# Fate of Fertilizer Nitrogen Applied to a Northern Great Plains Rangeland Ecosystem[1]

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## Highlight

**A field study was conducted at Mandan, North Dakota to provide information on the fate of fertilizer nitrogen (N) in a Northern Great Plains rangeland ecosystem. Mixed prairie grasses were fertilized with up to 540 kg N/ha applied (a) all in one year, (b) divided equally among 3 years, or (c) divided equally among 6 years. Up to 200 kg fertilizer N/ha was immobilized the first year in grass roots, soil organic matter, and fixed ammonium combined, plus gaseous losses (no leaching occurred). Immobilization and losses increased to about 350 kg fertilizer N/ha after 3 to 4 years, and remained rather constant thereafter. About half the immobilized N was found in the grass roots at the termination of the experiment. Collectively these results indicate that addition of high N rates to grasslands results in saturating the capacity of the soil-plant system to immobilize N. The system can then be maintained in an N-saturated condition if annual fertilizer additions plus mineralization equals immobilization plus irreversible losses. Thus, N can be eliminated as a growth-limiting factor, providing maximum grass production from the available water supply.**

Operation of the nitrogen (N) cycle in grassland soils is poorly understood (Harmsen and Kolenbrander, 1965; Harmsen and van Schreven, 1955). Under the natural environment, the quantity of N circulating annually through this cycle in temperate grasslands is too small to measure accurately with the research tools available. In addition, earlier investigators found that mineral forms of soil N ($NH_4^+$ and $No_3^-$-N primarily) failed to accumulate or rapidly disappeared from grassland soils compared to cultivated soils (Harmsen and van Schreven, 1955; Richardson, 1938). As a result, few acceptable theories on the operation of the N cycle in grassland soils have been promulgated. Consequently, the development of principles for N management in grasslands has been limited.

Many of the problems encountered in studying the N-cycle in grasslands could be overcome by utilizing the $^{15}N$ isotope. However, this procedure is not only very expensive, particularly for equipment and technically trained manpower, but is poorly suited for routine use in field experiments—only a very limited number of environments or conditions can be investigated. By applying ample fertilizer N to grasslands however, the amount of N circulating through the cycle annually is raised from just a few to 100 kg N/ha or more. The amount of N immobilized in many components of the N-cycle can then be reasonably estimated by routine sampling and analysis. Such an approach informs us of N transformations in fertilized grassland soils—knowledge of considerable value in establishing management programs for fertilized grasslands.

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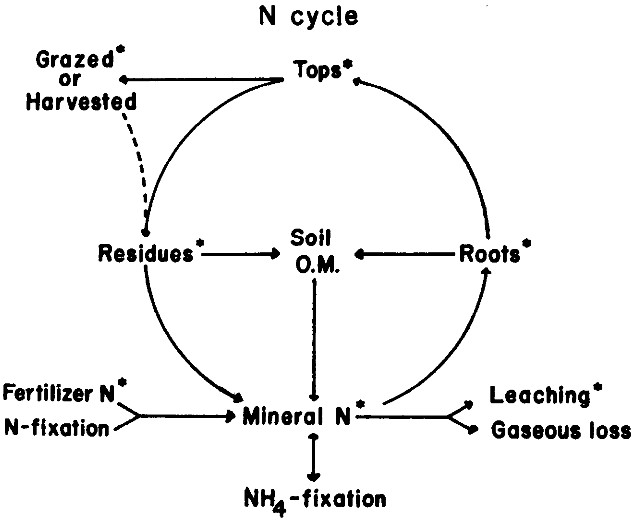

FIG. 1. Diagram of the basic elements of the N-cycle in a soil-plant system.

Basic elements of the N-cycle in grasslands are outlined by the diagram in Figure 1. No attempt is made here to outline all of the possible pathways, interactions, and points of lesser importance in the N-cycle. N is added to the ecosystem either by natural means of biological or nonbiological N-fixation or by N fertilization. N is irreversibly lost from the ecosystem by gaseous means (ammonia volatilization or denitrification), by leaching, and by removal in the harvested product (forage or livestock products). By detailed sampling and analysis, we can measure the amount of N immobilized in many components of the N-cycle. Thus, total N in grass tops, roots, mulch and residues, in soil inorganic forms, and that lost by leaching can be determined in field experiments with typical analytical error of about 20 kg N/ha or less. These components are therefore marked with an asterisk in Figure 1. Errors in determining total N in soil organic matter and fixed ammonium by Kjeldahl methods are usually about an order of magnitude larger than those for the N forms indicated above. No accurate methods exist for making field measurements of the amount of N lost in gaseous form or fixed by natural means.

