

# NITROGEN MANAGEMENT

## Corn Root Effects on the Nitrogen-Supplying Capacity of a Conditioned Soil

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### ABSTRACT

The design of sustainable N management strategies requires a better understanding of the processes influencing the ability of soils to supply N to a growing crop. Although commonly ignored, the release of C by plant roots may have a tremendous impact on soil organic matter turnover under certain soil conditions. The main objective of this study was to determine if living corn (*Zea mays* L.) roots would increase the N-supplying capacity of a soil with an enhanced mineralizable N pool. A rotation of corn–corn–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) in combination with cover crops and the application of composted manure were used to increase the mineralizable N pool. The N-supplying capacity of bare soil and soils planted with corn and wheat was calculated, and changes in N and C pool sizes were determined by laboratory incubations. Living corn roots increased the inorganic N-supplying capacity of the conditioned soil by >50%. We suggest that this increase is caused by an increase in net N mineralization. This is supported by the considerable size reduction of the 70-d N pool in the soil planted with corn. No significant increase in the soil N-supplying capacity was observed when wheat was planted, indicating the possibility that this effect may vary dramatically among plant species. The contribution of corn and wheat root rhizodeposition to the active C pool and as energy source to enhance microbial activity and organic matter turnover is discussed.

**N**ITROGEN MINERALIZATION, which is a microbiologically mediated process consisting of the transformation of organic N to  $\text{NH}_4$ , is a major contributor to the amount of soil N available for plant uptake. Corn may derive up to 70% of its required N from the mineralization of soil N (Meisinger et al., 1985; Sanchez and Blackmer, 1988). The presence of plant roots has significant effects on the soil microbial population because conditions for microbial growth are especially favorable in the rhizosphere (Barber and Lynch, 1977; Newman, 1985; Foster, 1988; Bazin et al., 1990). For example, the soil microflora is heavily influenced by C sources derived from rhizodeposition (Curl and Harper, 1990). Rhizodeposits are easily decomposable substrates translocated from the aboveground parts of the plant to the roots and subsequently transferred into the surrounding soil as root exudates, mucilage, and sloughed cells and tissues (Qian et al., 1997). The role of rhizodeposits in the turnover of soil organic matter has been controversial for many years. A number of studies have reported

that root presence increases decomposition rate of soil organic matter (Billes and Bottner, 1981; Fisher and Gosz, 1986b; Cheng and Coleman, 1990). Others reported no change (Cuenca et al., 1983; Harmer and Alexander, 1985) or even a reduction in presence of plant roots (Gadgil and Gadgil, 1975; Jenkinson, 1977; Sparling et al., 1982; Fisher and Gosz, 1986a; Staaf, 1988; Faber and Verhoef, 1991).

Reports on the influence of roots on N mineralization have also been contradictory. A stimulatory effect of plant roots on N mineralization has been observed in some studies (Bartholomew and Clark, 1950; Molina and Rovira, 1964; Clarholm, 1985a; Berg and Rosswall, 1987; Bottner et al., 1991; Haider et al., 1993). Others have found that the net effect of plant roots is to increase N immobilization (Huntjens, 1971; Texier and Billes, 1990; Qian et al., 1997). The discrepancy of these results reflects the diversity of soils, plant species, and experimental methods and the complexity of plant–soil interactions and their influence on C and N dynamics. Although the addition of N-rich plant residues (Bhattacharyya et al., 1986; Wang and Bakken, 1989) or N fertilizer (Liljeroth et al., 1990; Swinnen et al., 1995) may increase N mineralization in the presence of plant roots, previous workers have not attempted to identify soil conditions that enhance the stimulatory effect of plant roots on N mineralization.

