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Source of the soybean N credit in maize production

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Abstract

Nitrogen response trials throughout the United States Corn Belt show that economic optimum rates of N fertilization are usually less for maize (*Zea mays* L.) following soybean (*Glycine max* L.) than for maize following maize; however, the cause of this rotation effect is not fully understood. The objective of this study was to investigate the source of the apparent N contribution from soybean to maize (soybean N credit) by comparing soil N mineralization rates in field plots of unfertilized maize that had either nodulated soybean, non-nodulated soybean, or maize as the previous crop. Crop yields, plant N accumulation, soil inorganic N, and net soil mineralization were measured. Both grain yield (6.3 vs. 2.8 Mg ha^{-1}) and above-ground N accumulation (97 vs. 71 kg ha^{-1}) were greatly increased when maize followed nodulated soybean compared with maize following maize. A partial benefit to yield and N accumulation was also observed for maize following non-nodulated soybean. Cumulative net soil N mineralization following nodulated soybean, non-nodulated soybean, and maize was 112, 92 and 79 kg N ha^{-1}, respectively. Net mineralization of soil N appeared to be influenced by both quality (C:N ratio) and quantity of residue from the previous crop. In addition to an increase in plant available N from mineralization, the amount of soil inorganic N (especially in soil 5 cm from the row) was greater following nodulated soybean than non-nodulated soybean or maize. Based on these data, the soybean N credit appears to result from a combination of a decrease in net soil mineralization in continuous maize production and an increase in residual soil N from symbiotic fixation.

Introduction

Soil fertility benefits from a legume in rotation with a cereal crop have long been recognized, and today the predominant cropping system in the United States Maize Belt is a maize/soybean rotation. Numerous studies have shown that the N fertilizer requirements for economically optimum yields are less for maize following soybean than for maize following maize (Heichel and Barnes, 1984; Nafziger et al., 1984; Peterson and Varvel, 1988; Shrader et al., 1966). The lower N rate needed to optimize maize yields when following soybean compared with continuous maize is considered to be the legume N contribution or 'N credit'. A general guide for producers in several midwestern states is to adjust the N fertilizer rate downward by 45 kg N ha^{-1} when growing maize following soybean compared with maize following maize (Kurtz et al., 1984).

Throughout much of the Midwest, NO_3^- concentrations in surface waters that exceed the United States Environmental Protection Agency drinking water standard of 10 mg N L^{-1} have been linked to N fertilizer use (David et al., 1997; Fausey et al., 1995; Goolsby et al., 1999; Newbould, 1989). Furthermore, recent studies have shown that high rates of N fertilization results in soil NO_3^- pools that are susceptible to leaching, especially in tile drained areas (Gentry et al., 1998). Thus, a better understanding of the soybean N credit in maize/soybean rotations is needed to improve maize N fertilizer recommendations, reduce the tendency to over apply N, and limit losses of NO_3^- to surface waters.

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Attempts to quantify the observed soybean N credit indicate that it varies both spatially and temporally. Bundy et al. (1993) showed that maize following soybean produced a higher yield, and had greater plant N accumulation on silt loam soils, but not on irrigated sands. Others have shown that the soybean N credit varies with year, soil organic matter content, and yield of the previous soybean crop (Crookston et al., 1991; Hesterman, 1986; Meese et al., 1991).

Early speculation into the source of the soybean N credit focused on greater carryover of N associated with symbiotic N_2 fixation (Shrader et al., 1966; Sutherland et al., 1961). However, unlike a legume used for forage, soybean grown for grain removes more N from the soil than is added by symbiotic fixation (Heichel and Barnes, 1984; Zapata et al., 1987). Although this net removal of soil N from soybean production is well documented, root nodules of the soybean/Bradyrhyzobium association are known to contain high N concentrations (40–50 g kg^{-1}) (Harper, 1974). In addition, several studies have shown that up to 10% of the plant N is released from the root and nodules of legumes during the growing season (Brophy and Heichel, 1989), either through leakage from intact roots (Ta et al., 1986), or through an increase in root and nodule breakdown following harvest (Brophy and Heichel, 1989). Although this release of fixed N into the soil is believed to be the source of transferred N from intercropped legumes to non-legumes (Martin et al., 1991), other research does not support the view that N release plays a major role in the soybean N credit (Maloney et al., 1999).

Using soil incubations in the laboratory, Green and Blackmer (1995) found that N immobilization accompanying residue decomposition may be an important factor influencing the difference in N fertilizer requirement between maize following maize and maize following soybean More specifically, they suggested that net immobilization of-soil N could be affected by the quality (C:N ratio) and quantity of crop residue. While this laboratory work of Green and Blackmer (1995) furthers our understanding of the soybean N credit, we could not find similar published work done in the field which implicated N immobilization by maize residues as a major factor contributing to the soybean N credit

The objective of this study was to investigate the source of the soybean N credit by comparing soil N mineralization in field plots of unfertilized maize following either nodulated soybean, non-nodulated soybean, or fertilized maize. While Maloney (1999) used a similar approach to determine the impact of N_2 fixation of soybean on the yield of the subsequent maize crop, we could not find any other studies using nodulated soybean, non-nodulated soybean, and maize as previous crops to determine the extent of soil N mineralization. A secondary objective was to compare two independent methods for estimating net soil N mineralization; the buried N bag technique vs. N accumulation by unfertilized maize plants.

