ENHANCING SOIL NITROGEN AVAILABILITY IN CORN-BASED CROPPING SYSTEMS

Jose E. Sanchez, Richard R. Harwood, and Jeffrey Smeenk.

Abstract

The development of sustainable N management systems requires a better understanding of the contribution of on-farm resources to the active N pool size and its mineralization. This study explores the effect of substrate diversity and living corn roots on improving N supply through mineralization. A "diverse system", consisting of a corn (*Zea mays* L.)-corn-soybean (*Glycine max* L.)-wheat (*Triticum aestivum* L.) rotation with cover crops and fertilized with composted manure was compared with a corn monoculture with conventional fertilizers. Nitrogen mineralization was measured in situ and in laboratory incubations as was the ability of each soil to mineralize added compost and red clover (*Trifolium pratense*) residue. In addition, polyvinyl chloride (PVC) cylinders were placed in the "diverse system" plots before planting to confine or exclude roots of corn and wheat. The N supplying capacity of bare soil and soils planted with corn and wheat were calculated, and changes in N- and C-pool sizes were determined by laboratory incubations. Net mineralized N in the diverse system was 90 and 40% higher than that in the monoculture, at 70 and 150 days of laboratory incubations respectively. Comparable response was found in situ where a 70% higher net mineralization was observed in the diverse system at 70 d. The 70- and 150-d mineralizable N pools increased over time, but the ability of soil organisms to break down additional substrate did not change as a result of system diversity. At 150 d of laboratory incubation, a synergistic effect was observed when 5 Mg ha^{-1} of compost plus 5 Mg ha^{-1} of clover was added to both soils. The combination of the two organic materials mineralized more N than the sum of their individual mineralization results. Living corn roots increased the inorganic-N supplying capacity of the diverse soil by more than 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 that this effect may vary dramatically among plant species. A more diverse cropping system may increase the soil's capacity to supply N to a growing crop while maintaining desirable levels of soil organic matter. This is essential for the overall long-term productivity and sustainability of agricultural systems.

Introduction

Nitrogen mineralization makes a key contribution to the amount of available N in soil (Benedeti and Sebastiani, 1996), and its management could represent an excellent tool in achieving a sustainable N supply. Managing N mineralization efficiently is likely to result in a more synchronized N release, and has the potential to reduce N fertilizer dependence while promoting N recycling within agroecosystem boundaries. Nitrogen mineralization is regulated by abiotic factors such as soil moisture, temperature, and texture; and by the supply of above- and below-ground substrates (Jenny, 1980). In a practical sense, managing N mineralization implies managing organic inputs. The way in which organic materials influence mineralization is closely

related to their quality (Swift et al., 1979). The quality of a particular material is defined by its chemical composition, including C/N ratio, lignin, and polyphenol contents (Tian et al., 1997). Substrates with low N and high concentration of lignin and polyphenols decompose and release N slowly (Cornforth and Davis, 1968). In contrast, those rich in N with low lignin and polyphenol concentrations decompose rapidly (Handayanto et al., 1997). Therefore, a well-balanced diversity of materials entering the soil is expected to favor N availability for a growing crop while maintaining desirable levels of soil organic matter. It is accepted, from an ecological point of view, that enhanced species richness is beneficial for ecosystem performance (Kareiva, 1996; Tilman et al., 1996), but the question remains whether that is the case for below-ground subsystems (Wardle and Giller, 1996). Substrate diversity can be primarily achieved with the use of crop rotations, cover crops, and application of organic amendments (Gliessman, 1998). In this work we hypothesized that a "diverse system" would enhance the soil's active N pool size, therefore increasing its N mineralization potential. Two cropping systems were selected according to their level of diversity. The "diverse system" received residues of corn, soybean, wheat, red clover, crimson clover (*Trifolium incarnatum*), and annual ryegrass (*Lolium multiflorum*), as well as composted manure during each rotation cycle. This system was compared with a continuous corn monoculture where commercial fertilizer was the fertility source. Primary objectives were to determine if the diverse system would induce higher mineralization rates than the continuous corn monoculture, and to determine whether these two systems differ in their ability to mineralize added substrate. We also hypothesized that the presence of living corn roots would increase the soil's N supplying capacity in the "diverse system". Cylinders of PVC were placed in the "diverse" 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 study was conducted in the Living Field Laboratory (LFL), a long-term experiment established in 1993 at the W.K. Kellogg Biological Station located in Southwest Michigan. The LFL was designed to test various combinations of rotation and cover crops under several agronomic management regimes (Jones, 1998). The main goal is to test alternative strategies for achieving nutrient cycling efficiency and reducing chemical input requirements. The experimental design is a split-split-plot in four randomized complete blocks, with main plots for each management type. Both systems studied here used minimal application of pesticides, and banded herbicide plus cultivation for weed control. The main difference is in their fertility source and crop rotation: the monoculture system uses commercial fertilizer on continuous corn and the diverse system uses composted dairy manure to fertilize a corn-corn-soybean-wheat rotation. Red clover is frost-seeded into wheat, crimson clover is interseeded into first year corn, and annual ryegrass is interseeded into second year corn as cover crops. Before planting, approximately 4 Mg ha^{-1} (dry weight of non-sand material) of composted manure is added annually to all crops except soybean. Reduced tillage (chisel plow) was used throughout the LFL. The crop rotation was selected as the diverse system because residues of six plant species