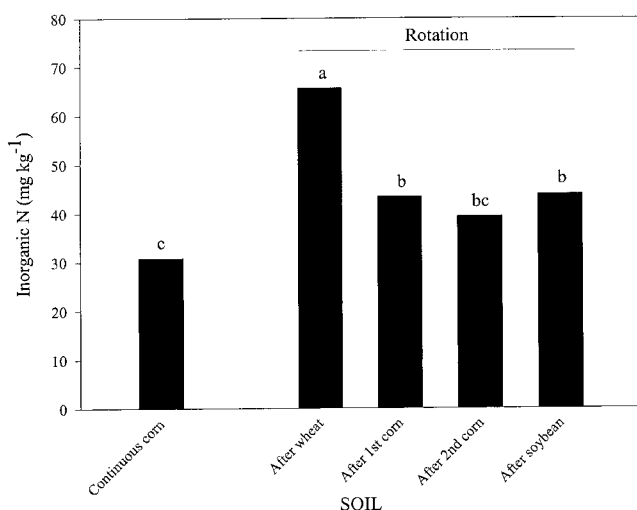
In this work, we hypothesize that the presence of living corn roots would increase the N-supplying capacity of a conditioned soil. Soil conditioning, as we define it, is the process of improving the quantity and quality of the mineralizable N pool. We use practices such as crop rotation, cover crops, and the addition of composted manure to enhance the mineralizable N pool. Cylinders of PVC were placed in the conditioned soil before planting to confine or exclude roots of corn and wheat. The soil N-supplying capacity was calculated for the bare soil, corn, and wheat treatments 70 d after planting. Mineralization potentials determined by laboratory incubations were used to quantify changes in the 70-d N (based on 70 d of incubation) and 150-d C (based on 150 d of incubation) pools in response to the presence or absence of plant roots.

### MATERIALS AND METHODS

#### Site Description

This research is part of the Living Field Laboratory, a long-term experiment established in 1993 at the Kellogg Biological Station in Hickory Corners, MI. Average precipitation has been 860 mm  $\text{yr}^{-1}$  (1988–1999), and potential evapotranspira-

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**Fig. 1.** Net mineralized N at 70 d of laboratory incubations for soils from a corn–corn–soybean–wheat rotation and continuous corn at the Living Field Laboratory. Sampling was done in May 1999. Units are based on a 10-cm sample depth. Letters indicate significant differences ( $P < 0.05$ ) in mineralized N after 70 d of incubation.

tion typically exceeds precipitation from May through September. The soil is a mixture of Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) sandy loams. The depth of the Ap horizon is 20 to 25 cm, and pH ranges from 6.3 to 6.8. The Living Field Laboratory is designed to test various combinations of rotation and cover crops under several agronomic management regimes (Jones, 1998). Its main goal is to test alternative strategies for achieving nutrient-cycling efficiency and reducing chemical input requirements. The plots used for this study received minimal application of pesticides, banded herbicide plus cultivation for weed control, and composted dairy manure as the nutrient source. Approximately 4 Mg ha<sup>-1</sup> composted manure (26 g N kg<sup>-1</sup>) is added annually to all crops and incorporated with chisel plow 7 to 14 d before planting. This study includes a field experiment using root-confining or root-excluding cylinders in the cover-cropped plots of first-year corn in a corn–corn–soybean–wheat rotation. Red clover (*Trifolium pratense*) is frost-seeded into wheat, crimson clover (*T. incarnatum*) is interseeded into first-year corn, and annual ryegrass (*Lolium multiflorum*) is interseeded into second-year corn as cover crops. The average organic C content of this soil is 13 g kg<sup>-1</sup>, with a C/N ratio of 10. Plots in first-year corn (immediately following wheat + clover) were selected because their soil has a larger 70-d organic N pool compared with other crops in the rotation or with continuous corn (Fig. 1). Previous work suggests that the 70-d N pool closely represents the portion of organic N available for mineralization during a growing season (Sanchez et al., 2001). In early May 1998, six PVC cylinders (70 cm long and 30 cm i.d.) were pressed 60 cm into the soil with minimal soil disturbance immediately after corn (cv. Pioneer 3751) planting. Two corn plants were allowed to grow in three of the cylinders of each plot, and the corn seeds were removed from the other three rings (bare treatment). Using new first-year corn plots, the experiment was repeated in 1999 with the addition of three cylinders planted with spring wheat (cv. Russ). Four grams (approx. 100 seeds) of wheat were planted in a radial distribution from the center of the rings.

