INTEGRATED AGRICULTURAL SYSTEMS

Managing Soil Carbon and Nitrogen for Productivity and Environmental Quality

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ABSTRACT

In this study, we investigated the impact of cropping system management on C and N pools, crop yield, and N leaching in a long-term agronomic experiment in Southwest Michigan. Four management types, conventional (CO), integrated fertilizer (IF), integrated compost (IC), and transitional organic (TO) were applied to two crop sequences, a corn (*Zea mays* L.)–corn–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) rotation and continuous corn, which were grown with and without cover crops in the IF, IC, and TO managements. Using compost as a fertility source and reducing the use of herbicides and other chemicals resulted in long-term changes in soil organic matter pools such TO ≥ IC > IF ≥ CO for total C and N and for the labile C and N measured through aerobic incubations at 70 and 150 d. Mineralizable N varied within the rotation, tending to increase after soybean and decrease after corn production in all systems. Corn yield was closely associated with 70-d N mineralization potential, being greatest for first-year corn with cover and least for continuous corn without cover under all management types. Although the TO and IC systems produced the lowest yield for second-year or continuous corn, the combination of soybean and wheat plus red clover (*Trifolium pratense* L.) always supported high yield for first-year corn. Fall nitrate level and nitrate leaching were higher for commercially fertilized corn than for any other crop or for compost-amended corn.

Modern agriculture is highly productive, but it is also highly dependant on nonrenewable resources (Pimentel, 1993) and is responsible for wide-scale environmental contamination, particularly with respect to water quality (Keeney, 1989). Soil is the most basic of all natural resources, and its quality affects both agricultural productivity and environmental quality (Doran and Parkin, 1994; Lal, 1998). Soil quality tends to decrease when new land is brought into production and may be lower in chemically based systems than in similar systems with organic inputs. Soil organic matter is a key attribute of soil quality (Christensen and Johnston, 1997; Carter, 2002) because it influences nutrient cycling, soil structure, water availability, and other important soil properties (Arshad and Coen, 1992; Yakovchenko et al., 1998). Increasing soil C, the basic constituent of soil organic matter, is an important objective for the sustainable use of soil resources (Lal and Kimble, 1997) and may have cash value to farmers if a viable system of CO_2 credits is established. The management of organic N is equally important. Mineralization is the primary source of N in most production systems (Paul and Clark, 1996), and a failure to account for the soil's ability to mineralize N during the growing season can result in dramatic overfertilization, N loss, and groundwater contamination (Keeney, 1989). A sustainable cropping system should provide adequate fertility for N-demanding crops while preventing the accumulation of excess soil nitrates when leaching is likely to occur.

In this work, we investigated how diverse crop rotations with organic inputs can enhance and manipulate soil C and N pools to produce competitive yield and better environmental performance than CO systems using greater chemical inputs and reduced plant diversity. The level of plant biological diversity is assumed to be related to the number of crop and cover crop species over time and the application of composted dairy manure. For example, plant diversity was highest in the TO and IC rotation plots with added cover crops where six plant species in combination with compost were used during the rotation cycle (Sanchez et al., 2001). In contrast, the continuous corn plots in the CO and IF treatments without cover crops received the lowest diversity of organic inputs, a single crop species in 4 yr. Decreased herbicide use also tends to increase diversity by allowing a greater biomass and diversity of weed species to proliferate. Increasing the diversity of cropping tends to increase the amount, quality, and variety of residues returned to the soil and lengthens the time that roots are active during the growing season (Franco-Vizcaino, 1997). All other things being the same, greater diversity is expected to result in increased storage of soil C and N and increased soil quality over time. The specific objectives of this study were to determine if chemical usage and biological diversity affect soil C and N levels, whether the various agronomic systems differ in their ability to provide N to a growing crop, and whether these differences in C and N status have a measurable effect on crop yield and NO_3 leaching losses.

MATERIALS AND METHODS

This study was conducted in the Living Field Laboratory (LFL), a long-term experiment established in 1993 at the W.K.

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Abbreviations: CO, conventional; IC, integrated compost; IF, integrated fertilizer; LFL, Living Field Laboratory; TO, transitional organic.

