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# Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems

L.E. Drinkwater[1,2,*], R.R. Janke[1,3] & L. Rossoni-Longnecker[1]
[1]*Rodale Institute, 611 Siegfriedale Road, Kutztown, PA 19530, USA;* [2]*Current address: Department of Horticulture, Plant Science Building, Cornell University, Ithaca, NY 14853-5908, USA;* [3]*Current address: Department of Horticulture, 2014 Throckmorton Plant Science Center, Kansas State University, Manhattan, KS 66506, USA*

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## Abstract

In 1988 an experiment was established at the Rodale Institute Experimental Farm to study weed control and nitrogen (N) management in rotations with grain crops and N-fixing green manures under reduced tillage without the use of herbicides. Tillage intensities ranging from moldboard plow (MP) to continuous no-till (NT) were compared. We present results for maize production in 1994, the seventh year of the experiment. Our goal was to further investigate reduced tillage regimes that alternated no-till with different forms of primary tillage in legume-based systems. In the chisel-disc (CD) and MP treatments comparable yields were achieved under so-called organic (weeds controlled with cultivation and green manure N source) and conventional management (weeds controlled with herbicides and mineral N fertilizer applied). Weed competition in these treatments was minimal and the N status of maize plants was essentially the same regardless of the N source (fertilizer or green manure). Of the four organic no-till maize treatments, only the mixed-tillage system with cultivation for weed control (CD-NTc) produced yields comparable to conventional NT maize. The fate of vetch N as well as temporal N dynamics were largely determined by tillage intensity and the handling of the vetch residues at maize planting. Treatments with primary tillage (CD and MP) had extremely high levels of mineral N early in the season and had greater average net N-mineralization, even though N content of hairy vetch in these treatments was equal to or lower than that in treatments with mow-killed vetch. In terms of soil mineral N concentrations, the CD-NTc treatment was similar to the other mow-killed vetch/no-till maize treatments. However, N availability in this treatment was greater, probably due to more complete decomposition of green manure residues. Cultivation for weeds not only helped control weeds but also increased mineralization of the vetch residues, which in turn increased the N supply during the period of maximum N demand by the maize. Carefully designed rotations combining tillage reductions with the use of leguminous N sources can have multiple benefits, including improved timing of N availability, reduced herbicide applications, and improved soil quality in the long term.

## Introduction

The use of winter-hardy annual legumes to supply N to cash crops can reduce soil erosion and nitrate leaching, increase soil organic matter, and improve aggregate stability and other soil structural properties (Drinkwater et al., 1998; Power, 1987; Roberson et al., 1991). However, the addition of green manures to rotations using conventional tillage regimes often increases tillage frequency. Furthermore, although annual losses through nitrate leaching may be reduced compared to mineral fertilizers, there is a 3- to 4-week period immediately after incorporation of leguminous residues when substantial N-mineralization occurs before crops begin to take up nitrate, making these systems susceptible to nitrate leaching in the early spring (Sarrantonio and Scott, 1988).

Interest in reduced-tillage or conservation tillage practices has grown over the last two decades as a result of government programs aimed at redu-

* FAX No: 607 255-0599. E-mail: led24@cornell.edu

cing soil erosion. The adoption of such practices has other potential benefits. For example, continuous no-till systems, which have been widely adopted in maize/soybean production systems, can result in significant savings in production costs and labor requirements (Phillips and Young, 1973). On the other hand, continuous no-till systems often require increased herbicide use (Hinkle 1985; Kells and Meggitt 1985), and fertilizers are often applied to no-till maize at higher rates (Lal et al., 1994; Meisinger et al., 1985; Randall and Bandel, 1987). Increased applications of herbicides and fertilizers usually lead to increased contamination of groundwater and surface water with these agricultural chemicals (Carpenter et al., 1998; Gumtang et al., 1999).

The development of cropping systems that combine the use of leguminous green manures with reduced tillage could resolve some of the problems that occur when only one of these practices is used. In 1988, an experiment was established at the Rodale Institute Experimental Farm to study management of agronomic crops and green manures under reduced tillage without the use of herbicides. Our goal was to develop economically viable legume-based systems that would conserve soil, maintain water quality, and meet the requirements for organic certification. Organically-managed rotations ranging from moldboard plow (MP) to continuous no-till (NT), including one mixed-tillage treatment where MP or chisel-discing (CD) was alternated with no-till were compared to conventionally-managed rotations that used established production practices. Both cropping systems had rotations that included maize and soybeans. The organically-managed rotations also included wheat. Herbicides and fertilizers were used at the recommended rates in each of the treatments in the conventional system. Herbicides and mineral fertilizers were not used in the organically-managed cropping systems. Leguminous cover crops and relay cropping were used in the organic rotations to supply N and help suppress weeds. Results from the first six years showed that in organically-managed treatments with some form of primary tillage and well-established leguminous green manures, crop yields were comparable to those of the conventionally-managed treatments (Wagoner et al., 1993). The organic continuous NT treatment produced extremely poor yields, but when NT was alternated with tillage in an organic system, grain yields and profits were comparable to those of a conventionally-managed continuous NT system.

In this paper we present results from 1994, the seventh year of the experiment. Our goal was to further investigate mixed-tillage options where no-till was alternated with different forms of primary tillage in the organic treatments. We used the same strategy that had been used in the mixed-tillage system for the previous six years: small-seeded crops (wheat) and cover crops (rye or hairy vetch) were planted after some form of primary tillage, while large-seeded crops (maize and soybeans) were no-till-planted. We compared weed biomass and crop productivity in organically and conventionally-managed treatments under the full range of tillage intensities. In addition, because our earlier work indicated that weed competition and N limitations were the most frequent causes of reduced yields under reduced-tillage regimes in organically-managed systems, we investigated tillage intensity effects on N availability and weed competition in those systems. We monitored decomposition of vetch residues, soil moisture, N-mineralization potential, and mineral N concentrations throughout the growing season in the organically-managed treatments.

## Materials and methods

The experiment was established in 1988 on a 4.0 ha site located at the Rodale Institute Experimental Farm in southeastern Pennsylvania. The predominant soil is a Berks shaley silt loam (Typic Dystrochrept, The soil texture was 38–40% clay, 40–43% silt and 17–22% sand) on a ridge top with less than 2% slope. The soil has a shale content (rock fragments > 2mm) ranging from 20 to 40% in the top 20 cm and is well-drained and prone to drought. Before initiation of this research, the site had been in organic grain production for 15 years. Agronomic crops were grown using conventional tillage, animal and green manures, and mechanical weed control. In 1987, before treatments were imposed, the site was moldboard plowed and maize was planted for baseline yield data. At the start of the experiment the plow layer (0–20 cm) had a pH of 7.1 and contained 109 mg kg$^{-1}$ extractable P and 181 mg kg$^{-1}$ extractable K.