### Field Measurements

Immediately after cylinder insertion, soil samples were taken at 0- to 10-, 10- to 25-, 25- to 50-, and 50- to 60-cm depths

from each of the four plots to determine initial inorganic N concentrations. Six extra cores were taken adjacent to each cylinder at 0- to 10-cm depth and used for laboratory incubations. Soil moisture was controlled in the cylinder, using temporary rain shelters and periodic addition of water, to prevent extreme wetting–drying events and to minimize NO<sub>3</sub> leaching and denitrification. We also assumed that controlling the soil moisture would concentrate root growth in the Ap horizon. Soil moisture was determined weekly using time domain reflectometry (Tektronix 1502B). The amount of water to be added was calculated by subtracting the actual soil moisture from the estimated water-holding capacity (Paul et al., 1999) for the 0- to 10-cm depth. The calculated amount of water to be added was divided in half, and each part was applied at two different days of the week. Soil moisture was adjusted weekly as needed. Removable plastic shelters were used as needed to exclude rain from the cylinders. Every 14 d, three soil cores (1.9 cm diam.) were taken at 0- to 10-cm depth from each cylinder. After each sampling, the open holes were plugged using small pieces of PVC pipes (15 cm long). The objective of this sampling was to monitor changes in inorganic N throughout the experimental period and to confirm soil moisture gravimetrically.

After 70 d, final soil samples were taken at 0- to 10-cm depth for laboratory incubations, and each cylinder and its intact soil core were removed using a front-end loader. The PVC pipe was separated from the soil core by sawing longitudinally and splitting the pipe, exposing the intact core. Soil samples at 0- to 10-, 10- to 25-, 25- to 50-, and 50- to 60-cm depth were taken from the cores to determine the final inorganic N concentrations in the confined soil profile (0- to 60-cm depth). Deep soil samples were also taken from beneath the tubes (60- to 70-cm depth) to determine N movement below the confined profile. Bulk densities were determined for the 0- to 10-, 10- to 25-, and 25- to 60-cm depths and used to calculate area-based values of soil inorganic N. The bulk densities of bare soils averaged 1.4 g cm<sup>-3</sup> in both 0- to 10- and 10- to 25-cm depths vs. the 1.3 g cm<sup>-3</sup> found for both corn and wheat soils at those depths. No differences were found among the three soils at 25- to 60-cm depth (1.6 g cm<sup>-3</sup>). Corn and wheat biomass were separated from the soil cores and analyzed for total C and N using a Carlo Erba N A 1500 Series 2 N/C/S analyzer (CE Instruments, Milan, Italy).

### Laboratory Measurements

Inorganic N (NO<sub>3</sub>-N + NH<sub>4</sub>-N) concentrations were determined using the extraction technique described by Keeney and Nelson (1982) and a Lachat automated colorimetric analyzer (Lachat Instruments, Milwaukee, WI). For clarity, we will use the terms *at planting* to describe the soil at Day 0 and *final* to describe the soil at termination 70 d after planting. During the preparation of final soils, most remaining roots were removed using a 6-mm sieve. Wheat roots were difficult to separate due to their small size and senescence at the time of sampling. Soil samples from the 0- to 10-cm depth of each plot were composited by sampling date and treatment and incubated to determine the size of the 70-d N and 150-d C pools in the laboratory. Three (20-g dry weight equivalent) aliquots of each sample were weighed into 100-mL plastic specimen cups and brought to 50% of water-holding capacity. The specimen cups were stored in plastic storage containers that had a thin layer of water on the bottom to maintain humidity. These containers were then placed in a controlled-temperature room at 25°C for 30 and 70 d. At the end of each incubation interval, the corresponding samples were removed and frozen temporarily to stop microbial activity. Inorganic N was determined using the previously described method. Net

N mineralization potential was calculated as the difference between inorganic N content at the end of the incubation period and that at Day 0. Separate laboratory incubations were used to determine cumulative C mineralization at 20, 30, 50, 70, 100, and 150 d of incubation. The cumulative mineralization after 150 d of incubation (150-d C pool) closely represents the active C pool (Paul et al., 2000). Changes in the 150-d C pool may explain the contribution of rhizodeposition to the active pool.

