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Transformation of Nitrogen Fertilizers in Greenhouse Experiments

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In intensive crop production technologies a high rate of nitrogen fertilizers is applied, which can be transformed into organic compounds very quickly (NÓTÁS et al., 1997). Field crops utilize about 20–80% of the N fertilizer directly (FAUST, 1981; HADARDSON, 1990; DEBRECZENI & SZLOVÁK, 1990). The remainder of the fertilizer N is immobilized either chemically and biologically, or is lost by leaching or denitrification processes and so may cause environmental damages (e.g. soil acidification, nitrate leaching, NO_x emission contributing to the greenhouse effect). The gaseous N losses may reach 20% of the fertilizers applied in ploughed fields (COLBOURN & DOWDELL, 1984). This loss can be higher (47–75%), as it was shown in a three-year period of microplot study with the application of 75–150 kg/ha fertilizer N (HANTING et al., 1990). Nevertheless, the rate of plant N uptake depends on the crop species and even its varieties, the dose and date of fertilization, and the soil moisture content, etc.

The quantity of immobilized nitrogen can make up for 10–25% of the applied fertilizer and can be incorporated in various organic nitrogen compounds of the soil, or may be fixed as ammonium (NH_4^+) in the crystal lattice of clay minerals. Part of the immobilized organic compounds remobilize again during the vegetation period but their significant portion remains in immobilized organic forms in the soil until harvesting. However, in the following years remobilization of fertilizer N can be experienced in long-term experiments. Such after-effect experiments are very important when the real plants' nutrient uptake and the soils' nutrient supplying capacity are to be estimated, as it was done in the present study.

The ^{15}N tracer technique has been used to supply data for dynamics and cumulative values of plant nutrient uptake by the quantitative determination of the ^{15}N-labelled N-source's recovery percent (BREMNER & KEENEY, 1966; HELTAI & FÜLEKY, 1992). In pot experiments the field processes can be

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modelled properly, but the results do not relate to field conditions directly. This was also proven by SMIRNOW (1970) (cit. DEBRECZENI, 1973.), who compared the transformation and recovery of N fertilizers in pot and field experiments. In the first year of this pot experiment 60% of the plant's total N content was found to originate from the fertilizers, while in field conditions this value was only as much as 40–50%.

Present paper reports about a three-year pot experiment as part of an eight-year long model agroecosystem study, in which a complex ecological approach was applied for studying the N flows (soil N, plant N uptake, gaseous N losses). The after-effect of N fertilization was also studied. Two- and three-year N balances were determined at the end of the experiments. Three compartments of cumulative plant N uptake, fertilizer N residue in the soil and gaseous losses were analyzed. The dynamic study of the nitrification and denitrification processes was provided by gas sampling with adequate frequency and the determination of gaseous N losses. The detailed data concerning accumulation of N containing gases were reported by DEBRECZENI (1995).

Materials and Methods

In a three-year period (1993–1995) of a longer greenhouse pot experiment the 1^{st} and 2^{nd} years' after-effect of mineral N fertilization was studied in a cascade system. For the after-effect experiments, all pots – with the exception of controls – were fertilized, and half of the pots were planted in the first year of the 1993–1994–1995 study period, followed by a resowing without further fertilization either in 1994 for the 1^{st}, or in 1995 for the 1^{st} and 2^{nd} years' after-effect studies. So a two year after-effect (set up in 1993) and one year after-effect (set up in 1994.) can be determined.

The brown forest soil with clay illuviation from Keszthely (pH_{KCl} = 7.7, C = 1.1%, NO_3-N = 17.5 mg/kg, NH_4-N = 12 mg/kg, humus = 1.9 %) was filled in plastic pots (40 kg soil/pot). Gas collecting traps of 1.8 dm^3 capacity with silicon pipe outlets were placed at a depth of 20 cm in the soil. The N fertilizers (KNO_3, NH_4Cl) were applied at a rate corresponding to 150 mg N/kg soil (6250 mg N/pot). All experiments were carried out at two soil moisture levels (water holding capacity, WHC = 65% and 80%) with and without sowing maize hybrids (two Volga and two Pioneer 3722/pot) as test plants. The plants were grown until full ripening. The experiment was carried out with four replications. In one of the replications ^{15}N-labelled fertilizer (5 atom% ^{15}N) was applied and the $^{15}N/^{14}N$ isotopic ratio was determined.

