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Nitrogen mineralization and nitrification in four Minnesota old fields

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Summary. Nitrogen availability and its response to fertilizer amendments was measured by in situ incubation in four old fields ranging in age from 16 to >100 years at Cedar Creek Natural History Area. Net nitrogen mineralization in control plots increased with field age, from 4.4 g/m^2 in the youngest field to 6.5 g/m^2 in the oldest field. The proportion of total N mineralized decreased with field age, from 6.2% of total N mineralized in the youngest field to 4.8% mineralized in the oldest field, suggesting a decrease in organic matter quality with time. Unlike many forests in the region, nitrogen mineralization was correlated with total soil nitrogen content. Greater than 90% of the mineralized N was nitrified in most months. Analyses of variance indicate significant effects of field age and month of year on N mineralization and nitrification, but no effect of fertilizer treatment except in the oldest field. Fertilizer additions did not significantly increase standing pools of mineral N in the youngest or oldest fields but did in the 26 and 50 year old fields. However, changes in mineral N pools did not account for the amount added in fertilizer. Strong plant and microbial sinks for fertilizer and possibly leaching losses may be the reasons why fertilizer additions did not stimulate N mineralizations during the first two years in most fields.

Key words: Cedar Creek – Minnesota – Nitrogen mineralization – Old fields – Succession

Many old fields are extremely low in soil organic matter and nutrients because of past agricultural practices. Nitrogen is the nutrient most often limiting plant growth in old fields (Lawes and Gilbert 1880; Milton 1934, Huffine and Elder 1960; Gay and Dwyer 1965; Owensby et al. 1970; Tilman 1984). Nitrogen availability is determined by nitrogen mineralization, the microbial conversion of organic nitrogen to ammonium, with possible further oxidation to nitrate. The amount of N mineralized depends not only on the total amount of organic N, but also on factors affecting microbial activity, such as temperature, moisture, and quality of the organic matter (Swift et al. 1979). Total nitrogen and organic matter often increase with succession in old fields (Billings 1938; Odum 1960; Rice et al. 1960; Inouye et al. 1987). Potential N mineralization in laboratory incubations is highly correlated with this general increase in total N (Robertson and Vitousek 1981), but changes in N availability under field conditions in these ecosystems have not been examined.

Inputs of nitrogen may increase litter production and thereby increase nitrogen abailability upon decay of the plant litter. This can happen either through release of nitrogen in the litter itself, or by the fresh litter or added inorganic nitrogen stimulating increased release of nitrogen from humus, otherwise known as a priming effect (Bingeman et al. 1953; but see Olson 1980 and Olson et al. 1979).

We studied N mineralization and nitrification in an old field chronosequence at Cedar Creek, Minnesota to examine changes with time and their responses to N inputs.

Study area

The Cedar Creek Natural History Area is located on a 20–40 m deep sandy outwash plain deposited by streams draining the receeding Wisconsin continental glacier around 14,000 years BP. Native, presettlement vegetation on the sand plain was a mosaic of prairie, wetland, oak savanna, and hardwood forest (Pierce 1954). The area was farmed starting in the late 1,800 s. From about 50 years ago through the present time, various fields have been abandoned.

Four fields, ranging in age from 16 yrs to greater than 100 yrs, were studied. Field A, the youngest, was farmed to soybeans before being abandoned in 1968. Field B was last farmed to soybeans before abandonment in 1957. Field C was last farmed to corn before abandonment in 1934. Field D is a native oak savanna which has never been clearcut or plowed but may have been grazed prior to 1940 but not since, and represents a probable endpoint of succession on these soils. Field D is one of several in a prescribed burn experiment and has been burned for 2 out of every 3 years for the past twenty years. Early successional species dominating younger fields are Eurasian and native annuals and native biennials, while later successional species dominating older fields are native prairie perennials and oaks (Table 1). Species compositions are comparable to those of other old fields and savannas of similar age in the area (Tilman 1983, 1984, 1986, Inouye et al. 1987). The soils in all fields are sands of the Sartell or Zimmerman series

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Table 1. Summary of field ages, vegetation and soil properties prior to fertilization. Soil properties are means of nine 20 × 50 m plots in Fields A, B and D and six 20 × 50 m plots in Field C. Nitrogen (N) is total soil nitrogen but P, K, Ca and Mg are extractable amounts. Standard deviations in parentheses

