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Root-Zone Mineral Nitrogen Changes as Affected by Crop Sequence and Tillage

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ABSTRACT

Crop sequence and tillage affect soil mineral N (NH_4 plus NO_3) and NO_3 leaching below the root zone following alfalfa (*Medicago sativa* L.). A 2-yr field experiment was conducted in south-central Idaho to determine the effect on soil NO_3 levels of a corn (*Zea mays* L.)-wheat (*Triticum aestivum* L.) rotation compared with a bean (*Phaseolus vulgaris* L.)-bean rotation and to demonstrate improved N utilization with a corn-wheat rotation. Alfalfa, growing on an irrigated Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid), was killed in October 1989 with herbicide. Treatments were: (i) BT-BT: conventional tilled bean grown in 1990 and 1991; (ii) CNT-WNT: no-till silage corn grown in 1990, and no-till winter wheat grown in 1990-1991; and (iii) CT-WT: same as CNT-WNT but under conventional tillage. Similar amounts of soil N were mineralized the first (275 kg N ha^{-1}) and second (213 kg N ha^{-1}) year after killing the alfalfa in all treatments. The BT-BT treatment had the highest growing-season soil mineral N (up to 251 kg ha^{-1}, 0-0.45-m depth) because the N uptake by bean was lower (187 kg N ha^{-1}) than corn (252 kg N ha^{-1}, average of CT-WT and CNT-WNT treatments) in 1990 and later than winter wheat uptake in 1991. Most wheat N uptake had occurred by late June when bean uptake was just starting. A rotation that follows alfalfa with corn or a crop with a similar N uptake pattern, instead of bean, will save N fertilizer, lower soil NO_3 levels, and reduce NO_3 leaching potential.

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CROP SEQUENCE AND TILLAGE should be employed so that N mineralization is synchronized with subsequent crop N uptake. Improving N utilization reduces potential NO_3 leaching into the groundwater from agricultural fields. The amount of NO_3 leaching out of the root zone is a function of the NO_3 concentration in the root zone and the water flux through this zone.

Large amounts of N are mineralized after alfalfa is killed, especially the first year. Fox and Piekielek (1988) reported that 70, 20, and 10% of the contribution from alfalfa was available the first, second, and third years, respectively. Varco et al. (1991) measured 31.5 mg kg^{-1} extractable NO_3-N in the upper 0.20 m of soil 28 d after alfalfa was killed. Calculations by Peterson and Russelle (1991) for the Corn Belt demonstrated that the N fertilizer applied to corn could be reduced by 8% if growers would properly credit the extra N mineralized following alfalfa. In south-central Idaho, 2 yr of bean are commonly grown following alfalfa, which means a legume following another legume that does not need fertilizer N. Robbins and Carter (1980) determined that 85 to 95 kg NO_3-N ha^{-1} yr^{-1} moved below the root zone when bean followed

Abbreviations: BT-BT, conventional-tilled bean grown in 1990 and 1991; CNT-WNT, no-till silage corn grown in 1990, and no-till winter wheat grown in 1990-1991; CT-WT, conventional-tilled silage grown in 1990 and conventional-tilled winter wheat grown in 1990-1991.

Table 1. Crop sequence for 1986 to 1991 for three treatments: BT-BT, conventional-tilled bean; CNT-WNT, no-tillage silage corn and winter wheat; CT-WT, conventional-tilled silage corn and winter wheat.

Time	BT-BT	CNT-WNT	CT-WT
1986–1989	Alfalfa	Alfalfa	Alfalfa
1990†	Bean	Silage corn	Silage corn
1991	Bean	Winter wheat‡	Winter wheat‡

† The 2 yr following the removal of alfalfa, 1990 and 1991, were studied in this experiment. The CT-WT plots were plowed in April 1990 and October 1990, and the BT-BT plots were plowed in April 1990 and June 1991.
‡ 90 kg N ha^{-1} would be the N requirement for winter wheat in this sequence based on past experience at this location.

alfalfa, but only 60 kg NO_3-N ha^{-1} yr^{-1} were lost when corn followed alfalfa.

The crop following alfalfa should have a large N uptake and an uptake curve that matches as closely as possible the N mineralized. Corn can be grown following alfalfa with adequate N (no fertilizer N applied) throughout the growing season, because N uptake by corn tends to parallel the rate at which NO_3 is released or mineralized after the alfalfa is killed (Carter et al., 1991). When winter wheat follows alfalfa, the alfalfa should be killed in early fall to allow sufficient time for adequate N mineralization to satisfy the N requirement of the winter wheat during early spring growth.