Materials and methods

Site description

The research site was located in the center of a 4.3 ha field on the Department of Crop Sciences Research and Education Center in Urbana, IL. This field was chosen because for the previous 10 years it had been divided into two equal halves where each half was alternately cropped to either maize or soybean in a maize–soybean rotation. The soil type along both sides of the centerline (which ran north/south) was a Drummer silty clay loam (fine-silty, mixed mesic Typic Haplaquolls) and all experimental plots were located within this soil type. The field slope was $<1\%$ with a downward gradient from south to north. The north end of the field is within the effective area of influence (50 m) of a 20 cm diameter drainage tile. Daily precipitation and soil temperature at the 10 cm depth was recorded within 1 km of the site.

Analysis of eight soil samples (four on each side of the field centerline) prior to the start of the experiment indicated that the Drummer soil was uniform throughout the entire research area. The range in organic matter for the 0–10 cm depth was 4.5–5.0% (mean of 4.8%) and 4.5–4.8% (mean of 4.7%) on the east and west sides, respectively. The average organic matter for the 10–30 and 30–50 cm depths was 4.4 and 3.2% on the east side, and 4.6 and 3.3% on the west side, respectively. The total N in the top 50 cm of soil was 8890 kg N ha^{-1} on the east side and 8940 kg N ha^{-1} on the west side. There was a slight field trend of increasing percent organic matter and total N from south to north, but no trend was observed from east to west.

Experimental design

In 1998, paired plots of a maize hybrid (Pioneer 33A 14) receiving either 0 or 168 kg ha^{-1} of N fertilizer were arranged in a randomized complete block experimental design with six replicates along the east side of the field centerline. Maize plots were planted on 20 May to obtain a plant density of 69 160 plants ha^{-1} and N fertilizer (as granular $(NH_4)_2SO_4$) was broadcast by hand on 2 June. Along the west side of the centerline, paired plots of nodulated and non-nodulated isolines of a MG III soybean cultivar (Williams 82) were arranged in a randomized complete block experimental design with six replicates to exactly align with the adjacent maize plots. Soybean plots were planted on 25 May at a density of 350 000 plants ha^{-1}. For both maize and soybean, an experimental unit consisted of a six-row plot, with rows 6.1 m long and spaced 0.76 m apart.

In 1999, the maize hybrid Pioneer 33A14 was grown without N fertilization on a portion of the research area established in 1998, to achieve the following three rotation treatments: nodulated soybean followed by unfertilized maize (Nod soy); non-nodulated soybean followed by unfertilized maize (Non-nod soy); and fertilized maize (168 kg N ha^{-1}) followed by unfertilized maize (Maize). The maize was planted on 3 May to achieve a density of 69 160 plants ha^{-1}. For the soil measurements we used six replicates through the 28 April 1999 samplings, and three replicates for the remainder of the experiment.

Plant sampling and analysis

To determine N accumulation by soybean plants, above-ground portions of consecutive plants in a representative 50 cm section of row were harvested from each plot at the late R6 growth stage (Ritchie et al., 1997). Plants were harvested at this stage to minimize loss of tissue due to natural leaf abscission. This growth stage occurred on 3 September for non-nodulated plants and 6 September for nodulated plants. For maize N accumulation, four representative plants from each of the two middle rows (a total of eight plants) were harvested at physiological grain maturity from each plot on 17 Sept. 1998 and 5 Sept 1999.

Soybean plants were divided into two fractions (leaves and stalk, and pods and seeds), and maize plants were divided into three fractions (leaves and stalk; husk, shank, tassel, and cob; and grain). For maize, the leaves and stalk fraction was weighed fresh, then shredded, and a sub-sample collected and weighed fresh. All plant fractions were dried to constant weight at 80 °C in a forced draft oven for biomass determination. Dried samples were then ground to pass through a 2 mm mesh screen and analyzed for total N using a combustion technique (Fissons NA 2000 N Analyzer).

For grain yield estimates of soybean, the two center rows of each plot were combine harvested on 24 Sept. 1998. Although peak plant N accumulation occurs by the late R6 growth stage, biomass accumulation and partitioning of dry weight into the seed is not quite complete at this stage (Crafts-Brandner et al., 1984). Therefore, seed sub-samples were taken during the combine harvest and analyzed for N concentration as described above. Soybean stover N was calculated as the difference between total plant N minus seed N. For estimates of maize grain yield, the two center rows were combine harvested on 12 Oct. 1998 and 16 Sept. 1999. The grain weight of the eight plants harvested for N accumulation was added to the weight of the combine-harvested maize to give the total yield.

Data for grain yield, plant N accumulation, and stover N were statistically analyzed by analysis of variance procedures and t-tests or a Fisher's protected LSD ($P \leq 0.05$) were used to compare means of the experimental treatments.

Soil sampling

In the spring of 1998 before N fertilizer was applied, four soil samples (each a composite of three cores), approximately 10 m apart and 10 m from the field centerline, were collected on each side of the centerline to a depth of 50 cm. Sample cores were divided into 3 depths (0–10, 10–30 and 30–50 cm) and analyzed for organic matter and total N content. Soil was air-dried, sieved (2 mm), and sub-samples ground (40 mesh). Moisture content was determined by oven-drying the sample cores at 105 °C for 48 h. Total N was determined on ground samples by Kjedahl digestion followed by an automated phenate method using a Technicon autoanalyzer. Organic matter was determined by the loss-on-ignition method (David, 1988).