Field	Age (yrs)	Dominant species	% O.M.	µg/g					Soil pH	Soil C/N
				N	P	K	Ca	Mg		
A	16	Ar, Bi	1.64 (0.21)	592 (76.7)	134 (21.8)	116 (18.7)	629 (102)	385 (81.8)	5.84 (0.14)	13.4 (2.01)
B	26	Ss, Pp	1.85 (0.39)	535 (77.2)	151 (24.2)	109 (20.9)	513 (98.3)	267 (99.6)	5.58 (0.08)	16.7 (3.04)
C	50	Ss, Al	2.38 (0.43)	802 (147)	220 (20.9)	190 (16.1)	824 (83.9)	531 (20.1)	5.68 (0.05)	14.6 (3.53)
D	>100	Cm, Al, Qm, Qe, Sn	3.24 (0.33)	1054 (54.3)	188 (6.3)	163 (15.9)	979 (116)	339 (29.6)	5.70 (0.12)	14.8 (1.40)

Ar *Agropyron repens*; Bi *Berteroa incana*; Ss *Schizachyrium scoparium*; Pp *Poa pratensis*; Al *Artemisia ludoviciana*; Cm *Carex muhlenbergii*; Qm *Quercus marcrocarpa*; Qe *Quercus ellipsoidalis*; Sn *Sorghastrum nutans*. See Tilman (1984, 1986)

(Typic Udipsamments and Alfic Udipsamments, respectively; Grigal et al. 1974).

Experimental design and methods

An experimental nitrogen gradient was established by fertilizing 20 m × 50 m plots with either 0.00 (control), 5.78, or 17.00 g/m^2/yr of N. The fertilizer was applied as NH_4NO_3 in a top dressing in two installations during the spring of each year beginning in 1983. All plots except the controls also received simultaneous additions of P(4.6 g/m^2/yr), K(6.1 g/m^2/yr), Ca(8.0 g/m^2/yr), Mg(3.0 g/m^2/yr), S(4.0 g/m^2/yr) and a mixture of trace metals (Cu, Zn, Co, Mn, Mo and B). There were three replicate plots per treatment in Fields A, B, and D and two replicate plots per treatment in Field C.

Forty uniformly spaced samples of the upper 10 cm of each plot were taken before fertilization and analyzed by standard methods. Total nitrogen was determined by persulfate digestion. Organic matter content was determined by loss on ignition at 550° C for 4 h. Carbon content was estimated as 50% of mass loss on ignition. Available phosphorus, calcium, potassium, and magnesium were extracted in a 1:10 soil:0.5 N HCl mixture which was shaken for 0.5 hr, allowed to settle, then filtered. The extract was analyzed for these nutrients using plasma emission spectroscopy. Soil pH was determined on 1:1 soil:water extracts.

Net nitrogen mineralization and nitrification was determined during the 1984 growing season (May-September) by the in situ buried bag incubation method (Eno 1960). This method correlates highly with estimates of N and P cycling in croplands, grasslands, forests and savannas (Bernhard-Reversat 1982; Westermann and Crothers 1980; Nadelhoffer et al. 1983; Pastor et al. 1984; Vitousek and Matson 1985; Schimel et al. 1985). Three samples were taken of the upper 10 cm of soil in each treatment in each plot in each field, placed in a polyethylene bag, and incubated monthly beneath the thatch in an adjacent portion of each field not receiving fertilizer treatments. Thus, all samples were incubated under the canopy and litter conditions representative of the unmanipulated field from which they were derived. Paired samples were also taken to estimate initial levels of NH_4-N and NO_3-N. Inorganic N was extracted from both incubated and initial samples with 1 N KCl within 24 h after sampling. The extract was analyzed by autoanalyzer (Technicon 1977, 1978). Net N mineralization is the increase in NH_4-N and NO_3-N while net nitrification is the increase in NO_3-N in the incubations relative to their paired initials. This was multiplied by bulk density and the appropriate conversions to obtain results on a g/m^2 basis. Following the terminology of Schimel et al. (1985), relative N mineralization or nitrification is the proportion of total N mineralized or nitrified.

Results

Bulk soil properties

The soils were extremely low in organic matter and nitrogen, although both increased with field age (Table 1). Calcium was the only other soil property measured which increased with field age. None of the other properties showed any trend with age.

