Tillage Effects on Soil Nitrogen and Plant Biomass in a Corn–Alfalfa Rotation

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ABSTRACT

Alfalfa (*Medicago sativa* L.) stands have been reported to either decrease or increase nitrate (NO_3) leaching, depending on tillage management. The fate of alfalfa-generated N and its interaction with N fertilization in a subsequent corn (*Zea mays* L.) crop remains uncertain. Alfalfa contributions to corn yields and soil mineral N pools were studied under conventional tillage (CT) and no-tillage (NT) systems over a 3-yr corn–alfalfa–corn sequence. The field experiment compared CT vs. NT managements in fertilized and nonfertilized Kalamazoo loam soils (Typic Hapludalf). Four of the nonfertilized plots were equipped with undisturbed monolith lysimeters to monitor NO_3 leaching. Living alfalfa stands lost 6 kg N ha^{-1} to deep leaching over a 1-yr period, which is much less than the 20 kg NO_3–N ha^{-1} yr^{-1} lost by nonfertilized corn following corn. Within the first 6 mo following the spray-killing of the stand, alfalfa plant tissue decomposition contributed to soil mineral N pools up to 115 kg N ha^{-1}. During a dry year, all corn N requirements were met by plant tissue decomposition of alfalfa and soil organic matter mineralization, while applied N fertilizer accumulated in the soil profile and was highly susceptible to spring leaching. Similar quantities of N were lost to deep leaching from CT and NT systems during corn production, as higher drainage rates in NT systems were compensated by lower NO_3–N concentration of the leachates.

Nitrogen-conservative agricultural systems are increasingly sought by agronomists and environmentalists. Nitrate leaching in soils under corn (*Zea mays* L.) production depends on tillage systems and N fertilizer inputs. Corn N fertilization tends to generate NO_3 leaching problems when applications are in excess of plant uptake (Angle et al., 1993; Gast et al., 1978). Gast et al. (1978) reported little NO_3 leaching differences between corn fields receiving from 20 to 112 kg N ha^{-1}. No-tilled (NT) soils present higher infiltration rates (Bissett and O'Leary, 1996; Dao, 1993), and higher drainage water flows (Huang, 1995; Randall and Iragavarapu, 1995; Weed and Kanwar, 1996) than conventional tillage (CT) soils. This difference is explained by the continuity of soil macropore networks, especially root-induced and earthworm macropores, in NT soils (Comia et al., 1994; Lal and van Doren, 1990; Rasse and Smucker, 1998; Reynolds et al., 1995; Waddell and Weil, 1996). Soil water leachates contain higher NO_3 concentrations in CT than in NT corn production systems (Randall and Ivaragarapu, 1995; Weed and Kanwar, 1996). Combining drainage flow and NO_3 concentration, total NO_3 losses by deep leaching are generally slightly higher for CT than NT soils, under corn production (Randall and Ivaragarapu, 1995; Weed and Kanwar, 1996).

Numerous studies have reported that previous alfalfa (*Medicago sativa* L.) stands increased yields of the subsequent nonlegume crop (Hesterman et al., 1986a, 1986b; Barnes et al., 1978, 1983; Groya and Sheaffer, 1985). Nitrogen replacement values of alfalfa to a succeeding corn crop were estimated to range from 90 to 125 kg N ha^{-1} (Bruulsema and Christie, 1987). Fox and Piekielek (1988) reported a total N replacement value for a 3-yr alfalfa stand followed by 3 yr of consecutive corn to be 167 kg N ha^{-1}. Nevertheless, the alfalfa N replacement values for succeeding corn crops is still underestimated or neglected by many farmers, resulting in wasted fertilizers and groundwater pollution problems (El-Hout and Blackmer, 1990; Peterson and Russelle, 1991).

Alfalfa stands have been reported to either decrease or increase NO_3 leaching, depending on field management. Alfalfa has a great ability for absorbing nitrates from late fall to early spring, when leaching is most intense (Lamb at al., 1995). The deep rooted system of alfalfa can recycle nitrates leached to depths inaccessible to other crops (Blumenthal and Russelle, 1996). On the other hand, mineralization bursts from decomposing alfalfa can lead to high levels of NO_3 leached to the ground water if not timely matched by crop consumption (Campbell et al., 1994; Philipps and Stopes, 1995). This study was conducted to investigate NO_3 leaching in corn systems as influenced by the combined effects of tillage, N fertilization, and rotation with alfalfa.