To determine the level of inorganic N in the soil, soil samples (composite of two adjacent cores) were collected from all plots between 12 August 1998 and 30 August 1999. Soil samples were collected from each plot based on the distance from the crop row (5, 19 and 38 cm from the row). All soil samples were collected at two depths using a 3.2 cm diameter corer for the 0–10 cm depth and a 1.9 cm diameter corer for the 10–30 cm depth. Because of a difference in soil bulk density between the two depths (average of 1.18

g cm^{-3} for 0–10 cm and 1.41 g cm^{-3} for 10–30 cm), these two core sizes contained approximately the same amount of soil. Inorganic N was extracted from field moist samples using 1 N KCl. The soil extract was analyzed for NO_3^- by cadmium reduction and NH_4^+ by an automated phenate method using a Technicon autoanalyzer (APHA, 1995).

To quantify N mineralization, a buried N bag experiment was initiated on 12 Oct. 1998 and continued until 30 Aug. 1999 (Eno, 1960; Paschke et al., 1989). Soil samples from each plot were collected as described above (three distances from the row, two core sizes, and two depths), except that three adjacent cores were taken. The middle cores (0–10 and 10–30 cm) were individually sealed in polyethylene bags, placed in a pit at the end of each plot, and buried horizontally at the midpoint of the core depth (5 and 20 cm). The two outer cores were composited by depth and analyzed for inorganic N, as previously described, in order to determine the initial concentrations of NO_3^- and NH_4^+ in the buried bag. Bags were allowed to incubate in the soil at ambient temperatures until they were removed at the next sampling date. Net mineralization was estimated as the sum of net changes in NO_3^- and NH_4^+ for each soil sample during the incubation period. All values were corrected for moisture content by oven-drying sub-samples at 105 °C for 48 h.

Data for the levels of inorganic soil N, the mean daily mineralization rates, and the cumulative N mineralization are presented in graphic form for individual sampling dates, or as a function of mid-point sampling periods. Because a variable number of replicates were used (i.e. six for the first 4 samplings, and 3 for the next four samplings), the data are presented with bars equivalent to one standard error of the mean to give some indication of experimental variability. For instances where the error bars are not present, the standard error of the mean was too small to depict on the figures. For soil N data, those measurements conducted between October 98 and April 99 were on plots which did not have an actively growing crop, and as such are indicative of the residual effects of the preceding crop on soil N levels. Conversely, those soil measurements taken after May 98 were on plots containing an actively growing maize crop, and thus include the interactive effects of crop uptake.

Table 1. Grain yield and N accumulation in all above-ground plant parts, and in the stover (all above-ground non-grain plant parts), in 1998 as a function of nodulation condition for soybean and fertilization level for maize

Crop	Grain yield Mg ha $^{-1}$	Above-ground N accumulation kg ha^{-1}	Stover N kg ha^{-1}
Nodulated soybean	2.3	157	17
Non-nodulated soybean	1.1	66	11
t-test	**	**	**
Maize (168 kg N ha^{-1})	8.5	173	48
Maize (0 kg N ha^{-1})	3.7	70	22
t-test	**	**	**

**Indicates significant difference ($P \leq 0.01$) between nodulated and non-nodulated soybean or fertilized and unfertilized maize according to a *t*-test.

Maize rootworm treatment and rating

To minimize any potential impacts of maize rootworm (*Diabrotica* sp.) larval feeding on maize roots, all plots in 1999 received an in-furrow insecticide application of Aztec at a rate of 8.1 kg ha^{-1}. Roots of maize plants were also rated for rootworm larval injury in order to assess any damage that might be related to this insect pest in continuous maize compared with the rotation treatments. This rating involved digging roots of three maize plants at the R3 growth stage (Ritchie et al., 1997) and using the Iowa scale of 1 to 6, where 1 equates to no damage and 6 equates to three or more nodes of roots destroyed (Hills and Peters, 1971). In addition to root ratings, adult rootworm beetle traps were installed to further evaluate whether rootworms were present. Because there was no significant difference in adult rootworm presence, or in root feeding damage, for continuous maize compared with the rotation treatments these data are not presented.

Results and discussion

Previous N titration studies with maize have consistently shown that this field is N responsive over a wide range of environmental conditions (Below, 1995). From 1989 through 1998, grain yield averages for maize on this field were 5.5 Mg ha^{-1} for unfertilized plots and 9.1 Mg ha^{-1} for plots receiving 168 kg N ha^{-1} (F.E. Below, unpublished data). In 1998, grain yields for unfertilized and fertilized maize plots were 3.7 and 8.5 Mg ha^{-1}, respectively, which is 49

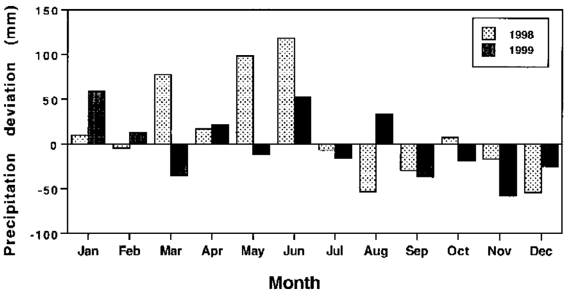

Figure 1. Monthly precipitation during 1998 and 1999 depicted as the deviation from the 30 year average. Bars above the zero line indicate months with precipitation in excess, and bars below the zero line months with precipitation lower than the 30 year average.

