, the N emissions ($N_2O + N_2$) were higher in NT than in CT systems. It has been reported that the NT causes long periods of flooding, particularly in vertisol soils due to the great amount of clays; yield losses in these systems may be associated with the deficiency in N uptake (Dudal and Eswaran 1988; Gintin and Eghball 2005; Liu et al. 2007; Olk et al. 2006; Siers et al. 2001). In the present study, the addition of ammonium sulphate generally led to higher N_2O and $N_2 + N_2O$ fluxes from NT and CT soils due to both nitrification and denitrification, as reported by Liu et al. (2007). Also Liu et al. (2005) observed that NT reduced NO emission significantly but did not affect N_2O emissions compared with CT. According to other authors, the N_2O emission is substantially higher in CT systems that in NT systems due to a change in soil physical conditions (Malhi et al. 2006; Reicosky 2001).

In the spring-summer cycle, the N emission ($N_2O + N_2$) varied from 3 to 28 kg N ha^{-1} 154 days^{-1} equivalent a loss of up to 12% of the N-fertilizer applied. The greatest loss of N (28 kg N ha^{-1}) occurred in W-M/NT/S, probably due to the flooding after irrigation in NT.

In the autumn–winter cycle, the N emissions were lower than in the spring-summer cycle, since in this period soil temperature was lower which, combined with slower decomposition of residues, reduced the availability of C. In this case, losses ranged from 14 to 24 kg N ha^{-1} 147 days^{-1} equivalent a loss of up to 8% of the N-fertilizer added. In W-M/NT/S, where ammonium nitrate was used as a source of N, losses amounted to 48 kg N ha^{-1}, accounting for 16% of the N-fertilizer added (Grageda-Cabrera et al. 2004). On the basis of these results, it is clear that proper water management is fundamental in the N cycle of these soils. Agricultural soils are a source of green-house gases (GHG) such as NO and N_2O. The soil management through tillage, fertilization and irrigation can potentially play a very important role in reducing the emission of these gases from soil to the atmosphere (Harrison and Webb 2001; Firestone and Davidson 1989; Martens 2004, Scheer et al. 2009).

Conclusions

Straw incorporation into the soil reduced N-fertilizer losses, and in the long term, may significantly increase the organic-N content in the soil, maintaining high yields and enhancing mineral-N immobilization in surface layers of soil. At the beginning, this system diminished yields but when stabilized, it exceeded all the treatments evaluated. This practice increases in the short term the SOM levels lost from traditional agricultural activities carried out in the region, sequesters organic C, improves the physical–chemical conditions of the soil, and N-fertilizer losses diminish.

The amounts of N-fertilizer normally applied for cereal production may be greatly in excess of crop needs; yet the N-fertilizer is not efficiently used and the residual effect of N has not been evident in these soils. The addition of fertilizers favoured N_2 and N_2O emissions, which amounted up to 12% of the N-fertilizer added.

The efficiency of N use was very low in Vertisol soils under irrigation and NT with cereal-cereal rotation, a practice that has spread among regional farmers, probably as a result of the great amount of surface residues, soil compaction and excess of moisture.

The ecological damage caused by the low assimilation of N-fertilizer, leading to the emission of gases into the atmosphere and to leaching of nitrates, represent important economical losses. Thus in the spring-summer cycle, economic losses amounted to 31, 71, 119 and USD\$153 ha^{-1} for W-P/CT/I, W-M/CT/I, W-M/CT/B and W-M/NT/S, respectively. In the autumn–winter cycle, they reached 111, 118 and USD\$186 ha^{-1} for W-M/CT/I, W-M/CT/B and W-M/NT/S, respectively.

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