Fate of Labeled Nitrogen Fertilizer Applied to Winter Wheat for Five Years[1]

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ABSTRACT

To assess the effect of time and rate of fertilizer N applications on fate of the applied N, a 5-yr field experiment was conducted with winter wheat (*Triticum aestivum* L.). Microplots confined in metal frames to a depth of 1.42 m received annual applications of $(NH_4)_2SO_4$ containing 7.65 atom % ^{15}N. Treatments, replicated four times, consisted of 50 and 100 kg N/ha applied in fall and spring on a Pachic Argiustoll soil. In four of the years, spring applications gave better fertilizer use efficiency than fall treatments, probably because of greater immobilization of fall-applied N. After 5 yr, 27 to 33% of the applied fertilizer N had been removed by the grain. Soil N use was increased by fertilizer in some years and in those cases was correlated highly with increased growth, suggesting that the cause was larger root systems rather than a priming effect. Amounts of fertilizer N in the 1.8-m soil profiles increased each year and at the end of the experiment averaged 54% of that applied during the 5 yr for 50-kg treatments and 47% for 100-kg treatment. From 71 to 77% of the surface-applied fertilizer N remaining in the profiles was in the 0- to 0.1-m soil layers. Most of the residual fertilizer N was immobilized in organic forms, but late applications and dry conditions in 1980 greatly reduced both nitrification and immobilization. There was good agreement between ^{15}N and difference measurements of crop removal of fertilizer N for the 5-year period, although difference measurements were more variable and did not agree well with ^{15}N measurements in individual years.

Additional Index Words: **immobilization, nitrification, N-balance, denitrification, ^{15}N.**

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FROM the standpoint of economics, conservation of energy, and environmental quality, it is important to maximize crop utilization of applied fertilizer N. That which is not utilized by the crop may be stored in the soil in organic or inorganic forms, or may be lost from the system. The use of ^{15}N-labeled fertilizer makes it possible to follow crop uptake and soil accumulation of fertilizer N, to estimate losses, and to determine how those fates are affected by fertilizer practices.

Relatively few field experiments have been conducted with wheat (*Triticum aestivum* L.) using labeled N fertilizer to assess the effects of time and rate of fertilizer applications on fate of the N. Myers and Paul (1971) found the same percentage plant uptake and total recovery of N for two N rates when two crops of spring wheat were grown. Campbell and Paul (1978) found a lower percentage crop utilization of labeled N with the two highest (125 and 164 kg N/ha) rates but no difference among four lower rates in a 1-yr experiment. Also in 1-yr experiments, Jones et al. (1981) found increasing percentage crop uptake of fertilizer N with three increasing rates on spring wheat, while Olson et al. (1979) observed equal utilization of two rates with winter wheat.

Continued fertilizer applications may give results that differ from those of single-year treatments, and allow for more than one set of environmental conditions. For that reason, an experiment was conducted to determine the effects of annual applications of fertilizer N at two times and two rates during a 5-yr period on the fate of the labeled N.

MATERIALS AND METHODS

A field experiment established near Manhattan, KS in the fall of 1975 and described previously (Olson et al., 1979) was continued with annual fertilizer applications for five crop seasons. The soil was Reading silt loam (Typic Agriudolls) containing 1.4 g total N/kg and a pH of 5.9 in the surface 0.1 m. Those values changed with depth to 0.7 g N/kg and pH 7.8 at 1.8 m. Microplots were separated from adjacent soil by pushing open-ended metal boxes 0.534 by 0.47 by 1.52 m into the soil to a depth of 1.42 m. Microplot treatments, each replicated four times, consisted of applications of $(NH_4)_2SO_4$ solution containing 7.65 atom % ^{15}N at rates of 50 and 100 kg N/ha in both fall and spring. Fall applications were mixed into the surface 0.1 m of soil just before wheat planting in early October. Spring applications were topdressed on the microplots, usually in early March. In 1980, rains in March and early April delayed spring treatments until 9 April. 'Centurk' winter wheat was planted in 0.178-m rows for the first three crops and 'Newton' was used for the 1979 and 1980 crops.

Plant tops and large roots within a radius of about 0.1 m from the crown were removed from microplots each year at maturity in late June or early July and dried at 65°C. Grain was separated from remaining plant parts which were returned to microplots after sampling. Soil samples were taken after crop harvest each year to a depth of 1.8 m. Composite samples consisting of 7 to 15 0.025-m cores from 0- to 0.1-m layers and 3 to 5 cores from other layers were taken from each microplot each year. Core holes below 0.1 m were filled with PVC pipe capped with rubber stoppers to prevent mixing of surface and subsoil layers. Soil samples were dried at 50°C and ground to pass a 0.149-mm screen.