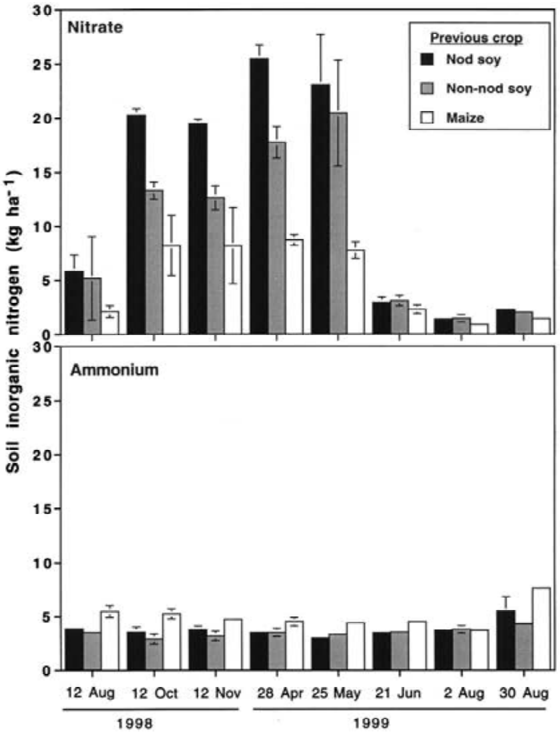

Figure 2. Mean contents of NO_3^- and NH_4^+ in the top 30 cm of soil over a one year period for plots containing three different cropping sequences. The initial measurement taken on 12 August 98 was from plots containing growing plants of the respective previous crops, while measurements taken between October 98 and 28 April 99 were on plots containing no growing crop, and those taken between May and 30 August 99 on plots containing growing maize. The standard error of the mean was calculated for each sampling date, and when absent it was too small to depict on the figures.

and 7% less than the 10 year averages at this site (Table 1). For nodulated soybean, the 10 year average grain yield was 2.9 Mg ha^{-1} at this site (F.E. Below, unpublished data). The nodulated soybean in 1998 yielded 2.3 Mg ha^{-1}, which was 26% less than the 10 year average (Table 1). A historical average yield of non-nodulated soybean was not available for this site, although the yield of non-nodulated plants in 1998 was lower than expected when compared to other studies (Crafts-Brandner et al., 1984; Harper, 1974; Vasilas et al., 1984). The amount and distribution of precipitation during the 1998 growing season are thought to have caused this reduced yield.

In May and June of 1998, the research site received well-above average precipitation (Figure 1), which likely leached residual soil NO_3^- below the rooting zone and/or created conditions conducive to denitrification. This pattern was followed by average, or drier than average, precipitation for the remainder of the growing season, and for the rest of the calendar year. Given the wet spring and the dry period during grain fill, N deficiency was readily apparent in both the unfertilized maize and the non-nodulated soybean crops.

Without supplemental N from either symbiotic fixation or fertilizer, the non-nodulated soybean and the unfertilized maize crops only accumulated 66 and 70 kg of N ha^{-1}, respectively (Table 1). Based on the similarity of these values we speculate that both crops absorbed any mineralized N as quickly as it was released from the soil.

The recovery of fertilizer N (calculated as the difference in plant N accumulation between the fertilized and unfertilized maize divided by the fertilization rate) was 61% in 1998, which is higher than the range (i.e. 30–50%) commonly found for high organic matter soils in the Midwest (Oberle and Keeney, 1990; Wienhold et al., 1995). Assuming that the uptake of soil N by nodulated and non-nodulated soybean was the same, the difference method indicated that 58% of the N accumulated by nodulated soybean plants resulted from atmospheric N_2 fixation (Table 1). Similar to the N fertilizer recovery efficiency observed for maize, the soybean N fixation estimate was also greater than the range (25–50%) typically found in high organic matter soils of the Midwest (Harper, 1987).

Results from the soil sampling conducted on 12 August 1998 showed that the inorganic N (NO_3^- and NH_4^+) content was less than 10 kg N ha^{-1} for all treatments (Figure 2). The 12 August sampling date occurred during the period of peak N requirement for both crops (Harper, 1987; Karlen et al., 1988), and apparently the available soil N was low as a result of plant uptake. Additionally the maize plots which had been fertilized with 168 kg N ha^{-1}, and were also low at this time indicative of depletion by plant uptake.

Soil inorganic N data showed that the H^+ content remained nearly constant for a given treatment throughout the experiment; therefore, most of the variation in total inorganic N resulted from changes in NO_3^- content (Figure 2). At the end of the 1998 cropping year (and just prior to the onset of the mineralization measurements via the buried N bags on 12 October 1998), the total inorganic N content in the top 30 cm of soil was 24, 17 and 14 kg N ha^{-1} when the previous crop was nodulated soybean, non-nodulated soybean, or maize, respectively (Figure 2). For all three cropping sequences, these values represented an increase in soil inorganic N compared with soil samples collected on 12 August when the crop was still growing, with the largest increase for nodulated soybean as the previous crop and the smallest for maize.

The difference in soil inorganic N between the soybean and maize plots following harvest may be the result of differences in the degradation rate of the crop residues. Although there was no fall tillage on any of the experimental plots, the soybean stover appeared to quickly degrade (especially the leaves). Power et al. (1986) found that mineralization of organic N in soybean residue is relatively rapid compared with maize, and thus can contribute N to the soil inorganic N pool almost immediately following crop harvest. Similarly, Broder and Wagner (1988) showed that soybean residue contains a greater proportion of water soluble components than maize residue, which allows for more rapid decomposition. We speculate that little N was released from the maize residue between the time of crop harvest and the October sampling date.