The following parameters were determined in each sample:

– For soil atmosphere analysis (N_2, NO_x gaseous losses): gaseous samples were collected 7–11 times in the different experimental years. The gaseous samples were taken with (5 cm^3) syringe in three replications. The composition of the N containing gases (N_2, NO, NO_2, N_2O) was determined by a Carlo Erba type gas chromatograph. From these data the cumulative gaseous N losses were calculated.

– For plant fertilizer N uptake: following the cutting of test plants the different parts (leaves, grain, stalk, shank, tassel, husks) were separated. The plant N uptake was determined separately in the plant parts and the total N uptake was calculated by summarizing these data for a pot (4 plants). The total N content was analyzed by the Kjeldahl-method followed by Parnass-Wagner distillation and titration. The ^{15}N isotopic analysis was performed by the emission spectrometric method using a microwave induced plasma optical emission spectrometer (HELTAI & JÓZSA, 1995; HELTAI et al., 1995). The ^{15}N-concentrations were separately determined for both maize hybrids in the experiment set up in 1993.

– The change of the concentration of mineral N forms (ammonium- and nitrate-N) of the soil was determined by 1 *M* KCl extraction method followed by distillation and titration according to BREMNER & KEENEY (1966). In these extracts the ^{15}N-atom % was also determined.

The nitrogen amounts originating from the fertilizer were calculated in two ways: the ^{15}N-traced recovery and the difference calculation method. This difference method was applied for all three compartments (plant N uptake, soil mineral N, gaseous N losses). The recovery percentage of fertilizer N in the plants and fertilizer N residue in the soil were calculated by the ^{15}N-tracer method. The results of the two methods were also compared.

Results and Conclusions

The distribution of nitrogen within the soil mineral N compartment, the plant N uptake and the gaseous losses in the year the experiment was set up are shown in mg/pot unit in Table 1, while distribution of N in the first- and second year after-effects are presented in Table 2. The two-year (experiment set up in 1994) and the three-year (set up in 1993) balances of gaseous losses and plant N uptake are shown in Table 3.

The soil mineral N content of the planted and N treated pots were several times lower than those of the controls (mainly as a result of the after-effect processes). In planted pots the after-effect differences were not significant between the controls and the treated samples, which is a supposed consequence of the immobilization or the usage of fertilizer N from the soil–plant system through plant N uptake and gaseous N losses. On the contrary, in the unplanted and N treated pots the soil mineral N contents were significantly higher than in the controls. It was also observed that in the unplanted pots – as compared to the planted pots – the soil mineral N contents were obviously higher, due to the absence of any N uptake by plants.

Table 1
The distribution of nitrogen in the year the experiments were set up (mg/pot)

Treat-ment*	Soil mineral N			Gaseous losses			Plant N uptake		
	1993	1994	1995	1993	1994	1995	1993	1994	1995
1.	456	431	274	132	130	125	1171	1975	677
2.	383	515	433	964	970	951	4772	6027	6354
3.	346	377	442	912	877	853	4237	5905	4974
4.	3130	3293	3122	93	131	93	-	-	-
5.	7923	3834	12886	1559	1593	1576	-	-	-
6.	8828	4679	-	1483	1447	1472	-	-	-
7.	291	356	294	122	114	112	1257	2192	821
8.	434	656	395	929	903	941	4772	6135	6283
9.	378	479	400	851	822	824	4265	6877	3749
10.	2715	3960	6477	81	62	77	-	-	-
11.	9384	7358	15814	1489	1423	1475	-	-	-
12.	10926	11180	15673	1435	1368	1420	-	-	-

Treatments: 1–3: with plant, 80% WHC, 4–6: without plant, 80% WHC, 7–9: with plant, 65% WHC, 10–12: without plant, 65% WHC. Fertilizers applied: None (control) Treatment No. 1, 4. 7. 10; KNO_3: 2., 5., 8., 11; NH_4Cl: 3., 6., 9., 12.