Reasonable estimates of fertilizer N in a given component of the N-cycle can be made by subtracting total N values for unfertilized treatments from those of respective N-fertilized treatments (Carter, et al., 1967). Therefore, with these techniques we can estimate the amounts of fertilizer N immobilized in tops, roots, mulch and residues; removed in harvested product; lost by leaching; and remaining in the soil in mineral form. Fertilizer N not accounted for in the sum of these forms would be found in soil organic N (including microbial cells), fixed ammonium, or irreversibly lost in gaseous form.

Table 1. Fertilizer N (kg N/ha) removed from the N-cycle in grass tops when applied at different rates (kg/ha/yr).

| N rate | Years applied | Year 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | Total |
|---|---|---|---|---|---|---|---|---|
| 0[1] | – | 8 | 6 | 7 | 3 | 2 | 9 | 45 |
| 34 | 1 | 1 | 0 | – 3 | 0 | 0 | 0 | – 2 |
| 68 | 1 | 7 | 4 | 2 | 0 | 1 | 1 | 15 |
| 135 | 1 | 13 | 11 | 3 | 1 | 1 | 2 | 31 |
| 270 | 1 | 27 | 30 | 20 | 6 | 6 | 7 | 96 |
| 540 | 1 | 30 | 41 | 30 | 10 | 11 | 24 | 146 |
| 11 | 3 | – 2 | 0 | 0 | 0 | 0 | 2 | 0 |
| 22 | 3 | 1 | 4 | 7 | 2 | 3 | 3 | 20 |
| 45 | 3 | 2 | 9 | 5 | 2 | 2 | 2 | 22 |
| 90 | 3 | 11 | 24 | 24 | 7 | 7 | 11 | 84 |
| 180 | 3 | 19 | 45 | 41 | 12 | 17 | 21 | 155 |
| 6 | 6 | 0 | 1 | 1 | 1 | 0 | 2 | 5 |
| 11 | 6 | 1 | 4 | 2 | 2 | 3 | 6 | 18 |
| 22 | 6 | 0 | 4 | 4 | 2 | 4 | 10 | 24 |
| 45 | 6 | 2 | 9 | 18 | 9 | 9 | 21 | 68 |
| 90 | 6 | 8 | 25 | 28 | 13 | 18 | 36 | 128 |
| LSD 0.05 | | 3.8 | 4.5 | 4.8 | 2.4 | 2.4 | 4.0 | – |

[1] Total N in tops for check only, fertilizer N in tops for all others.

These techniques of sampling and calculating have been used extensively in grassland experiments at Mandan, North Dakota in recent years. The purpose of this paper is to present results from one of the first of these experiments, providing information on the fate of fertilizer N, and also providing data whereby a hypothesis can be developed to explain the principles regulating N transformations in grassland ecosystems.

## Methods

A replicated field experiment was initiated at Mandan, North Dakota in 1963 wherein ammonium nitrate at rates up to 540 kg/ha (480 lb./acre) was broadcast on native mixed prairie grasses either all in one year, one-third in each of 3 consecutive years, or one-sixth of the total in each of 6 consecutive years. Predominate grasses were western wheatgrass (*Agropyron smithii*), green needlegrass (*Stipa viridula*), and blue grama (*Bouteloua gracilis*), plus threadleaf sedge (*Carex filifolia*). Soil type was Grail silt loam, with no free $CaCO_3$ in the upper 15 cm and a surface pH of 6.6. Fertilizer P was surface broadcast at 28 kg/ha at the initiation of the experiment and 3 years later. Ditches were constructed between each replication to prevent foreign water from flowing over the plots.

Soil samples were collected to 90-cm depth (180-cm at the end of 6-years) before fertilization each spring, immediately frozen, and later extracted with 2N KCl and analyzed for $NO_3^-$, $NO_2^-$, and $NH_4^+$–N by steam distillation (Bremner, 1965). The neutron method was used to monitor soil water content at approximately monthly intervals. Grass tops above the 2.5-cm height were harvested in early August (after mid-grasses had matured), dried, weighed and analyzed for total N. After the sixth growing season 12 cores 37 mm in diameter were taken from the 0- to 30- and 30- to 90-cm depths of each plot; roots, stubble, and mulch were washed free of soil by an elutriation process, dried, weighed, and analyzed for total N.

