2001

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ABSTRACT

Spring wheat (*Triticum aestivum* L.) is generally produced in the northern Great Plains using tillage and a crop–fallow system. This study evaluated the influence of tillage system [conventional-till (CT), minimum-till (MT), and no-till (NT)] and N fertilizer rate (0, 22, and 45 kg N ha^{-1}) on grain N, grain N removal from cropping system, and changes in residual postharvest soil NO_3–N during six rotation cycles of a dryland spring wheat–fallow (SW–F) cropping system. Grain N concentration increased with increasing N rate and was higher with CT (33.3 g kg^{-1}) than with NT (32.3 g kg^{-1}) at 45 kg ha^{-1} N rate. Grain N removal per crop was greater with CT (70 kg N ha^{-1}) and MT (68 kg N ha^{-1}) than with NT (66 kg N ha^{-1}) and tended to increase with increasing N rate, but varied with rotation cycle. Total grain N removal in six rotation cycles was in the order: CT > MT > NT. Total grain N removal by six SW crops was increased by N fertilization, with only 21 and 17% of the applied N removed in the grain for the 22 and 45 kg ha^{-1} N rates, respectively. Postharvest soil NO_3–N levels in the 150-cm profile varied with N rate and rotation cycle, with residual NO_3–N increasing during consecutive dry crop cycles. In contrast, some leaching of NO_3–N below the SW root zone may have occurred during wetter crop cycles. Soil profile NO_3–N levels tended to be greater with CT and MT than with NT. Variation in precipitation during rotation cycles and N fertilization impacted grain N removal and residual soil NO_3–N levels more than tillage system within this SW–F cropping system.

In the Great Plains, plant-available water and soil erosion are major factors limiting agricultural production (Deibert et al., 1986; Peterson et al., 1996; Stewart, 1990). Farmers need to manage crop residues and tillage to reduce soil erosion and store the limited precipitation for crop production. No-till and MT systems are an effective step in efficiently saving more precipitation for crop production (Aase and Schaefer, 1996; Black and Bauer, 1990; Peterson et al., 1996; Tanaka and Anderson, 1997).

The traditional CT, crop–fallow system of farming with a 20- to 21-mo fallow period often fails to use water efficiently. Minimum-till and NT systems used with crop–fallow have the potential to increase water movement through the soil profile, leading to development of dryland saline-seeps (Halvorson and Black, 1974, Halvorson, 1990). The work of Tanaka (1985, 1989) showed more soil water storage and surface residue cover with chemical fallow than with stubble mulch fallow in northeast Montana.

Increased water storage with MT and NT may result in increased movement of NO_3–N through and below the root zone of SW in a SW–F system. Movement of NO_3–N below the root zone of crops has potential to increase the NO_3–N content of ground water used for human consumption. Soil NO_3–N movement below the root zone under crop–fallow conditions has been reported in the northern Great Plains (Campbell et al., 1993; Halvorson and Black, 1985; Izaurralde et al., 1995; Grant and Lafond, 1994).

Tillage and N fertilization practices may influence the quantity of postharvest residual soil N remaining in the root zone. Adequate soil fertility has been shown to increase water-use efficiency by increasing crop yields (Black et al., 1981), thus reducing the NO_3–N leaching potential. A 12-yr study evaluating the influence of tillage system and N fertility rate on SW yields in a SW–F system was recently completed (Halvorson et al., 2000). This paper reports the effects of tillage and N fertilization rate on grain N, quantity of N removed in the grain during six rotation cycles of a SW–F cropping system, and residual fall soil NO_3–N following SW harvest.

MATERIALS AND METHODS

The study was initiated in 1984 on a Temvik-Wilton silt loam soil (fine-silty, mixed Typic and Pachic Haploborolls) located near Mandan, ND. Surface soil pH was 6.4, soil organic C was 21.4 g kg^{-1}, and $NaHCO_3$-extractable soil test P was 20 to 26 mg kg^{-1} in the spring of 1984 (Black and Tanaka, 1997). Hard-red SW was produced in a crop–fallow system under three tillage systems, CT, MT, and NT. Nitrogen fertilizer was applied in early spring each crop year as a broadcast application of NH_4NO_3 at rates of 0, 22, and 45 kg N ha^{-1}, except for 1991 and 1992 (Rotation Cycle 4), when no N was applied because of a buildup of residual soil NO_3–N due to drought conditions and low yields in 1988 and 1989. Each main block of the study was 137.2 by 73.1 m in size. Tillage plots (45.7 by 73.1 m) were oriented in a north-south direction,

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Published in Agron. J. 93:1130–1135 (2001).