Kellogg Biological Station located in Southwest Michigan. The experimental design is a four-replicated split-split plot in four randomized complete blocks, with main plots for each management system. The management systems were CO, IF, IC, and TO. Synthetic fertilizer was the N source in the CO and IF systems while composted dairy manure was used in the IC and TO systems. Weeds were controlled with broadcast applications of herbicide in CO (typically *S*-metolachlor {2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide} at 1.4 kg ha^{-1} a.i. and bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) at 0.4 kg ha^{-1} a.i. in corn and glyphosate [*N*-(phosphonomethyl)glycine] at 0.8 kg ha^{-1} a.i. in soybean), banded herbicide (one-third of the CO rate) plus cultivation in the IF and IC, and cultivation only in TO. Insecticide {chlorpyrifos [*O,O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] at 1.3 kg ha^{-1} a.i. in second-year corn and continuous corn when needed} was used in CO, IF, and IC according to integrated pest management best management protocols. The four management systems were imposed on a corn–corn–soybean–wheat rotation and a continuous corn cropping system. All crops in TO, IC, and IF except soybean were grown with and without a cover crop. Cover crops include red clover frost-seeded into wheat, crimson clover (*Trifolium incarnatum* L.) interseeded into first-year and continuous corn, and annual ryegrass (*Lolium multiflorum* Lam.) interseeded into second-year corn. Corn plots historically treated with fertilizer received P in the form of superphosphate (0–46–0) and K in the form of potassium chloride (0–0–63) before planting at a rate determined by a preplanting soil test. Nitrogen was applied at planting (liquid fertilizer 20–25 kg ha^{-1} N) and sidedressed (ammonium nitrate 100–140 kg ha^{-1} N) as recommended by presidedress NO_3 test (Magdoff et al., 1984). The fertilized wheat crop normally received 60 to 70 kg ha^{-1} of urea N, all applied in mid-March. Soybean received no fertilizer. In the compost plots, approximately 4 Mg ha^{-1} of composted dairy manure was added annually before tillage to all crops except soybean. The compost chemical composition in g kg^{-1} (dry weight basis) averaged 340 of C, 26 of N, 90 of lignin, 692 of cellulose, and 53 of hemicellulose. Reduced primary tillage (chisel plow) was used throughout the experiment. Additional information of site and farming practices are described elsewhere (Jones et al., 1998; Willson et al., 2001; Fortuna, 2001; Sanchez et al., 2001, 2002; Smeenk, 2003).

Sampling and Laboratory Procedures

During the 1993 to 2000 growing seasons, each of the 140 plots were soil-sampled in the 0- to 25-cm profile at least once a month, depending on soil conditions. Nitrate concentrations were determined using a KCl extraction (Keeney and Nelson, 1982) and a Lachat automated colorimetric analyzer (Lachat Instruments, Milwaukee, WI). Soil samples from May 1993, 1996, 1999, and 2000 were analyzed for total C and N using a Carlo Erba N A 1500 Series 2 N/C/S analyzer (CE Instruments, Milan, Italy). Samples from 0- to 10-cm depth were collected in May 1999 and 2000 and also analyzed for total organic C and N. In addition, these soils were aerobically incubated for 0, 30, 70, and 150 d to determine the N mineralization potential (Sanchez et al., 2001). Separate laboratory incubations were used to determine cumulative C mineralization at 20, 30, 50, 70, 100, and 150 d of incubation (Paul et al., 2001). Intact core lysimeters were placed at 1.0 m below the surface to measure the amount of NO_3 leached below the root zone of each cover-cropped IC and IF plot plus selected plots of the TO and CO, totaling 60 lysimeters. Leachate was regularly (monthly during late fall, winter, and early spring; less often otherwise) collected from each lysimeter, its volume recorded, and a subsample was analyzed for NO_3 content. Agronomic management systems were expected to influence the amount of NO_3 leached during the following winter. A *leaching year* was defined as beginning in mid-April and running through the following mid-April. Grain yield was obtained annually from each plot.