The experiment was a randomized complete block design consisting of three different cropping systems with four replications (Wagoner et al., 1993). This was a systems experiment meaning that the cropping systems were designed to reflect a cohesive management strategy and therefore differed by more than one factor, i.e. in this case there were differences in rotational sequences, tillage and N source. All three cropping systems included maize (*Zea mays*) and soybean (*Glycine max*) in their rotations (Table 1). One system was conventionally-managed and consisted of a two-year rotation of maize-soybean managed with well-established techniques. The other two were organically-managed cropping systems with diversified rotations. Both of the organic cropping systems also included a green manure (hairy vetch, *Vicia villosa*), small grains (winter wheat, *Triticum aestivum*, barley, *Hordeum vulgare* and/or oats,*Avena sativum*) however, the specific rotational sequence of these crops differed during the first four years of the experiment (1988–91).

Nitrogen fertility in all organic treatments relied upon hairy vetch residue prior to planting maize. All conventional treatments were fertilized with starter fertilizer (30-30-10 at 112 kg N ha$^{-1}$) and side-dressed with urea (112 kg N ha$^{-1}$) at planting (May 8–15). No vetch was planted in conventional treatments.

Each cropping system had four tillage regimes: moldboard plow (MP), chisel-disc (CD), ridge-till and no-till (NT). There was also a legume-based mixed-tillage regime where NT techniques were used to establish three of the five crops, and MP or CD were used to establish the other crops giving a total of 13 treatments (3 cropping systems $\times$ 4 tillage regimes + organic mixed tillage). Plots were 12 m $\times$ 30.5 m. The ridge-till systems, which were experimental, had several unanticipated problems and were therefore not included in the detailed study we are reporting here.

In 1991 the rotations in all three cropping systems converged to maize and were modified to a three-year rotation of maize-soybean-wheat. The organic rotations continued to include a hairy vetch green manure prior to maize and a non-leguminous cover crop (winter rye, *Secale cereale*) was added to overwinter between maize and soybean resulting in identical rotational sequences in all organic plots beginning in 1991. The intention was to introduce additional mixed tillage treatments into the organic rotations. In 1993 at the time of vetch planting, selected organic treatments were modified to alternate no-till with the existing tillage regimes, resulting in two additional mixed-tillage treatments. For example, continuous CD from Organic System #2 was modified to CD hairy vetch/NT maize. Tillage and weed control practices for the treatments sampled in this study are reported in Table 2. Vetch was planted after winter wheat harvest in all organic treatments on August 24, 1993, with or without tillage, as noted in Table 2. The next spring, maize was planted on May 17, 1994. In the tillage treatments, vetch was incorporated May 5, 1994; in the no-till treatments, vetch was mowed May 31, 1994 while maize plants were small enough to remain undamaged by the mowing operation.

Field operations were as follows:

MP – Primary tillage was with a moldboard plow to a 20-cm depth. Secondary tillage was done with a disc or field cultivator and cultipacker. Maize was planted with a Buffalo 4-row planter and hairy vetch was planted with a John Deere 8250 grain drill.

CD – Soil preparation was done with a mulch tiller (a combination chisel plow and disc tillage implement) to 20-30 cm; secondary tillage was done with a disc. Maize was planted with a Buffalo 4-row planter; hairy vetch was planted with a John Deere 8250 grain drill.

NT – Crops were no-till planted using a Tye No-Till grain drill (vetch) and Buffalo 4-row planter (maize). In the organic treatments, the hairy vetch cover crop was killed by mowing two weeks after planting maize but while the maize growing point was below the level of the mower.

### *Sample collection*

All plant biomass samples were taken from specified data areas in each plot and residues were dried at 60 °C to determine biomass dry weights. Percent winter cover by hairy vetch, weeds, and senescent crop residues were sampled nondestructively on December 3 using the knotted-rope method in two transects per plot (Sarrantonio, 1991). Biomass samples of hairy vetch were collected from three randomly selected 0.25 m$^2$ areas within each plot. Samples were taken immediately before the first tillage operation in MP and CD treatments or mowing in NT treatments.

Maize ear leaves were collected at 50% silking (July 27; 12 per plot) and analyzed for N. Weed biomass was collected on August 23 from within the data area. Two stratified random samples (each 0.5 m$^2$) were taken per plot. All weeds were clipped at ground level, sorted by species, and then combined to give one composite sample per plot. Any surface residue (primarily hairy vetch) in the sampling quadrant areas was also collected and bagged separately.

Whole maize plants were sampled at physiological maturity (formation of black layer, October 6) to determine crop biomass and N content. Samples were collected from two 5-m segments of row in each plot. Whole plants were counted, cut, weighed, and chopped. Subsamples of the chopped material, which

*Table 1.* Chart depicting rotational sequences in the conventional (CNV) and two organic (ORG 1 and 2) cropping systems for 1988–1994. Rotations in all three systems converged to maize in 1991 and cash crops were grown in the same sequence thereafter. After 1991, the two organic systems were identical. Cover crops and green manures are in italics

| System | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|---|---|---|
| | July Jan | July Jan | July Jan | July Jan | July Jan | July Jan | July |
| CNV | SB[¶]---- | Maize | SB---- | Maize | SB---Wheat--- | | Maize |
| ORG 1 | Barley -*HV*[*]--<br>SB--- | Maize | Barley -*HV*--<br>SB--- | *Rye*<br>Maize | SB---Wheat--- | *HV*---- | Maize |
| ORG 2 | *HV*<br>Maize | Wheat--<br>SB--- | *Clover-HV*--<br>Oats--- | *Rye*<br>Maize | SB---Wheat--- | *HV*---- | Maize |