From the samples collected and analyses performed, total N was calculated for the following components of the N-cycle; (a) grass tops—above 2.5-cm height, (b) inorganic soil N to 90-cm depth, and (c) root, stubble and residues (1969 only). Since neither water nor nitrate-N moved below the 90-cm depth, leaching losses of N were zero. Likewise absence of runoff eliminated overland flow as a vehicle for removing fertilizer N. An accurate record of the amount of fertilizer N applied was available. Therefore the amount of fertilizer N immobilized in grass tops was calculated by the difference method (Carter, et al., 1967):

$$F_T = N_T - Ck_T \qquad [1]$$

Where $F_T$ = fertilizer N in tops, and $N_T$ and $Ck_T$ = total N in tops from N fertilized and check plots respectively.

Similar calculations were performed to determine the amount of fertilizer present in soil inorganic forms and also immobilized in roots, residues, and stubble (hereafter referred to as roots). Prior to 1969 no data were available on root-bound N. Therefore fertilizer N not accounted for in tops plus inorganic forms was designated as "Immobilized N" and was calculated by the equation:

$$\text{Immobilized N} = \text{Fertilizer N applied (cumulative)} - \text{fertilizer N in (tops + inorganic N)} \qquad [2]$$

In addition to fertilizer N immobilized in roots, soil organic matter, and fixed ammonium, the "immobilized N" fraction also included gaseous losses.

## Results

The effects of the treatments on dry matter accumulation, root weights, and water use have been discussed in earlier publications (Power, 1970; Power and Alessi, 1971). Cumulative dry weights for the 6-year period were essentially equal for the 3 methods of fertilizer N addition. In this publication only the fate of fertilizer N will be considered.

Fertilizer N removed in plant tops (equation [1] above) is shown by the data in Table 1. As expected, fertilizer N in tops generally increased with increased fertilization rate. Considerable year-to-year variation existed as a result of variability in available water supply—uptake was very low in the relatively dry years of 1966 and 1967. At the higher N rates, fertilizer N was still being absorbed into the tops at the end of the experimental period, indicating that some of the fertilizer N was still available for plant growth. Like dry weights, cumulative fertilizer N uptake by tops for the 6-year period varied little for equal N rates, whether applied either all in one year or one-third in each of the first 3 years. Cumulative uptake for the 6-year treatment was generally somewhat lower, probably because residual effects of fertilization had not yet had the opportunity to show up fully for this treatment.

Fertilizer N present in the soil in inorganic form in early spring of each year is given by the data in Table 2, again calculated by equation [1]. This represents the sum of the fertilizer N found as soil nitrate N plus exchangeable ammonium N. Since no nitrite-N accumulation could be detected the first several years, this analysis was not made in later years. Inorganic N in soil of the check plot was generally in the 20 to 40 kg/ha range. Inorganic N analyses were not made on soils from the two lower N rates—from the data presented one would assume such values to be similar to those of check plots.

**Table 2. Fertilizer N (kg N/ha) present as soil inorganic N prior to fertilization each spring when applied at different rates (kg/ha/yr).**

| N rate | Years applied | Year 1964 | 1965 | 1966 | 1967 | 1968 | 1969 |
|---|---|---|---|---|---|---|---|
| 0[1] | — | 27 | 19 | 24 | 22 | 40 | 46 |
| 34 | 1 | — | — | — | — | — | — |
| 68 | 1 | — | — | — | — | — | — |
| 135 | 1 | 3 | 4 | 0 | − 3 | 1 | − 8 |
| 270 | 1 | 42 | 27 | 2 | 4 | 32 | − 8 |
| 540 | 1 | 308 | 250 | 134 | 115 | 30 | 64 |
| 11 | 3 | — | — | — | — | — | — |
| 22 | 3 | — | — | — | — | — | — |
| 45 | 3 | 2 | 4 | 3 | 9 | − 1 | 0 |
| 90 | 3 | 2 | 4 | 1 | 3 | 8 | 9 |
| 180 | 3 | 22 | 73 | 134 | 53 | 65 | 14 |
| 6 | 6 | — | — | — | — | — | — |
| 11 | 6 | — | — | — | — | — | — |
| 22 | 6 | 0 | 3 | 1 | − 1 | − 6 | −12 |
| 45 | 6 | 0 | 3 | 4 | − 1 | 1 | − 7 |
| 90 | 6 | 1 | 4 | 5 | 23 | 23 | 31 |
| LSD 0.05 | | 22 | 15 | 17 | 17 | 23 | 16 |

[1] Total inorganic N for check only, fertilizer N in soil for all others.