The inorganic N-supplying capacity of soil was calculated using an N balance approach:

$$N_{SC} = N_{\text{harvested}} + \Delta N_{\text{inorganic (soil)}}$$

where  $N_{SC}$  is the cumulative inorganic N supplied by soil during the 70 d in the field,  $N_{\text{harvested}}$  is the harvested shoot and root biomass N,  $\Delta N_{\text{inorganic}}$  is the N difference between initial and final content of soil inorganic N measured at 0- to 60-cm depth. This simplified equation assumes that deep N leaching was prevented and gaseous N loss minimized. One can argue against our assumption concerning the lack of gaseous N loss because no measurement was attempted. Accurate data for denitrification and volatilization are rarely available for upland farming systems (Robertson, 1997). But in a different location within Southwest Michigan, a short-term field experiment using  $^{15}\text{N}$  on a poorly drained soil showed that denitrification amounted to only 1 to 2% of the immobilization-plus-nitrification rates (Christensen et al., 1990). Linn and Doran (1984) reported that in a well-drained soil, the relative activity of anaerobic denitrification is negligible. Also, a recent study in an adjacent field with nearly identical agronomic treatments indicated that N loss due to denitrification ranged from 1.3 to 0.4 kg ha<sup>-1</sup> yr<sup>-1</sup> (Robertson et al., 2000).

### Data Analysis

The same statistical model was applied to the plant biomass N, final inorganic N, and N supplied by soil data sets. Factors used in the model were field plot, treatment, and replication. The inorganic N concentration and bulk density in the soil profile data sets used depth as an additional factor. The factors used to analyze the N and C mineralization data sets were treatment, date, field replication, and incubation time. In both cases, during the analysis of variance (ANOVA), the data from each incubation interval were treated as repeated measurements of the corresponding experimental unit. The optimal covariance structure was determined using Schwarz's Bayesian Criterion (Littell et al., 1997). The N and C mineralization data sets were best explained by a compound-symmetry covariance structure, which assumes constant variance and covariance for each diagonal element of the variance-covariance matrix (SAS Inst., 1999). After using ANOVA to identify effects

that produce significantly different N or C mineralization, the Tukey-Kramer test was used to compare least square means.

## RESULTS AND DISCUSSION

The inorganic N-supplying capacity of soil in the field was increased >50% in the presence of corn roots compared with bare soil (Table 1). We suggest that this increase is influenced by the stimulating effect of corn roots on N mineralization. The effects of roots on soil include uptake of nutrients and water, movement of soil caused by root penetration, and release of rhizodeposits (Priha et al., 1999). The production of rhizodeposits is a direct root control of N mineralization (Clarholm, 1985b). The plant's release of these organic materials is a significant energy input to the soil microbial community (Bakken, 1990; Texier and Billes, 1990). Whipps (1985) reported that in young corn, 47 to 69% of the total C transferred to the roots could be lost in the form of rhizodeposition. Helal and Sauerbeck (1987) estimated that the amount of C released by corn roots from 7 to 30 d after planting was equivalent to >1000 kg ha<sup>-1</sup> organic matter. This root-derived C acts as a *fuel* for a sequence of events that would not occur in the absence of roots (Clarholm, 1985b). First, the presence of these high-energy C materials increases N immobilization because soil microorganisms are typically C limited (Paul and Clark, 1996). Second, N mineralization also increases because of the abundance of low C/N ratio substrate in the conditioned soil. The ability of this soil to supply N in presence of corn roots is enhanced because the expected increased immobilization was counterbalanced by much greater mineralization. It is also possible that some of the additional N may have come from increased microbial turnover resulting from predation of the enhanced microbial biomass by nematodes and protozoa (Elliott et al., 1979; Clarholm, 1985a, 1985b; Robinson et al., 1989; Kuikman et al., 1990). During these simultaneous processes, corn roots continue releasing organic compounds and removing any surplus of inorganic N, continuously affecting N dynamics.

According to Martin and Puckridge (1982), wheat plants release considerable amounts of C into the rhizosphere, but we observed no significant increase in the N supplied by wheat soil compared with bare soil (Table 1). This difference may be related to the amount and

**Table 1.** Calculation of N supplied by the planted and bare soils using plant biomass N and the soil inorganic N content at 0- to 60-cm depth at planting and 70 d after planting.