Plant and soil samples were analyzed for total N by a micro-Kjeldahl procedure modified to include NO_2^- and NO_3^- with $KMnO_4$ and reduced Fe (Bremner, 1965; Bremner and Edwards, 1965). Extractable inorganic N from soil samples was determined in KCl extracts as described by Bremner and Keeney (1966). Titrated samples were acidified and evaporated to a small volume for analyses of isotope ratios using a CEC Model 21–621 mass spectrometer.

RESULTS AND DISCUSSION

Crop Utilization of Fertilizer Nitrogen

There was a significant grain yield increase from N in 4 of the 5 yr. Applications of 100 kg N/ha yielded significantly more than 50 kg in 3 of the years with fall treatments and in 1 yr with spring treatments. Yields of treated plots were in the range of 2 to 4 Mg/ha. Differences between fall and spring were significant only in 1980 when delayed applications of N in spring resulted in lower grain yields.

Table 1 shows yearly uptake of fertilizer N by plant tops and large roots. Except for the spring of 1980, uptake for the 100-kg treatments was more than 2× that for 50 kg applied at the same time, averaging

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Table 1—Yearly plant uptake of fertilizer N.

Year	Plant uptake of fertilizer N for indicated treatment			
	50 kg N/ha		100 kg N/ha	
	Fall	Spring	Fall	Spring
	kg N/ha			
1976	22 c*	23 c	48 b	57 a
1977	12 d	19 c	35 b	44 a
1978	22 d	27 c	51 b	59 a
1979	23 c	24 c	51 b	57 a
1980	16 b	10 c	35 a	18 b

* Means on the same line followed by the same letter do not differ significantly (Duncan's multiple range test, 0.05).

Table 2—Yearly plant uptake of soil N.

Year	Soil N uptake for indicated treatment				
	50 kg N/ha		100 kg N/ha		
	Fall	Spring	Fall	Spring	No N
	kg N/ha				
1976	78 ab*	64 b	80 ab	72 ab	87 a
1977	73 a	79 a	82 a	78 a	44 b
1978	58 ab	63 ab	69 a	54 ab	47 b
1979	69 a	61 a	71 a	70 a	64 a
1980	45 ab	39 b	50 a	37 b	51 a

* Means on the same line followed by the same letter do not differ significantly (Duncan's multiple range test, 0.05).

2.3× as much for all treatments. That would indicate the existence of a sink for inorganic N in the soil, probably immobilization capacity, that must be filled before inorganic N becomes available for plant use.

During the first 4 yr of the experiment, spring applications resulted in greater fertilizer N uptake than fall applications, probably because the long period prior to rapid spring growth permitted immobilization of N to take place with fall applications. In 1980, the reverse was true: uptake was significantly greater for fall treatments. Spring applications were made too late that year to obtain full utilization of the fertilizer N.

After the first year, plant uptake values (Table 1) reflect effects of both yearly applications of labeled fertilizer and fertilizer N remaining in the soil from previous years. Uptake varied from year to year reflecting seasonal growth differences, but there was no upward trend in amounts recovered. Evidently, contributions from residual fertilizer N and that in crop residues were small.

Labeling the fertilizer permitted calculation of amounts of soil N utilized by crops. Values are shown in Table 2. Effects of treatments on utilization of soil N varied from year to year. There was little or no effect in 1976, 1978, and 1979. In 1980, spring treatments resulted in lowered soil N uptake, while in 1977 all treatments caused soil N uptake increases. Some investigators (Jansson and Persson, 1982) have suggested that increases in soil N uptake with N fertilization may be due to a priming effect, in which stimulation of microbial growth results in increased net mineralization of soil N. In this experiment, increases in soil N uptake appeared to be related to increases in plant growth, which might result in increased soil N uptake because of larger root systems. In 1977, when all treated plots had significantly more soil N uptake than untreated plots, the correlation between grain yield and soil N uptake gave a r value of 0.94. In 1978, the 100-kg fall application gave significantly higher soil N uptake than no N, and was the highest yielding treatment. The correlation coefficient between yield and soil N uptake in 1978 was 0.62. In 1980, when soil N uptake was reduced by spring treatments, yield and total N uptake of spring treatments did not differ significantly from untreated plots. Evidently the late spring applications failed to increase growth but caused substitution of some fertilizer N for soil N in the plant.