MATERIAL AND METHODS

Experimental Design and Treatments

A corn–alfalfa–corn sequence was studied from 1994 to 1996 as part of a long-term field experiment investigating N supply and tillage effects on soil–plant interactions. Field plots, 40 by 27 m each, were established in a randomized complete block design in 1986 in a Kalamazoo loam soil (fine-loamy, mixed, mesic Typic Hapludalf) at the Long-Term Ecological Research (LTER, http://lter.kbs.msu.edu) site of the Kellogg Biological Station (KBS, http://www.kbs.msu.edu) in southwestern Michigan. Previous crops on these plots were corn in 1992 and 1993. Soil horizons are a loamy Ap from 0 to 0.30 m, which overlays a clay loam Bt_1 from approximately 0.30 to 0.55 m, then a Bt_2 enriched in coarse material from approximately 0.55 to 0.75 m, which is underlain by a coarse glacial outwash parent material. Treatments, replicated four times, consisted of (i) conventional tillage and N fertilization (CT-F), (ii) no tillage and N fertilization (NT-F), (iii) conventional tillage and no fertilization (CT-NF), and (iv) no tillage and no fertilization (NT-NF). Undisturbed monolith lysimeters, 1.2 by 1.8 m of surface area and 2.1 m deep, were installed in two CT-NF and two NT-NF plots in 1990. Agronomic operations for the 1994, 1995, and 1996 growing seasons are summarized in Table 1. Lysimeters, which were identically managed

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Abbreviations: CT, conventional tillage; NT, no-tillage; KBS, Kellogg Biological Station; F, fertilization; NF, no fertilization; TDR, time domain reflectometry; LSD, least significant difference; K_{sat}, saturated hydraulic conductivity.

Table 1. Summary of field operations for 1994 to 1996.

	Corn 1994	Alfalfa 1994–1996	Corn 1996
Plowing (CT plots only)	Moldboard to 22 cm and disking April 1994	Moldboard to 22 cm and disking 29 Aug. 1994	Moldboard to 22 cm and disking 8 May 1996
Herbicide	Glyphosate† 3 May 1994	Glyphosate 30 Aug. 1994	Glyphosate and 2,4 D‡ 2 May 1996
Planting	Pioneer hybrid 3573 67 700 seeds ha^{-1} 6 May 1994	Pioneer 5246 22 kg seed ha^{-1} 1 Sept. 1994	Pioneer hybrid 3573 67 700 seeds ha^{-1} 13 May 1996
N Fertilization (F plots only)	Ammonium-nitrate 123 kg N ha^{-1} 11 June 1994	none	Ammonium-nitrate 123 kg N ha^{-1} 21 June 1996
Other fertilization		112 kg K_2O ha^{-1} 337 kg lime ha^{-1} 7 Apr. 1995	
Harvest	Silage: 23 Aug. 1994	Hay: 12 June 1995; 22 July 1995; 1 Sept. 1995 Spray-killing: Glyphosate and 2,4 D 2 May 1996	Silage: 4 Sept. 1996

† Glyphosate = N-phosphonomethyl glycine.
‡ 2,4 D = 2,4-dichlorophenoxy acetic acid.

to the field plots, were manually tilled, planted, and harvested. Corn was planted at high density in the lysimeters and later thinned to guarantee a uniform plant density matching field conditions. Total biomass per lysimeter was recorded and, as for field plots, subsamples were taken for moisture content and total N analyses.

Instrumentation and Measurements

Each monolith lysimeter is enclosed on five sides by stainless steel. An access chamber is positioned directly along the lysimeter and gives access to one full side of the monolith. Access ports for instrumentation were cut in the metal wall separating the monolith from the access chamber. Each monolith lysimeter is equipped with a drainage outlet at the bottom of the soil profile. The drainage solution was collected in a 58-L graduated container, allowing for the measurement of instantaneous and cumulative drainage rates, with an accuracy of ±1 L. Drainage samples were analyzed for NO_3 and NH_3 using a QuickChem automated ion analyzer (Lachat Instruments, Milwaukee, WI). Soil water contents of each horizon were estimated by time domain reflectometry (TDR). The TDR probes, inserted above and below previously determined horizon interfaces, were composed of two metal rods, 30.5 cm long and 0.5 cm in diameter, and were installed horizontally at a spacing of 5 cm apart in the soil profile. Soil water data were collected with a TDR-meter model 1502C (Tektronix, Beaverton, OR). Transformation of TDR readings into volumetric soil water contents was performed using Topp's equation (Topp et al., 1980).

Destructive soil sampling of the main field plots was conducted to depths of 150 cm in spring and fall of 1996 with a Giddings hydraulic probe of 7.5 cm core diameter (Giddings Machines Co., Ft. Collins, CO). Two cores were extracted from each plot and visually divided into Ap, Bt_1, Bt_2, C_1, and C_2 horizons, rather than to specific depths. Gravimetric soil water contents were determined on subsamples from each of the five horizons oven-dried for 24 h at 105°C. Field moist 20-g subsamples were extracted for NO_3–N and NH_4–N by shaking for 1 h in 50 mL of 1 *M* KCl solution. Solutions were analyzed for NO_3–N and NH_4–N with a QuickChem automated ion analyzer (Lachat Instruments, Milwaukee, WI). Plant materials were randomly subsampled from the total harvested biomass from each plot, weighed, oven dried at 70°C, and reweighed for determination of the moisture content. Finely ground (≤0.5 mm) subsamples (0.150 g), one per plot, were digested using standard total Kjeldahl procedures (Bremner and Mulvaney, 1982). Total mineralized N, as NH_4 in solution, was analyzed by a QuickChem automated ion analyzer.

Statistical Analyses

Statistical analyses were conducted using the general linear model of the SAS system (SAS Inst., 1989). Field replicated measurements were analyzed using Fisher's least significant difference ($LSD_{0.05}$). Monolith lysimeter data, based on two sets of replicated measurements taken at multiple dates, were used to analyze temporal dynamics of NO_3 leaching. Error bars were represented by standard deviations, as standard errors of duplicated samples can be misleading with respect to the significance of mean separation.