Treatments	At-planting inorganic soil N (A)	Shoot N (B)	Root N (C)	Final inorganic soil N (D)	N supplied by soil (E)†
kg ha <sup>-1</sup>					
<u>1998</u>					
Bare	35.7‡	—	—	148.0a§	112.3b
Corn	35.7	159.0	30.3	18.7b	172.3a
<u>1999</u>					
Bare	32.9‡	—	—	138.4a	105.5b
Corn	32.9	149.1a	26.9a	21.0c	164.1a
Wheat	32.9	82.4b	10.2b	56.7b	116.4b

† E = B + C + D - A.

‡ A single bulk sample was used for all treatments at planting.

§ Statistical comparisons are made within years. Least square means within a column followed by the same letter are not significantly different at  $P < 0.05$ .



**Table 2. Inorganic N concentration in the soil profile at the end of the experiment (70 d after planting).**

Soil depth cm	Treatments		
	Bare	Corn	Wheat
	mg kg <sup>-1</sup>		
	1998		
0–25	35.6a†	3.5a	–
25–60	5.9b	1.3b	–
	1999		
0–10	60.6a	8.0a	19.3a
10–25	19.2b	3.2b	9.1b
25–50	7.1c	2.0c	4.8c
50–60	3.7d	2.1c	3.2c
60–70	2.6d	1.7c	2.1c

† Statistical comparisons are made within years. Least square means within a column followed by the same letter are not significantly different at  $P < 0.05$ .

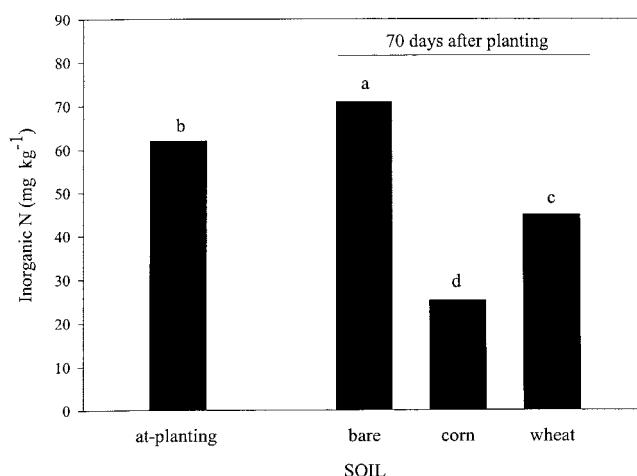
quality of rhizodeposits released into the soil. Merckx et al. (1987) reported that materials released from corn roots were incorporated into the microbial biomass to a higher degree than materials from wheat roots. In addition, corn roots may possess a more vigorous growth habit than wheat, allowing them to expose more organic material to decomposition and compete more efficiently with microbes. Wedin and Tilman (1990) found dramatic divergences of net N mineralization rates for five different grass species growing in initially identical soils, confirming the potential for strong interactions between plant species and N cycling. The length of the active growth period may be an additional factor influencing the higher N-supplying capacity found in the soil planted with corn. Corn plants were actively growing at the final days of the experiment, contrasting with the maturing stage observed in wheat plants. This longer period of active growth observed in corn plants may be important because of the additional period for rhizodeposit production and N uptake. Furthermore, the cropping sequence may have affected wheat performance compared with corn. Planting corn and wheat in a soil planted with wheat the previous year may be beneficial to corn but not necessarily to wheat.

The high N concentration in the Ap and the small amount in the C horizon indicate that deep N leaching was insignificant (Table 2). A more detailed sampling in 1999 shows that the concentration of N in the 60- to 70-cm depth was  $<3$  mg kg<sup>-1</sup> in all treatments. This low

**Table 3. Distribution of root biomass dry weight and root N in the soil profile based on recovered roots at the end of the experiment (70 d after planting).**

Soil depth cm	Corn		Wheat	
	Biomass	N	Biomass	N
	kg ha <sup>-1</sup>			
	1998			
0–60	3236	30.3	–	–
	1999			
0–25	3333a†	25.2a	625a	9.6a
25–50	205b	1.4b	13b	0.5b
50–60	41c	0.3c	2c	0.1c

† Statistical comparisons are made within years. Least square means within a column followed by the same letter are not significantly different at  $P < 0.05$ .