Abbreviations: CT, conventional-till; F, fallow; MT, minimum-till; NT, no-till; SW, spring wheat.

N plots (137.2 by 24.4 m) in an east-west direction across all tillage plots with each individual tillage by N plot being 45.7 by 24.4 m. Experimental design was a strip-split plot with tillage and N rate treatments stripped with three replications. Duplicate sets of plots (SW–F and F–SW cropping sequences) were established in 1984 to allow all phases of the crop–fallow system to be present each year from 1985 through 1996. Data presented here represent an average from the duplicate set of plots to get an overall long-term representation of the SW–F system. Six rotation cycles of the SW–F system were completed in the 12 yr (1985–1996) of this study (Table 1). The total quantity of N applied during the 12 yr was 0, 112, and 224 kg N ha^{-1} for the 0, 22, and 45 kg N ha^{-1} treatments, respectively.

The fallow period began in September each year following SW harvest in August and continued for about 20 mo until SW planting in May. Precipitation for the fallow period and crop period, and total for each rotation cycle (average for duplicate sets of plots) are reported in Table 1. Agronomic practices used for each tillage treatment were previously described by Halvorson et al. (2000).

Grain samples collected at harvest each year were analyzed for N content using a wet acid digest procedure (Lachat Instruments, 1992). The samples were ground to pass a 0.85-mm screen prior to analysis. In 1994 and 1996, grain N was determined with a Carlo-Erba C-N analyzer (Schepers et al., 1989).[1] The grain N concentration and total amount of N removed each year in the grain was determined.

Soil samples, one 3-cm-diam. core per plot, were collected from each tillage and N fertilizer treatment each fall after SW harvest from the fallow and crop phases of the rotation cycle for NO_3–N analyses. Samples were collected in 30-cm increments to a depth of 150 cm. Soil NO_3–N was determined by autoanalyzer (Lachat Instruments, 1989; Technicon Industrial Systems, 1973) on a 5:1 extract/soil ratio using 2 *M* KCl extracting solution from 1985 to 1993 and a 0.01 *M* $CaSO_4$ extracting solution from 1993 through 1996. Laboratory check soils were run to assure that the NO_3–N analyses were similar for both extraction methods and instruments used in this study.

Precipitation was measured from April through October each year with a recording rain-gauge at the field site. November through March precipitation was estimated from the U.S. Weather Bureau measurements made at the Northern Great Plains Research Laboratory at Mandan, ND located approximately 5 km northeast of the site.

Analysis of variance procedures were conducted using SAS statistical procedures (SAS Institute Inc., 1991). All differences discussed are significant at the 0.05 probability level unless otherwise stated. An LSD was calculated only when the analysis of variance *F*-test was significant at the 0.05 probability level unless otherwise indicated.

RESULTS AND DISCUSSION

Grain Yields

There was substantial variation in precipitation received during the six rotation cycles of this study. For the rotation cycles of this SW–F system, precipitation during the fallow (328 mm) and crop (156 mm) periods were lowest for Rotation Cycle 3 with a total average precipitation amount of 484 mm (Table 1). Rotation Cycles 5 and 6 were the wettest with 1002 and 1122 mm total precipitation for the rotation cycles, respectively.

Table 1. Average precipitation received during fallow (20 mo) and crop (4 mo) periods for each rotation cycle at the research site southwest of Mandan, ND, from 1983 through 1996.

Rotation cycle	Crop years in rotation	Fallow	Crop	Rotation total
		mm		
1	1985–1986	531	328	859
2	1987–1988	662	220	882
3	1989–1990	328	156	484
4	1991–1992	403	236	639
5	1993–1994	645	357	1002
6	1995–1996	794	328	1122
Average		561	271	831

Annual grain yields were the subject of a previous paper (Halvorson et al., 2000) and will not be discussed in detail here. Average grain yields for each rotation cycle are presented briefly to assist the reader in understanding the relationship of grain yields to grain N removal as affected by tillage and N treatments. Grain yields decreased as tillage intensity decreased [CT (2267 kg ha^{-1}) > MT (2167 kg ha^{-1}) > NT (2101 kg ha^{-1})].