Tillage may increase the N mineralization rate. Nitrogen may be mineralized during a longer time period using no-till, which would allow more time for N uptake. Doran (1980) concluded that mineralization rates were higher in conventional-tilled soils, and the potential for denitrification was higher in no-till soils. Eck and Jones (1992) found a greater accumulation of soil NO_3-N to 1.2 m under stubble mulch compared with no-till under some cropping systems, but not under others. They found that NO_3 moved deeper in the profile under no-till than under stubble mulching, indicating that differences may have been caused by differential leaching rather than differential mineralization.

The objectives of this study were to: (i) evaluate the soil mineral-N status of the root zone following alfalfa and (ii) demonstrate improved N utilization with a recommended cropping system.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted in south-central Idaho on a Portneuf silt loam. The study area's yearly precipitation averages 210 mm. The field has a slope of 0.6%. Alfalfa was grown the previous 4 yr and was killed with glyphosate [N-(phosphonomethyl) glycine] on 26 Oct. 1989. The field was divided into 18 plots, each 243 m long and either 8.8 m (bean) or 6.1 m wide (corn or wheat). Treatments are listed in Table 1 with the corn and wheat being grown under both corn no-till-wheat no-till (CNT-WNT) and corn tilled-wheat tilled (CT-WT) treatments.

Fertilization

Fertilizer was applied to the complete plot area on 18 and 19 Apr. 1990 (P, all plots; Zn, bean plots) and 15 Oct. 1990 (urea, wheat plots). Triple super phosphate was applied at 56 kg P ha^{-1}. Zinc (11 kg ha^{-1}) was applied as Zn SO_4 to the bean plots only. Urea (82 kg N ha^{-1}) was applied to only the wheat plots before the wheat was planted but after the CT-WT plots were plowed and roller harrowed. Also, urea was also applied on 19 Apr. 1990 and 9 Apr. 1991 to 9.1-m strips, across the width of the field including all 18 plots, to evaluate whether cropping systems had adequate N for economic optimum yield. This urea was applied to the strips each time at rates of 0, 82, and 164 kg N ha^{-1}.

Operations

The seedbed for bean was prepared by plowing, roller harrowing, applying herbicides, roller harrowing, and furrowing out between every other row. 'Viva Pink' bean (not inoculated) was planted without preirrigation in (16 rows $plot^{-1}$) 0.55-m-wide rows on 6 June 1990 and 3 June 1991. Bean plots were cultivated on 5 July 1990 and 7 July 1991.

Silage corn (3389 Pioneer[1]) was planted (8 rows $plot^{-1}$) in 0.76-m-wide rows on 15 May 1990. The CT-WT plots were prepared by plowing and roller harrowing. Furrows were either made (CT-WT) or cleaned out (CNT-WNT) between every row at the time of planting. The CNT-WNT received no tillage but was planted into killed alfalfa stubble with only slight disturbance during planting and cleaning out of the furrows used to irrigate the alfalfa. Conventional-tilled plots were cultivated on 6 July. All corn plots were sprayed with 2,4-D [(2, 4-dichlorophenoxy) acetic acid] on 2 July to control weeds.

'Stephens' wheat was planted in the CNT-WNT and CT-WT treatments on 15 Oct. 1990. Tilled plots were plowed and roller harrowed before planting and roller harrowed again (to incorporate the fertilizer) after planting and fertilization. Irrigation furrows 0.76 m wide were either cleaned out (CNT-WNT) or constructed (CT-WT).

Irrigation

The water application rate was measured using a bucket and stopwatch in one of the furrows in the middle of each plot. Runoff water, for the full length of the field, for the same furrow was measured using automated flumes. Corn was irrigated with water applied to alternate furrows with a change to previously nonirrigated furrows in the middle of the season. Water was applied to each furrow for bean but furrows were constructed only between alternate rows. Water was applied to every furrow during irrigation of wheat. Distances between irrigated furrows were 1.52 m for corn, 1.1 m for bean, and 0.76 m for wheat. Leaching fractions were calculated for April to October 1990 and March to October 1991 (BT-BT) or April to October 1991 (CT-WT and CNT-WNT) using water infiltrated, evapotranspiration, and change in water content (Meek et al., 1994). Leaching fractions (calculated from the water balance) were 0.48 and 0.38 (CT-WT), 0.43 and 0.37 (CNT-WNT), and 0.41 and 0.37 (BT-BT) for 1990 and 1991, respectively.

