Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain

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Interpretive summary

Reducing nitrogen discharge from cropland has been identified as critical to the restoration of water quality in Chesapeake Bay. In the Coastal Plain region of the Bay watershed, nitrogen loss from cropland occurs primarily via leaching of nitrate from the crop rooting zone during winter months. Nitrate leached from the root zone eventually enters shallow groundwater. Elevated groundwater nitrate concentrations are widespread in the Coastal Plain and contribute to elevated nitrogen loads in Bay tributaries. This study evaluated the effect of cereal grain winter cover crops on nitrate leaching following corn production. Cereal grain cover crops remove nitrate from the soil profile, thereby reducing the potential for nitrate leaching. Nitrate leaching following no-till corn production was reduced approximately 80% by rye cover crops planted immediately following grain harvest. Groundwater nitrate concentrations decreased by more than 60% in field-scale watersheds during a nine year period as a result of the use of rye cover crops. Cereal grain cover crops can make significant contributions to soil carbon pools depending on nitrogen availability.

Key words: cover crop, groundwater, nitrate.

*ABSTRACT: Nitrate contamination of shallow groundwater has been widely documented in association with agriculture in the Coastal Plain region of the Chesapeake Bay watershed. Elevated groundwater nitrate levels limit the use of shallow groundwater for human consumption and also result in elevated nonpoint source nitrogen (N) loads to Chesapeake Bay via elevated stream baseflow nitrate concentrations. This study investigated the effects of cereal grain winter cover crops on nitrate leaching rates, profile nitrate storage, and nitrate concentrations in shallow groundwater in two field-scale watersheds planted continuously in corn (*Zea mays *L.) from 1984 through 1996. Winter-fallow conditions were maintained following the 1984 through 1987 growing seasons and cereal rye (*Secale cereale *L.) as a cover crop was planted immediately after grain harvest from 1988 through 1996. Cover crop effects on nitrate leaching rates also were evaluated in continuous no-till corn plots from 1990 through 1995. Nitrate leaching losses from the root zone and recharge of shallow aquifers occurred primarily during winter months under conditions of low evapotranspiration. The potential for nitrate leaching losses was determined primarily by the availability of nitrate in the root zone at the onset of the winter groundwater recharge period. Rye winter cover crops planted after corn harvest consistently reduced nitrate-N concentrations in root zone leachate to less than 1 mg/L during most of the groundwater recharge period, and reduced annual nitrate leaching losses by approximately 80% relative to winter-fallow treatments. Shallow groundwater nitrate-N concentrations under long-term continuous corn production decreased from the 10 to 20 mg/L range to less than 5 mg/L after seven years of cover crop use. Cover crops appeared to increase corn yields under adverse growing season conditions, but limited residual nitrate availability during the growing season relative to winter-fallow settings. Cover crop growth was generally N limited, suggesting that increased N inputs would have little effect on nitrate leaching, but would increase cover crop contributions to soil carbon pools.*

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Elevated levels of nitrate in shallow groundwater in association with agricultural activities have been widely documented (Hallberg 1986; Spalding and Exner 1993). In the Chesapeake Bay watershed, evidence of groundwater contributions to nonpoint source nitrogen (NPS-N) loads has drawn attention to nitrate leaching losses from cropland (Bachman and Phillips 1996; Staver et al. 1996). Reducing NPS-N loads will be critical to restoring water quality in Chesapeake Bay, because excessive algal production in the Bay is primarily controlled by N availability (Malone et al. 1993). Subsurface N transport has generated particular concern in Coastal Plain regions of the watershed where agriculture is the dominant land use. Surface topography and soil drainage characteristics promote the partitioning of precipitation into subsurface rather than overland flow paths. (Phillips et al. 1993; Staver et al. 1989; Valiela and Costa 1988). Groundwater nitrate-N concentrations greater than 10 mg/L have been reported as a result of concentrated cash grain and poultry production in the region (Bachman 1984; Magette et al. 1989; Ritter and Chirnside 1984; Staver et al. 1988; Weil et al. 1990). Studies of sub-basin stream water quality (Bachman and Phillips 1996; Staver et al. 1996) and shoreline groundwater seepage patterns (Reay et al. 1992; Staver and Brinsfield 1996) have indicated that a major fraction of nitrate in shallow groundwater is being transported into surface waters.