Grain yields were affected differently by N fertilization during the earlier rotation cycles when growing season conditions were drier than during the later rotation cycles that were wetter (Table 2). For Rotation Cycles 1 to 3, N fertilization had no effect on grain yields. In Rotation Cycle 4, grain yields were depressed at the 22 kg ha^{-1} N rate. During Rotation Cycles 5 and 6, grain yields were generally increased by N fertilization, which probably should be expected due to the high level of precipitation during the crop period (Table 1).

Grain Nitrogen

Grain N concentration, averaged over rotation cycles, was influenced by a significant tillage × N interaction. Grain N concentration increased with increasing N rate for each of the tillage treatments (Fig. 1). Grain N concentrations were similar for all tillage treatments with no N applied. At the 22 kg ha^{-1} N rate, grain N concentrations were greater with CT and MT than with NT. At the 45 kg ha^{-1} N rate, grain N concentrations were higher with CT than with NT. Grain N concentration varied with rotation cycle with N concentrations of 32, 33, 38, 34, 25, and 29 g kg^{-1} for Rotation Cycles 1, 2, 3, 4, 5, and 6, respectively ($LSD_{0.05}$ = 1 g kg^{-1}). Grain

Table 2. Grain yields of six spring wheat crops over 12 yr in a spring wheat–fallow cropping system as a function of N rate, averaged across tillage system, at Mandan, ND.†

N Rate	Rotation cycle 1	2	3	4	5	6	Mean
kg ha^{-1}	kg ha^{-1}						
0	2600‡	1514	2173	2832	1695	1847	2110
22	2625	1471	2098	2673	2085	2084	2173
45	2568	1507	2166	2741	2238	2050	2212

† Significant N rate × rotation cycle interaction.
‡ $LSD_{0.05}$ = 148 kg ha^{-1} for comparing N rates within rotation cycle; $LSD_{0.05}$ = 198 kg ha^{-1} for comparing rotation cycles within N rates; $LSD_{0.05}$ = 50 kg ha^{-1} for comparing means.

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the USDA-ARS.

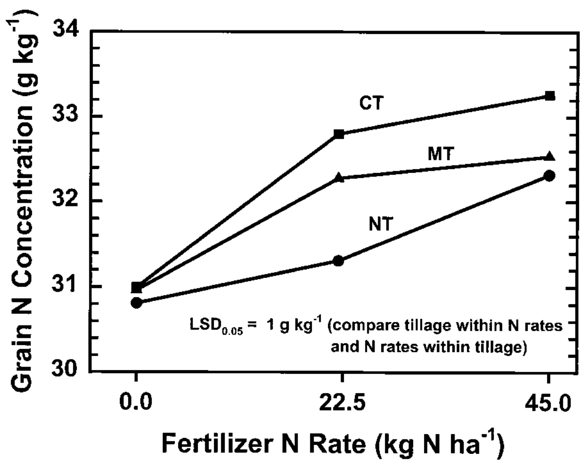

Fig. 1. Grain N concentration as a function of N rate for the conventional-till (CT), minimum-till (MT), and no-till (NT) treatments.

N concentrations were higher during the earlier drier rotation cycles (1–3) than the wetter later Rotation Cycles 5 and 6.

Grain N removal per crop, averaged over N rates and rotation cycles, was affected by tillage treatment, with a greater grain N removal (70 kg N ha^{-1}) with CT than with NT (66 kg N ha^{-1}). Grain N removal was greater with MT (68 kg N ha^{-1}) than with NT.

Grain N removal per crop varied with N rate and rotation cycle. Grain N removal was generally increased by N fertilization and increasing N rate during each of the rotation cycles, except for Rotation Cycles 4 and 6 (Table 3). For the six rotation cycles, grain N removal for the 22 kg ha^{-1} N rate was significantly greater than with the zero N rate for Rotation Cycles 1, 5, and 6, or 50% of the time. Applying 45 kg N ha^{-1} increased grain N removal above that of the zero N rate during Rotation Cycles 1, 2, 3, and 5, or 67% of the time. Differences in grain N removal were observed between the 22 and 45 kg ha^{-1} N rates for Rotation Cycles 2, 3, 4, 5, and 6. In Rotation Cycle 4, an unexplainable decrease in grain N removal was observed with application of 22 kg N ha^{-1}. In Rotation Cycle 6, the application of 45 kg N ha^{-1} resulted in an unexplained decrease in grain N removal. Grain N removal was lowest during Rotation Cycle 2 when grain yields were depressed due to drought. The overall trend for all rotation cycles was for grain N removal to increase with increasing N rate (Table 3).