Data Analysis

The total C, total N, available soil NO_3^-, NO_3^- leaching, and yield data sets used the same statistical model. Factors used in the model were year, replication, management system, crop, and cover crop. The C and N mineralization analyses used incubation time as an additional factor. Individual observations at each time interval (year and/or incubation time) from all data sets were treated as repeated measurements of the corresponding experimental unit. The SAS Mixed procedure (SAS Inst., 1999) was used to fit a mixed linear model with a corresponding covariance structure for each data set. The optimal covariance structure was determined using Schwarz's Bayesian Criterion (Littell et al., 1997). The total C and N from two depths, C and N mineralization, and available soil NO_3^- data sets were explained by compound symmetry covariance structures. An unstructured covariance structure was the best fit for the leaching data set. Yields were analyzed using the first-order autoregressive covariance structure where correlations increase as the time interval decreases. After significant effects were identified, differences between least square means were considered significant at 0.05 based on the Tukey adjustment type I error rate. Pearson correlation analysis was used to relate the parameters under study.

RESULTS AND DISCUSSION

Management systems significantly influenced total soil C and N concentrations at the 0- to 25-cm profile (Fig. 1 and 2). The long-term changes in C and N (1993–2000) followed a gradient of decreasing chemical usage and increasing plant biological complexity from the CO system to the TO system. The effects of compost addition and decreased chemical use appear to have been additive, with the difference between the IF and IC systems due to compost additions and the difference between the TO and IC systems and the IF and CO systems due to reduced chemical applications, which are more likely to encourage a larger and more diverse weed population. There was a significant difference between the TO and CO systems from the very first year

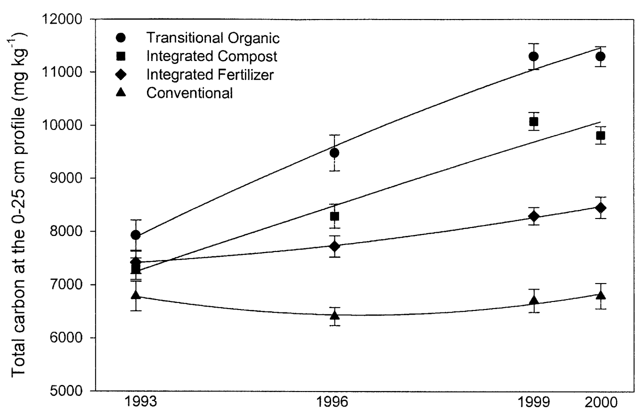

Fig. 1. Long-term changes in total C at the 0- to 25-cm soil profile of four management systems averaged across crops. Error bars represent the standard errors of the means.

of the study, but the lack of difference between IF and IC at that point suggests that most of this difference was due to noncrop biomass (cover crops and weeds) and that differences due to compost additions accumulated more gradually. On the other hand, there was little difference between cover and no-cover splits in the IF, IC, and TO treatments either in 1993 or 2000 because the overall amount and diversity of residues returned was similar. Only small amounts of cover crop biomass (<1.0 Mg ha^{-1} dry matter) were produced under corn, and the much larger production of red clover (>3.0 Mg ha^{-1} dry matter) after wheat harvest was matched in biomass (and perhaps exceeded in diversity) by the luxuriant growth of weeds in the noncover system. Generally, increases in total C were associated with increases in total N ($r = 0.8$, $P < 0.05$, $N = 280$), but correlations varied according to management and to a lesser degree among crops. Carbon and N concentrations were considerably higher near the surface (0–10 cm) than at greater depth (10–25 cm) in all treatments.