in combination with composted manure are incorporated into the soil throughout the rotation cycle. These substrates have a wide range of C/N ratios. The lowest C/N ratio is provided by the red clover cover crop (14:1) and the highest by wheat stubble (80:1). This study used the 1st year corn (immediately following wheat + clover) plots because, historically, its grain yields have been comparable to those where fertilizer was used. In contrast, the continuous corn plots receive only corn residues (C/N ratio of 60:1) as organic substrate. These plots historically received P (triple superphosphate) and K (potassium chloride) before planting at a rate determined by a pre-planting soil test. Nitrogen was applied at planting (20-25 kg ha^{-1}) and sidedressed (ammonium nitrate) as recommended by the pre-sidedress nitrate test (Magdoff et al., 1984). For clarity we use the terms "diverse system" to describe the first year corn, and "monoculture" when referring to continuous corn. The C, N, and C/N ratios of soil from these cropping systems are described in Table 1. In early May 1998 and 1999, soil samples were taken at 0-10 cm depth from the diverse and monoculture cropping systems following tillage and immediately before planting and used in long-term laboratory incubations. Also in both years immediately after planting, microplots were established in the plots of the two cropping systems and were used for in situ incubations. No fertilizer was applied to microplots in the monoculture cropping system during the experimental period. Confining rings were also established in the "diverse system" plots to measure the effect of corn root on the soil N supplying capacity. PVC cylinders (70-cm long and 30-cm internal diameter) were used as confining rings. In 1998, six cylinders were inserted into the soil of each plot right after planting. The cylinders were pushed 60 cm deep to control root growth. Two corn plants were allowed to grow in 3 rings only. The remaining 3 rings were the control (bare) treatment. In 1999 we added 3 more cylinders to each subplot and wheat was included as new treatment. The corn hybrid used was Pioneer 3751, and the spring wheat variety was Russ. Immediately after insertion, soil samples at 0-10, 10-25, 25-60 cm depths were taken to determine initial mineral-N (NO_3 and NH_4) concentrations. Soil moisture was controlled to prevent deep leaching loss and enhance corn growth and soil microbial activity.