[¶] Soybeans
[*]Hairy vetch

*Table 2.* Summary of tillage and weed control practices in the organic and conventional systems for the time period covered by the current experiment

| Cropping system description | Treatment abbreviation | Primary tillage prior to planting | | Weed control Maize (Spring 1994) |
|---|---|---|---|---|
| | | Vetch (Fall 1993) | Maize (Spring 1994) | |
| *Organic* | | | | |
| Continuous moldboard plow | MP | moldboard plow | moldboard plow | rotary hoe (2×), cultivate[a] (2×) |
| Continuous chisel disk | CD | chisel disk | chisel disk | rotary hoe (2), cultivate (2×) |
| Continuous no-till | NT | no till | no till | vetch mulch |
| Mixed tillage, chisel disk/ no-till /weed cultivation | CD-NTc | chisel disk | no till | vetch mulch, cultivate (2×) |
| Mixed tillage, chisel disk/ no-till | CD-NT | chisel disk | no till | vetch mulch |
| Mixed tillage, moldboard plow/no-till | MP-NT | mold board plow | no till | vetch mulch |
| *Conventional* | | | | |
| Continuous moldboard plow | MP | No vetch was planted | moldboard plow | Bicep @ 4.68 L/ha |
| Continuous chisel disk | CD | No vetch was planted | chisel disk | Bicep @ 4.68 L/ha, Dual @ 1.17 L/ha |
| Continuous no-tillage | NT | No vetch was planted | no till | Bicep @ 4.68 L/ha, Dual @ 1.17 L/ha, Gramatone @ 1.75 L/ha, Charger E @ 62.2 ml/100 L |

[a]Rotary hoeing and cultivation for weeds are shallow tillage operations. Only the surface soil between maize rows is disturbed to approximately 5 cm.

*Table 3.* Analysis of variance of tillage, cropping system (organic vs. conventional) and block effects on plant parameters. In this analysis, tillage refers to whether or not there was primary tillage at maize planting in May 1994.

| | DF | Maize plant density | Maize biomass | Maize yield | Maize ear leaf nitrogen | Weed biomass |
|---|---|---|---|---|---|---|
| Tillage (T) | 1 | * | **** | **** | **** | **** |
| Cropping system (CS) | 1 | NS | * | * | * | * |
| Block | 3 | NS | NS | NS | NS | * |
| T × CS | 1 | NS | NS | * | **** | * |
| T × Block | 3 | NS | NS | NS | NS | * |
| CS × Block | 3 | NS | NS | NS | NS | NS |

Significance at the 0.05, 0.01, 0.001, 0.0001 probability levels is designated by *, **, ***, **** respectively; NS is $P > 0.05$.

*Table 4.* Tillage treatment effects on hairy vetch biomass and N content at the time of incorporation (May 1994) and the amount of vetch residues remaining on the soil surface late in the growing season (August 1994). Values with different letters are significantly different (protected Duncan's, $p<0.05$). Nitrogen content data are for the initial aboveground biomass

| Vetch characteristics | Continuous Tillage | | | Mixed Tillage | | |
|---|---|---|---|---|---|---|
| | MP | CD | NT | CD-NTc | CD-NT | MP-NT |
| Initial biomass (kg ha$^{-1}$)* | $2860^b$ | $3340^b$ | $4620^a$ | $5310^a$ | $4820^a$ | $4920^a$ |
| Shoot N (%) | $5.0^a$ | $4.7^{ab}$ | $3.2^c$ | $4.1^{abc}$ | $3.9^{bc}$ | $4.0^{abc}$ |
| N in biomass (kg ha$^{-1}$) | $140^b$ | $160^b$ | $150^b$ | $220^a$ | $190^a$ | $200^a$ |
| Residue remaining in August 1994 (kg ha$^{-1}$) | 0 | 0 | $1990^a$ | $470^b$ | $1420^{ab}$ | $1990^a$ |

*Depending on treatment, the biomass is given for either the time of incorporation (MP, CD) or mowing (all other treatments).

included cobs and grain, were used for total N and dry matter determination. To determine harvest index, ears were counted and grain yields were calculated based on a sample of 10 ears per plot.

To determine maize yields, grain was harvested mechanically from an interior 3 m × 30.5 m area of each 12 m × 30.5 m plot (November 3–7) . This was the designated 'harvest only' area and no destructive sampling was allowed in this portion of the plots.

Composite soil samples (15 cores per plot, stratified random sample) were collected 10 times during the growing season at depths of 0–5 cm and 5–20 cm, using a corer 2.5 cm in diameter. Soil samples were analyzed for $NO_3^-$, $NH_4^+$, N-mineralization potential and moisture content.

### *Litter decomposition study*

Mesh bags (1.5 mm mesh) containing hairy vetch residues were used to study decomposition rates in the four treatments with mow-killed vetch (NT, CD-NT, MP-NT, CD-NTc). Hairy vetch samples for the decomposition study were collected immediately after mowing. The samples were a mix of freshly cut green hairy vetch and brown material that had been killed earlier by the planting operation. The vetch samples were stored in large brown plastic bags at 4 °C for 24 hours. To prepare litter bags, vetch was chopped into pieces smaller than 7 cm and mixed well in a large basin. Pre-weighed, oven-dried (60 °C) mesh bags were filled with 10–12 G of the chopped vetch and re-weighed. As bags were filled and weighed, vetch sub-samples were collected periodically to be tested for moisture levels. The vetch-filled bags were placed randomly in the plots with mow-killed vetch (eight bags per plot). Field residues were moved aside, thin wires were pushed through the bag into the soil to anchor them at the soil surface, and field residues were replaced over the litter bags. During the next five months, litter bags were collected at each soil sampling date (one bag per plot, except for the last sampling date when two bags were collected). Any adhering soil was gently brushed from the mesh bags and they were dried at 60 °C.

*Analytical methods*

Anaerobic N-mineralization potential and soil mineral N content ($NO_3^-$, $NH_4^+$) were determined as in Drinkwater et al. (1996). Briefly, immediately after sampling, field moist soil was sieved at 2 mm to remove shale and large organic debris. Approximately 8 g of sieved soil was placed into pre-weighed centrifuge tubes containing either 10 mL di$H_2O$ or 40 ml of 2.0 M KCl. Tubes were then re-weighed and the tubes containing soil in 2.0 M KCl were placed on a shaker for 1 hour for $NO_3^-$ and $NH_4^+$ extraction. Tubes containing soil in di$H_2O$ were purged with $N_2$ and sealed with a rubber stopper. After a seven day anaerobic incubation at 37 °C, $NH_4^+$ released by mineralization was extracted with 2 *M* KCl as before. Potentially mineralizable N was calculated by subtracting the initial amount of $NH_4^+$ in the soil from the amount of $NH_4^+$ released during the incubation.