Although compost additions and weed control practices appear to have had a large impact on total C and N accumulation, the total quantity of C returned to the soil was not a good predictor of C retention. For example, Fortuna (2001) reported that the continuous corn plots at the LFL received 22 to 29% greater C inputs than the corresponding rotation plots over a 6-yr period (1992–1998), but this greater C input has not resulted in greater soil C or N accumulation in the monoculture treatments. Similarly, the TO rotation was found to have virtually the same total C input as the CO monoculture, but the former had accumulated 50% more soil C by 2000 than the latter. These results are generally consistent with the findings of Drinkwater et al. (1998), who noted a poor correlation between C return and C accumulation in their Farming Systems Trial near Kutztown, PA. Apparently, in situ C mineralization was greater in the corn monoculture than in the rotation plots. While

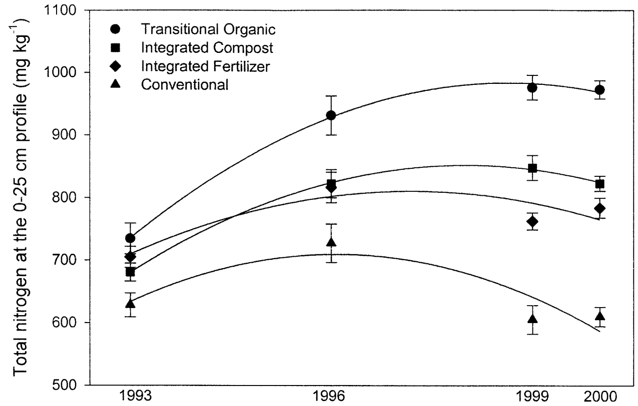

Fig. 2. Long-term changes in total N at the 0- to 25-cm soil profile of four management systems averaged across crops. Error bars represent the standard errors of the means.

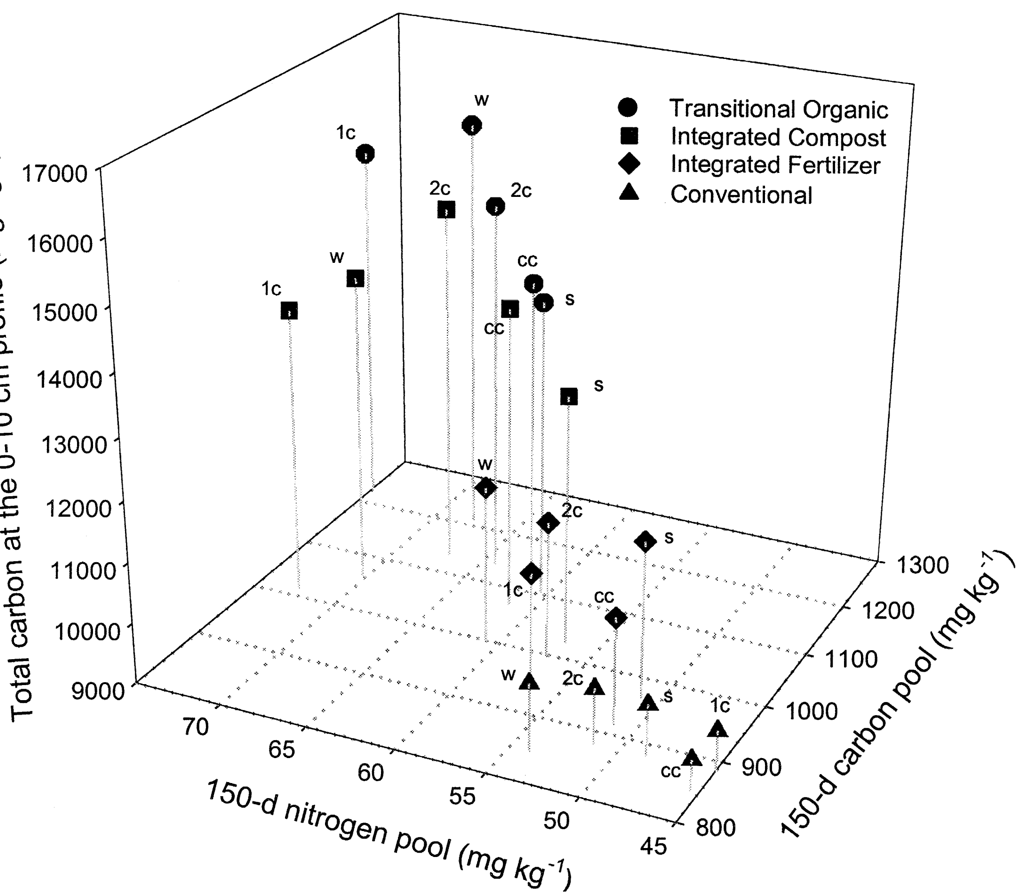

Fig. 3. The total C at the 0- to 10-cm profile and its relationship to the labile C and N (expressed by their 150-d pools) of soils from each crop in the rotation (first-year corn, 1c; second-year corn, 2c; soybean, s; wheat, w) and continuous corn (cc) under four management systems.