Soil Nitrogen Levels

Soil mineral-N status (NH_4-N and NO_3-N) and N-mineralization measurements were made near the center of the length of the plot. Measurements were not made in the N strips. Nitrogen mineralization (0–0.45 m depth) was measured by taking soil samples during periods between crops (six cores per plot). Soil mineral N (NH_4-N plus NO_3-N) was measured during the cropping season by taking soil samples 0 to 0.45

[1] Trade names are provided for the benefit of the reader and do not imply endorsement by the USDA.

m deep, usually every 2 to 3 wk, with a 50-mm-diam. bucket auger. Six cores were sampled from each plot for bean and corn during the cropping season (two from the irrigated furrow, two from the middle of the bed, and two from the dry furrow). Eight cores were sampled from each plot for wheat during the cropping season (four from the furrow and four from the middle of the bed). Soil samples (six cores per plot, 0- to 4.6-m depth in 0.30-m increments) were sampled in the fall and spring between cropping seasons using a Giddings soil sampler.

Soil mineralization was determined using the buried bag technique (Westermann and Crothers, 1980). Measurements were made near the center of the length of the plot. Soil was removed from holes 50 mm in diameter and 460 mm deep using an auger. Usually 18 holes were dug per plot (six samplings of three bags each). Soil removed from one plot was composited and mixed, and the soil moisture was adjusted to the range of 0.18 to 0.20 kg kg^{-1} (50–100 kPa soil matric pressure). Bags (50 mm-diameter and 410 mm long) of 5-mm-thick polyethylene were filled with the soil, sealed, and inserted into the holes from which the soil had been previously removed. Bags were covered with 50 mm of soil. Bags with large changes in moisture from the initial content, or that had roots in them, were discarded (averaged ≈ 1 in 10).

Crop Nitrogen Uptake

Crop nitrogen uptake was measured for each crop in 1990 by sampling at intervals during the growing season. In both corn and bean, plants were removed from two 0.9-m rows per plot. Samples were not taken from the rows (four for corn or eight for bean) used for yield or from the outside rows. Plant stands were uniform with about 15 corn plants or 17 bean plants in the two 0.9-m rows. Corn was cut 50 to 80 mm above the soil surface, chopped, mixed, and subsampled. The subsample was dried at 55°C and run through a Jacobson hammer mill with a 1-mm screen. Corn was sampled four times between 9 July and 6 September. Bean plants were pulled and roots clipped off at the first node. Samples were then dried and ground in a Wiley mill with a 1-mm screen. Bean plants were sampled five times between 9 July and 7 September.

In 1991, wheat plants were sampled five times between 15 May and 30 July. A metal frame 660 by 762 mm (0.5 m^2) was laid on the soil surface at two locations in each plot and the plants within the frame harvested. Plants were clipped 30 to 50 mm above the soil surface, dried, and ground in a Wiley mill with a 1-mm screen. Bean plants were sampled in the same manner as 1990 except that six samples were obtained between 15 July and 6 September.

Crop Yield at Harvest

Corn, bean, and wheat yields were obtained by harvesting the center portion of each plot for the full length of the field (243 m). A sample (≈ 1 kg) was obtained for Kjeldahl analysis. The area harvested included the N strips, which were a small part of the total length (18.2 out of 243 m). Corn was harvested 27 Sept. to 1 Oct. 1990. The center two rows of corn were chopped and each truckload containing one plot was weighed to determine yield. Bean were harvested on 7 to 12 Sept. 1990 and 20 to 30 Sept. 1991. Bean plants were cut and raked, with six center rows thrown into a single windrow. The six rows were threshed and weighed. Wheat was harvested 3 or 4 Sept. to 1 Oct. 1990, combining the center 2.4 m of each plot for the length of the field (243 m).

Three areas in the CNT–WNT and CT–WT treatments (one in each N strip and an area adjacent to the strips) were harvested by hand in each plot outside the center area used for plot yields to evaluate the effect of N on yield. These areas consisted of 3.65 m of row for corn and 9.7 m^2 for wheat.