Soil KCl extracts were analyzed on a Technicon Autoanalyzer II (Bran and Luebbe, Buffalo Grove, IL). Soil moisture was determined gravimetrically. Total carbon (C) and N were determined for the last soil sample collected (Oct. 5) as well as for the litter bag vetch residues using a LECO 2000 CN analyzer (LECO, St. Joseph, MI). To determine plant tissue N, plant sub-samples were ground in a Wiley Mill to pass through a 2 mm screen, then sent to the Pennsylvania State University analytical laboratory for analysis of total N by Kjeldahl digestion method.

*Nitrogen budget*

Nitrogen in standing maize biomass was determined from the biomass cuts taken at physiological maturity. Estimates of N inputs from leguminous green manures were based on aboveground shoot biomass N content. Literature values for N-fixation in clovers and vetch range from 75–88% (LaRue and Patterson, 1985; Papastylianou and Danso, 1991) and belowground biomass accounts for 15–30% of the total plant biomass (Kuo et al 1996). Therefore, use of shoot biomass N content as the estimate of N-fixation results in N-fixation rates within the range of those previously reported. Nitrogen in the weed biomass was estimated by assuming an N content of 1.2% based on N content data from a hay variety of oats (Drinkwater, unpublished) and N in partially decomposed vetch residues on the surface of no-till treatments was based on the %N content of vetch residues in the litter bags on Oct 5.

*Data analysis*

All statistics were done using SAS (SAS Institute, Raleigh, NC). ANOVA of unequal treatments was done using Proc GLM. ANOVA for cropping system (organic versus conventional), tillage (primary tillage at maize planting or not), block effects and interactions were performed. ANOVA were also run to compare all six organic tillage treatments and the three conventional tillage treatments (main effects treatment and block). After analyses of variance showed statistical significance, pairwise comparisons were either Scheffe's (in cases where more than six treatments were involved) or Duncan's (in cases with six or fewer treatments).

## Results

*Maize yields*

Overall, tillage effects were more pronounced than were cropping system effects on maize production (Table 3). Tillage effects on maize yields were highly significant (ANOVA, $p<0.0001$), with yields ranging from 1320 to 8690 to kg ha$^{-1}$ (Figure 1). Yields fell into four groupings related to tillage intensity. The organic and conventional MP and CD treatments had the highest yields, with no significant differences among these four treatments. Yields in CD-NTc were not significantly different from organic CD yields. This was the only organic treatment where no-till planted maize produced yields equal to that of conventional NT maize (6630 and 6610 kg ha$^{-1}$, respectively). The three organically-managed treatments that grew maize under a no-till regime without cultivation operations produced the lowest yields. Yields in the mixed-tillage treatments (CD-NT and MP-NT) were nearly threefold greater than those in the organic strict no-till treatment (NT).

Weed competition was substantial in organic treatments where no-till maize was grown without mechanical cultivation, resulting in reduced maize biomass production. Weed biomass was significantly reduced in the CD-NTc maize relative to other mixed-tillage treatments (CD-NT and MP-NT), and was not significantly different from the organic CD treatment (Figure 2). Among MP-NT, CD-NT and NT treatments, weed biomass was not significantly different; however, maize biomass in the organic NT treatment was greatly reduced so that total above ground plant biomass was predominantly weeds by the end of the

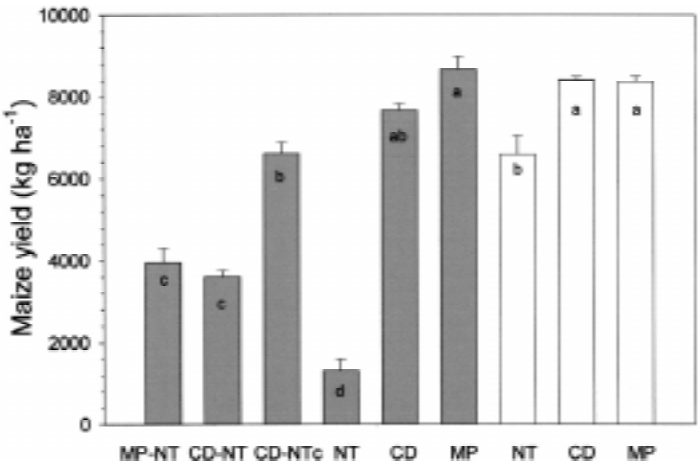


*Figure 1.* Maize yields in organically-managed (gray bars) and conventionally-managed (open bars) treatments. Tillage intensity is indicated on the x-axis. Bars with different letters are significantly different (protected Scheffe's, $p<0.05$).

growing season (6010 and 3320 kg ha$^{-1}$, for weeds and maize, respectively; Figure 2). The dominant weed in all organically-managed treatments was giant foxtail (*Setaria faberii* Herrm.) which accounted for nearly 90% of the total weed biomass. There were no significant weed biomass differences between organic and conventional CD and MP treatments.

Maize ear leaf N was significantly lower in organic treatments without weed cultivation, compared to MP, CD, and CD-NTc treatments (data not shown, protected Scheffe's, $p<0.005$) suggesting the N limitation contributed to reduced yields. Maize ear leaf N was positively correlated with yields among the six organic treatments (Pearson correlation ($n$=24), $r$=0.83, $p<0.0001$) and negatively correlated with weed biomass (Pearson correlation ($n$=24), $r$=0.81, $p<0.0001$) suggesting that competition from weeds affected maize N status. There were no significant differences in maize ear leaf N among the three organic treatments that had severe weed competition (MP-NT, CD-NT and NT). Within this group, maize ear leaf N at silking and yield were inversely related indicating that N was not the major factor contribution to the lower yields in the strict NT (Pearson correlation ($n$=12), $r= -0.30$, $p<0.05$).

### *Vetch biomass and stand establishment*

Tillage effects on vetch biomass production and stand establishment were also significant (Table 4). Because no-till maize could be planted into the living vetch stand, vetch was allowed to grow 3.5 weeks longer in these treatments than it was in the MP and CD treatments. This resulted in significantly greater aboveground biomass and hence greater N in the mixed-tillage plots compared to the MP and CD treatments, which used primary tillage 12 days prior to maize planting (Table 4). Nitrogen content of the green manure biomass in the NT treatment was lower compared to that in the mixed-tillage regimes, probably because of the higher proportion of non-leguminous weeds (Table 4). Primary tillage at hairy vetch planting improved stand establishment and reduced weeds. Tillage intensity effects were evident in early December 1993, when weed establishment in the NT vetch stand was significantly greater than in treatments where the vetch seed bed had been prepared by either moldboard plowing or chisel-discing (protected Duncan's, $p<0.05$; 23% compared to 4–8%, respectively).