The amount of fertilizer N remaining in the soil one year after application increased as fertilizer rate increased. The application of 540 kg N/ha in one year immediately established a sizeable pool of inorganic N in the soil, and pool size progressively diminished in the following years. When 540 kg N/ha was applied over a 3- or 6-year period, the inorganic N pool increased progressively, with maximum values occurring the spring after the last application. In no instance did the application of 135 kg N/ha, either in 1, 3, or 6 years, result in a significant increase in the size of the inorganic N pool. Applying 270 kg N/ha in one year slightly increased inorganic N for 2 years—a temporary increase also occurred in the fifth year. However, applying the same amount of N in either 3 or 6 years resulted in no significant increase in the inorganic N pool.

One year after the initial application of fertilizer N (spring, 1964), fertilization rates less than 180 kg N/ha failed to maintain an inorganic N pool in

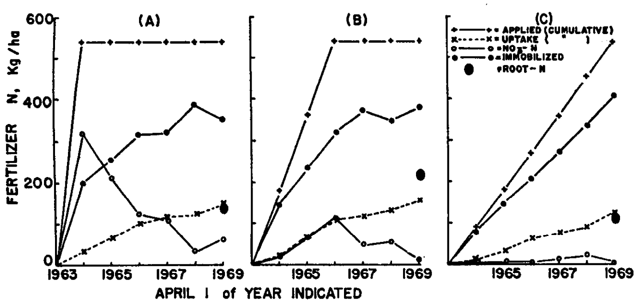

FIG. 2. Fate of 540 kg fertilizer N per ha applied to grassland (A) all in one year, (B) one-third in each of 3 years, and (C) one-sixth in each of 6 years.

the soil. In other words, all fertilizer N applied at this or lower rates had become immobilized within the N-cycle or was lost within one year. At higher fertilization rates, approximately 230 kg fertilizer N/ha disappeared from the inorganic N pool during the first year, being immobilized in the N-cycle or lost in gaseous form. Only about 30 of this 230 kg N/ha was immobilized by absorption into grass tops (Table 1). This left approximately 200 kg N/ha immobilized in the other components of the N-cycle during the first year—that is, immobilized in grass roots, soil organic matter and microbial cells, fixed ammonium, or lost by gaseous means.

By subtracting the cumulative amount of fertilizer N removed in tops plus that in the soil as inorganic N from the cumulative amount of fertilizer N applied to each plot, in accord with equation [2], the amounts of fertilizer N immobilized in roots, soil organic forms, and fixed ammonium, plus that lost in gaseous form, were calculated. Results are plotted in Figure 2 for the 540 kg N rate applied either in 1, 3, or 6 years. Similar calculations could also be made from the data given for the lower N rates.

When the entire 540 kg N/ha was applied the first year, an inorganic N pool was established (Fig. 2A). The size of this pool rapidly decreased for the next 4 years, then began to level off in the 30 to 60 kg N/ha range. Applying first-order kinetics to this curve gives a half-life ($t\frac{1}{2}$) to the inorganic pool of about 1.5 years ($k = 0.460$). Cumulative fertilizer N uptake by grass tops increased with time. In accord with equation [2], about 200 kg N/ha was immobilized or lost in undetermined forms the first year. This value increased to the 320 to 380 kg/ha range within about 3 years, and remained relatively constant thereafter.

When fertilizer N was applied at the rate of 180 kg N/ha for each of the first 3 years of study (Fig. 2B), fertilizer N in the inorganic N pool slowly increased with time to a maximum after the last year of fertilization, then declined toward the level of the check. Cumulative fertilizer N uptake in tops again increased in approximate linear fashion. Consequently, for this treatment, "immobilized N" increased from about 150 kg/ha the first year to about 350 kg/ha by the end of the fourth year, and remained at about that level.

When 90 kg N/ha was added for each of 6 years, only in the later years did a small accumulation of inorganic N occur (Fig. 2C). Again cumulative fertilizer N uptake by tops was almost linear. Since rate of fertilizer addition was linear, the increase in "immobilized N" was also almost linear with time. In every year, approximately 75% of the fertilizer N added went into immobilized forms. The entire 6-year period was required for "immobilized N" to reach 350 kg/ha, the level at which the other two treatments began to level off. Unfortunately, fertilizer additions were terminated after 6 years, so no information is available to determine if immobilized fertilizer N for this treatment would also level off at about 350 kg/ha.