Table 2
The distribution of N in the 1st year (experiments set up in 1993 and 1994) and 2nd year (experiment set up in 1993) after-effects (mg/pot)

Treat-ment*	1st year after-effect						2nd year after-effect		
	1993	1994	1993	1994	1993	1994	1993	1993	1993
	Soil mineral N		Gaseous loss		Plant N uptake		Soil N	Gas. loss	Plant uptake
1.	270	423	123	121	976	1305	316	42	1042
2.	273	475	562	519	859	1505	366	135	1217
3.	366	424	449	454	680	1421	382	118	1052
4.	3531	5064	74	68	-	-	13949	48	-
5.	4739	-	882	896	-	-	12939	207	-
6.	6989	-	800	751	-	-	16863	185	-
7.	297	427	122	101	1032	1172	306	35	1014
8.	267	409	481	469	1152	1852	374	117	872
9.	289	376	357	415	823	1503	426	102	715
10.	6692	18268	51	52	-	-	11392	36	-
11.	-	23382	827	687	-	-	-	181	-
12.	12295	24876	766	672	-	-	16637	171	-

Treatments: See Table 1.

The amount of developed N containing gases (calculated in mg N/pot) was significantly higher in all fertilizer treatments than in the control samples. The amount of molecular N_2 gas – as compared to other N containing gas forms –

Table 3
Two-year and three-year nitrogen balances (mg/pot) in the experiment set up in 1994 and 1993, respectively

Treat-ment*	2-year balance		3-year balance		Treat-ment*	2-year balance		3-year balance	
	1994	1994	1993	1993		1994	1994	1993	1993
	Gas. loss	Plant uptake	Gas. loss	Plant uptake		Gas. loss	Plant uptake	Gas. loss	Plant uptake
1.	251	3280	297	3189	7.	215	3364	279	3303
2.	1489	7532	1661	6848	8.	1372	7987	1527	6796
3.	1331	7326	1479	5969	9.	1237	8380	1310	5803
4.	199	-	215	-	10.	114	-	168	-
5.	2489	-	2648	-	11.	2110	-	2497	-
6.	2198	-	2468	-	12.	2040	-	2372	-

Treatment: See Table 1

was the highest in each case, which is related to a more intensive denitrification in case of KNO_3 treatments as compared to NH_4Cl treatments. In the unplanted samples the gaseous loss was significantly higher than in the planted samples.

The plant N uptake was significantly higher in the N fertilizer treatments than in the controls.

The distribution of fertilizer N between the different compartments (soil mineral N, gaseous losses, plant N uptake) calculated on the basis of the difference method (as percentage of applied fertilizer N) is shown in the first year of the experiment (Table 4), and in the after-effects (Table 5). Two- and three-year balances of the plant N uptake are given in Table 6. The recovery of fertilizer N in the plants and fertilizer N residue in the soils, calculated on the basis of the ^{15}N-tracer method, are presented in Tables 7 and 8 for the experiment set in 1993.

Table 4
The distribution of fertilizer N calculated on the basis of the difference method (as % of applied N) in the experiments set up in 1993, 1994 and 1995

Treat-ment	Soil mineral N, %			Gaseous losses, %			Plant N uptake, %		
	1993	1994	1995	1993	1994	1995	1993	1994	1995
2.	-	1	3	13	13	13	57	65	90
3.	-	-	3	12	12	12	49	63	68
5.	76	9	155	23	23	24			
6.	91	22	-	22	21	22			
8.	2	5	2	13	13	13	56	63	87
9.	1	2	2	12	11	11	48	75	47
11.	106	54	149	22	22	22			
12.	131	115	146	22	21	21			

Treatments: See Table 1

Table 5
The distribution of fertilizer N calculated on the basis of the difference method (as % of applied N) in the 1st year (experiments set up in 1993 and 1994) and 2nd year (experiment set up in 1993) after-effects