Subsurface nitrate transport has been a vexing problem in the decade-old effort to restore water quality in Chesapeake Bay. Efforts to reduce water quality problems associated with agriculture historically have focused on erosion control. However, strategies to mitigate surface runoff sediment and nutrient transport appear to do little to reduce nitrate leaching losses from Coastal Plain cropland (Staver et al. 1989). Although it was recognized early in the Bay restoration effort that reductions in subsurface nitrate discharge would be needed to achieve NPS-N reduction goals (U.S. EPA 1988), tributary and Bay water quality data indicate that little progress has been made thus far toward reducing NPS-N inputs (U.S. EPA 1995). The potential for long groundwater residence times within Coastal Plain aquifers (Dunkle et al. 1993) has raised questions regarding the time required for changes in management practices to affect nonpoint source N discharge via subsurface flow paths. However, both vadose zone studies (Parkin and Meisinger 1989) as well as aquifer studies (Bohlke and

Denver 1995), have indicated that under oxygenated conditions, nitrate that has been leached below the crop rooting zone will eventually be discharged to surface waters, even if residence time within the subsurface flow system exceeds several decades. This suggests that there are no short-term solutions to the problem of subsurface nitrate delivery to surface waters, and that implementation of practices that reduce nitrate leaching losses from cropland will be necessary if reductions in NPS-N loads are ever to be achieved.

Currently, the two basic strategies being promoted for reducing nitrate leaching losses are to match N inputs with crop needs (Bock and Hergert 1991), and to use winter annual grasses to scavenge nitrate remaining in the root zone following harvest of summer annual crops (Meisinger et al. 1991). Management of nutrient inputs to cropland has been highly promoted in the Chesapeake Bay restoration effort through educational programs, technical support in developing nutrient management plans, and cost-share funding for manure containment structures. While it has long been generally recognized that reducing N application rates tends to reduce nitrate leaching losses (Chichester 1977), many questions remain regarding the extent to which NPS-N loads can be reduced through management of inputs. In Maryland, soybean (*Glycine max* L. Merr.) production has increased in recent decades such that soybean acreage is now nearly equivalent to corn (*Zea mays* L.) acreage (Maryland Department of Agriculture 1994). Although much less data have been collected on nitrate leaching in soybean versus corn production systems, there is evidence that nitrate leaching losses in soybean systems can be as high as those during corn production (Angle 1990) and can contribute to groundwater nitrate-N concentrations above 10 mg/L (Owens et al. 1995). Since N fertilizers generally are not applied during soybean production, little opportunity exists for reducing nitrate leaching losses through management of inputs. Even during corn production there are limitations to the reductions in nitrate leaching that can be achieved using management of N inputs. Drought conditions during the growing season can limit corn N uptake, resulting in elevated post-harvest soil nitrate levels even though N applications were at or below recommended levels (Staver and Brinsfield 1990). Even when corn yield goals are met using economically optimum N fertilization rates, post-harvest root zone nitrate pools can be substantial (Dou et al. 1995; Roth and Fox 1990). In the Coastal Plain region of the Chesapeake Bay watershed this problem results in part from corn N uptake ceasing in late-August, while conditions for mineralization of soil N tend to remain favorable well into October (Staver and Brinsfield 1990).

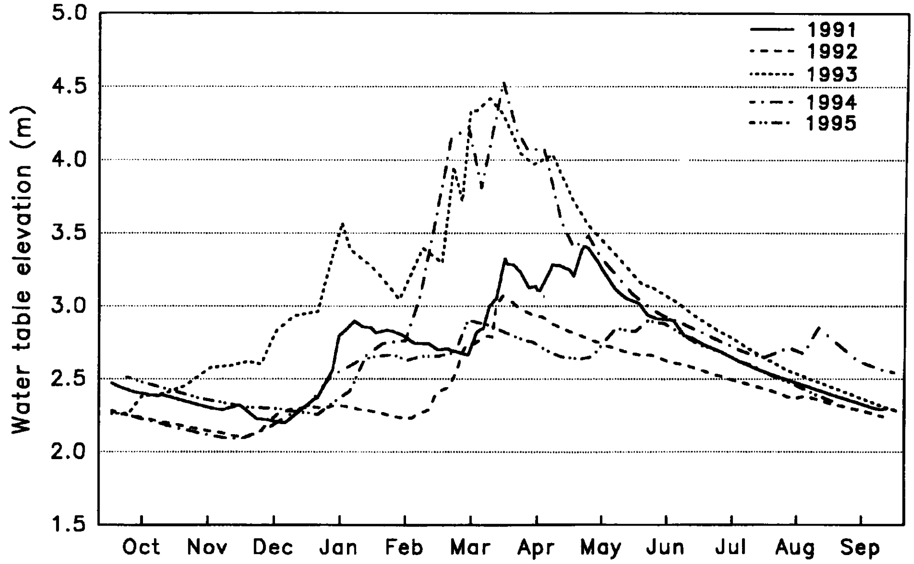

Figure 1. Water table elevation in the conventional till watershed during the 1991-95 water years