### *Nitrogen availability and soil moisture*

In May, before vetch incorporation or maize planting, mineral N concentrations were very low in all treatments at both sampled depths (Figures 3a, b). Tillage operations significantly affected mineral N concentrations at both sampled depths. At the 0–5 cm depth, both primary and secondary tillage treatments had significant effects (Figure 3a). Mineral N rose rapidly in surface soils of the CD treatment and remained greater in that treatment than in other treatments for most of the growing season (Figure 3a). Cultivation in no-till planted maize significantly increased mineral N concentrations relative to the other treatments with no-till planted maize. In the CD-NTc treatment, mineral N peaked at the 0–5-cm depth after cultivation and was

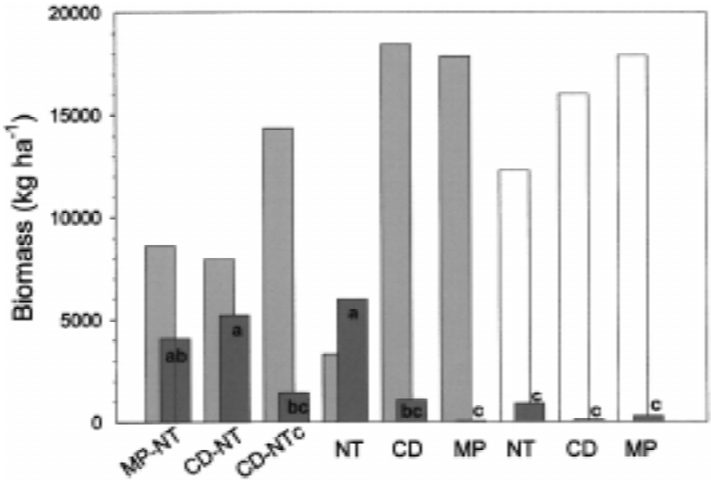


*Figure 2.* Total maize biomass at black layer in organically-managed (gray bars) and conventionally-managed (open bars) treatments compared to maximum weed biomass (dark gray bars in front). Tillage intensity is indicated on the x-axis. Weed biomass bars with different letters are significantly different (protected Scheffe's, $p<0.05$).

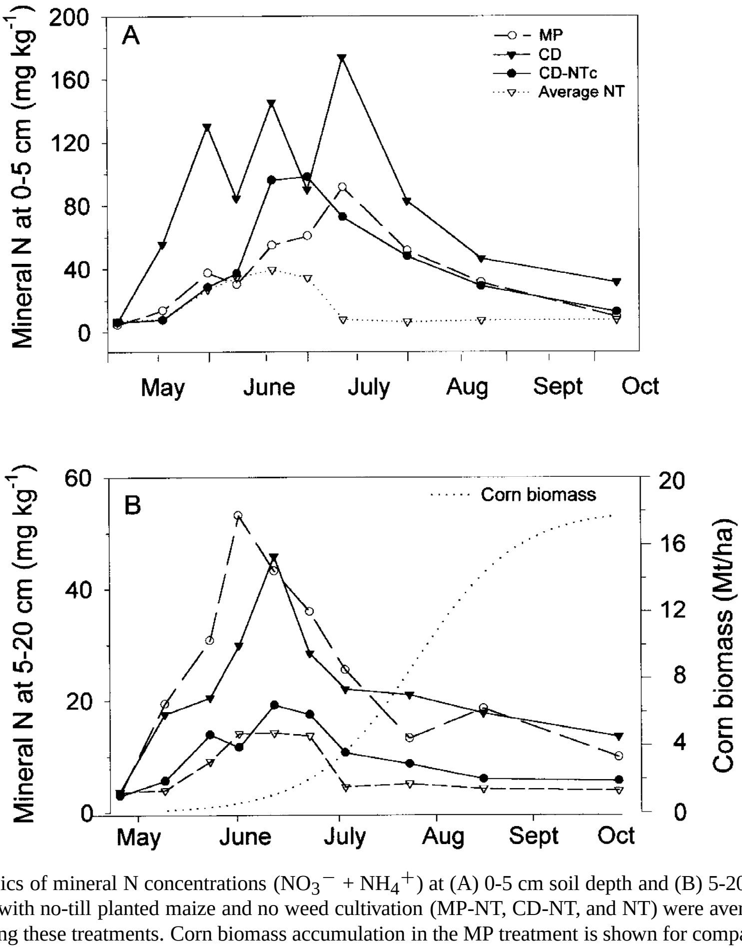


*Figure 3.* Temporal dynamics of mineral N concentrations ($NO_3^- + NH_4^+$) at (A) 0-5 cm soil depth and (B) 5-20 cm depth during the maize crop. The three treatments with no-till planted maize and no weed cultivation (MP-NT, CD-NT, and NT) were averaged because there were no significant differences among these treatments. Corn biomass accumulation in the MP treatment is shown for comparison to timing of N release in B.