Nitrogen mineralization and nitrification

Net nitrogen mineralization in control plots increased with field age, from 4.4 g/m^2 in the youngest field (A) to 6.5 g/m^2 in the oak savanna (D) (Fig. 1). Average annual N mineralization was significantly correlated with the average total *N* content of the soil:

$$y = 17.69 + 0.029x \ (r = 0.915,\ P < 0.05,\ N = 4)$$

where y is annual N mineralization in µg per g soil and x is total N in the same units. This is in contrast to the findings of Pastor et al. (1984) and Nadelhoffer et al. (1983) who found no relation between N mineralization and total N in a variety of old growth forests in Wisconsin. Nitrogen mineralization was less strongly correlated with calcium ($r = 0.885$, $P < 0.05$) and with organic matter ($r = 0.905$, $P < 0.05$), but not correlated with any other measured property.

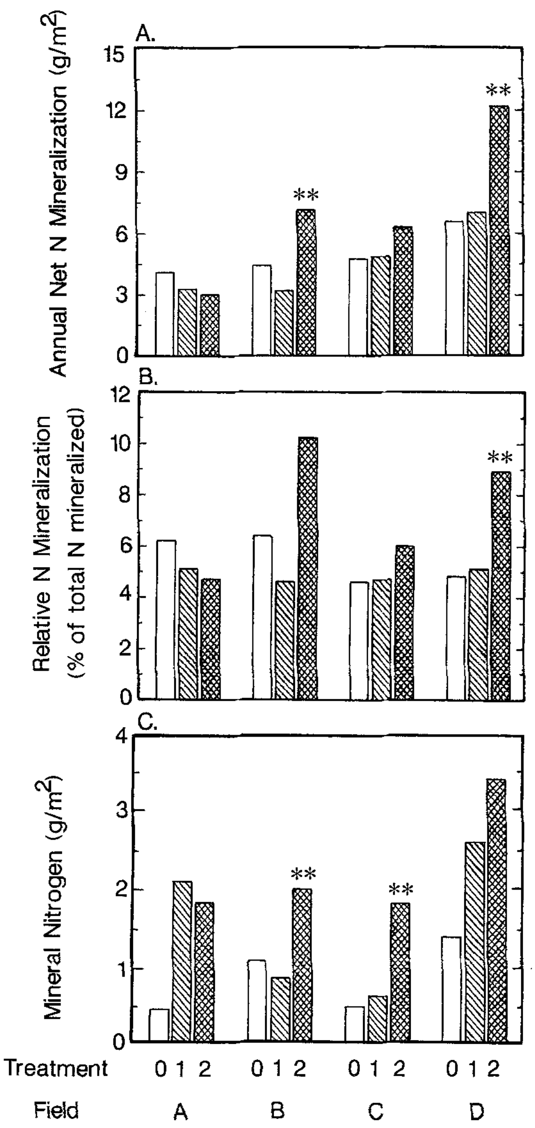

Fig. 1A–C. Net **A** and relative **B** N mineralization and average mineral N pool sizes **C** for four fields and three N fertilizer treatments. Explanantion of treatments: $0 = 0.0$ g/m^2 added N; $1 = 5.78$ g/m^2 added N; $2 = 17.0$ g/m^2 added N. ** indicates fertilizer effect was significant at $P < 0.01$

Greater than 90% of the monthly N mineralization was nitrified, except in July, when an average of 65% over all fields and treatments was nitrified. The proportion of total N mineralized in control fields (relative N mineralization) decreased with field age, from 6.2% in field A to 4.8% in field D.

Analyses of variance were performed on both relative and net N mineralization and nitrification rates. The main effects of field age and month were highly significant ($P < 0.001$) in all cases, but neither the main effect of fertilizer treatment across all months and fields nor the field age × treatment interaction were significant.

To examine this further, analyses of variance were performed on each field's data, testing main effects of month and fertilizer treatment. The oldest field (D) was the only field with significant effects of fertilizer treatment, month, and treatment × month interaction on both net and relative N mineralization ($P < 0.01$ in all cases).

Mineral nitrogen pools

Analysis of variance showed that standing pools of mineral nitrogen (NH_4-N+NO_3-N) were not related to month, field age, nor fertilizer additions. Further analyses on each field's data showed that average pool sizes over the growing season increased significantly with fertilizer additions in fields B and C ($P < 0.01$, Fig. 1). Pool sizes also increased in the youngest field (A) and the oak savanna (D), but high spatial variance prevented these increases from being statistically significant.