The difference in soil inorganic N between the nodulated and non-nodulated soybean plots on 12 October 1998 may have also resulted from the decomposition of N-rich root nodules. At this time, soil core data averaged by distance from the row showed greater inorganic N content in cores collected 5 cm from the rows of nodulated soybean plants compared with cores collected 19 cm from the rows (Figure 3). Inorganic N contents were similar between cores collected 19 and 38 cm from the rows. The higher N level closer to the row of nodulated soybean plots persisted through the 28 April sampling. There was also a trend for differences in soil inorganic N based on distance from the row for the non-nodulated soybean, but the magnitude of the values was less and there was greater variability. The soil inorganic N content in maize plots was lower than in the soybean plots and showed no observable trend based on distance from the row (Figure 3).

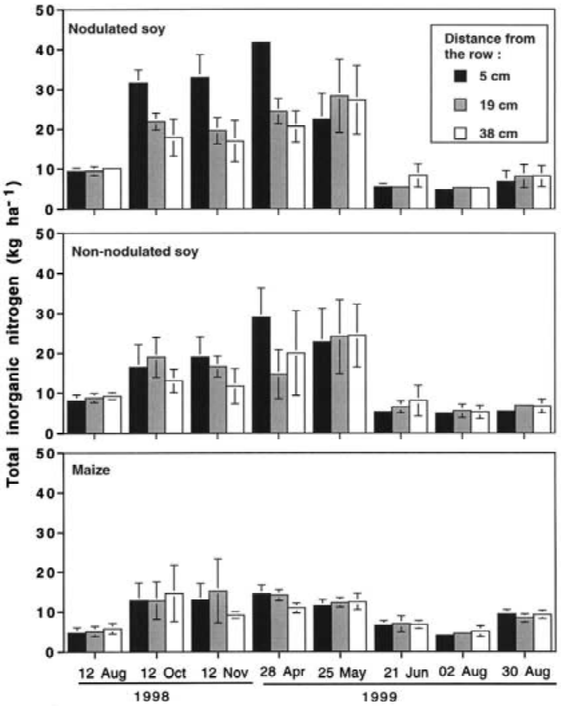

Figure 3. Total inorganic soil N content based on distance from the crop row in the top 30 cm of soil for plots containing three different cropping sequences. The initial measurement taken on 12 August 98 was from plots containing growing plants of the respective previous crops, while measurements taken between October 98 and 28 April 99 were on plots containing no growing crop, and those taken between May and 30 August 99 on plots containing growing maize. The standard error of the mean was calculated for each sampling date, and when absent it was too small to depict on the figures.

Some studies have shown that recently fixed N is released from soybean root nodules throughout the season, as well as after harvest (Brophy and Heichel, 1989; Ta et al., 1986). This N, however, may be lost prior to crop uptake, especially on coarse textured soils (Angle, 1990; Bundy et al., 1993). Although NO_3^- has been shown to quickly flush through a tile-drained Drummer soil (David et al., 1997; Gentry et al., 1998), the inorganic N data in this study showed that there was more plant available N at planting following nodulated soybean than following fertilized maize (Figure 2). Although the inorganic N contents indicate clear differences in instantaneous amounts of available N among all three treatments, they do not facilitate quantification of mineralization.

Mineralization was determined by measuring the net change of NO_3^- and NH_4^+ in the buried N bags

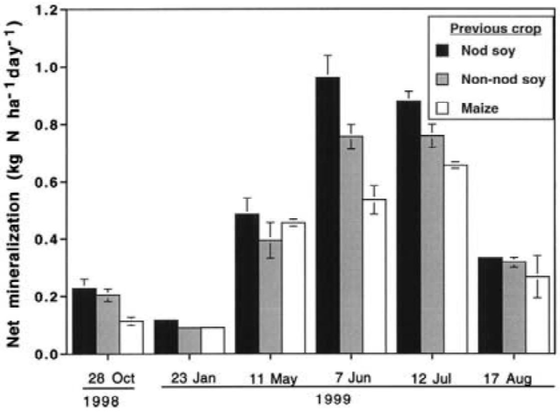

Figure 4. Mean daily net mineralization rates in the top 30 cm of soil prior to (i.e. during the fall and winter), and during, the 1999 growing season for plots containing three different cropping sequences. Data are plotted as a function of the mid-point of each incubation period. The standard error of the mean was calculated for each sampling date, and when absent it was too small to depict on the figures.

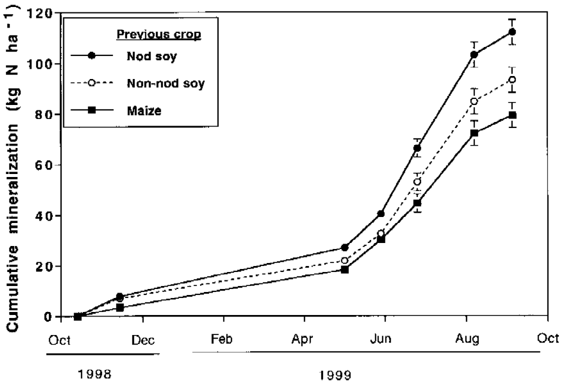

Figure 5. Mean cumulative mineralization in the top 30 cm of soil for plots containing three different cropping sequences. The standard error of the mean was calculated for each sampling date, and when absent it was too small to depict on the figures.

at intervals following the 1998 growing season and continuing through the 1999 growing season (Figure 4). Because the NH_4^+ content in the buried bags exhibited little change for all the incubation periods, the net mineralization rate was determined by the increase in NO_3^- content. The consistently small content, and minimal change in NH_4^+ in the bags, indicated a steady state between NH_4^+ formation and its conversion to NO_3^-.