Table 3. Grain N removal with six spring wheat crops over 12 yr in a spring wheat–fallow cropping system as a function of N rate, averaged across tillage system, at Mandan, ND.†

	Rotation cycle							
N Rate	1	2	3	4	5	6	Mean	Total
kg ha^{-1}	kg N ha^{-1}							
0	79‡	45	81	90	40	58	66	388
22	83	46	82	87	53	60	69	411
45	83	48	85	91	58	54	70	425

† Significant N rate × rotation cycle interaction.
‡ $LSD_{0.05}$ = 2 kg N ha^{-1} for comparing N rates within rotation cycle; $LSD_{0.05}$ = 2 kg N ha^{-1} for comparing rotation cycles within N rates; $LSD_{0.05}$ = 2 kg N ha^{-1} for comparing means; $LSD_{0.05}$ = 14 kg ha^{-1} for comparing total grain N removal.

Table 4. Total fall NO_3–N level in soil profile (0- to 150-cm depth) in fallow (Sept.–Oct.) prior to spring wheat planting (May) for each rotation cycle as a function of N rate, averaged across tillage system, in a SP cropping system at Mandan, ND.†

	Rotation cycle						
N Rate	1	2	3	4	5	6	Mean
kg ha^{-1}	kg NO_3–N ha^{-1}						
0	136‡	75	144	169	70	77	112
22	144	77	177	218	134	76	138
45	125	80	157	241	117	86	136

† Significant N rate × rotation cycle interaction.
‡ $LSD_{0.05}$ = 33 kg NO_3–N ha^{-1} (compare N rate within rotation cycle); $LSD_{0.05}$ = 37 kg NO_3–N ha^{-1} (compare rotation cycle within N rates); $LSD_{0.05}$ = n.s. and $LSD_{0.10}$ = 19 kg NO_3–N ha^{-1} (compare means).

Total grain N removal in six crops decreased with decreasing tillage intensity [CT (422 kg N ha^{-1}) > MT (409 kg N ha^{-1}) > NT (393 kg N ha^{-1})], which reflects the trends in grain yields and grain N concentrations for the tillage treatments.

The total quantity of N removed in the grain of six crops averaged 388 kg N ha^{-1} with no N applied. Only 23 kg ha^{-1} more N was removed in the grain with the application of 22 kg N ha^{-1} compared with the zero N rate with a N use efficiency of 21% of the 112 kg ha^{-1} fertilizer N applied. Only 37 kg ha^{-1} more N was removed in the grain with the application of 45 kg N ha^{-1} compared with no N applied with a N use efficiency of 17% of the 224 kg ha^{-1} fertilizer N applied. Thus, more N was being applied to the SW–F system at the two highest N rates than was being removed in the grain.

Soil Nitrate–Nitrogen Accumulation and Distribution

Fall (September–October) NO_3–N levels in the 0- to 150-cm soil depth in fallow (at the end of the second summer) varied with N rate and rotation cycle (Table 4). Fall soil NO_3–N levels were similar for all N rates during Rotation Cycles 1 and 2. Fall soil NO_3–N levels in fallow increased with N fertilization rate during Rotation Cycles 3, 4, and 5; however, N fertilization had no effect on soil NO_3–N in Rotation Cycle 6. When averaged over all rotation cycles, N fertilization increased the level of fall soil NO_3–N in fallow (Table 4). Soil NO_3–N levels increased following the low crop yields of Rotation Cycle 2 due to low precipitation during the crop phase of the rotation. Soil NO_3–N levels in fallow were highest for Rotation Cycles 3 and 4, then decreased during Rotation Cycle 6.