In each of the three parts of Figure 2, a point is shown on the right representing the amount of fertilizer N immobilized in the grass roots of each treatment at the end of the experiment. These values range from about 120 to over 200 kg fertilizer N/ha. In most instances the amount of fertilizer N immobilized in roots represents about half of the total "immobilized N" fraction. This leaves up to 200 kg fertilizer N/ha immobilized in the combined forms of soil organic matter and microbial cells, and fixed ammonium, plus gaseous losses.

## Discussion

The foregoing data provide an accounting of the fate of fertilizer N applied to a grassland ecosystem. In all instances where sufficient fertilizer N was added, approximately 350 kg/ha was immobilized in the various components of the N-cycle. A period of 3 to 4 years was required for immobilization to come to equilibrium. Only about 200 kg/ha could be immobilized the first year. This value increased by 50 to 75 kg N/ha each of the following years until the 350-kg/ha level was attained.

In earlier work with bromegrass growing on a sandy loam, again with no leaching or runoff, about 80% of the fertilizer N applied could be accounted for in tops, roots, and soil inorganic form combined (Power, 1967). In the present experiment approximately 60% of the fertilizer N applied could be accounted for, leaving about 200 kg N/ha not accounted for and presumably immobilized in soil organic matter and fixed ammonium or lost by gaseous means. No data are available to indicate how much of this 200 kg N/ha was in each of these components. Consequently, it is possible that a major part of this unaccounted for fertilizer N escaped the system in gaseous form.

The data presented here suggest that each component of the N-cycle has some fairly definite capacity to immobilize inorganic N. Although a multitude of factors probably influence fertilizer N immobilization within a grassland soil (root growth, lignin content of organic matter, soil oxygen and water, amount and mineralogy of soil clays, etc.), data given here indicate that the total immobilizing capacity of a given system is relatively constant.

A 3- to 4-year period was required for the N-immobilizing capacity of the soil-plant system to become saturated (provided sufficient fertilizer N was added); about half of the immobilized N was found in grass roots; and 50 to 75 kg N/ha was immobilized or lost each year after the first year. Since root absorption is a major factor in N immobilization, these results suggest that rate of N turnover in the root material must also operate on a 3- to 4-year cycle. Thus, it appears that 40 to 50 kg fertilizer N is immobilized in new root growth each year (about 8000 kg new roots/ha/year with N content about 0.5% higher than in roots of check). This leaves as much as 25 kg N/ha to be immobilized or lost by other means in all years except the first, when approximately 150 kg N/ha was so immobilized. Once the N-immobilizing capacity of the ecosystem is saturated, a new equilibrium level is attained wherein annual N immobilization and losses can be balanced by N mineralization plus fertilizer additions. Such additions would have to equal irreversible losses minus natural N fixation.

A review of the literature gives support to the above conclusions. Other investigators, utilizing various means, have calculated the turnover rate of root systems for temperate grasses to be 3 to 5 years (Dahlman and Kucera, 1965; Weaver and Zink, 1946). Dilz and Woldendorp (1960) found that about 45% of the N applied as $^{15}N$ was immobilized in soil plus roots, and about half this quantity was found in roots. An earlier paper by Power (1968) shows that incubation of unfertilized grass roots with soil resulted in net immobilization of inorganic N, but incubation of fertilized grass roots with soil resulted in the net mineralization of inorganic N. In another paper by Power (1967) it was shown that the availability of water was the dominant factor controlling the rate at which inorganic N was converted to biologically immobilized N, primarily by grass roots and tops. Interpretations given to the present study are based primarily on carbon-nitrogen balances in the ecosystem. No evidence was found that materials in grass roots inhibitory to the nitrification process (Lyon, et al., 1923; Theron, 1963) were of any consequence to N circulation in the soil-plant system.

In summary, the hypothesis developed from the results of this study may be stated as follows:

> "Nitrogen may be eliminated as a growth-limiting factor within a soil-plant system by providing sufficient inorganic N to completely saturate the capacity of the system to immobilize N, thereby setting up new equilibrium conditions whereby annual immobilization and irreversible losses are balanced by mineralization plus inorganic N additions."

The N-immobilizing capacity of a given system may vary somewhat with soil texture, vegetation, and other environmental parameters. Once an approximation of this value is made, however, nitrogen management systems may be devised wherein immobilization and removal of N from the system is balanced by mineralization plus inorganic N additions. Such an approach may apply to all types of ecosystems, but is of prime importance in grasslands because of their high capacity to immobilize N. By utilizing such an approach, N may be eliminated as a growth-limiting factor and maximum production for the prevailing conditions may be obtained.

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