Laboratory incubations

Soils were sieved through a 6 mm screen and sub-sampled for moisture determination. Sixty-three 20-g dry weight equivalent aliquots of each sample were weighed into 100-mL plastic specimen cups. Treatments consisted of control, Com, 2Com, Clo, 2Clo, Com + Clo, Com + 2Clo, 2Com + Clo, and 2Com + 2Clo, where Com is 5 Mg ha^{-1} of composted manure and Clo is 2.5 Mg ha^{-1} of red clover. Both compost and clover were dried, finely ground, and sub-sampled for chemical analysis using the acid and neutral fiber detergent method (Goering and Van Soest, 1970). Selected chemical properties of added clover and compost are presented in Table 1. Calculations for the actual amount of material added to cups were based on a soil bulk density of 1.3 Mg m^{-3} and depth of 10 cm. The quantity of compost was based on dried weight of non-sand material. Following the additions, each cup was manually agitated to uniformly mix the soil and substrates. The soils were 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 20, 30, 50, 70, 100, and 150 d. At the end of each incubation interval, the corresponding samples were removed and frozen temporarily to stop microbial activity. Nitrate-N and NH_4-N concentrations were determined using the extraction technique described by Keeney and Nelson (1982) and a Lachat automated colorimetric analyzer (Lachat Instruments Inc. Milwaukee, WI).

In situ incubations

Four microplots of 2 m^2 were established in each plot and used for in situ incubation experiments (Raison et al., 1987). Red clover (5 Mg ha^{-1}, 2Clo), composted manure (10 Mg ha^{-1}, 2Com), and the combination 2Com + 2Clo were used in this experiment along with control. The clover was dried, and applied unground. The treatments were randomly assigned to microplots, the materials uniformly added to the soil surface, and mostly incorporated in the 0-10 cm depth using a long-tined hand cultivator. Fifteen PVC tubes (30-cm long and 5-cm i.d.) were inserted to a depth of 25 cm in the corn row of each microplot to prevent root in-growth. After tube insertion, soil samples were taken at 0-10 cm from each microplot to measure initial mineral N. Soil moisture was controlled in the cylinder by use of temporary rain shelters and periodic addition of water to prevent extreme wetting-drying events, and to minimize NO_3 leaching and denitrification. On days 14, 28, 42, 56, and 70 after insertion, three cylinders from each microplot were randomly selected and removed. Samples were taken from 0-10 cm depth within each cylinder using a 1.9-cm diam-soil probe. Soil mineral N was determined according to the method mentioned in the laboratory incubation section.

Plant roots effect on N supplying capacity

After 70 d, corn and wheat biomass were collected and the cylinder removed from the ground. Soil samples at 0-10, 10-25, 25-50, 50-60 cm depth were taken from the intact cores. The inorganic-N supplying capacity of soil was calculated using an N balance approach:

$N_{SC}=N_{Harvested} + \Delta N_{Inorganic\ (soil)}$ where N_{SC} is the cumulative inorganic-N supplied by soil during the 70 d in the field, $N_{Harvested}$ is the harvested shoot and root biomass N, $\Delta N_{Inorganic}$ is the N difference between initial and final soil inorganic-N content measured at 0-60 cm depth. Laboratory incubations using soil samples collected at May 13 (initial) and July 20 (final) at 0-10 cm depth were implemented to measure the 70-d N pool sizes.

Mineralized Nitrogen Calculations

Net N mineralization using laboratory and in situ incubations was calculated using the difference between inorganic N content at the end of the incubation period and at day 0. For the in situ incubation we assumed that deep N leaching was prevented and gaseous N loss minimized. Linn and Doran (1984) reported that in a well-drained soil the relative amount of anaerobic denitrification is negligible. Also, a recent long-term study in an adjacent field indicated that N loss due to denitrification ranged from 1.3 to 0.4 kg ha^{-1} per year (Robertson et al., 2000). Our agronomic treatments were nearly identical to that study. The amount of net N mineralized from added substrate was calculated by subtracting the mineralized N of the control from the treatments with added substrate. The calculated amount is expressed as a percentage of the initial amounts of N added as clover, and/or compost.