Fall soil NO_3–N levels in the fallow phase of the SW–F rotation varied with tillage treatment, rotation cycle, and soil depth (Table 5). Soil NO_3–N levels tended to be higher in the upper soil depths than lower soil depths of the 150-cm profile for all tillage treatments during Rotation Cycles 1, 2, and 3. The NO_3–N levels increased in the lower soil depths during Rotation Cycles 4 and 5. Soil NO_3–N levels in the lower soil depths were lower for Rotation Cycle 6 than for Rotation Cycle 5, which may be an indication that some NO_3–N may have been lost below the root zone of SW during the wetter environments of Rotation Cycles 5 and 6. Variations in soil

Table 5. Fall soil NO_3–N level in fallow (Sept.–Oct.) prior to SW planting (May) with depth for each rotation cycle as a function of tillage system, averaged across N rates, in a SW-F cropping system at Mandan, ND.†

		Rotation cycle						
Tillage	Soil depth	1	2	3	4	5	6	Mean
	cm	kg NO_3–N ha^{-1}						
CT	0–30	74‡	33	85	53	30	36	52
	30–60	21	16	41	49	10	18	26
	60–90	12	13	21	56	12	14	21
	90–120	16	10	14	27	28	9	17
	120–150	17	15	16	21	31	8	18
	§Total	140	87	176	207	110	84	134
MT	0–30	67	27	60	64	30	31	46
	30–60	29	16	41	49	11	17	27
	60–90	12	13	20	63	32	13	26
	90–120	13	10	11	28	10	10	14
	120–150	14	9	10	14	25	8	13
	Total	135	76	142	218	108	79	126
NT	0–30	26	23	72	57	30	24	39
	30–60	58	15	39	39	12	16	30
	60–90	18	14	24	53	32	15	26
	90–120	15	10	14	38	12	11	17
	120–150	12	9	11	16	18	9	13
	Total	129	71	160	204	103	76	125

† Significant tillage × rotation cycle × soil depth interaction.
‡ $LSD_{0.05}$ = 17 kg NO_3–N ha^{-1} (compare tillage within rotation cycle × soil depth); $LSD_{0.05}$ = 17 kg NO_3–N ha^{-1} (compare rotation cycle within tillage × soil depth); $LSD_{0.05}$ = 17 kg NO_3–N ha^{-1} (compare soil depth within tillage × rotation cycle).
§ Tillage × rotation cycle interaction was not significant for total NO_3–N in soil profile.

NO_3–N within a given soil depth among tillage treatments may have resulted in this significant interaction. Differences between tillage treatments are not obvious.

Total fall NO_3–N in the 150-cm soil profile following SW harvest varied with N rate and rotation cycle (Table 6). Nitrogen rate had no effect on residual soil NO_3–N in Rotation Cycle 1, but increased residual soil NO_3–N in Rotation Cycles 2 through 4. Overall, the trend was for N rate to increase the level of residual NO_3–N in the soil profile. During Rotation Cycles 2 through 4 when precipitation was low during the crop phase, residual soil NO_3–N increased in the 150-cm soil profile. Residual NO_3–N levels were much lower for Rotation Cycles 5 and 6, which had above average precipitation during the fallow and crop phases of the SW–F rotation. Good yields and high grain N removal during Rotation Cycle 4, without further N fertilizer application, probably contributed to the lower postharvest NO_3–N levels in Rotation Cycle 5 for the previously fertilized treatments. Leaching of NO_3–N below the root zone of the SW during the wet Rotation Cycles 5 and 6 could have also contributed to the lower postharvest NO_3–N levels since more soil NO_3–N was present at the end of the crop phase of Rotation Cycle 4 and fallow phase of Rotation Cycle 5 than was removed by the SW crop. Total postharvest soil NO_3–N levels were not significantly affected by tillage treatment with average postharvest NO_3–N levels of 81, 81, and 74 kg N ha^{-1} in the 0- to 150-cm soil profile for the CT, MT, and NT treatments, respectively.

A tillage × N rate × rotation cycle × soil depth interaction (Table 7) shows that NO_3–N levels throughout the soil profile were relatively low for all tillage and N treatments following SW harvest for Rotation Cycle 1. During the drier Rotation Cycles 2 and 3, postharvest NO_3–N levels within the soil profile increased at all depths in the profile with N fertilization increasing the level of NO_3–N. Residual NO_3–N levels were still fairly high for all tillage treatments and increased with N rate following SW harvest in Rotation Cycle 4, which was not fertilized, had high yields, and a high level of grain N removal. The very low levels of postharvest NO_3–N observed throughout the soil profile for all tillage and N rates for Rotation Cycle 5 would indicate that some NO_3–N was potentially lost from the root zone due to leaching. This is supported by the high level of fall soil NO_3–N found in the soil profile of the fallow phase of Rotation Cycle 5, the fall prior to planting of the SW crop for Rotation Cycle 5 (Table 4). The quantity of N in the 150-cm soil profile was twice that removed in the grain (Table 3) during Rotation Cycle 5. Thus, crop N uptake and grain N removal would not account for the low level of postharvest NO_3–N in the soil profile for Rotation Cycle 5. Postharvest soil NO_3–N levels remained low in the profile for Rotation Cycle 6 for all tillage and N rate treatments.