Mineralization Index

Soil samples taken from the 0- to 0.3-m and 0.3- to 0.6-m soil depths in March 1990 and 1991 were incubated to determine potential N mineralization rate. Fifteen grams of water were added to a 50-g soil sample (matric pressure of ≈ 15 kPa) and incubated for 21 d at 35°C.

Plant and Soil Analysis

Soil samples from each plot were composited, screened (3.5-mm screen) and mixed, and a subsample frozen for later analysis. Soil samples were extracted with 2 *M* KCl (10 g soil to 50 mL of extracting solution) after a 30-min shake and filtered. Soil NO_3 and NH_4 concentrations were determined by shaking 10 g of soil in 50 mL of 2 *M* KCl, filtering, and analyzing with a Lachet QuickChem AE (Lachat Instruments, 1993, Method no. 12-107-06-2-A for NH_4–N and Method no. 12-107-04-1-B for NO_3–N). Plant samples were analyzed for total N using the Kjeldahl procedure.

Experimental Design

The design consisted of three treatments and six replications in a randomized complete block. Data were analyzed by analysis of variance. Yields in the N strips (where N fertilizer was applied in narrow strips across the plots) were analyzed as a split block. When the *F* test was significant at a probability of 0.05, we used the least significant difference test to separate means. Standard deviation was calculated for yields of bean.

RESULTS

Crop Yields

Crop yields are presented in Table 2. The yield of silage corn in 1990 was higher ($P \leq 0.05$) for the CT–WT treatment than the CNT–WNT. There was no significant difference in winter wheat yield between CNT–WNT and CT–WT. Additional N fertilizer applied to strips caused a significant yield increase when applied

Table 2. Crop yield in 1990 and 1991 for the three treatments: BT-BT, conventional-tilled bean; CNT-WNT, no-tillage silage corn and winter wheat; CT-WT, conventional-tilled silage corn and winter wheat.

Crop year	N applied to strips	Yield		
		BT-BT	CNT-WNT	CT-WT
	kg ha^{-1}	Mg ha^{-1}		
Silage corn 1990 (oven dry weight)	0		16.5	18.2
	82		17.9	19.5
	164		18.5	20.3
LSD(0.05)			1.09	1.09
Winter wheat 1991 (weight of grain, field moisture)	0		7.6	7.7
	82		8.1	8.1
	164		8.1	8.5
LSD(0.05)			0.65	0.65
Bean† (weight of seed)				
1990		3.7 ± 0.24‡		
1991		4.3 ± 0.19		

† Separate yield samples were not taken in the N stripes so yields are for the whole plot.
‡ Standard deviation.

to silage corn at 82 or 164 kg N ha^{-1}, compared with the zero rate. The increase in yield for silage corn when fertilizer application was increased from 82 to 164 kg N ha^{-1} was not significant. The only significant yield increase for wheat (compared with the zero rate) was for the no-till wheat when 164 kg N ha^{-1} was applied. The yield of bean was higher for 1991 than 1990.

Nitrogen Uptake

Silage corn had the highest plant N uptake, and winter wheat took up N sooner in the season than other crops (Fig. 1). Nitrogen uptake by bean was similar in 1990 and 1991, so data are presented as one curve. Symbiotic N fixation by bean was small because soil mineral N content (0–0.45-m depth) was high: 231 kg N ha^{-1} in 1990 and 251 kg N ha^{-1} in 1991. There was no difference in wheat yield or N uptake between CNT–WNT and CT–WT, so only the average is shown. The lower uptake late in the season may have resulted from low soil NO_3–N levels late in the season in this experiment. There was a greater N uptake for silage corn under CT–WT than CNT–WNT for the first two sample times but not for the last two sample times ($P \geq 0.05$). This lack of differences during the latter part of the season may have been the result of switching in midseason to previously unirrigated furrows, which would have higher NO_3 levels and which may have been adequate for both treatments. Essentially all of the N in the silage corn was removed from the field. About 16% of the N contained in the aboveground material would have been returned as residue for the bean crop (Westermann et al., 1985).