Summary of Results

Net mineralized N in the diverse system was 90 and 40% higher than the monoculture at 70 and 150 d of laboratory incubation respectively (Fig. 1). When substrates were added, the diverse system still mineralized more N than the monoculture when comparing the same treatment and incubation time. The net N mineralization was highest when 5 Mg ha^{-1} of clover was applied to this cropping system. The lowest net mineralization was observed in the monoculture without clover. The monoculture was able to produce as much mineral-N as the diverse system when it

received an extra 2.5 Mg ha^{-1} of clover. In general, the addition of compost did not significantly alter net mineralization. The percentage of N (from added substrates) mineralized at 70 and 150 d of laboratory incubation were not significantly different between cropping systems (Table 2). Clover additions released considerable N during the first 70 d, and small amounts from 70 to 150 d of incubation. The proportion of N mineralized from each substrate remained constant as the rate of added substrate doubled. At 150 d of incubation, the proportion of each substrate N mineralized increased, as calculated from weighted average calculation, when 5 Mg ha^{-1} of compost and 5 Mg ha^{-1} of clover were combined (calculation not shown). The in situ net N mineralization in the diverse system was 70% higher than that of the monoculture after 70 d (Fig. 2), agreeing with the pattern observed in the laboratory. When substrates were applied, the diverse system also produced more N than the monoculture. The highest N mineralizations were obtained when 5 Mg ha^{-1} of clover was added to the diverse system. The monoculture without clover produced the lowest net mineralized N but released N in comparable amount to the diverse system (in absence of clover) when 5 Mg ha^{-1} of clover was added. The addition of compost did not significantly increase mineralized N in either soil. The percentages of mineralized N in situ from the additions were consistent with those measured in the laboratory (Table 2). Thus, no significant differences between the two cropping systems in the %N mineralized of added materials were observed. The low mineralization rates of compost caused a dilution effect on the percentage of mineralized N from the combined materials. The soil N supplying capacity was increased over 50% in the presence of corn roots compared to bare soil for the two years (Fig. 3). We suggest that this increase is influenced by the stimulating effect of corn roots on N mineralization. The production of rhizodeposits is a direct root control of N mineralization. This root-derived C acts as a "fuel" for a sequence of events that would not occur in the absence of roots (Clarholm, 1985). First, the presence of these high-energy C materials increases N-immobilization because soil microorganisms are typically C-limited. Second, N mineralization also increases because of the abundance of low C/N ratio substrate in the "diverse system" soil. The ability of this soil to supply N in presence of corn roots is enhanced because the expected increased immobilization was counter-balanced by much greater mineralization. No significant difference was found when comparing bare and wheat soils in their ability to supply N (Fig. 3). In the presence of an enhanced active N pool, corn roots appear to increase N mineralization to a greater extent than wheat roots. It is likely that root-derived C is a relatively more important energy source for microbial activity under corn than under wheat. In this study, we suggest that enhancing the active N pool is necessary before any stimulation can be realized. At 70 d of incubation, the active N pool size for the corn treatment was a third the size of the bare treatment (Fig. 4). These results demonstrate that the additional mineralized N in presence of corn roots was primarily obtained from the active N pool. We conclude that farming practices promoting diversity have the potential to dramatically increase the size of the active N pool and decrease fertilizer N requirement, because the use of diverse crop rotations, legume cover crops, and organic amendments from animal sources adds significant organic N to the soil. The ability of soil organisms to break down additional substrate did not change as a result of previous input diversity, but it may have increased due to simultaneous input diversity. The additional gain in N mineralization by adding clover and compost combined was not definitely answered by this research. A possible synergistic effect was shown in the laboratory but was not found in situ, where incubations were not as extensive as in the laboratory. Corn roots stimulate N mineralization in the presence of an enhanced active N pool. There is evidence of varying level of stimulation among crops. Further studies are needed to classify plant species

and cultivars according to their level of stimulation in presence of a large active N pool. This information is vital for designing sustainable cropping systems.

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Table 1. Selected chemical properties of soil from the diverse and monoculture cropping systems, and the organic materials added in the laboratory and in situ incubations.

Material	C/N	Total C	Total N	Lignin	Cellulose	Hemi-cellulose
				g kg^{-1}		
Diverse soil	11.5	15.0	1.3	-	-	-
Monoculture soil	11.0	11.0	1.0	-	-	-
Young red clover	10.6	433.0	41.0	106.0	100.0	94.0
Composted manure†	13.1	340.0	26.0	90.0	692.0	53.0

† Chemical properties based on weight of non-sand materials. Sand had been added as bedding in the dairy, and was present in the compost at approximately 50% as determined by water column separation.