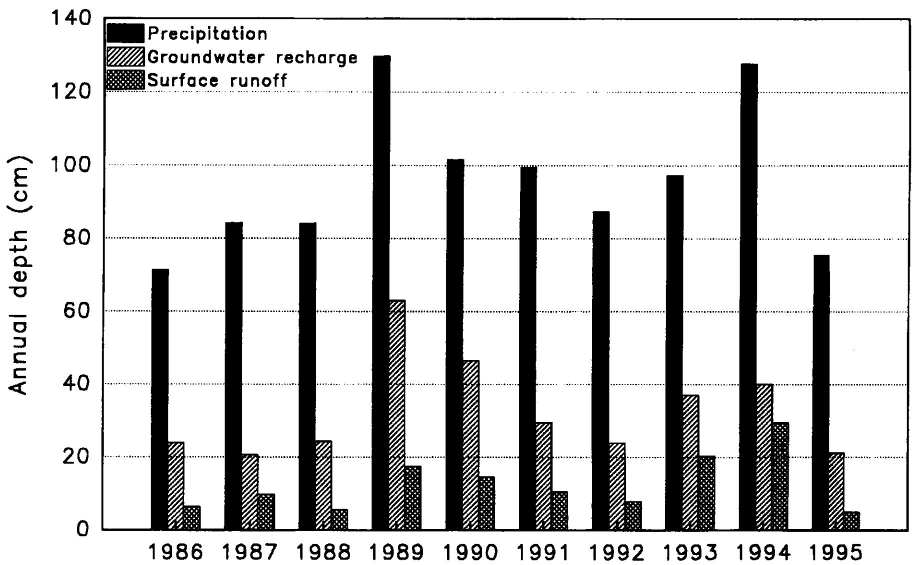

Figure 2. Precipitation and area-normalized runoff and groundwater recharge volumes in the conventional till watershed for the 1986-1995 water years

The limits on reductions in nitrate leaching losses that are possible by improved management of N inputs suggest that winter cover cropping strategies may be necessary if desired reductions in NPS-N inputs to Chesapeake Bay are to be achieved. Short-term root zone studies have indicated that cereal grain winter cover crops have the potential to reduce groundwater nitrate concentrations to levels below those attainable using economically-based N input management strategies (Staver and Brinsfield 1990; Meisinger et al. 1991; Shipley et al. 1992; McCracken et al. 1994). However, less is known about the long-term value of cereal grain winter cover crops for reducing groundwater nitrate concentrations. The objectives of this research were to 1) determine the long-term reductions in groundwater nitrate concentrations that can be achieved using cereal grain winter cover crops, and 2) evaluate the effects of cereal grain winter cover crops on root zone nitrate availability and total carbon inputs.

Study methods

Overview. The long-term effects of cereal grain winter cover crops on subsurface nitrate concentrations were evaluated in two field-scale watersheds planted continuously in corn from 1984 through 1996. Conventional tillage methods were used in one watershed and no-till methods in the other. The watersheds remained fallow during winter months from 1984 through 1987. From 1988 through 1995 a rye (*Secale cereale* L.) winter cover crop was planted following corn harvest. Throughout the entire study N inputs remained nearly constant at 156 kg/ha (140 lb/a), as recommended by the University of Maryland Cooperative Extension Service. A grid of shallow wells was used to monitor groundwater nitrate concentrations throughout the period, while post-harvest and preplant soil coring were used to trak changes in vadose zone nitrate storage. Intensive hydrologic data collection in the conventionally tilled watershed was used to quantify groundwater recharge patterns throughout the period. To augment the time-series data from the watershed studies, split-plot treatments were added in 1990 to permit side-by-side comparisons of nitrate leaching patterns in winter-fallow versus cover crop settings, and also to assess the effect of cereal grain winter cover crops on corn yields during the following growing season.