Nitrogen Mineralization

Mineralization of N in the soil (0–0.45-m depth), determined by changes in the soil mineral N between crops and the buried bag technique during the cropping season, was higher in 1990 than in 1991 (Fig. 2). There were not significant differences in mineralized N among treatments in 1990. About 268 kg N ha^{-1} was mineralized by 4 Sept. 1990 but only 210 kg N ha^{-1} in the 1991 season. Nitrogen mineralization was not affected by treatments in 1990. There were significant differences in mineralization between treatments on only two dates in 1991 (data not shown).

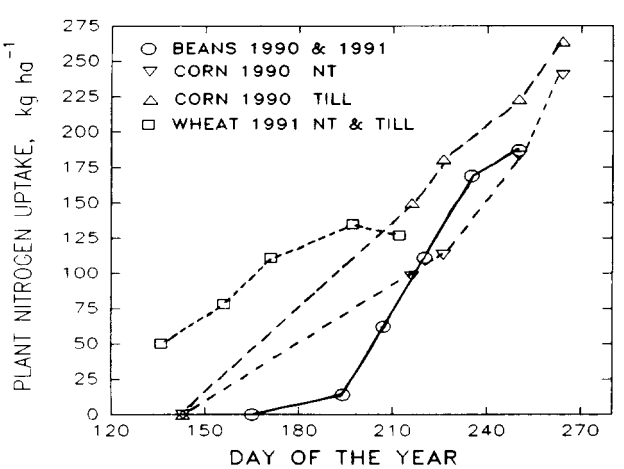

Fig. 1. Aboveground plant uptake of N for different crops with time (Day 110 is 20 April).

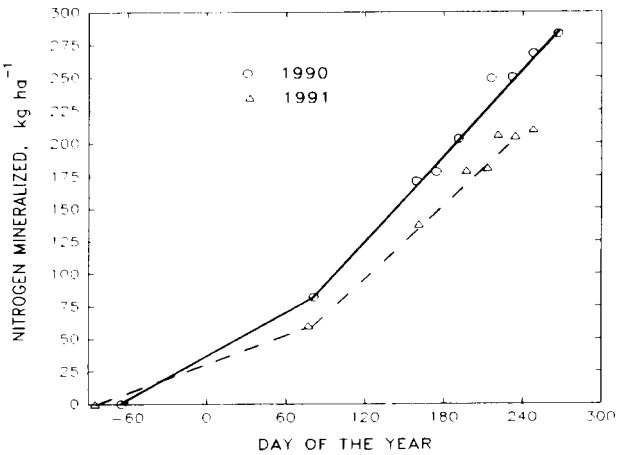

Fig. 2. Mineralization of N in the 0- to 0.45-m depth of soil in 1990 and 1991 (average of all treatments; Day 60 is 1 March).

The N mineralization index for soil samples taken in the spring of 1990 was 168 and 51 kg N ha^{-1} for the 0- to 0.3-m and 0.3- to 0.6-m depths, respectively; for spring 1991 samples, the values were 154 and 49 for the 0- to 0.3-m and 0.3- to 0.6-m, respectively. Mineralization index (incubated) N was less than the field measurement of mineralized N in 1990 (219 compared with 268 kg N ha^{-1}), but the amounts were similar in 1991.

Soil Mineral Nitrogen

The BT–BT treatment had the highest mineral-N content in the soil during the growing season, especially during the second season (Fig. 3). The higher mineral N content was caused by a later or lower plant uptake of N compared with other cropping treatments. The other treatments were only higher during the winter and early

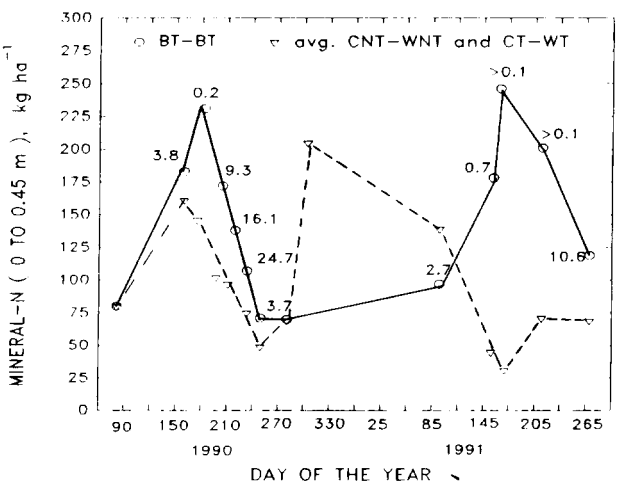

Fig. 3. Soil mineral-N levels (0–0.45-m depth) in 1990 and 1991 for conventional-tilled bean (BT–BT) and the average of no-till corn followed by no-till wheat (CNT–WNT) and conventional-tilled corn followed by conventional-tilled wheat (CT–WT). An application was made of 82 kg N ha^{-1} on Day 288 (15 Oct. 1990) to wheat. The number near the symbol for the BT–BT treatment gives the $P > F$ (%) for that treatment compared with the other treatment on the closest sampling date.