For all three cropping sequences, the net mineralization rate was lowest during 12 November 1998–28 April 1999 (midpoint of the incubation period was 23 January 1999), which was expected based on the lower winter temperatures. When nodulated soybean was the previous crop, the mineralization rates peaked at 0.96 kg N ha^{-1} d^{-1} during the 7 June 1999 incubation period, compared to a mineralization rate peak of 0.66 kg N ha^{-1} d^{-1} during the 12 July 1999 incubation period when maize followed maize. When non-nodulated soybean was the previous crop, the mineralization rate remained constant at 0.76 kg N ha^{-1} d^{-1} during both of these incubation periods (Figure 4).

Contrary to the findings of Gentry et al. (1998), we did not observe a period of net N immobilization in the fall after crop harvest Although there was a trend for greater mineralization of soil N immediately following the soybean crop in 1998, the differences in cumulative net mineralization between the cropping sequences became more pronounced during the maize growing season in 1999 (Figure 5). We speculate that the previous-crop induced differences in soil mineralization may have been delayed in this study, as a result of the crop residue being incorporated in the spring rather than in the fall (Crookston and Kurle, 1989; Smith and Sharpley, 1990). The period when mineralization rates were most affected by previous crop coincided with the time of linear N uptake (V10–R2) by the maize crop (Bundy and Malone, 1988; Johnson et al., 1975). Cumulative mineralization values showed the soil released a total of 112 kg of N ha^{-1} when nodulated soybean was the previous crop, compared to 92 kg of N ha^{-1} for maize following non-nodulated soybean and 72 kg of N ha^{-1} for maize following maize (Figure 5). Regardless of how these differences occurred, these data confirm that the previous crop can alter the amount of inorganic N available to the subsequent maize crop. The fairly large difference (40 kg N ha^{-1}) between nodulated soybean and maize as the previous crop confirms laboratory studies of Green and Blackmer (1995) that maize residue mineralizes slower than soybean residue. Although smaller in magnitude, the difference in cumulative mineralization between nodulated soybean and non-nodulated soybean as the previous crop (20 kg N ha^{-1}) also shows that nodules (N_2 fixation) play at least some role in this enhanced mineralization, and as a result in the soybean N credit.

Similar to soil inorganic N levels and mineralization, grain yield (dry weight basis) and total plant N accumulation of the 1999 maize crop were significantly affected by the crop grown in 1998 (Table 2). The grain yield of maize receiving no fertilizer N in 1999 was similar to the 10-year field average as pre-

Table 2. Seasonal soil N mineralization based on buried N bags, along with grain yield and plant N accumulation of unfertilized maize in 1999 as a function of the previous crop in 1998

Previous crop	Grain yield Mg ha^{-1}	Above-ground N accumulation kg ha^{-1}	Soil mineralization kg ha^{-1}
Nodulated soybean	6.3	98	106
Non-nodulated soybean	5.2	88	86
Maize	2.8	71	65
LSD (0.05)	1.0	14	11

cipitation was more evenly dispersed than in 1998 and did not limit crop N accumulation (Figure 1). For a direct comparison between the soil mineralization rate and maize plant N accumulation, we estimated the cumulative net mineralization during the 1999 maize growing season by summing the four incubation periods from 28 April to 30 August 1999, adding the soil inorganic N content on 28 April, and then subtracting the soil inorganic N content on 30 August. From this estimate we determined that 106, 86 and 65 kg of N ha^{-1} were made available to the plant during the 1999 growing season when the previous crop was nodulated soybean, non-nodulated soybean, or maize, respectively (Table 2). For each cropping sequence, net mineralization of soil N during the growing season was similar to the amount of N accumulated by the unfertilized maize crop, which supports the technique of using N accumulation by unfertilized maize plants as an estimate of soil mineralization (Meisinger, 1984).

Based on the N accumulation of unfertilized maize following nodulated soybean, there was 28% less net N mineralization in 1998 compared with 1999 (70 vs. 98 kg of N ha^{-1}; Tables 1 and 2). The relatively low N accumulation by unfertilized maize plants, and by non-nodulated soybean plants, in 1998, suggests that low mineralization rates may have limited N availability during the 1998 growing season. We believe that this difference in net mineralization was likely an important factor contributing to the 41% lower maize grain yields (3.7 vs. 6.3 Mg ha^{-1}) obtained in 1998 compared with 1999 (Tables 1 and 2). In addition, low soil mineralization may help to explain the high degree of N fertilizer recovery observed for maize in 1998 as well as the high percentage of soybean N derived from N_2 fixation.

Several studies have suggested that the soybean N credit is predominantly the result of greater net mineralization of soil N following soybean than maize (Crookston et al., 1991; Bundy et al., 1993; Vanotti and Bundy, 1995). More specifically, Green and Blackmer (1995) concluded that variation in residue-induced immobilization could provide an explanation for the observed differences in the N fertilizer requirement for maize following soybean compared with continuous maize. Additionally, they suggested that both the quality (C:N ratio) and quantity of the crop residue could affect the timing and the duration of soil N immobilization. Because of our use of non-nodulated soybean as a previous crop, we were able to differentiate the role of N_2 fixation from the impact of the quantity and quality of the residues in a field environment.