**Fig. 2. Net mineralized N at 70 d of laboratory incubation for at-planting soils and 70-d-after-planting soils in 1999. Units are based on a 10-cm sample depth. Letters indicate significant differences ( $P < 0.05$ ) in mineralized N after 70 d of incubation.**

N concentration and the high root concentration in the Ap horizon (Table 3) support the effectiveness of the experimental method in preventing leaching and deep root growth.

The increased net N mineralization suggested by the increase in the soil N-supplying capacity in presence of corn roots is supported by the laboratory incubations. The 70-d N pool size for the corn treatment was a third of the size of that for the bare soil treatment (Fig. 2). This implies that the additional inorganic N, supplied by the soil in presence of corn roots, was obtained primarily from that particular pool. The significant reduction in the size of the 70-d N pool for the soil planted with wheat was probably caused by greater N mineralization during root growth. It is possible that a portion of the mineralized N became unavailable for wheat plants due to microbial competition. In addition, N mineralization appears to be significant during wheat senescence at the final days of the experimental period. During this period, wheat uptake is minimal, and the mineralized N is expected to accumulate. Results from the monitoring sampling (data not shown) indicate that inorganic N decreased after Day 28 in both corn and wheat soils. In the soil planted with corn, this reduction continued in each sampling date thereafter. In contrast, the soil planted with wheat experienced a substantial increase in inorganic N after Day 56. The increase in the 70-d N pool for the bare soil compared with the at-planting soil (Fig. 2) may be due to the transformation of a portion of the less active N pool into more readily available forms during the May–June period with optimal soil moisture and temperature.

The greater mineralization of soil N in the presence of growing corn is undoubtedly linked to an increase in the mineralization of soil C. However, the laboratory incubation data indicate that the size of the 150-d C pool was not decreased after corn growth, whereas it was decreased in the wheat and bare soil treatments (Fig. 3). Rhizodeposition was sufficient to compensate for the C used during N mineralization in the soil planted

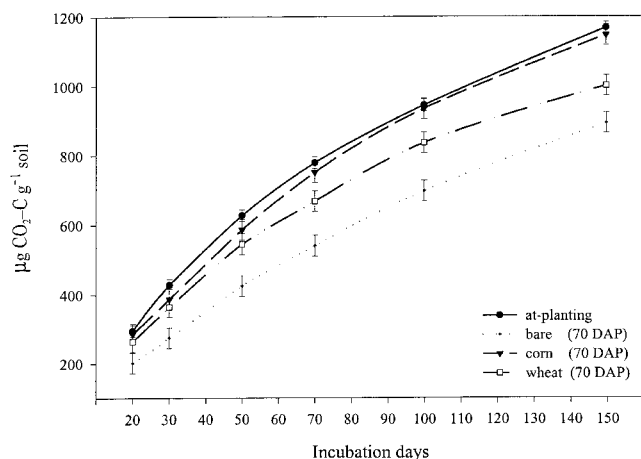


Fig. 3. Net mineralized C based on  $\text{CO}_2\text{-C}$  released during laboratory incubations for at-planting and 70-d-after-planting (70 DAP) soils in 1999. Units are based on a 10-cm sample depth. Error bars represent the standard errors of the least square means.

with corn but not in the soil planted with wheat. It is likely that root-derived C is a relatively more important energy source for microbial activity under corn than under wheat. Our data agree with those of Shields and Paul (1973), Reid and Goss (1982, 1983), and Haider et al. (1989, 1993) showing that growing plants tend to maintain soil C levels, whereas bare soil tends to decrease it.

We conclude that in the presence of an enhanced mineralizable N pool, corn roots increase N mineralization to a greater extent than do wheat roots. Further studies are needed to classify plant species and cultivars according to their level of stimulation in the presence of varying N pool sizes.

## ACKNOWLEDGMENTS

Our special thanks to the C.S. Mott Chair of Sustainable Agriculture and Michigan State Agricultural Experiment Station for their financial support that made this study possible.

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