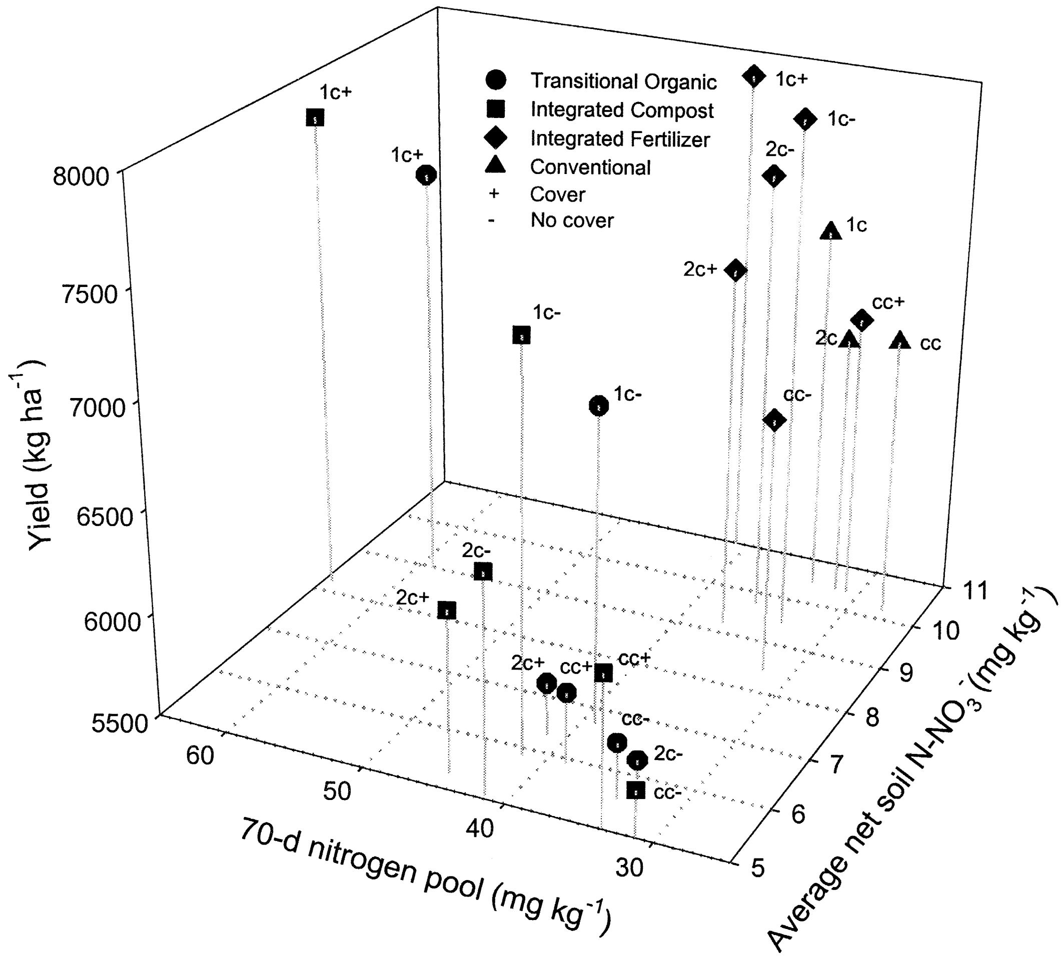

Fig. 4. Relationship of corn (first-year corn, 1c; second-year corn, 2c; continuous corn, cc) yield to the 70-d N pool and available soil NO_3^- as influenced by management and cover crop.

this could conceivably be an artifact of residue quality (corn residue is somewhat lower in lignin than most other residue types), it is also consistent with the observation of Sanchez et al. (2002) that corn roots themselves stimulate a more rapid decomposition of organic matter than bare soil or wheat. The nature of the soil food web beyond the rhizosphere may also be a factor. Larger labile C and N pools may also stimulate interactions among soil biota, which can play a significant role in nutrient transformations and plant nutrient availability (Coleman et al., 1984).