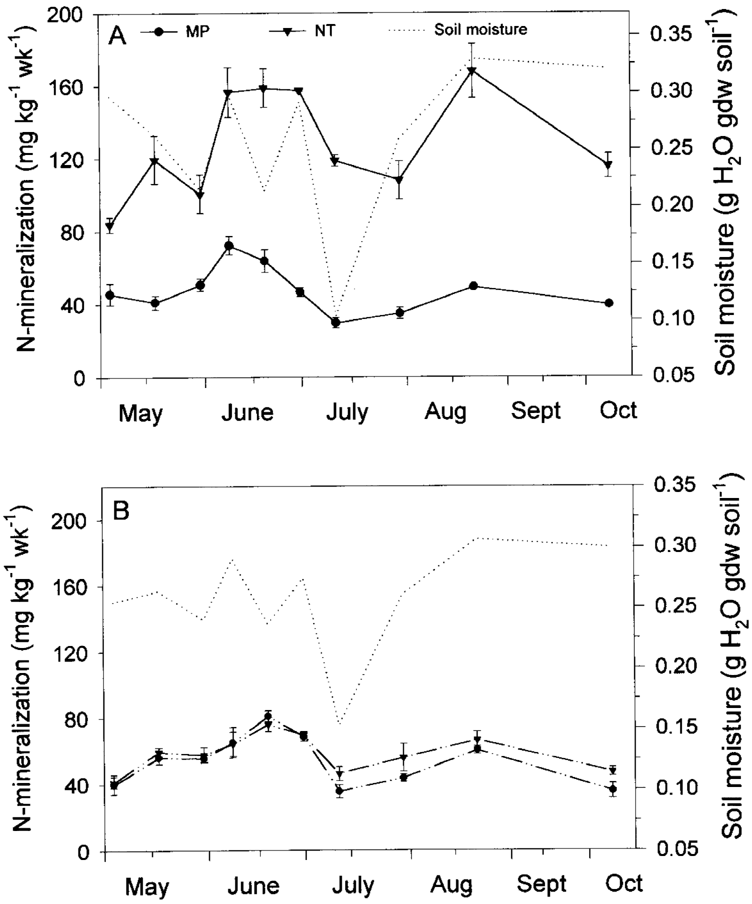


*Figure 4.* Temporal dynamics of N-mineralization potential and soil moisture at (A) 0-5 cm soil depths and (B) 5-20 cm depths during the maize crop. Only two treatments are shown, MP and NT, which had the greatest differences. All other treatments fall between the two that are shown here. At the 5–20 cm depth, there were no significant differences among treatments. Soil moisture shown is the average of the MP and NT treatments.

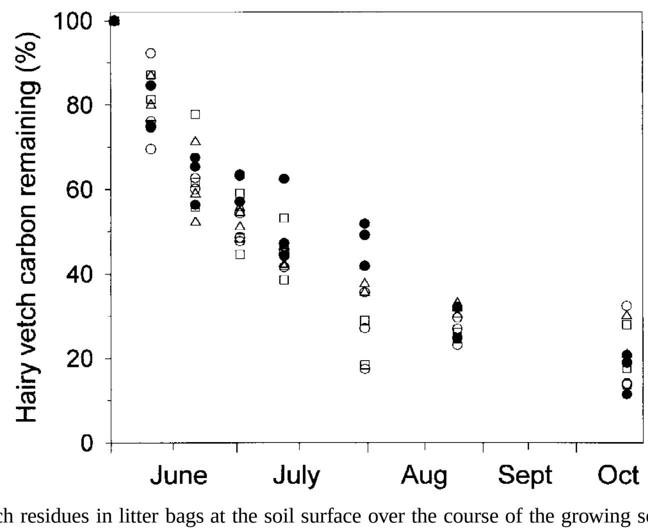


*Figure 5.* Carbon loss from vetch residues in litter bags at the soil surface over the course of the growing season. The four treatments shown are as follows: CD-NTc (●), CD-NT (○), MP-NT(△), and NT (□).

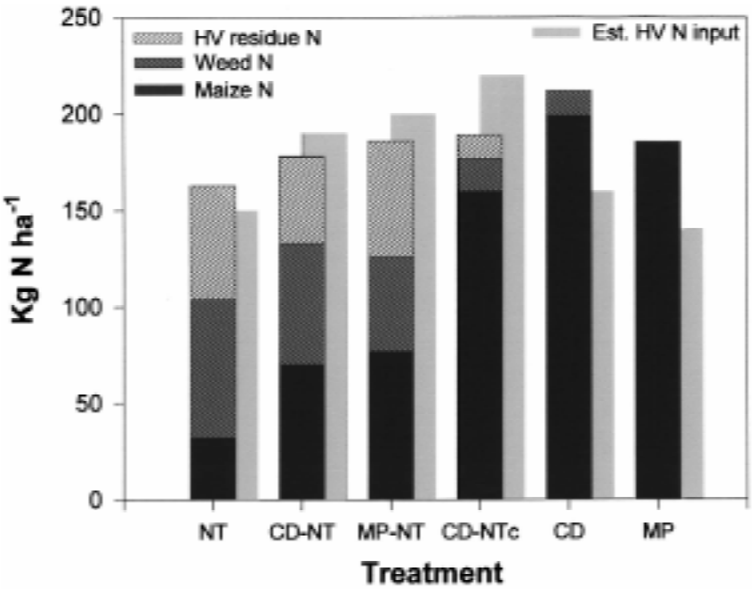


*Figure 6.* Nitrogen distribution among aboveground plant biomass and remaining surface residues relative to estimated total N fixed by hairy vetch. Stacked bars show aboveground N in maize and weed biomass and N remaining in vetch residues on the soil surface at the end of the growing season. Light gray bars behind each stacked bar show total N in aboveground vetch residues at the time of incorporation or mowing.

not significantly different from the MP treatment for much of the growing season. After the end of June, when maize was growing most rapidly, mineral N was significantly lower in the three treatments with no-till maize (NT, MP-NT, CD-NT) compared to the other three treatments.

Mineral N concentrations at the 5–20 cm depth were significantly greater in the two treatments where vetch was incorporated with primary tillage compared to no-till planted maize (Figure 3b). The greatest concentrations occurred within five to six weeks after tillage in the MP and CD treatments, long before maize had reached the exponential growth phase. In contrast, mineral N never reached concentrations above 20 mg $kg^{-1}$ in any of the no-till maize treatments, and there were no significant differences at any date between the CD-NTc and other NT maize treatments (Figure 3b). After late June, mineral N declined rapidly in all treatments as plant uptake increased.

Tillage effects on N-mineralization potential were most evident in the surface soils. Seasonal averages at depths of 0–5 cm were twofold to threefold greater in soils where vetch residues were left on the surface compared to the MP treatment, which had the lowest average N- mineralization potential (48 mg $NH_4^+$-N $kg^{-1}$ $week^{-1}$; data not shown). Average N-mineralization potential was greatest in soils in the organic strict NT treatment (129 mg $NH_4^+$N $kg^{-1}$ $week^{-1}$; protected Duncan's, $p<0.05$; data not shown). Average N-mineralization potential in the 5–20 cm soil depths was not significantly different across treatments (ANOVA, $p>0.05$; data not shown) and ranged from 53-59 mg $NH_4^+$-N $kg^{-1}$ $week^{-1}$. Seasonal trends were similar at both depths for all treatments (Figures 4a, b). Nitrogen-mineralization potential peaked shortly after vetch incorporation or mowing and then dropped precipitously in mid-July when soils were extremely dry, resulting in the lowest values of the growing season (Figures 4a, b).

Treatment effects on soil moisture dynamics differed at the two soil depths. Seasonal averages of moisture content in surface soils were not affected by treatment (ANOVA, $p>0.1$), however, at the 5–20 cm depth average soil moisture was significantly lower in the strict NT maize compared to the MP, CD, CD-NT, and CD-NTc treatments (protected Duncan's, $p<0.05$; data not shown). Soil moisture content in mid-July, the driest sampling date, followed this pattern and was 20% lower in the NT maize plots compared to the CD-NTc treatment. Among the no-till planted maize treatments, soil moisture in mid-July in the 5–20 cm layer was inversely related to weed biomass (Pearson correlation, ($n$=16); $r = -0.70$, $p<0.05$).