RESULTS AND DISCUSSION

Mineral Nitrogen Leaching

Consistently higher NO_3 concentrations were observed in CT-NF than in NT-NF lysimeter leachates, from 22 Feb. 1994 to 28 Feb. 1995 (Fig. 1A). Higher NO_3–N concentrations in CT vs. NT leachates have also been reported in previous studies (Randall and Iragavarapu, 1995; Weed and Kanwar, 1996). Nitrate concentrations in lysimeter leachates showed little variation from 22 Feb. 1994 to 28 Feb. 1995, with a small increase during the summer of 1994 (Fig. 1A), suggesting a delayed response to spring mineralization. Leachate concentrations fluctuated at approximately 4 mg NO_3–N L^{-1} for CT-NF lysimeters and 2 mg NO_3–N L^{-1} for NT-NF lysimeters throughout 1996 (Fig 1B).

Mineralized N from spray-killed alfalfa was not detected in the drainage solutions in 1996 (Fig. 1B). There was an abrupt increase in soil solution NO_3–N from 2 to 4 mg L^{-1} to 10 to 15 mg L^{-1} in early February 1997 (Fig. 1B). Nitrate concentrations rose to their highest levels in 3 yr during February 1997, suggesting that 9 mo were necessary for alfalfa-generated NO_3–N to leach through 2 m of the Kalamazoo soil profile.

Cumulative drainage volumes of solutions through soil profiles of NT-NF treatments were consistently higher than drainage volumes through CT-NF profiles, from 1994 to 1997 (Fig. 2). Higher drainage through NT soils is consistent with previous reports (Huang, 1995; Randall and Iragavarapu, 1995; Weed and Kanwar,

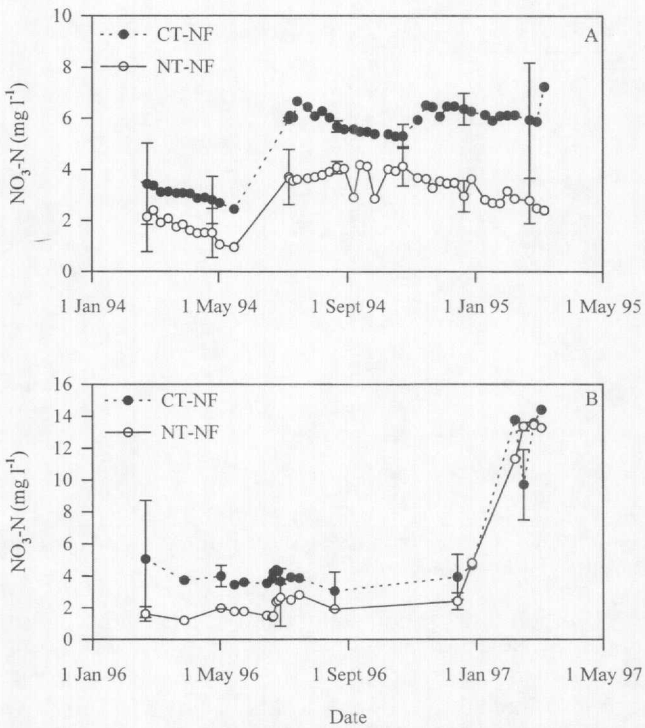

Fig. 1. Nitrate concentrations of drainage solutions from nonfertilized conventional tillage (CT) and no-tillage (NT) monolith lysimeters from (*A*) winter 1994 to early spring 1995 and from (*B*) winter 1996 to early spring 1997. Standard deviations for two replicates. Reduced number of error bars given for graphical clarity. Some error bars are smaller than symbols.

1996). Drainage volumes were quite low during the alfalfa crop, from spring 1995 to spring 1996 (Fig. 2). Most of the differences in drainage flows between CT-NF and NT-NF lysimeters were observed during the wetter year of 1994, following 3 yr of continuous corn. No apparent tillage-induced modifications of drainage flow were observed during or following alfalfa growth (Fig. 2). Soils remained untilled for 21 mo under alfalfa cover, which may have decreased tillage-induced differences in soil hydraulic properties. Following corn, alfalfa root distributions below the Ap horizon appeared to be unaffected by tillage (Rasse and Smucker, 1998). Therefore, we concluded that rooting intensity and possibly rooting patterns of the contemporary alfalfa crop masked tillage-induced differences in soil hydraulic properties, which were observed during the previous corn crop. Some authors have reported increased saturated hydraulic conductivity (K_{sat}) by alfalfa root-induced macropores or RIMs (Li and Ghodrati, 1994; Meek et al., 1992; Mitchell et al., 1995). However, in our study, we observed these increases in K_{sat} only after substantial decomposition of alfalfa root tissues had occurred (Rasse et al., 1999). These data imply that 21 mo of alfalfa growth has the potential for reducing tillage effects on soil drainage during alfalfa growth and for several months following the spray-killing of alfalfa, as soil drainage increased only after comprehensive decomposition of alfalfa root systems, resulting in greater drainage flow (Rasse and Smucker, 1998).