Table 2. Net mineralized N from added substrates for two cropping systems at two incubation dates, expressed as percentage of added N.

Treatments	Diverse system		Monoculture	
	%			
	Laboratory incubation			
	70 days	150 days	70 days	150 days
Com	0	0	2	2
Clo	30	30	31	31
2Com	0	6	3	4
2Clo	30	34	32	32
Com + Clo	11	15	13	16
Com + 2Clo	21	30	19	29
2Com + Clo	9	12	11	12
2Com + 2Clo	14	18	14	17
	In situ incubation			
2Com	6	-	1	-
2Clo	29	-	24	-
2Com + 2Clo	13	-	12	-

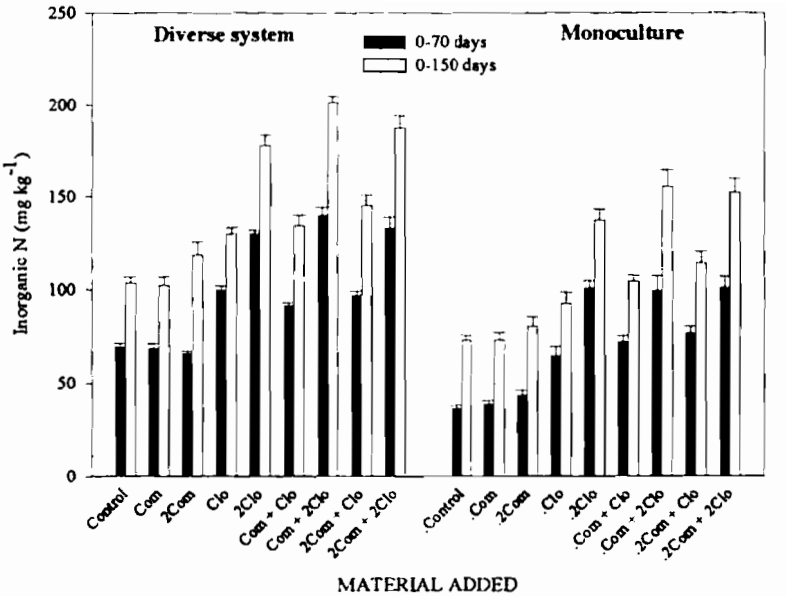

Fig. 1 Net mineralized N after 70 and 150 d of laboratory incubation for soil sampled from the diverse and monoculture cropping systems. Error bars represent the standard errors of the means.

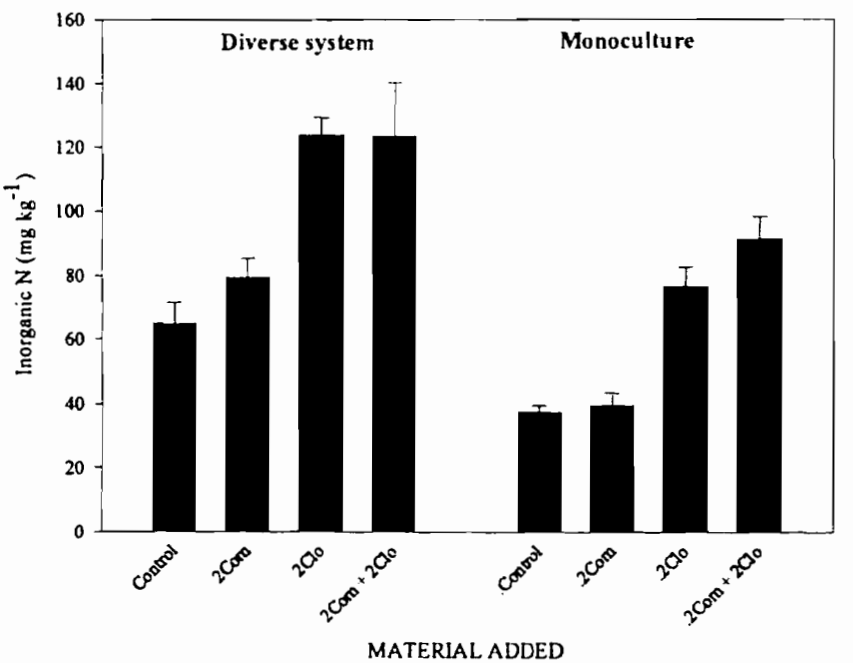

Fig. 2. Net mineralized N after 70 d of in situ incubation for the diverse and monoculture cropping systems. Error bars represent the standard errors of the means.