### *Vetch residue decomposition*

Treatment effects on vetch residue decomposition were not evident in the litter bag experiment (Figure 5). By early October, when the litter bag experiment was terminated, there were no significant differences across treatments in the proportion of C remaining (ANOVA, $p>0.05$), which averaged 21%. The kinetics of N-mineralization from the litter paralleled those of C, although slightly more N than C was mineralized so that by the end of the growing season, C:N ratio had increased from 10.8:1 to 14:1. In contrast, samples of aboveground residues collected in August indicated significant differences in vetch decomposition among the various no-till treatments (Table 4). The differences in these results can probably be explained by our experimental design. In the litter bag experiment, we chose to place litter bags on the soil surface in all NT maize treatments. Our results indicate that there were no treatment effects at the soil surface. The major difference between undisturbed and cultivated vetch was that the process of cultivation deposits some soil on top of vetch residues, increasing contact between soil and residue. In retrospect, two placement sites–one on the soil surface, the other on top of the vetch residues–would have more accurately reflected decomposition dynamics of the residues in the NT, MP-NT, CD-NT and CD-NTc treatments.

### *Aboveground nitrogen budget*

The fate of available N differed significantly among treatments (Figure 6). Aboveground maize biomass in CD-NTc plots accumulated two to five times as much N as did maize biomass in the three no-till treatments without cultivation. However, weeds in the non-cultivated treatments captured significant amounts of N, bringing the total plant uptake to 110–140 kg N ha$^{-1}$ or 60–80% of total plant uptake in the CD-NTc treatment. At the end of the growing season, four times as much vetch residue remained on the surface in the no-till treatments without cultivation as in the CD-NTc treatment, and this residue contained up to 60 kg N ha$^{-1}$. Nitrogen captured in aboveground biomass of the CD and MP treatments was significantly greater than the N content of vetch at the time of incorporation (Figure 6). This was not the case in the MP-NT, CD-NT and NT treatments where plant uptake was significantly lower than vetch N at mowing.

## Discussion

### *Cropping system effects*

Organic maize yielded well as long as some form of soil disturbance in maize compensated for the absence of herbicides. Yields were not significantly different under organic and conventional management regimes in the CD and MP treatments where weed competition was minimal and the N status of maize plants was essentially the same regardless of the form of N inputs. Strict NT organic maize yields were only 20% of yields in the conventional NT maize even though an excellent vetch stand had been established. In previous years, organic NT maize yields in this experiment were 10–45% of conventional NT yields and these reductions coincided with a poor vetch stand (Wagoner et al., 1993). Alternating tillage with no-till improved organic maize yields significantly, however, only the mixed tillage system with weed cultivation had yields similar to conventionally-managed NT maize. Yields in the other mixed tillage treatment were 60% of those in conventional NT maize (MP-NT and CD-NT).

Comparisons of organic and conventional cropping systems have been conducted on working commercial farms and in replicated experimental plots, usually under conventional tillage regimes. Most recent farm and experiment station studies have reported comparable crop yields in established organic cropping systems such as our experiment (Creamer et al., 1996; Drinkwater et al., 1995, 1998; McGuire et al., 1998; Reganold et al., 1987, 1993). A few studies have found yield reductions in organic agricultural systems, although these reduced yields commonly occurred during the first five years under organic management, which has been called the transition phase (Liebhardt et al., 1989; Temple et al., 1994; Varis et al., 1996).

### *Tillage effects under organic management*

In the organically-managed systems, tillage practices had significant impacts on both the vetch biomass production and maize yields. The 3.5 week delay in killing the green manure resulted in greater biomass production in all four treatments with no-till planted maize. However, this did not always translate into greater N inputs. Total N in aboveground vetch biomass averaged 200 kg ha in the three mixed tillage treatments (CD-NT, CD-NTc and MP-NT) where tillage prior to vetch planting ensured excellent stand establishment and a relatively high N concentration was maintained. In the strict NT system, the advantage of greater vetch biomass production under NT was off-set by lower N concentration, probably due to the greater proportion of non-N-fixing weeds in the vetch cover crop. In the two treatments with primary tillage, the early incorporation of the vetch prior to maize planting resulted in a smaller vetch biomass. As a result, total N in the vetch stand was not significantly different among these three treatments (NT, MP and CD), and averaged 150 kg ha.

Biomass production by no-till planted leguminous green manures is frequently lower since most winter-hardy annual legumes are small-seeded plants and can be difficult to establish under high-residue conditions (Groffman et al., 1987; Wagoner et al., 1993). While total N in the hairy vetch biomass under the strict NT regime in 1994 was comparable to that of the MP and CD treatments, in past years the success of the vetch cover crop has been highly variable. Typically, N contained in the aboveground biomass was only 20–50% of that in vetch stands planted with primary tillage (Wagoner et al., 1993). Clearly, the risk of reduced N inputs due to poor productivity of the green manure can be greatly reduced by investing in some seed bed preparation at planting. In the long term, leguminous cover crop germplasm could be selected for improved germination under high-residue conditions.

Despite the comparable or greater N inputs in the four treatments with no-till maize, only the (CD-NTc) had yields comparable to those achieved in the organically-managed conventional tillage regimes (CD and MP). In the other three no-till maize treatments weed biomass was very high and a significant amount of available N was captured by weeds. The large weed biomass coupled with lower maize ear leaf N concentrations in no-till maize treatments suggests that competition for N was a major factor contributing to lower yields. Given that 1994 was a fairly dry year, competition for water may have also played a role, however if water limitation was the dominant factor we would expect to see greater concentrations of tissue N coincide with lower biomass production. Instead, maize ear leaf N at silking was positively correlated with yields.

Reasons for the striking differences in maize yield among the three no-till maize treatments without weed cultivation are not as clear. Despite the formidable weed pressure and comparable N status at silking, corn biomass was more than two-fold greater in the two mixed tillage systems compared to the strict NT. We have identified several possible explanations. First, at mowing, green manure N in the strict NT was only 75% of that in the two mixed tillage systems, so N may have been less available in that system compared to the MP-NT and CD-NT treatments. Second, maize plant density was significantly lower in the strict NT (38,400 plants ha in NT compared to 52,000 plants ha in MP-NT and CD-NT). Finally, weed competition may have been more severe earlier in the growing season since there were weeds already established in the hairy vetch to carry over into the early spring. All of these factors may have resulted in greater competition for N and water from weeds in the strict NT plots.