In spite of lower cumulative water drainage through CT-NF soils, total amounts of NO_3–N lost to deep drainage were higher in CT-NF than in NT-NF lysimeters. Total amounts of NO_3–N leached from profiles during the period from 22 Feb. 1994 to 28 Feb. 1995 averaged 24.8 and 21.0 kg ha^{-1} for CT-NF and NT-NF, respectively (Fig. 3). Baseline leaching levels, an average of NF treatments on Kalamazoo loam soils, approximated 23 kg NO_3–N ha^{-1} for this 12-mo period. During the subsequent alfalfa crop early growth of alfalfa during the winter and spring months contributed negligible quantities to the soil N pool. Volumes of soil solution leached through soil profiles under alfalfa in 1995 were lower than for the previous corn crop (Fig. 2), as 2 and 6 kg NO_3–N ha^{-1} were leached through CT-NF and NT-NF profiles, respectively (Fig. 3). These data and others (Lamb at al., 1995; Blumenthal and Russelle, 1996; Randall et al., 1997) confirm the superior potential that living alfalfa root systems have for preventing NO_3 leaching. During the subsequent 12-mo period following the spray-killing of alfalfa, NO_3 leaching increased greatly. Nitrate losses from CT-NF soil profiles were

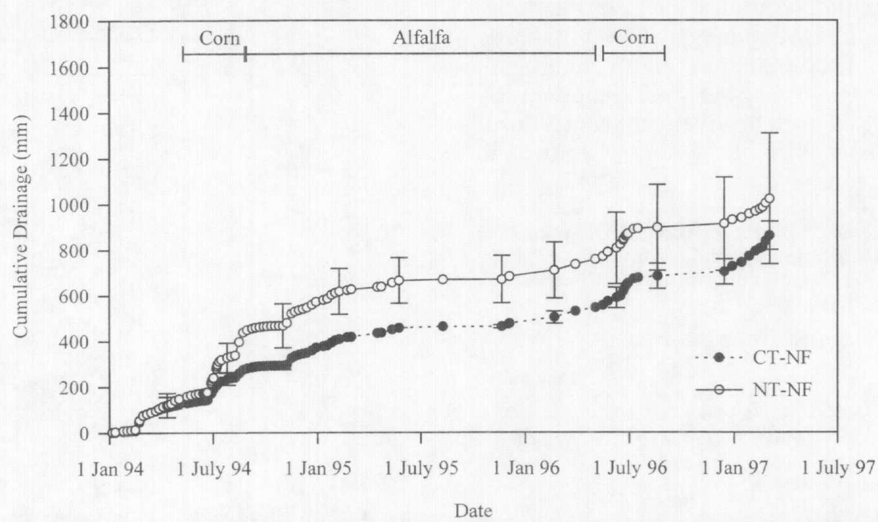

Fig. 2. Cumulative water drainage out of nonfertilized conventional tillage (CT) and no-tillage (NT) lysimeters from February 1994 to March 1997. Standard deviations for n = 2. Reduced number of error bars given for graphical clarity. Some error bars are smaller than symbols.

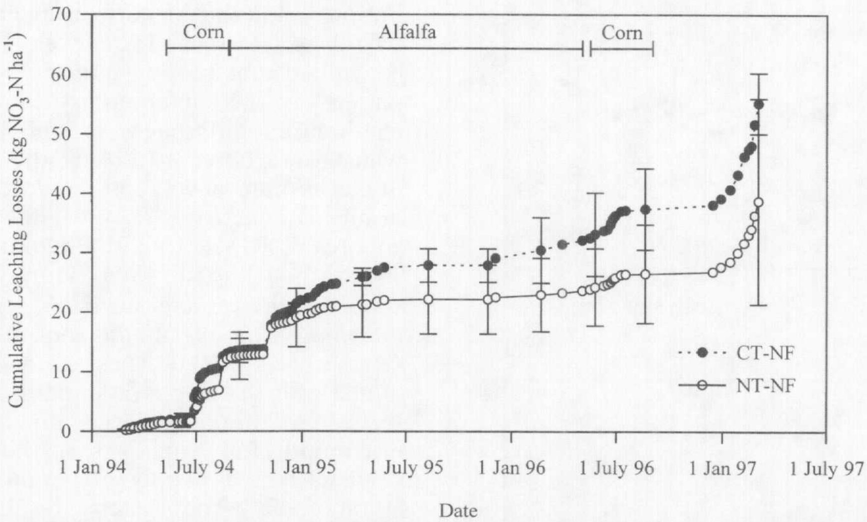

Fig. 3. Cumulative NO_3 leaching losses from nonfertilized conventional tillage (CT) and no-tillage (NT) field lysimeters from February 1994 to March 1997. Standard deviations for n = 2. Reduced number of error bars given for graphical clarity.

57% greater, i.e., 25 vs. 16 kg NO_3–N ha^{-1} for NT-NF. Greatest leaching rates were observed during the spring thaw and early season drainage between January and March 1997. Although higher drainage flows are frequently reported for no-tilled soils, total amounts of NO_3–N leached are similar to slightly lower from NT vs. CT profiles, due to higher NO_3–N concentrations in CT leachates (Randall and Iragavarapu, 1995; Weed and Kanwar, 1996). Enhanced by-pass flow through root-induced macropores reported by Gish et al. (1998) and Rasse and Smucker (1998) in NT soils allows soil water to percolate without displacing much of the soil solution in the soil matrix (Singh and Kanwar, 1991).