Treat-ment*	1st year after-effect						2nd year after-effect		
	1993	1994	1993	1994	1993	1994	1993	1993	1993
	Soil mineral N		Gaseous loss		Plant N uptake		Soil N	Gas. loss	Plant uptake
2.	0	1	7	6		3	1	2	3
3.	2	0	5	5		2	1	1	0
5.	19	-	13	13				3	
6.	55	123	12	11			46	4	
8.			6	6	2	11	1	1	
9.			4	5		5	2	1	
11.	-	81	12	11			-	3	
12.	89	105	11	10			84	3	

Treatments: See Table 1

Table 6
Two-year and three-year nitrogen balances (mg/pot) in the experiment set up in 1994 and 1993, respectively

Treat-ment	Two-year N balance (set up in 1994)			Three-year N balance (set up in 1993)		
	Gaseous losses	Plant N uptake	Sum	Gaseous losses	Plant N uptake	Sum
2.	20	68	87	22	60	82
3.	17	64	82	19	49	68
5.	36		36	39		39
6.	32		32	38		38
8.	18	74	92	20	58	78
9.	16	80	96	16	48	64
11.	32		32	38		38
12.	31		31	36		36

Treatments: See Table 1

The portion of fertilizer N remaining in the soil in mineral form was very low in the planted pots. At the end of the first year, these values – calculated on the basis of the ^{15}N-tracer technique – changed and ranged between 0.2–0.8% (as % of the applied N) (Table 7). These values decreased continuously during the after-effect. The results of the difference calculation method showed similar trends (Tables 4 and 5). In the unplanted pots the mineral N amounts in the soil originating from the fertilizer – on the basis of the ^{15}N-tracer technique – ranged between 32% and more than 100% at the end of the first year (Table 7), and were 34–47% in the 1st year after-effect (Table 8). The mineral N residue of fertilizer N in the soil, calculated on the basis of the difference method (Table 4), was significantly higher, probably due to the "priming effect" of the fertilizers, which results in a virtual excess-recovery through the accelerated mobilization of soil organic N (KUDEYAROV, 1989).

Table 7
The distribution of fertilizer N between the different compartments, calculated on the basis of the ^{15}N recoveries in 1993

Treat-ment	Soil mineral N		Plant N uptake				Plant N uptake	
			Volga		Pioneer			
	mg/pot	% *	mg/ 2plants	% **	mg/ 2plants	% **	mg/pot	% ***
2.	24	*0,4*	1796	*57*	1411	*45*	3207	*51*
3.	14	*0,2*	1200	*38*	1305	*42*	2505	*40*
5.	4419	*71*	-	-	-	-	-	-
6.	5423	*87*	-	-	-	-	-	-
8.	48	*0,8*	1996	*64*	986	*32*	2982	*48*
9.	11	*0,2*	1438	*46*	763	*24*	2201	*35*
10.	6721	*108*	-	-	-	-	-	-
11.	2029	*32*	-	-	-	-	-	-

* : the remainder of fertilizer N (as the % of applied N); **: recovery of fertilizer N (as the % of half of the applied N); *** recovery of fertilizer N (as the % of applied N)

Table 8
The remainder of fertilizer N in mineral N form in the after-effects calculated on the basis of the ^{15}N-tracer technique in the experiment set up in 1993

Treat-ment	Soil mineral N				Treat-ment	Soil mineral N			
	1st year		2nd year			1st year		2nd year	
	mg/ pot	%	mg/ pot	%		mg/ pot	%	mg/ pot	%
2.	8	***0,1***	5	***0,1***	8.	9	***0,1***	19	***0,3***
3.	9	***0,1***	15	***0,2***	9.	8	***0,1***	11	***0,2***
5.	-	-	-	-	11.	2148	***34***	-	-
6.	2392	***38***	-	-	12.	2946	***47***	-	-

The cumulative gaseous loss was calculated on the basis of difference method. Results of the 1993–1994–1995 experiments showed similar trends. The quantities of gaseous losses were different in the planted and in the unplanted samples. In the first year of the experiment with plant, the gaseous loss changed between 11–13% (Table 4) and in the after-effects between 1–7% (Table 5), while in the experiment without plant the value doubled to 21–24%

in the first year, and 3–13% in the after-effects. On the basis of the summarized three-year balance, the gaseous loss in the planted and unplanted pots was 16–22% and 36–39%, respectively (Table 6). The gaseous loss was higher in KNO_3 treatments than in NH_4Cl treatments. It was found that the gaseous loss was not influenced significantly by soil moisture, but in most cases higher values were measured at WHC = 80% than at WHC = 65%.