The severe weed competition in the three no-till planted maize plots occurred in spite of the excellent mulch layer produced by mowing the green manure indicating that the vetch mulch was not an adequate form of weed control in 1994. In previous years, weed suppression by the vetch mulch in the mixed-tillage treatment was more successful (Wagoner et al., 1993). Recent cover crop/conservation tillage experiments have also achieved successful weed suppression without the use of herbicides (Creamer et al., 1996; Teasdale, 1993), suggesting that use of cover crops as mulches could replace herbicide use in no-till systems. However, few long-term studies of herbicide-free mulched systems without tillage have been conducted. Our results indicate that mulch-based weed suppression is not a reliable form of weed control. Additional research is needed to identify the climatic factors and plant species characteristics that influence the success of cover crop establishment and mulch-based weed control in reduced tillage systems.

*Nitrogen dynamics*

Based on our results and those of earlier studies, there is no doubt that annual legumes can provide adequate N for subsequent cash crops under conventional tillage regimes (Drinkwater et al., 1998; Mitchell and Teel, 1977; Neely et al., 1987; Sarrantonio and Scott, 1988; Stivers and Shennan, 1991; Touchton et al., 1982, 1984). However, the incorporation of these low C:N residues frequently results in very rapid net release of mineral N shortly after incorporation when plant uptake is still minimal (Sarrantonio and Scott, 1988). In the MP treatment, N availability peaked at nearly 120 kg N ha$^{-1}$ in early-June, well before the maize crop was taking up significant quantities of N. Studies with conventional fertilizers have shown that nitrate leaching is greater in systems where heavy pre-plant fertilizer applications result in large pools of soil nitrate compared to management schemes that avoid major applications of N fertilizer early in the season before crop demand has developed (Kanwar et al., 1988; Kanwar and Baker, 1991). Although we did not measure nitrate leaching, previous studies clearly show that nitrate leaching potential is greatest when large pools of soil nitrate are present in the absence of significant plant uptake (Brandi-Dohrn et al., 1997; McCracken et al., 1994; Staver and Brinsfield, 1998). Thus, large pools of nitrate resulting from the rapid net mineralization of vetch residues in the MP and CD treatments would be susceptible to leaching in years with rainy springs.

Optimizing the timing of net N-mineralization relative to crop uptake is a central to the development of cropping systems that maintain yields while minimizing environmental impacts. This is a significant challenge in annual cropping systems because of the need for pulsed delivery of N, and because the complex biological processes that govern N availability cannot be managed precisely using current practices. While tillage at the time of incorporation results in excess N release before crop demand has developed, in green-manured systems without primary tillage, N limitations frequently occur and mineralization of adequate N for uptake by the cash crop at the appropriate time is a major concern (Doran, 1980; Groffman et al., 1987; Power et al., 1991; Sarrantonio and Scott, 1988; Varco et al., 1989).

Several mechanisms contribute to the apparent reduction in available N reported under no-till. Both reduced mineralization rates and increased immobilization have been reported in no-till soils (Power et al., 1991; Powlson, 1980). The reduced net N-mineralization results from both a decrease in N-mineralized from green manure residues, which are left on the soil surface, as well as reduced mineralization of soil organic matter in the absence of tillage. Increased assimilation of N by decomposers (or immobilization of N) could be particularly important in systems that have accumulated high C:N residues on the soil surface. In our experiment, this would only be the case in the continuous NT plots. However, over the long term, increased immobilization at the surface leads to increased labile pools of organic N, as indicated by the very high N-mineralization potential we observed in these plots at soil depths of 0–5 cm. It is likely that N-mineralization potential could increase sufficiently under long-term no-till so that enough N could be supplied to achieve high yields. Finally, denitrification may contribute to reductions in available N, since the denitrification potential is often greater in NT soils (Doran, 1980) but this is probably not of major importance since the relative losses through denitrification tend to be small (Groffman et al., 1987; Powlson, 1980).

Soil mineral N concentrations in all four no-till maize treatments never reached the levels seen in treatments where vetch residues were incorporated with tillage. The only significant difference in mineral N concentrations was at the soil surface following weed cultivation when mineral N temporarily increased in the CD-NTc treatment indicating that disturbance of the vetch mulch stimulated N-mineralization. Although mineral N at soil depths of 5–20 cm was similar to the other mow-killed vetch/no-till maize treatments, N accumulation in maize biomass was three to five times greater in the CD-NTc treatment than in the other NT treatments, suggesting that more N was available to support crop growth. Thus, cultivation of no-till planted maize not only helped control weeds but also increased the N supply, probably during the period of maximum N demand by the maize. Furthermore, while the potential for nitrate leaching was significantly reduced in all the mow-killed vetch/no-till maize treatments, only the CD-NTc achieved reasonable maize yields while maintaining relatively low mineral N pools.

At maize harvest, the total aboveground N budget indicates there were significant differences in net N-mineralization that correspond with tillage intensity. In the CD and MP treatments, total N in the green manure was much lower than total N in standing biomass suggesting that mineralization of N from soil organic matter was significant under conventional tillage. In the no-till treatments, mineralization of the green manure was clearly reduced and less N was captured by weeds and maize.

## Conclusions

The fate of vetch N as well as temporal N dynamics were largely determined by tillage intensity and the handling of the vetch residues at maize planting. Treatments with primary tillage (CD and MP) had substantially greater net N-mineralization even though N input from hairy vetch green manure in these treatments was equal to or lower than the four treatments with mow-killed vetch. Mineral N pools generally rose until mid- to late-June and then declined as plant uptake increased. Properly timed surface disturbance through mechanical cultivation demonstrated dual benefits: weed suppression and increased control of the timing of N-mineralization from green manure residues. Strategic use of tillage both decreased soil nitrate concentrations in early spring, thus reducing the potential for nitrate leaching, and increased N availability at times of maximum maize demand, resulting in maize yields comparable to those in the conventionally-managed NT system. An additional benefit of using green manures in no-till systems is the potential for reductions in herbicide applications. Use of some tillage in seedbed preparation for winter-hardy annual green manures increased the likelihood of establishing a successful stand. For the long term, leguminous green manure crops that can germinate under the high-residue conditions common to no-till systems should be developed. Carefully designed rotations that combine tillage reductions with the use of leguminous N sources can have significant advantages in terms of both yields and reduced adverse environmental impacts.

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