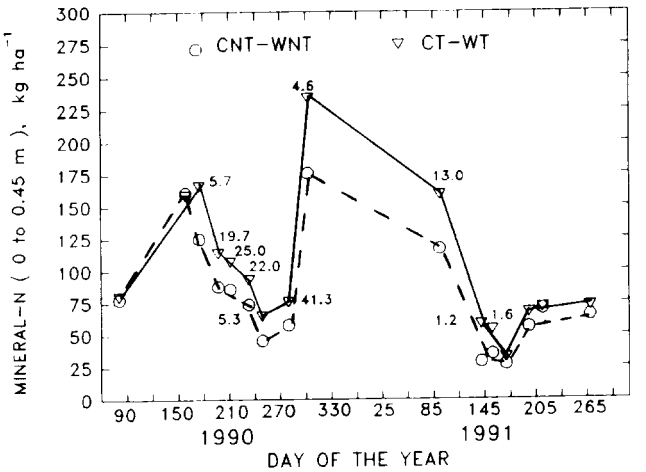

Fig. 4. Soil mineral-N levels (0–0.45-m depth) in 1990 and 1991 for no-till corn followed by no-till wheat (CNT-WNT) and conventional-tilled corn followed by conventional-tilled wheat (CT-WT). An application was made of 82 kg N ha^{-1} as urea on Day 288 (15 October) and irrigation on Days 289 to 290 of 1990. The number near the symbol for the CT-WT treatment gives the $P > F$ (%) for that treatment compared with the other treatment on that date.

spring after application of 82 kg N ha^{-1} to wheat in the fall of 1990.

There was a loss of mineral N from the CNT-WNT and CT-WT treatments during 3 Oct. 1990 to 3 Apr. 1991 (Fig. 3). In contrast, the BT-BT treatment gained mineral N from 10 Sept. 1990 to 3 Apr. 1991. The differences may have been due to leaching, because winter wheat received an irrigation (infiltration 152 mm) on 20 Sept. 1990 and the bean treatment did not.

The CNT-WNT and CT-WT treatments had similar soil mineral N contents (Fig. 4). There were no differences ($P \geq 0.05$) between treatments when soil mineral contents were averaged for 23 June to 5 Sept. 1990. Differences occurred after fertilizer was applied, with the CT-WT treatment having higher amounts ($P > 0.05$) on 30 Oct. 1990 and 20 May and 2 June 1991.

Nitrogen Balance

Nitrogen balance was calculated for the main part of the growing season (Table 3). Initial soil N levels were high, especially for bean. Ninety five percent of the available N was recovered by plant uptake and change in residual soil N (average of all years and treatments). When available N was not recovered, it would indicate NO_3 removal by leaching, immobilization, volatilization, or denitrification. An example of this was when bean or wheat was grown. The high plant N uptake of corn resulted in recovery of all the available N. Because of the lower N uptake of bean in 1990 compared with corn, an excess of soil N (251 kg N ha^{-1}) was present at the start of the season for bean in 1991.

DISCUSSION

The crop sequence of silage corn followed by winter wheat left lower residual soil mineral N (0–0.45-m depth) than the crop sequence of bean followed by bean. Residuals on 20 May were 251 kg N ha^{-1} for bean and 30 kg N ha^{-1} for corn-wheat (Fig. 3). The higher soil NO_3 levels under bean were probably the result of a lower N uptake of the bean compared with the corn. Nitrogen fixation would have been low because of the high soil NO_3 levels found in the soil. Westermann et al. (1981) measured only 10 kg ha^{-1} fixed by this cultivar when 223 kg N ha^{-1} was present in the soil at the start of the season. Lower levels should result in less NO_3 leaching below the root zone under normal irrigation practices.