Discussion

Although there were no replicate fields for each field age (pseudoreplication sensu Hulbert 1984), the soils and vegetation of these four fields are fairly representative of old fields and savannas in the area, based on a survey of 22 Cedar Creek old fields (Inouye et al. 1987). Nitrogen and organic matter contents of the soils of the three younger old fields (A, B, C) are comparable to those of other fields of similar age in the area except that the nitrogen content of field A is somewhat, but not significantly, greater than the value of 480 μg/g for 16 year old fields predicted from a regression of nitrogen vs. age (Inouye et al. 1987). Nitrogen content of the oak savanna soil (D) is within the range of other oak savannas at Cedar Creek (Tilman, unpublished data). Species composition is comparable to other fields (Inouye et al. 1987). With some caution, we can therefore make inferences about changes in soil nitrogen dynamics with succession on old fields in the area.

These mineralization rates, the proportion of total N mineralized, and the inverse relation between net and relative N mineralization are comparable to those measured with the same techniques in shortgrass prairies in Colorado (Schimel et al. 1985). The rates are at the low end of the range reported for forests in nearby Wisconsin (Nadelhoffer et al. 1983; Pastor et al. 1984).

With increasing age, there is apparently a decline in organic matter quality. This is indicated by the decrease in relative N mineralization in control plots (Fig. 1). Schimel et al. (1985) found similar trends in a toposequence of shortgrass prairie soils and hypothesized that this indicates an increase in recalcitrant, older forms of humus. This hypothesis may also apply here. In addition, the presence of oaks in the oldest field (D) contributes highly lignified material to the soil, which may further increase its recalcitrance. A model of soil C and N dynamics in cropland soils (Parton et al. 1983) indicates that increases in both older recalcitrant humus and inputs of lignified material could decrease relative N mineralization rates. The results reported here lend some support to that model.

Differences in organic matter quality control N mineralization from forest soils in Wisconsin as well as at Cedar Creek (Nadelhoffer et al. 1983, Pastor et al. 1984, McClaugherty et al. 1985). However, Cedar Creek old fields are in marked contrast to these forests in that N mineralization was also correlated with total N soil content, whereas in these Wisconsin studies, mineralization rates were independent of soil N content. The reasons for this difference are not clear but may be due to the much wider variation in organic matter quality between tree species as diverse as pine, oak, and sugar maple compared with most prairie grasses at Cedar Creek, and to the extremely low N contents of Cedar Creek soils, so that any increase results in increased N availability. This indicates that in addition to changes in organic matter quality, accretion of nitrogen in soil is an important process controlling N availability in these successional fields.

Fertilizer additions over two years significantly increased net and relative N mineralization only in the oak savanna (D). Such an apparent priming effect may occur only in soils of low organic matter quality (low relative N mineralization), which are perhaps formed as a result of highly lignified litter inputs (i.e., oak litter). This may explain some of the disparity between experiments on the priming effect reported in the literature (Jansson and Persson 1982).

Increases in pool sizes of mineral N during the first two years of fertilization account for less than 20% of the added N. What, then, has been the fate of the added N? The most likely sink for the added N is plant uptake and retention associated with enhanced net primary production, which increased 2 to 4 fold in the highest N treatment (Tilman, unpub. data). Increased dominance by perennials after fertilization (Tilman 1984) would also enhance the strength of the vegetation sink. Even that portion of the N returned to the soil in litter is not released for at least 18 months (Pastor et al., in review), and microbial immobilization is an additional sink. Leaching may account for some additional nitrogen loss. Denitrification is not likely in these excessively drained soils. Plant and microbial sinks and leaching losses therefore appear sufficient to delay fertilizer-induced increases in N mineralization for several years.

In these fields, fertilizer additions change competitive abilities of various species (Tilman 1984, 1986). Growth of early successional species with greater maximal growth rates and greater nitrogen use and extraction efficiencies is first increased; this in turn decreases canopy light penetration and favors growth by other species that are better light competitors (Tilman 1984, 1985; unpublished work. Together with these additional studies, the results reported here suggest that old field succession at Cedar Creek (Inouye et al., in press) and elsewhere where soils are initially very nitrogen poor (Billings 1938, Odum 1960, Rice et al. 1960) may be caused, in part, by increases in available N with time and the differential competitive abilities of species for different resources.

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