In 1999 and 2000, spring soil samples were taken at the 0- to 10-cm depth and analyzed for C and N mineralization potential in 70- and 150-d incubations at 25°C. The relationship between total C and the 150-d C and N pools in these samples is shown in Fig. 3. As was true for total C content, the 150-d C mineralization potential was greatest in the TO system and least in the CO system, with the IC and IF systems intermediate. The 150-d N pool was significantly greater in the TO, IC, and IF treatments than in the CO soils. Within each management type, 150-d N tends to increase after soybean and wheat production (w and 1c in Fig. 3) and decrease after multiple years of corn production (s and cc in Fig. 3). Cover crops (not shown in Fig. 3) were associated with significant increases in N mineralization potentials only within the TO and IC managements. It would appear that the 150-d N pool is more sensitive to incorporation of legumes (soybean and clover) rather than nonlegume residues. The extra noncrop biomass observed in the TO systems may be responsible for the greater 150-d C storage, but not 150-d N storage, compared with the IC treatment.

This study also highlights the effectiveness of soybean and winter wheat frost-seeded with red clover green manure as a pretreatment to corn production. This crop sequence maximizes the storage of readily mineralizable N in support of high corn yield while reducing the need for external fertilizers. The relationship among corn yield, soil $N\text{-}NO_3^-$ content, and 70-d N mineralization is shown in Fig. 4. Within each management type, all three indices are at their maximum for first-year corn with cover, followed by first-year corn without cover, followed by all other corn treatments. It is interesting to note that the positive relationship between 70-d N and corn yield exists within the fertilized treatments (CO and IF) even though fertilization levels varied and $N\text{-}NO_3^-$ content was relatively high in all treatments. The yield of first-year corn with cover was just as high under IC treatment as it was in the IF treatment, indicat-