Mineralization rates (April–August) were 1.1 kg N ha^{-1} d^{-1} in 1990 and 0.9 kg N ha^{-1} d^{-1} in 1991. Stanford and Smith (1972) also measured high mineralization rates for this soil, with the rate being higher for the Portneuf soil than for most of the other soils tested. Also, there was only a slight reduction in the mineralization rate the second year after alfalfa, compared with the first year. The N contribution from the alfalfa is only part of the soil N being mineralized. Mineralization measured in the laboratory was three times higher at the 0- to 0.30-m depth than at the 0.30- to 0.60-m depth for both years. Levin et al. (1987) measured a low residual N fertilizer equivalent of 126 kg N ha^{-1} for first-year corn following alfalfa. In contrast, Carter et al. (1991) conducted research in the same area as this experiment and also measured high rates of N mineralization.

Soil mineral-N contents for the CNT-WNT and CT-WT treatments were similar, except after fall application of urea to the wheat. The application of urea to winter wheat in the fall of 1990 increased mineral N more in the CT-WT treatment than the CNT-WNT treatment

Table 3. Soil N balance for treatments with time during the main part of the growing season (0–0.45-m soil depth); treatments: BT-BT, conventional-tilled bean; CNT-WNT, no-tillage silage corn and winter wheat; CT-WT, conventional-tilled silage corn and winter wheat.

Treatment and crop	Year	Time period	Initial soil N	N mineralized	N available	Crop N uptake	Residue soil	Total N recovery	Difference
		d of yr	kg/ha						
BT-BT									
Bean	1990	183–249	231	68	299	187	71	258	−41
Bean	1991	164–238	251	61	312	187	107	294	−18
CNT-WNT									
Corn	1990	159–280	161	125†	286	240	67	307	21
Wheat	1991	93–213	117	105	222	135	70	205	−17
CT-WT									
Corn	1990	159–280	159	125	284	264	75	339	55
Wheat	1991	93–213	159	105	264	135	71	206	−58

† Values for CNT-WNT and CT-WT are an average when there were no significant differences.

(Fig. 4). The large amount of mineral N measured for the winter wheat tilled treatment on Day of the Year 303 (30 Oct. 1990) seems unreasonably high because the mineral N on Day of the Year 280 (7 Oct. 1990) was 76 kg N ha^{-1}, and a fertilizer application of 82 kg N ha^{-1} would have resulted in only 158 kg N ha^{-1}. The lower mineral N in the no-till treatment could be from NH_3 loss because the urea fertilizer was not mechanically incorporated in this treatment. It could have also been caused by more leaching of the surface-applied fertilizer in the CNT–WNT treatment because of a greater number of macropores (Shipitalo and Edwards, 1993). Shipitalo and Edwards (1993) measured much greater leaching of surface-applied NH_4–N fertilizer through 750-mm-long columns under no-till than tilled soil.

There were mineral-N losses during the winter under wheat, which received a fall irrigation, but an increase in soil mineral N for the bean treatment, which received no fall irrigation. The average loss was 67 kg N ha^{-1} (0–0.45 m) for winter wheat. Winter precipitation from 1 Oct. 1990 to 1 May 1991 was 130 mm. Drainage below 1.35 m from 20 Oct. 1990 to 25 Mar. 1991, determined by calculating the water balance, was 49, 114, and 117 mm for the BT–BT, CNT–WNT, and CT–WT treatments, respectively (Meek et al., 1994). Larger drainage losses for the CNT–WNT and CT–WT treatments resulted from starting the winter with a wet profile because of the 16 to 17 Oct. 1990 irrigation applied to these treatments. The NO_3–N concentration of the soil solution was 25, 7, and 6 mg kg^{-1} (using the average of the soil solution concentration at the last sampling in 1990 and the first sampling in 1991) for the BT–BT, CNT–WNT, and CT–WT treatments, respectively (Meek et al., 1994). Losses of NO_3–N would be 12, 8, and 8 kg N ha^{-1} for the BT–BT, CNT–WNT, and CT–WT treatments, respectively. Additional research is needed to determine if the reduction in soil NO_3 in the root zone during the winter is a result of leaching, denitrification, or immobilization.

The N uptake of winter wheat in this experiment was less than determined by Westermann and Crothers (1993), who measured 137 and 196 kg N ha^{-1} when wheat was fertilized at the rate of 56 or 112 kg N ha^{-1}.

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