Plant Biomass and Nitrogen Contents

Alfalfa biomass harvested in 1995 was significantly modified by previous tillage and fertilization treatments (Table 2). Differences induced by previous managements were more substantial for the first harvest, on 14 June 1995, than for the two subsequent cuttings. During the 1995 season, cumulative alfalfa shoot biomass decreased significantly on NT-F managed soils, compared with the three other treatments. A highly significant factorial interaction ($P \leq 0.01$) between tillage and N fertilization, implied that both no-tillage and N fertilization of the previous corn crop had synergetic effects in decreasing alfalfa biomass yields.

Table 2. Dry herbage yields of alfalfa for three harvests in 1995 and cumulative over the growing season for conventional tillage (CT) and no tillage (NT) treatments, with N fertilization (F) and with no N applied (NF).

	Alfalfa dry herbage yields			
Treatments	14 June	31 July	5 Sept.	Cumulative
	kg ha^{-1}			
CT F	4026a†	2870a	2983a	9879a
CT NF	3796ab	2712a	2861a	9369a
NT F	3319b	2677a	2652a	8648b
NT NF	4237a	2800a	2809a	9846a

† Within columns, averages indexed with same letter are not significantly different by Fisher's $LSD_{0.05}$.

Nitrogen fertilization significantly increased biomass yields of corn by 149 and 117% in CT and NT plots, respectively, in 1994 (Fig. 4). In 1994, conventional tillage also increased biomass yields of fertilized corn by 39% compared with NT. Volumetric soil water contents in 1994 were higher and less variable in the Bt_1 horizons of NT than in CT profiles (Fig. 5). These findings agree with a previous report that no-tillage promoted higher soil water contents (Dao, 1993), suggesting higher soil water contents for NT treatments were not beneficial to corn growth in 1994. This was an exceptionally wet year (913 mm), with a combined rainfall of 510 mm from 1 May to 31 August. Higher corn yields have also been reported for CT than for NT of poorly drained soils (Randall and Iragavarapu, 1995), while the opposite was observed in well drained soils (Angle et al., 1993). Late-planted corn, following plowed-down or spray-killed cover crop, produced more under CT than NT managements in Wisconsin (Smith et al., 1992), but less in Kentucky (Zhang and Blevins, 1996). Delayed emergence

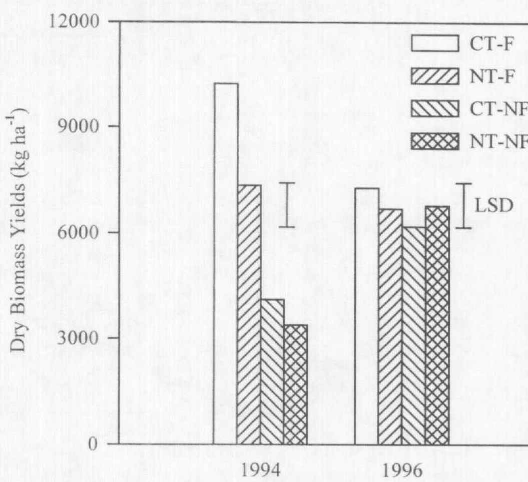

Fig. 4. Corn silage yields in 1994 and 1996, in conventional tillage (CT) and no-tillage (NT) plots, with N fertilization (F) and with no N (NF) applied.

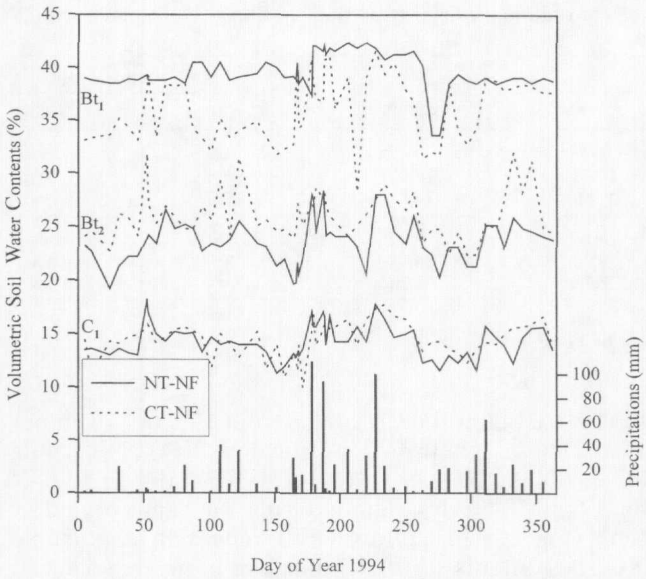

Fig. 5. Precipitation events and volumetric soil water contents in the Bt_1, Bt_2, and C_1 horizons of no-tillage (NT) and conventional tillage (CT) lysimeters in 1994, reported on a weekly basis.

and slower plant growth of NT compared with CT corn appear to diminish NT corn yields in the northern Corn Belt (Carter and Barnett, 1987; Smith et al., 1992). Emerging corn plants of this study were subjected to a frost in late May 1994. Visual estimation of the damages showed that corn plants in NT plots had suffered more from the frost than in CT plots. Apparently surface residues in NT plots confined more of the latent heat in the soil during the night creating cooler aboveground conditions, as reported by Fortin (1993).