Table 6. Total fall NO_3–N level in soil profile (0- to 150-cm depth) after spring wheat harvest for each rotation cycle as a function of N rate, averaged across tillage systems, in a spring wheat–fallow cropping system in Mandan, ND.†

	Rotation cycle						
N Rate	1	2	3	4	5	6	Mean
kg ha^{-1}	kg NO_3–N ha^{-1}						
0	38‡	72	111	59	13	36	55
22	40	108	154	122	27	44	82
45	49	113	197	166	30	41	99

† Significant N rate × rotation cycle interaction.
‡ $LSD_{0.05}$ = 28 kg NO_3–N ha^{-1} (compare N rate within rotation cycle); $LSD_{0.05}$ = 29 kg NO_3–N ha^{-1} (compare rotation cycle within N rates); $LSD_{0.05}$ = 21 kg NO_3–N ha^{-1} (compare means).

Although the effects of tillage treatment on postharvest soil NO_3–N is not very obvious, the general trend appears to be for postharvest soil NO_3–N levels to be lower with NT than with CT and MT treatments (Table 7). This would be consistent with the soil NO_3–N observations made among tillage treatments in the adjacent annual cropping rotation (Halvorson et al., 2001). Differences in soil NO_3–N among tillage treatments in the SW–F system were not as obvious as in the annual crop (SW–winter wheat–sunflower) rotation. Although grain N removal was greater with CT than with NT, soil NO_3–N in the profile tended to be greater with CT than with NT. The higher soil NO_3–N levels for CT probably reflects the effects of tillage on decomposing crop residues and increased N mineralization compared with the NT system where residue decomposition is slower (Wienhold and Halvorson, 1999). Wienhold and Halvorson (1998) reported that the NT system had a slightly higher level of total soil N than the CT system in the surface soil. Thus under NT, more of the N appears to be tied up in soil organic matter and crop residues than in the CT system, resulting in lower soil profile NO_3–N levels with NT than with CT.

Table 7. Soil NO_3–N after spring wheat harvest with depth for each rotation cycle as a function of tillage and N treatments in a spring wheat–fallow cropping system at Mandan, ND.†

Tillage	N Rate	Soil depth	Rotation cycle 1	2	3	4	5	6
	kg ha^{-1}	cm	kg NO_3–N ha^{-1}					
CT	0	0–30	8‡	30	56	16	7	16
		30–60	8	14	35	6	1	4
		60–90	11	14	13	5	1	3
		90–120	5	11	9	8	1	5
		120–150	7	12	13	12	4	9
MT	0	0–30	9	33	46	13	6	14
		30–60	8	9	30	9	2	4
		60–90	7	9	22	20	7	3
		90–120	5	8	8	9	2	4
		120–150	5	11	10	15	6	9
NT	0	0–30	9	27	43	15	5	13
		30–60	8	10	19	9	1	4
		60–90	8	12	12	12	1	4
		90–120	9	8	7	11	1	6
		120–150	9	8	7	16	2	9
CT	22	0–30	10	69	64	28	8	23
		30–60	7	12	36	10	2	6
		60–90	5	9	16	37	2	5
		90–120	6	10	11	20	3	6
		120–150	15	12	11	18	19	12
MT	22	0–30	9	76	92	24	4	19
		30–60	5	13	45	15	5	6
		60–90	5	13	19	24	12	5
		90–120	10	10	12	21	2	7
		120–150	6	9	11	35	11	10
NT	22	0–30	8	41	56	16	4	14
		30–60	7	9	46	11	2	4
		60–90	5	12	22	31	1	3
		90–120	5	16	12	47	2	5
		120–150	17	10	11	28	5	8
CT	45	0–30	8	56	105	32	5	17
		30–60	8	13	55	27	2	4
		60–90	5	10	20	66	3	4
		90–120	8	9	14	57	7	6
		120–150	10	9	16	30	10	9
MT	45	0–30	8	83	66	29	5	15
		30–60	8	13	56	35	1	5
		60–90	9	14	26	44	2	5
		90–120	9	11	15	29	9	7
		120–150	11	13	12	15	22	12
NT	45	0–30	12	57	112	21	7	15
		30–60	16	13	52	12	2	4
		60–90	9	16	20	29	1	3
		90–120	13	12	12	48	3	5
		120–150	14	10	9	26	13	9