The difference between N removal by fertilized and unfertilized plots frequently is used as a measure of fertilizer N removal. With this experiment, values calculated by difference for individual years varied considerably, even giving negative values for some replications some years. Total values for the 5-yr period, however, showed remarkably good agreement between difference values and values measured by crop content of labeled fertilizer (Table 3). The difference method resulted in much greater variability as shown by the high SD values.

Table 3—Comparison of ^{15}N and difference methods for measuring crop removal of fertilizer N during 5 yr.

Treatment	Fertilizer N removed by crops, kg/ha	
	^{15}N method	Difference method
50 kg, fall	71 ± 3*	86 ± 11
50 kg, spring	79 ± 5	80 ± 30
100 kg, fall	161 ± 9	175 ± 40
100 kg, spring	170 ± 8	165 ± 20

* Mean ± SD.

Fertilizer N Remaining in the Soil

Measurements of amounts of total N from fertilizer in soil profiles to a depth of 1.8 m were made following crop maturity each year for each treatment. Results are shown in Table 4. After the first year about half the applied N remained in the soil profile. At harvest time in 1980, 50-kg treatments had an average of 136 kg N/ha, 54% of that applied during the 5 years, while 100-kg treatments averaged 234 kg, 47% of that applied. Amounts of total N from fertilizer in soil layers at the end of the experiment in 1980 are shown in Table 5. Most of the fertilizer N was in the 0- to 0.1-m layer. The residual fertilizer N in that layer averaged 71% of that in the profile for 50-kg treatments and 77% for 100-kg treatments. Amounts became less with depth, until only small concentrations of fertilizer N were found at the deepest depths where amounts shown are for layers 0.3 m thick.

Most of the residual fertilizer N was immobilized in organic forms. Table 6 shows amounts of fertilizer N in 0- to 0.1-m layers as NH_4^+ and NO_3^- in 1979 and

Table 4—Yearly amounts of total N from fertilizer found in 1.8-m soil profiles.

Year	Fertilizer N in soil profile, kg/ha			
	50 kg N/ha		100 kg N/ha	
	Fall	Spring	Fall	Spring
1976	18 ± 2*	17 ± 2	29 ± 1	23 ± 3
1977	55 ± 5	55 ± 10	92 ± 17	99 ± 11
1978	87 ± 10	74 ± 14	128 ± 15	112 ± 8
1979	117 ± 10	101 ± 7	187 ± 14	153 ± 12
1980	139 ± 10	132 ± 8	227 ± 24	240 ± 25

* Mean ± SD.

Table 5—Total N from fertilizer found in soil layers after 5 yr of treatment.

Soil layer, m	Fertilizer N found, kg/ha			
	50 kg N/ha		100 kg N/ha	
	Fall	Spring	Fall	Spring
0 -0.1	94.7 ± 1.6*	98.0 ± 4.8	169.4 ± 24.7	191.4 ± 20.7
0.1-0.2	8.8 ± 4.4	4.6 ± 1.3	10.6 ± 2.9	8.5 ± 4.1
0.2-0.3	4.1 ± 1.5	2.6 ± 1.0	7.3 ± 2.9	4.3 ± 0.4
0.3-0.5	5.5 ± 1.6	3.1 ± 1.0	7.3 ± 1.0	5.4 ± 2.2
0.5-0.7	5.0 ± 1.2	3.3 ± 1.3	4.6 ± 1.0	4.8 ± 2.2
0.7-0.9	3.9 ± 0.8	3.5 ± 1.5	4.7 ± 2.7	6.3 ± 2.1
0.9-1.2	5.0 ± 3.7	7.4 ± 0.8	7.0 ± 3.6	6.3 ± 1.2
1.2-1.5	5.6 ± 0.9	3.1 ± 2.0	7.5 ± 2.1	6.9 ± 2.6
1.5-1.8	6.1 ± 2.1	6.3 ± 3.0	9.1 ± 2.2	5.8 ± 1.3

* Mean ± SD.

1980 and percent in organic forms for those years. Values for 1979 are typical of those for earlier years. That year over 97% of the residual fertilizer N in the surface layer was organic for all treatments. In 1980, spring applications were made in late spring and were followed by abnormally dry conditions, resulting in large amounts of residual inorganic N with spring treatments. That reduced the percent as organic with spring treatments to 82 where 50 kg were applied and 76 where 100 kg were applied.

Amounts of inorganic N in the soil derived from fertilizer were always greater when 100 kg N were applied than when 50 kg N were applied. In 1979, fall applications at the 100-kg rate resulted in significantly more NH_4^+-N than spring applications, but application times did not affect NO_3^- contents. In 1980, spring applications resulted in significantly larger amounts of both forms of inorganic N at both rates. Amounts of fertilizer N in the NH_4^+ form were considerably greater than amounts as NO_3^- with the spring applications. Rainfall between time of spring fertilizer application and harvest in 1980 was 0.183 m less than normal. The dry conditions, together with the delayed time of application, interfered with normal movement of fertilizer N into the soil and its nitrification and immobilization.