In 1996, corn biomass yields increased by 50 and 100% in nonfertilized CT and NT treatments when compared with 1994 (Fig. 4), while fertilized CT corn biomass decreased 29%. Lower than average yields were obtained for CT and NT fertilized corn in 1996 at different production sites of the Kellogg Biological Stations due to a prolonged summer drought (Robertson and Harwood, 1997; Harwood et al., 1997). Precipitation in July 1996 was exceptionally low compared with previous years. Total precipitation for the growing season from May to August of 1994, 1995, and 1996 were 513, 394, and 268 mm, respectively. Consequently, corn biomass production was similar for all tillage and fertilizer treatments in 1996.

Total N in whole corn plants increased significantly when fertilized with N in the wetter 1994 growing season (513 mm), but not in the drier 1996 growing season (268 mm) (Fig. 6). Tillage did not significantly modify plant N contents in either wet (1994) or dry (1996) years. Total N contents of whole corn plants in 1996, following alfalfa, were 22% lower for fertilized plots and 11% higher for NF plots, when compared with values recorded in 1994. Nitrogen fertilization significantly increased the export of total plant biomass N by 273 and 235% in CT and NT plots, respectively, in 1994 (Fig. 7). Nitrogen exports by fertilized corn plants were 58% higher from CT plots than from NT plots in 1994. Tillage did not significantly modify the export of corn N from

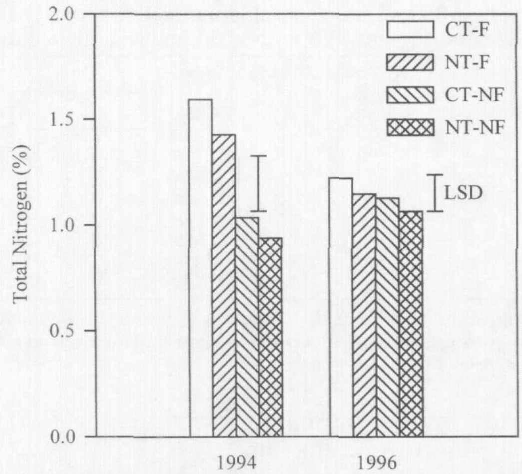

Fig. 6. Average N contents of whole corn plants in 1994 and 1996, in conventional tillage (CT) and no-tillage (NT) plots, with N fertilization (F) and with no N applied (NF).

nonfertilized plots in 1994 (Fig. 7). Neither tillage nor fertilization treatments significantly modified corn N exports in 1996. However, average N exports by unfertilized CT and NT corn plants increased by 92% in 1996 when following alfalfa compared with 1994 when following corn. The opposite was observed in the fertilized plots, where corn plants exported 35% less N during the dry growing season of 1996 than the wetter growing season of 1994 (Fig. 7).

Nitrogen fertilization appeared nonessential for corn production following alfalfa, particularly when corn biomass yields were reduced during the dry 1996 growing season. Absence of significant increases in corn grain yields by N fertilization following 3 yr of alfalfa has been previously reported (Fox and Piekielek, 1988). Bruulsema and Christie (1987) estimated N replacement values of alfalfa to a succeeding corn crop to be in the range of 90 to 125 kg N ha^{-1}. Our treatments resulted in exports of 70 to 90 kg N ha^{-1} in 1996, and from 30 to 165 kg N ha^{-1} in 1994 (Fig. 7). Consequently, corn N requirements following alfalfa might not be met with-

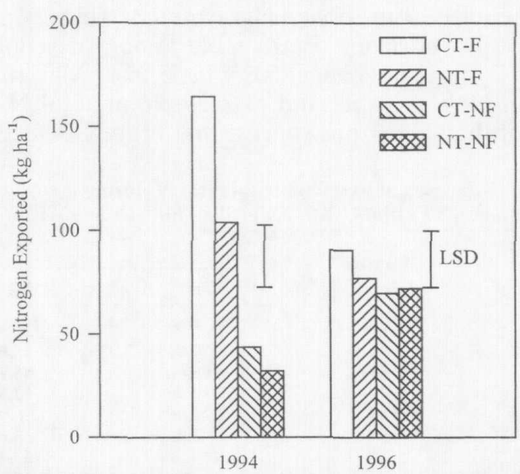

Fig. 7. Total N exported by whole corn plants out of conventional tillage (CT) and no-tillage (NT) corn plots, with N fertilization (F) and with no N applied (NF), in 1994 and 1996.

Table 3. Distribution of extractable mineral N within the soil profile of conventional tillage (CT) and no-tillage (NT) plots, with N fertilization (F), and with no N (NF) applied, on 26 Nov. 1996.