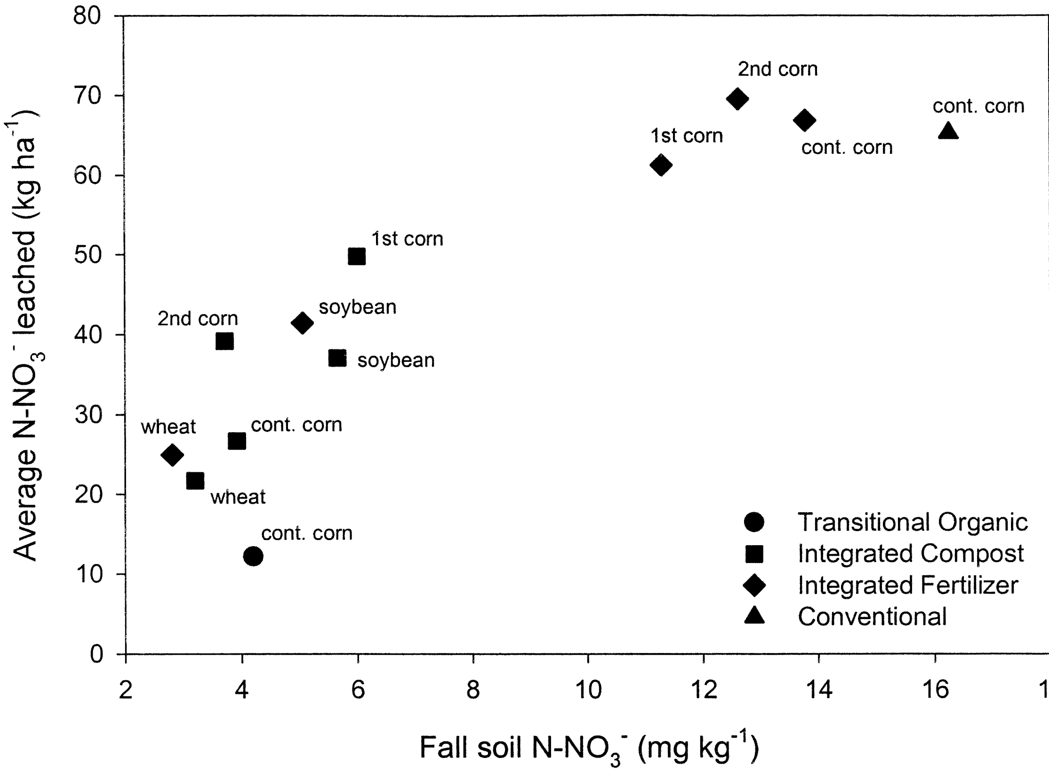

Fig. 5. Impact of agronomic management on soil NO_3^- concentrations in the fall (October) at the 0- to 25-cm soil profile and NO_3^- leaching losses. Soil and leached NO_3^- are means from 1993 to 1999.

ing that the combination of compost additions and a red clover incorporation provided sufficient N to produce optimal corn production at that point in the rotation. In contrast, both first-year corn without cover and second-year corn had much lower yield and smaller 70-d N pools. Soybean, which receives neither fertilizer nor compost during its production season, usually yielded slightly more in the historically composted plots (2403 kg ha^{-1}) than in the historically fertilized plots (2359 kg ha^{-1}). Wheat yield, however, was significantly lower in the TO and IC plots (2686 kg ha^{-1}) than in the CO and IF plots (3225 Kg ha^{-1}), probably due to N limitation. Because it requires inorganic N when the soil is cool and mineralization is minimal, winter wheat is less able to benefit from enhanced organic N than summer crops. A more readily available form of organic fertilizer (e.g., chicken manure) would have been preferable as a source of nutrition both for wheat and for repeated corn production. Limited applications of N fertilizer may also be a desirable strategy for supplemental plant nutrition in sustainable cropping systems. We speculate that overall grain production in the cover-cropped IC system would be comparable to that of the IF system if modest amounts of N fertilizer are applied to the IC wheat and second-year corn crops. Assuming that a total of 60 to 80 kg ha^{-1} of N fertilizer is needed to increased yield of the IC wheat and second-year corn to the IF levels, this amount would account for all the fertilizer needs in the IC system instead of 300 to 400 kg ha^{-1} commonly used in the IF or CO systems throughout the rotation cycle.

When the C/N ratios were calculated using the labile C and N pools measured at 70-d incubations, the lowest C/N ratio was found in the cover-cropped IC first-year corn (11), followed by the IC wheat (14) and TO first-year corn (15). The C/N ratio of the remaining crops across the four management systems ranged from 16 to 23. A lower C/N ratio indicates a greater N mineralization potential per unit organic matter decomposed. Where mineralizable C/N ratios are similar, a larger labile N pool indicates greater N supply. This is best exemplified by the IC treatment during first-year corn production (Fig. 4). Greater N mineralization is also linked to increased C mineralization (Watkins and Barraclough, 1996; Sanchez et al., 2002). For example, with a soil C/N ratio of 10:1 to 13:1, achieving a 150-d mineralizable N pool above 55 mg kg^{-1} requires a 150-d C pool > 1000 mg kg^{-1} (Fig. 3). Apparent C demands were somewhat lower when a legume cover crop was used. In general, maintenance of a large labile C pool in the soil is essential to the management of soil organic N. We contend that both labile C and N pools are necessary to achieve high efficiency of N use, regardless of its source.

Soil NO_3^- availability is one of the most important factors affecting crop performance. Yield was significantly correlated to available NO_3^- in all managements ($r = 0.7, P < 0.05, N = 280$) and all crops except soybean. On the other hand, soil NO_3^- levels do not explain the yield differences within the fertilized treatments. Corn following corn always exhibited lower yield than first-year corn. As was noted earlier, there is a positive relationship between fertilized corn yield and 70-d mineralizable N. It appears that one of the reasons for poor yield performance of continuous corn is its dramatic depletion of mineralizable N.