† Significant tillage × N rate × rotation cycle × soil depth interaction.
‡ $LSD_{0.05}$ = 14 kg NO_3–N ha^{-1} (compare tillage within N rate × rotation cycle × soil depth); $LSD_{0.05}$ = 14 kg NO_3–N ha^{-1} (compare N rate within tillage × rotation cycle × soil depth); $LSD_{0.05}$ = 14 kg NO_3–N ha^{-1} (compare rotation cycle within tillage × N rate × soil depth); $LSD_{0.05}$ = 14 kg NO_3–N ha^{-1} (compare soil depth within tillage × N rate × rotation cycle).

Soil profile NO_3–N levels (0–150 cm depth) in this SW–F cropping system tended to be as great as those found in the adjacent annual cropping sequence that had no fallow period but higher levels of N fertilizer applied (Halvorson et al., 2001). Total soil profile NO_3–N levels following the dry years were high in both cropping systems. Even with no N fertilizer applied, total soil profile N reached a high of 169 kg NO_3–N ha^{-1} in Rotation Cycle 4 (Table 4) with the zero N rate, and a high of 241 kg NO_3–N ha^{-1} with 45 kg N ha^{-1} applied every crop cycle, except for Rotation Cycle 4. This is comparable with the 1992 average total soil profile NO_3–N level of 161 kg ha^{-1} with 34 kg N ha^{-1} applied and 352 kg ha^{-1} with 101 kg N ha^{-1} applied annually in the adjacent annual cropping system (Halvorson et al., 2001). This comparison demonstrates the potential to have N in excess of crop needs in the soil profile following dry years.

SUMMARY

The quantity of N removed in grain varied with tillage, N rate, and available moisture during the rotation cycle for this SW–F cropping system. Nitrogen fertilization generally increased the amount of N removed in the grain during each rotation cycle and increased the total amount of N removed in the grain with six SW crops. Only 21 and 17% of the N applied as fertilizer was removed in the grain for the 22 and 45 kg ha^{-1} N rates, respectively, by six SW crops. These low N use efficiencies indicate that more N was being applied than was being removed by the crop, thus contributing to excess residual NO_3–N in the soil profile. Grain N concentration increased with increasing N rate, but varied with tillage system. Grain N concentrations for the fertilized treatments were higher with CT than with NT.

Soil NO_3–N levels did not show signs of accumulating in the soil profile with respect to N fertilization or tillage treatments prior to the dry crop seasons. During and following the dry crop cycles, postharvest soil NO_3–N levels increased with increasing N rate and tended to be greater with CT and MT than with NT. The data indicate that even with no N fertilizer applied, soil NO_3–N levels increased in the soil profile during the dry crop cycles. During the wetter rotation cycles, some NO_3–N may have moved below the root zone of SW, as evidenced by a low level of postharvest soil NO_3–N in the profile, which cannot be accounted for by grain N removal. This would be consistent with the observations reported by Campbell et al. (1975) and Campbell et al. (1984) for cultivated systems in semiarid areas of Canada.

The results show that in a SW–F system, grain N and residual soil NO_3–N responses to N fertilization and tillage system will vary with cropping season and climatic conditions. Following dry years, where N use is low, reducing N fertilizer applications rates may be necessary to reduce the level of NO_3–N in the root zone and reduce the potential for ground water contamination. Soil testing for residual NO_3–N is essential for efficient N management within tillage and cropping systems.

ACKNOWLEDGMENTS

The authors acknowledge the contribution of the Area IV Soil Conservation Districts in North Dakota for providing the land and assisting with financial resources to conduct this long-term study; the assistance of Dr. Gary Richardson, USDA-ARS Statistician, Fort Collins, CO, with the statistical analyses; and the assistance of F. Jacober, J. Harms, L. Renner, M. Hatzenbuhler, and G. Brucker in conducting the study and collecting the field and laboratory data.

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