Table 7 shows percentages of total N, NH_4^+-N, and NO_3^--N derived from fertilizer in the 0- to 0.1-m layer of soil in 1976, 1979, and 1980. For each form of N, the portion derived from fertilizer increased with time in all treatments. Residual fertilizer N evidently was incorporated into the same chemical forms as indigenous soil N. Percentages derived from fertilizer were

Table 7—Percentages of total N, NH_4^+-N, and NO_3^--N derived from fertilizer in 0- to 0.1-m layers of fertilized soils.

From of N	Year	% of given form of N in soil from fertilizer			
		50 kg N/ha		100 kg N/ha	
		Fall	Spring	Fall	Spring
Total	1976	0.9 bc*	0.7 c	1.4 a	1.0 b
	1979	4.6 c	3.8 d	7.5 a	5.7 b
	1980	5.5 b	5.5 b	9.3 a	10.1 a
NH_4^+	1976	3.5 c	3.0 d	5.7 a	5.2 b
	1979	11.5 bc	8.8 c	17.3 a	13.3 b
	1980	15.6 d	50.1 b	31.1 c	72.3 a
NO_3	1976	4.1 c	3.6 c	6.8 b	7.9 a
	1979	13.7 b	14.1 b	20.6 a	25.0 a
	1980	20.7 d	56.2 b	34.6 c	65.3 a

* Means on the same line followed by the same letter do not differ significantly (Duncan's multiple range test, 0.05).

Table 6—Inorganic and organic fertilizer N in 0- to 0.1-m soil layers in 1979 and 1980.

Treatment	Fertilizer N in indicated form				Fertilizer N in organic forms	
	1979		1980			
	NH_4^+	NO_3^-	NH_4^+	NO_3^-	1979	1980
	kg N/ha				%	
50 kg, fall	1.01 c*	0.72 b	1.21 c	1.56 c	97.7 a	97.1 a
50 kg, spring	0.78 c	0.71 b	10.59 b	6.44 b	97.7 a	82.6 b
100 kg, fall	2.01 a	1.69 a	4.44 c	3.34 c	97.2 a	95.3 a
100 kg, spring	1.38 b	1.42 a	34.56 a	10.79 a	97.3 a	76.3 c

* Means in the same column followed by the same letter do not differ significantly (Duncan's multiple range test, 0.05).

always significantly greater for 100-kg treatments than for comparable 50-kg treatments. With total N and NH_4^+-N, fall applications caused higher values than spring applications except in 1980 when utilization of spring-applied N was poor. In 1980, spring applications resulted in greatly increased proportions of NH_4^+ and NO_3^- of fertilizer origin (50 and 56% for 50 kg N/ha; 65 and 72% for 100 kg N/ha). The percent N derived from fertilizer was always larger for inorganic forms than for total N, showing that fertilizer N had not yet been immobilized to the same extent as indigenous soil N, even though as much as 97.7% had been converted to organic forms (Table 6).

Nitrogen Balance

Each year, the amounts of labeled fertilizer N used by the crop, remaining in the soil, and lost from the system were calculated. Fig. 1 shows results for 50-kg fall treatments. Values for fertilizer N in the soil profile and removal by straw and large roots are those found each year, whereas those for removal by grain and loss are cumulative. Straw and large roots were returned to the plots each year.

While some losses occurred, most of the fertilizer N not removed by the crop remained in the soil profile, which was the largest sink for fertilizer N. Amounts lost were determined by difference and included accumulated errors of sampling, sample preparation, and analyses. When six 0.1-kg samples of soil were treated with the labeled fertilizer solution, dried, and analyzed, recovery of fertilizer N was 98.8 ± 1.1%. It is believed that most of the observed loss, therefore, was due to gaseous loss and leaching.

Figure 2 shows the yearly disposition of fertilizer N

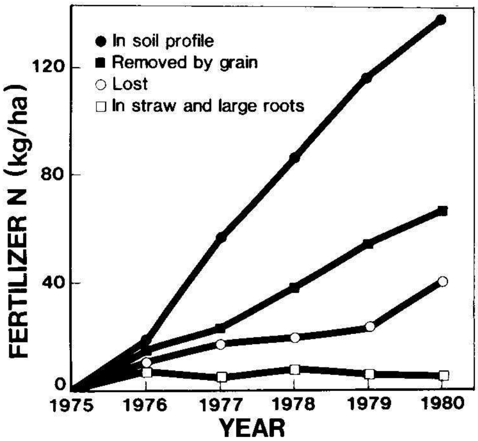

Fig. 1—Disposition of fertilizer N with 50 kg N/ha applied in fall. Values for removal by grain and loss are cumulative.