Horizon	Avg. depth	Treatments				Factors	
		CT-F	NT-F	CT-NF	NT-NF	Fertilizer	Tillage
	cm	kg NO_3–N + NH_4–N ha^{-1}					
Ap	30	82.7a†	54.8a	16.3b	12.5b	***	NS‡
Bt_1	55	114.3a	92.2ab	27.8bc	11.7c	**	NS
Bt_2	75	14.4a	15.7a	9.1a	6.8a	*	NS
C_1	110	7.8a	13.5a	10.1a	9.8a	NS	NS
C_2	150+	7.1a	13.1a	8.8a	10.0a	NS	NS
Total		226.3a	189.3a	72.1b	50.7b	***	NS

*,**,*** Significant at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively.
† Within horizons, averages indexed with same letter are not significantly different by Fisher's $LSD_{0.05}$.
‡ NS = nonsignificant at $P \leq 0.05$.

out N fertilization during a growing season favorable to maximum corn production.

Extractable Mineral Nitrogen in 1996

Extractable mineral N contents of CT and NT soils were low on 3 May 1996, 21 mo after alfalfa planting. No significant differences were observed between treatments (data not reported). Total amount of extractable mineral N within the upper 150 cm of the soil profile averaged only 35 kg N ha^{-1} across fertilization and tillage treatments. Alfalfa root systems appeared to have absorbed large quantities of N throughout the soil profile during the 1995 growing season, rendering differences among treatments insignificant. This confirms previous reports that NO_3 leaching under alfalfa stands is minimal (Owens, 1990; Peterson and Russelle, 1991). In contrast, fertilization had a significant effect on soil mineral N contents in the Ap and Bt horizons, on 26 Nov. 1996 (Table 3), whereas little effect was observed for deeper horizons. These data suggest that little N leaching had occurred below the Bt_2 horizon by the end of November 1996. Increases in extractable mineral N between 3 May and 26 Nov. 1996 proved to be 66 and 30 kg N ha^{-1} greater than the amount of N fertilizer applied to CT and NT plots (Table 4). Consequently, alfalfa tissue decomposition and soil organic matter mineralization produced mineral N in excess of corn crop requirements for 1996.

Mineralized and applied N accumulated mostly in the Ap and Bt_1 horizons. Extractable mineral N contents in the C_2 horizon changed very little from May to November 1996. Soluble and extractable mineral N contents of the C horizons suggest that little NO_3 leaching took place below the C_1 horizon from May to November 1996. This is confirmed by the low NO_3–N leaching losses of 7 kg NO_3–N ha^{-1} for CT-NF and 4 kg NO_3–N ha^{-1} for NT-NF lysimeters during the same period of time (Fig. 3). Insignificant differences in extractable NO_3–N contents of the C_2 horizon between fertilized and nonfertilized plots suggest that there was minimal leaching of NO_3-N, even though large quantities (51 to 226 kg NO_3 + NH_4–N ha^{-1}) of mineral N were retained within the profiles (Table 3). This may be the result of low rainfall during this period of time (Fig. 5).

Assuming negligible losses by leaching and denitrification due to the dry conditions from 3 May to 26 Nov. 1996, total production of mineral N within the soil profile of CT and NT plots can be inferred from the following formula:

$$\text{Total production of mineral N} = \text{Gain in soil mineral N} + \text{Corn N exports} - \text{N fertilization}$$

Total mineral N productions from 3 May to 26 Nov. 1996 were 157 kg N ha^{-1} for CT-F, 107 kg N ha^{-1} for NT-F, 108 kg N ha^{-1} for CT-NF, and 91 kg N ha^{-1} for NT-NF. These values were not significantly different and averaged 116 kg N ha^{-1}, which is comparable to published N replacement values of 90 to 125 kg N ha^{-1} by alfalfa to a succeeding corn crop (Bruulsema and Christie, 1987). Although differences among treatments could not be proven significant, higher mineral N production was observed in CT vs. NT treatments (+47% for F, and +19% for NF). Mineralization rates of alfalfa residues and soil organic matter appeared modified by tillage management. Angle et al. (1993) reported consistently higher soil NO_3 concentrations under CT compared with NT corn, whether N fertilizer is applied or

Table 4. Increases in extractable mineral N during a corn crop following alfalfa within the soil profile of conventional tillage (CT) and no-tillage (NT) plots, with N fertilization (F) and with no N applied (NF), between 3 May and 26 Nov. 1996.

Horizon	Avg. depth	Treatments				Factors	
		CT-F	NT-F	CT-NF	NT-NF	Fertilizer	Tillage
	cm	kg NO_3–N + NH_4–N ha^{-1}					
Ap	30	70.9a†	45.0a	6.4b	3.1b	***	NS‡
Bt_1	55	108.6a	85.7ab	22.2bc	6.7c	**	NS
Bt_2	75	10.4a	12.5a	5.6a	3.6a	NS	NS
C_1	110	1.4a	6.9a	4.5a	5.5a	NS	NS
C_2	150+	−2.0a	3.2a	−0.1a	0.1a	NS	NS
Total		189.2a	153.4a	38.6b	18.9b	***	NS

,* Significant at $P \leq 0.01$ and $P \leq 0.001$, respectively.
† Within horizons, averages indexed with same letter are not significantly differnt by Fisher's $LSD_{0.05}$.
‡ NS = nonsignificant at $P \leq 0.05$.

not. Alfalfa incorporation to soils might have increased soil organic matter decomposition rates, or basal mineralization. Broadbent and Nakashima (1974) report increased rates of soil organic matter mineralization, called *priming effect*, when plant residue was incorporated into soils.