Leaching was greater after fertilized corn production than after corn production with compost or soybean and wheat production under any system (Fig. 5). As a result, the IF system averaged 50 kg N-NO_3^- ha^{-1} compared with 35 kg ha^{-1} for the IC system, and the IF monoculture leached more (67 kg N-NO_3^- ha^{-1}) than the IF rotation (53 kg N-NO_3^- ha^{-1}). Although fewer lysimeters were used in the TO and CO plots, measured NO_3^- leaching patterns in these systems were similar to those of the IC and IF, respectively. Regardless of management, the majority of NO_3^- leached in the rotation is lost in the winters following corn, but a wet spring sometimes caused significant leaching from soybean plots. Using wheat in the rotation has significant benefits to the environment. Our data shows that wheat leached less than any other crop, about 22 kg ha^{-1} annually. Furthermore, the planting of wheat immediately after soybean may have reduced leaching losses during the following winter and spring by drying the soil and immobilizing N mineralized from soybean residues. While increasing soil NO_3^- availability is essential for good yield, high NO_3^- levels when plant uptake is minimal can be lost to the environment (Khakural and Robert, 1993). Nitrate leaching was significantly correlated to the fall soil NO_3^- levels as measured by October concentrations at the 0- to 25-cm soil profile. Correlation was higher in the IF ($r = 0.4$, $P < 0.05$, $N = 60$) than in the IC treatment and was influenced by important correlations in the first-year corn and continuous corn ($r = 0.5$, $P < 0.05$, $N = 36$) plots. The absence of lysimeters in the no-cover plot in the IF, IC, and TO treatments makes it difficult to speculate on whether there is any direct effect of cover on N leaching.

CONCLUSIONS

The LFL is a unique long-term agriculture experiment that shows clearly how a production system integrating reduced chemical inputs and a well-designed crop rotation can produce higher yield and lower leaching than a comparable CO system. By simply switching from broadcast to banded herbicides and allowing the free growth of weeds after wheat production, higher average corn yield and greater organic matter storage was achieved in the IF system (with or without cover crops) compared with the CO system. Using a corn–corn–soybean–wheat rotation rather than continuous corn increased the average corn yield by 14% in the IF system and decreased the overall leaching rate by 17%. Although the IC systems with cover crops could not supply enough N for optimal wheat or second-year corn yield, it was otherwise just as productive as the IF rotation and reduced leaching by 27% overall. Organic C and N storage increased up to 43 and 33% in the IC and TO systems, which decreased the need for additional fertilizers and should tend to improve soil structure and physical condition. Cover crops were particularly important in the IC and TO system where red clover within wheat stubble resulted in a 13% increase in first-year corn yield. Finally, while the TO system's greater weed biomass produces slightly lower yield overall than the IC system, the TO system had greater C storage and may have been more profitable in the long run, depending on the opportunities for marketing organic grain.

Many of these results are general and can be applied to corn-based agroecosystems anywhere. In general, agroecosystems that make better use of short- and long-term C and N pools will tend to be more productive and environmentally sustainable than systems that rely on heavy applications of chemical fertilizers and herbicides. Applying a properly structured diverse crop rotation to soils under limited tillage, utilizing cover crops where appropriate, taking an IPM approach to weed management, and supplementing fertility with animal waste products all tend to increase soil organic C and N, including their labile forms. Increasing labile organic N before corn production triggers the corn plant's unique ability to stimulate N mineralization and appears to be a key factor in enhancing corn yield and reduces the need for external fertilizers. Relying on organic N sources reduced soil nitrate levels and leaching potential in this study, even for the first-year corn with cover, which produced consistently high yield. Additional studies would have to be performed to determine whether reductions in fertilizer rates in the IF system or increases in the IC system would have narrowed the gap between the systems in terms of N leaching.

Sequestering C in soils has a significant impact on the global C cycle and enhances the mineralizable forms of C and N, resulting in greater soil N supplying and recycling capacity. This may be useful in all production systems but is essential where synthetic fertilizers are not the primary N source. Widespread adoption of the strategies suggested in this study have the potential to improve soil and water quality without affecting yield and are likely to contribute to a cleaner environment on a global scale.

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