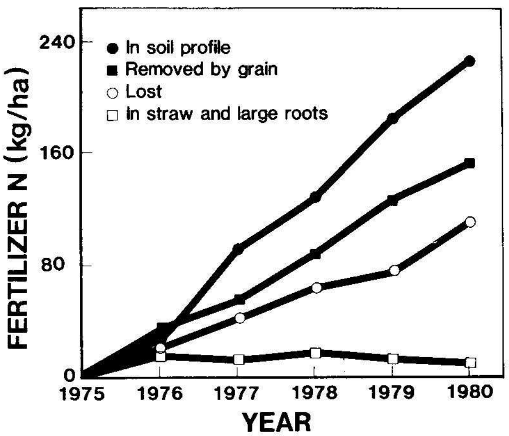

Fig. 2—Disposition of fertilizer N with 100 kg N/ha applied in fall. Values for removal by grain and loss are cumulative.

for 100 kg/ha fall treatments. Values for all parameters with 100 kg/ha applications were approximately double those with 50-kg/ha rates. That emphasizes the importance of using no more N fertilizer than is required for most economic returns, since only a portion of the excess fertilizer is stored in the soil and that is largely in organic forms which become available only slowly.

Table 8 gives the N balance for the 5-yr period of the experiment. Of 250 kg fertilizer N/ha applied during the 5 yr with the 50-kg rate, 66.8 kg (26.7% of that applied) were removed in the grain with the fall treatment and 76.2 kg (30.5%) with the spring treatment. With 500 kg/ha applied during 5 yr with the 100-kg rate, 151.9 kg (30.4% of that applied) were in the grain for the fall application and 165.8 (32.2%) for spring. In each case, spring applications gave a significantly higher fertilizer use efficiency than fall treatments. That was true even though late applications and dry conditions severely reduced fertilizer N uptake from spring treatments in 1980 (Table 1). Amounts of fertilizer N found in the soil and lost did not differ significantly with fall and spring applications. Losses averaged 15.6% of N applied for 50-kg treatments and 20.2% for 100-kg treatments.

CONCLUSIONS

It is noteworthy that about half the fertilizer N applied during the 5 years of this experiment remained in the soil profile and most of that was in the 0- to 0.1-m soil layer. In field experiments conducted by other workers utilizing labeled N, amounts found in the soil after cropping have varied widely (Legg and Meisinger, 1982). Factors contributing to the results in this experiment probably include use of moderate rates and the NH_4^+ form of N, applications to the soil surface, a silt loam soil texture, and moderate rainfall. Most of the fertilizer N not used by the crop was immobilized in the surface layer. That prevented excessive downward movement in the profile and limited N losses. Immobilization was also a major cause of the low fertilizer use efficiency. Continued accumulations of fertilizer N in surface layers over extended periods of time should result in improved soil fertility and somewhat lower fertilizer N requirements in future years, if erosion of surface soil is prevented.

Table 8—Nitrogen balance after 5 yr of annual fertilizer N applications.

	Kg fertilizer N/ha for indicated treatment			
	50 kg N/ha		100 kg N/ha	
Fate of fertilizer N	Fall	Spring	Fall	Spring
Removed by grain	66.8 d*	76.2 c	151.9 b	165.8 a
Present in straw and large roots†	4.3 b	3.0 b	9.1 a	4.2 b
Present in total soil N	138.8 b	131.8 b	227.4 a	239.5 a
Total recovered	209.9	211.0	388.4	409.5
Lost	40.1 b	39.0 b	111.6 a	90.5 a

* Means on the same line followed by the same letter do not differ significantly (Duncan's multiple range test, 0.05).
† 1980 only; returned to plots other years.

Spring applications of fertilizer resulted in more efficient fertilizer use in four of the five years of the experiment. The possibility exists, however, that weather conditions may interfere with spring applications, as they did in 1980, resulting in very low fertilizer use efficiency.

Losses of fertilizer N from the system probably were caused by both leaching and denitrification. Only small quantities of fertilizer N were found in the deeper layers at the end of the experiment, indicating that leaching was not a major factor. Soluble nitrates, however, may have leached out of the profile during periods of low evapotranspiration and high precipitation. Some leaching of fertilizer N from fall applications occurred in 1980 in another experiment nearby (Olson, 1982).

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