CONCLUSION

A baseline of NO_3–N leaching of 23 kg ha^{-1} was observed under nonfertilized corn, corresponding to NO_3–N concentrations of 6 to 7 mg L^{-1} under CT management. Therefore, annual N leaching under corn, without winter cover crops, cannot be reduced to <23 kg N ha^{-1} on Kalamazoo loam soils. Although higher drainage flows were observed under NT conditions, total amounts of NO_3–N leached were identical to slightly lower from NT than from CT lysimeters, due to higher NO_3–N concentrations in CT leachates. This suggests that tillage management is not a decisive factor in the control of NO_3 leaching from corn fields. Living alfalfa stands kept NO_3 leaching at very low levels. However, NO_3 concentrations in the soil solutions during winter months in 1997 exceeded the maximum level of 10 mg NO_3–N L^{-1} set by the USEPA (Fig. 1). High NO_3 leachates occurred in spite of the fact that corn was planted directly after spray-killing the alfalfa stand and that no N fertilizer was applied. During a dry growing season, N fertilization did not increase corn yields, when following alfalfa. In fact, all N fertilizer applied to corn, planted directly after spray-killed alfalfa, became available for winter and spring leaching, especially when mineral N contents of fertilized plots averaged >200 kg N ha^{-1} in late November 1996. These data demonstrate the need for drastically reducing N fertilization of corn following alfalfa, to avoid substantial groundwater contamination by nitrates.

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Longleaf Pine Photosynthetic Response to Soil Resource Availability and Elevated Atmospheric Carbon Dioxide

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ABSTRACT

Gas exchange responses during a drought cycle were studied in longleaf pine (*Pinus palustris* Mill.) seedlings after prolonged exposure to varying levels of atmospheric CO_2 (≈365 or ≈730 μmol CO_2 mol^{-1}), soil N (40 or 400 kg N ha^{-1} yr^{-1}), and water ("adequate" and "stressed"). Elevated atmospheric CO_2 concentration increased photosynthesis, tended to decrease stomatal conductance, and increased water-use efficiency (WUE). Although soil resource availability influenced gas exchange measurements, it generally did not affect the magnitude or direction of the response to CO_2 concentration. However, significant interactions among treatment variables were observed for plant xylem pressure potential. In seedlings grown with high N, a positive growth response to elevated atmospheric CO_2 increased whole-plant water use resulting in more severe plant water stress, despite increased leaf-level WUE; however, under low N conditions the lack of a growth response to elevated CO_2 reduced whole-plant water use, decreased water stress severity, and increased WUE. Photosynthetic response to CO_2 was greatest in the high N treatment at the beginning of the drought cycle, but diminished as water stress increased; however, plants grown with low N showed greater photosynthetic responses to CO_2 later in the drought cycle. Therefore, plant gas exchange rates interact with growth response in determining the severity of water stress under drought and, thus, the ability of elevated atmospheric CO_2 to ameliorate the effects of drought and allow plants to maintain increased rates of photosynthesis may be influenced by the availability of other resources, such as N and water.

THE CONCENTRATION of CO_2 in the atmosphere is increasing at an unprecedented rate (Houghton et al., 1990) and plants will be directly affected by this rise in CO_2. In general, studies have shown positive effects of CO_2 enrichment on plants including increased growth and WUE (Rogers and Dahlman, 1993; Allen and Amthor, 1995; Wittwer, 1995) and, although more variable, increased rates of photosynthesis (Chaves and Pereira, 1992; Amthor, 1995). However, the majority of CO_2 research has focused on crops under optimal growth conditions, rather than on native plants under limiting soil resources (Ceulemans and Mousseau, 1994; Amthor, 1995), despite the fact that natural terrestrial ecosystems are often limited by suboptimal levels of soil resource availability (e.g., N and water).

Understanding how forest species respond to this CO_2 buildup, and to potential associated climatic changes, is critical for predicting changes in stand structure and growth (McGuire and Joyce, 1995), which is particularly important due to the long-lived nature of trees and the economic and ecological values of forests. Coastal plain forests of the southeastern USA were once dominated by nearly pure stands of longleaf pine with a diverse understory plant community (Peet and Allard, 1993). The longleaf pine savanna ecosystem now occupies only 2% of its former range, a loss comparable to or exceeding that of most endangered communities throughout the world (Noss, 1989).

Longleaf pine forests currently occupy sites at the more xeric end of the moisture continuum and are often found on soils with low N availability; therefore, understanding how availability of differing soil resources affect plant response to CO_2 is also critical in predicting future productivity of southern pine forests. Prior et al. (1997) reported that a growth response to elevated atmospheric CO_2 was observed for longleaf pine growing under high, but not low, N conditions; in contrast, however, plants exposed to water stress showed a

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Abbreviations: R/S, root to shoot ratio; WUE, water-use efficiency; P_n, photosynthesis; g_s, stomatal conductance; XPP, xylem pressure potential.