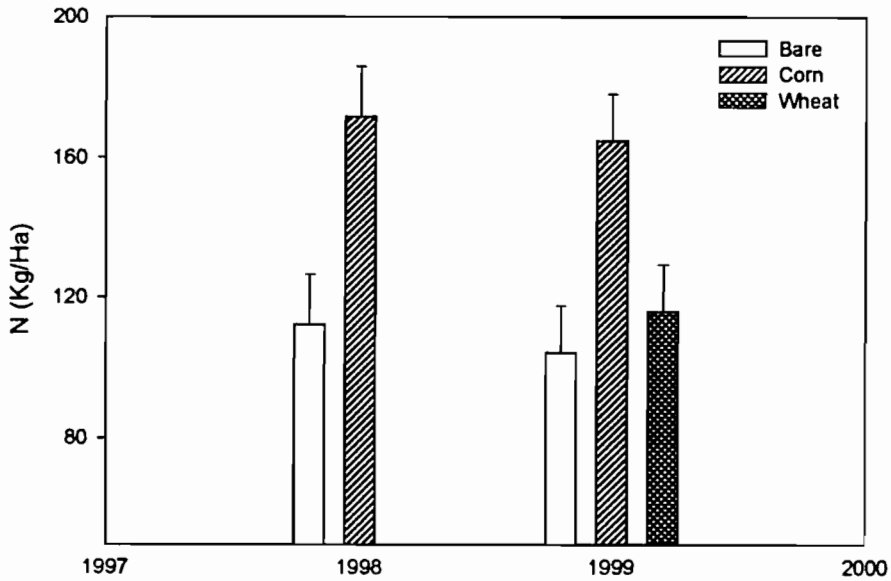

Fig. 3. Nitrogen supplied by the planted (corn and wheat) and bare soils 70 d after planting. Calculations were based on a 0-60 cm soil profile depth. Error bars represent the standard errors of the means.

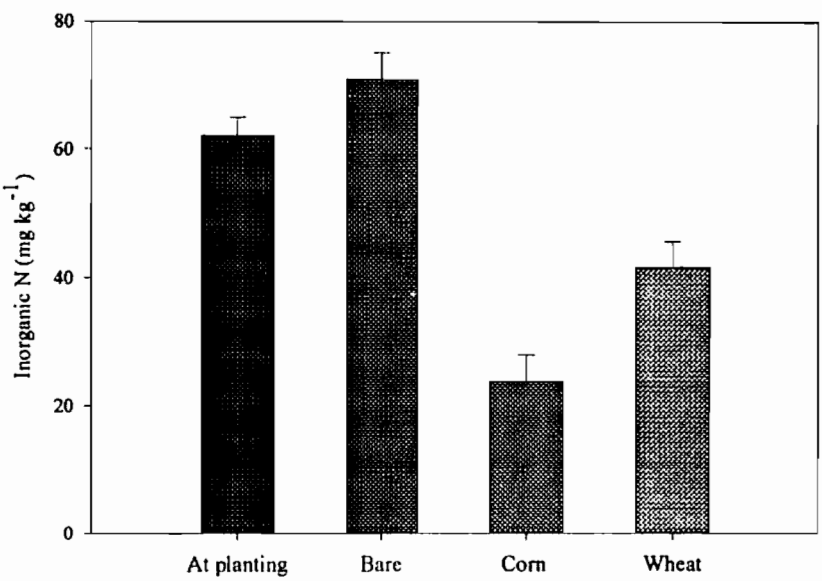

Fig. 4. Net mineralized N at 70 d of laboratory incubation for at-planting and 70 d after planting soils in 1999. Units are based on a 10 cm sample depth. Error bars represent the standard errors of the means.

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