Based on an average C content in plants equal to 50% of the biomass, we estimated stover C:N ratios (mol mol^{-1}) of 22:1, 41:1, and 49:1 for the 1998 crops of nodulated soybean, non-nodulated soybean, and maize, respectively. The stover C:N ratio may help to explain the difference in net mineralization between nodulated soybean and maize as the previous crop. The stover C:N ratio for the non-nodulated soybean, however, was similar to the maize and cannot account for the partial soybean N credit associated with the non-nodulated soybean crop in 1999. In this case, the partial N credit may be the result of less stover production, and thus less immobilization of soil N following non-nodulated soybean than following maize.

Overall, our results suggest that the higher grain yield for maize following nodulated soybean compared with maize following maize is the result of greater plant N accumulation (Table 2). This greater plant N accumulation is a reflection of a higher level of soil inorganic N, which we believe results from greater net mineralization, and/or the release of fixed N from soybean nodules and residues. In either case, our results indicate that N availability plays a large role in the improved productivity of maize grown in rotation with soybean. However, despite the importance of N in this rotation credit, we cannot completely dismiss the possibility that autotoxicity accounts for some of the lower yield in continuous maize (Maloney et al., 1999).

In practice, the soybean N credit is the amount of fertilizer N that can be subtracted from the total N needed to produce a given historic yield of maize, and is generally of the order of 45 kg N ha^{-1}. Although the maize crop grown after soybean in this study accumulated only 27 kg ha^{-1} more N than when grown following maize (Table 2), this value does not represent the soybean N credit. Rather, the actual N credit in terms of fertilizer usage would be higher because the recovery of fertilizer N by maize crops is always less than 100%. While this experiment provided insight into the importance of previous crop residues and soybean nodules on soil N availability, it will be complemented with additional field studies using the same experimental approach (i.e. comparing N requirements by maize following nodulated and non-nodulated soybean, and maize) to assess the impact of nodules on the magnitude of the soybean N credit, and on the N requirement of the subsequent maize crop.

Conclusions

The soybean N credit appears to result from a combination of a decrease in net mineralization in continuous maize production and an increase in residual N from symbiotic fixation. This field experiment supports the laboratory findings of Green and Blackmer (1995) and suggests that the quality, quantity, and time of incorporation of crop residues are important factors in regulating net soil N mineralization. Similar estimates of soil N mineralization were obtained using either the buried bag technique or the N accumulation by unfertilized maize plants.

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References

Angle J S 1990 Nitrate leaching losses from soybeans (*Glycine max* L. Merr.). Agric. Ecosystems Environ. 31, 91–97.

APHA 1995 Standard Methods for the Examination of Water and Wastewater, 18th edn., Am Public Health Assoc., Washington, DC.

Below F E 1995 Nitrogen metabolism and crop productivity. *In* Handbook of Plant and Crop Physiology. Ed. M Pessarakli. pp 275–301. Marcel Deeker, Inc. New York.

Broder M W and Wagner G H 1988 Microbial colonization and decomposition of corn, wheat and soybean residue. Soil Sci. Soc. Am. J. 59, 453–459.

Brophy L S and Heichel G H 1989 Nitrogen release from roots of alfalfa and soybean grown in sand culture. Plant Soil 116, 77–84.

Bundy L G and Malone E S 1988 Effect of residual profile nitrate on corn response to applied nitrogen. Soil Sci. Soc. Am. J. 52, 1377–1383.

Bundy L G, Andraski T W and Wolkowski R P 1993 Nitrogen credits in soybean-corn crop sequences on three soils. Agron. J. 82, 229–232.

Crafts-Brandner S J, Below F E, Harper J E and Hageman R H 1984 Effect of nodulation on assimilate remobilization in soybean. Plant Physiol. 76, 452–455.

Crookston R K and Kurle J E 1989 Corn residue effect on the yield of maize and soybean grown in rotation. Agron. J. 82, 229–232.

Crookston R K, Kurle J E, Copeland P J, Ford J H and Lueshchen W E 1991 Rotational cropping sequences affects yield of corn and soybean. Agron. J. 83, 108–113.

David M B 1988 Use of loss-on-ignition to assess soil organic carbon in forest soils. Commun. Soil Sci. Plant Anal. 19, 1593–1599.

David M B, Gentry L E, Kovacic D A and Smith K M 1997 Nitrogen balance in and export from an agricultural watershed. J. Environ. Qual. 26, 1038–1048.

Eno C F 1960 Nitrate production in the field by incubating soil in polyethylene bags. Soil Sci. Soc. Am. Pro. 24, 277–279.

Fausey N R, Brown L C, Belcher H W and Kanwar R S 1995 Drainage and water quality in great lakes and cornbelt states. J. Irrig. Drain. Eng. 121, 238–288.

Gentry L E, David M B, Smith K M and Kovacic D A 1998 Nitrogen cycling and tile drainage nitrate loss in a corn/soybean watershed. Agric. Ecosystems and Environ. 68, 85–97.

Goolsby D A, Battaglin W A, Lawrence G B, Artz R S, Aulenbach B T, Hooper R P, Keeney D R and Stensland G J 1999 Flux and sources of nutrients in the Mississippi-Atchafalaya river basin: Topic 3 Report for the integrated assessment on hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17. NOAA Coastal Ocean Office, Silver Spring, MD, 130 p.

Green C J and Blackmer A M 1995 Residue decomposition effects on nitrogen availability to corn following corn and soybean. Soil Sci. Soc. Am. J. 59, 1065–1070.