The plant N uptake was found to depend significantly on the fertilizer N form, but it was not influenced significantly by soil moisture. The recovery of fertilizer N in the plants varied between 47–90% of the applied N on the basis of the difference method in the year the experiment was set up (Table 4), but the typical value was not more than 70%. In the 1st and the 2nd year of after-effects these values were very low (0–11%) (Table 5) as a consequence of the usage of the significant amount of fertilizer N from the soil–plant system during the first year. The recovery of fertilizer N in the plants ranged between 48–80% during the two and three years (Table 6). It was observed that the maize hybrids (Volga and Pioneer 3732) utilized nitrate-N (56–90%) better than ammonium-N (47–75%). The recovery of fertilizer N in the plants was determined – in addition to the difference method – by the ^{15}N-tracer technique as well, in the experiment set up in 1993. The amount of plant N uptake – on the basis of the difference method – was slightly higher (by 6–13%) (Table 4) than that obtained by the ^{15}N-tracer method (35–51%) (Table 7). The results obtained by both methods show agreement in the following: the maize hybrids together utilized more from the KNO_3-fertilizer, and the plant N uptake was higher at higher soil moisture (WHC = 80%) in both fertilizer treatments. The Volga hybrid utilized more fertilizer N at WHC = 65%, while the Pioneer at WHC = 80%. It can also be concluded that the N uptake is affected by the variety of the plants, as N uptake was higher in case of the Volga hybrid than in the Pioneer. Considering the values of plant N uptake and gaseous loss it can also be concluded that 20–40% of the applied N remains in the soil at the end of the first year. These values changed between 10–20% in the 1st year after-effect and between 5–15% in the 2nd year after-effect.

Summary

The primary (1st year) and the after-effects (2nd, 3rd year) of N fertilizers (KNO_3, NH_4Cl) on the soil–plant–atmosphere system were studied in a three-year greenhouse pot experiment with and without maize plants. The two- and three-year balances of the fertilizer N uptake and gaseous N losses were also analyzed. The cumulative values of the gaseous losses showed a similar trend in all years, significant differences were not obtained. On the basis of the three-year balance, the gaseous loss in the planted and unplanted pots was 18–22% and about 37–39%, respectively. Consequently, there was a 50% decrease in denitrificated gaseous losses of fertilizer N due to plant N uptake. The cumulative gaseous loss, calculated by the difference method, was significantly higher in cases of KNO_3 applications than in NH_4Cl treatments, as an assumed consequence of the intensive denitrification. It was found that the gaseous loss was not influenced by soil moisture.

In contrast to the gaseous losses, the values of plant N uptake and soil mineral N content showed significant differences in the years studied, as a result of the quick transformation of mineral N to organic N, the non-complete homogenization of the total soil amount, the seasonal climatic differences in the greenhouse during the years studied, and consequently the different microbiological activity.

The plant N uptake was found to depend significantly on the fertilizer N form. Results obtained by the difference method and the ^{15}N-tracer technique were very similar. In the case of KNO_3 treatment and higher soil moisture (WHC = 80%) plant N uptake was more intensive, ranging between 48–57% (calculated by the difference method), and 35–51% (calculated by the ^{15}N-tracer method) in the first year (1993). It can be concluded that 60–100% of the fertilizer N was used from the soil by plant uptake and gaseous losses, which depends mainly on the treatments and the soil moisture during the first year. These values changed between 7–17% in the 1st year after-effect and between 1–5% in the 2nd year after-effect.

Key words: soil mineral N, gaseous N losses, plant N uptake, N balances, ^{15}N tracer technique

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