Harper J E 1974 Soil and symbiotic nitrogen requirements for optimum soybean production. Crop Sci. 14, 255–260.

Harper J E 1987 Nitrogen metabolism. *In* Soybean: Improvement, Production and Uses, 2nd edn. Ed. Wilcox JR. pp 487–533. Agronomy Monograph.

Heichel G H and Barnes D K 1984 Opportunities for meeting crop nitrogen needs from symbiotic fixation. *In* Organic farming: Current technology and its role in sustainable agriculture. pp. 49–59. Spec. Publ. No. 46. ASA, CSSA, and SSSA, Madison, WI.

Hesterman O B, Sheaffer C C, Barnes D K, Lueschen W E and Ford J H 1986 Alfalfa dry matter production, and fertilizer nitrogen response in legume-corn rotations. Agron. J. 78, 19-23.

Hills T M and Peters D C 1971 A method for evaluating postplanting insecticide treatments for control of western corn rootworm larvae (*Dibrotica virgifera*). J. Econ. Entomol. 66, 764-765.

Karlen D L, Flannery R L and Sadler E J 1988 Aerial accumulation and partitioning of nutrients by corn. Agron. J. 80, 232–242.

Johnson J W, Welch F E and Kurtz L T 1975 Environmental implications of N fixed by soybeans. J. Environ. Qual. 4, 303–306.

Kurtz L T, Boone L V, Peck T R, Hoeft R G 1984 Crop rotation for efficient nitrogen use. *In* Nitrogen in Crop Production. Ed. R D Hauck. pp 295–306. ASA, CSSA, SSSA, Madison, WI.

Maloney T S, Silveira K G and Oplinger E S 1999 Rotational vs. nitrogen-fixing influence of soybean on corn grain and silage yield and nitrogen use. J. Prod. Agric. 12, 175–187.

Meese B G, Carter P R, Oplinger E S and Pendleton J W 1991 Corn/soybean rotation effect as influenced by tillage, nitrogen, and hybrid/cultivar. J. Prod. Agric. 4, 74–80.

Martin R C, Voldeng H D and Smith D L 1991 Nitrogen transfer from nodulating soybean [*Glycine max* (L.) Merr.], to corn (*Zea mays* L.) and non-nodulating soybean in intercrops: direct 15N labeling methods. New Phytol. 117, 233–241.

Meisinger J J 1984 Evaluating plant-available nitrogen in soil-crop systems. *In* Nitrogen in Crop Production. Ed. RD Hauck. pp 391–416. ASA, CSSA, SSSA, Madison, WI.

Nafziger E D, Mulvaney R L, Mulvaney D L and Paul L E 1984 Effect of previous crop on the response of corn to fertilizer nitrogen. J. Fert. Issues 1, 136–138.

Newbould P 1989 The use of nitrogen fertilizers in agriculture. Where do we go practically and ecologically? Plant Soil 115, 297–311.

Oberle S L and Kenney D R 1990 Factors influencing maize fertilizer N requirements in northern U.S. corn belt. J. Prod. Agric. 3, 527–534.

Paschke M W, Dawson J O and David M B 1989 Soil nitrogen mineralization in plantations of *Juglans nigra* interplanted with actinorhizal *Elaeagnus umbellata* or *Alnus glutinosa*. Plant Soil 118, 33–42.

Peterson T A and Varvel G E 1988 Crop yield as affected by rotation and nitrogen rate. III. Corn. Agron. J. 81, 735–738.

Power J F, Doran J W and Wilhelm W W 1986 Uptake of nitrogen from soil, fertilizer, and crop residue by no-till corn and soybean. Soil Sci. Soc. Am. J. 50, 137–142.

Ritchie S W, Hanway J J and Benson G) 1997 How a corn plant develops. Spec Rep. No. 48. Iowa State University and Corp. Ext. Serv. Ames, IA. 21 p.

Ritchie S W, Hanway J J, Tompson H E and Benson G O 1997 How a soybean plant develops. Spec Rep. No. 53. Iowa State University and Corp. Ext. Serv. Ames, IA. 20 p.

Shrader W D, Fuller W A and Cady F B 1966 Estimation of a common nitrogen response function for corn in different crop rotations. Agron. J. 58, 397–401.

Smith S J and Sharpley A N 1990 Soil nitrogen mineralization in the presence of surface and incorporated crop residues. Agron J. 82, 112–116.

Sutherland W N, Shrader W D and Pesek J T 1961 Efficiency of legume residue nitrogen and inorganic nitrogen in corn production. Agron. J. 53, 339–342.

Ta T C, McDowall F D H and Faris MA 1986 Excretion of nitrogen assimilated from N_2 fixed by nodulated roots of alfalfa (*Medicago sativa*). Can. J. Bot. 64, 2063–2067.

Vanotti M B and Bundy L G 1995 Soybean effects on soil nitrogen availability in crop rotations. Agron. J. 87, 676–680.

Vasilas B L and Ham G E 1984 Nitrogen fixation in soybeans: An evaluation of measurement techniques. Agron. J. 76, 759–764.

Wienhold B J, Trooien T P and Reichman G A 1995 Yield and nitrogen use efficiency of irrigated corn in the northern great plains. Agron. J. 87, 842–846.

Zapata F, Danso K A, Hardason G and Fried M 1987 Time course of nitrogen fixation in field-grown soybean using nitrogen-15 methodology. Agron. J. 79, 172–176.

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