Site description. This study was conducted in the Wye River drainage basin in Queen Anne's County, Maryland (38° 55' N, 76° 09' W). Two adjacent field-scale watersheds, one under conventional tillage management and the other under no-till management, were used to evaluate the long-term effects of cereal grain winter cover crops on vadose zone nitrate storage and groundwater nitrate concentrations in continuous corn production. Soils within these watersheds are classified within the Elkton, Matapeake, and Mattapex Series (Typic Ochraquults, Typic Hapludults, and Aquic Hapludults), which exhibit gentle slopes (0 to 3 percent) and a range in hydraulic characteristics from poorly to moderately well-drained (USDA 1966). The soil surface ranges from 4 to 6 m (13 to 20 ft) above sea level and the water table is located at a seasonally variable depth of 1 to 4 m (3 to 13 ft) below the soil surface.

The split-plot studies were conducted in a grid of 15 × 46 m (50 × 150 ft) plots established in 1990 approximately 500 m (1600 ft) from the experimental watersheds. Soils within this site are classified within the Matapeake and Mattapex Series, which are moderately well-drained. Due to soil drainage characteristics and

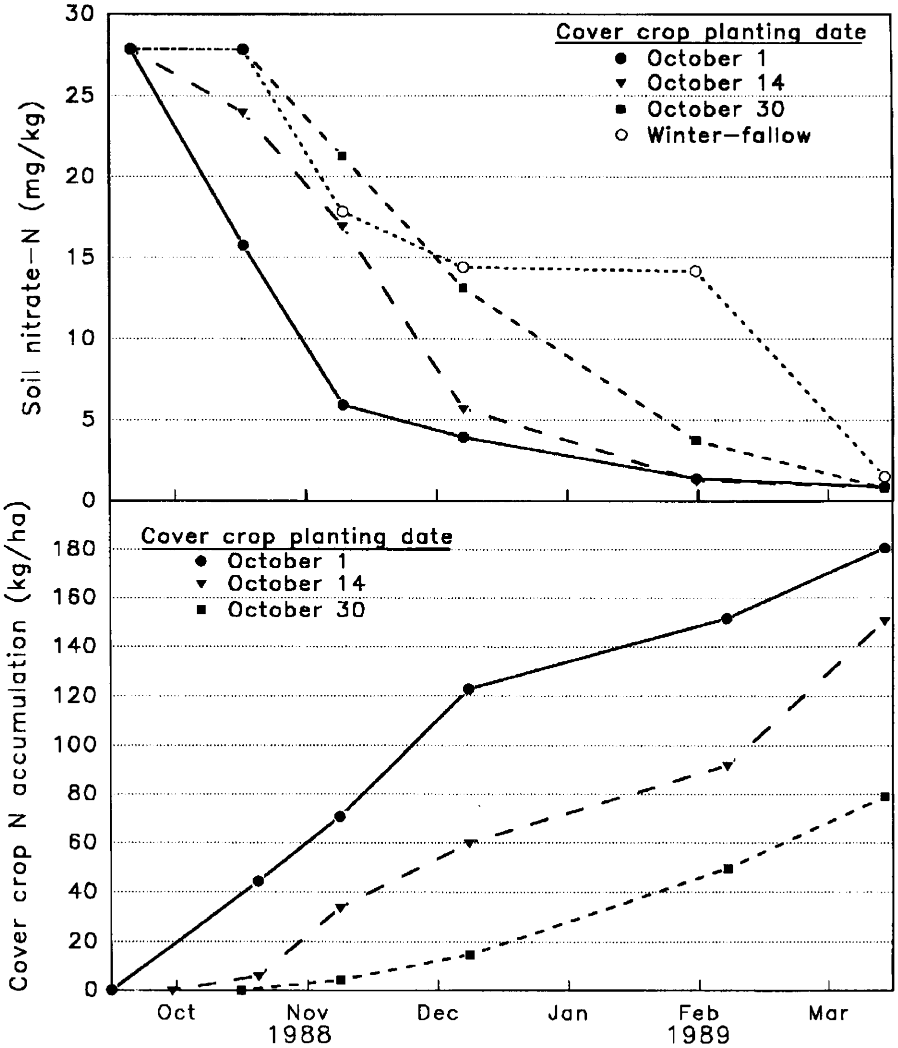

Figure 3. Nitrogen (N) accumulation by a rye cover crop and changes in root zone (0-30 cm) nitrate as affected by cover crop planting date following 1988 corn harvest in the conventional till watershed

the level topography, surface runoff at the site is minimal.

Agronomic practices. Corn was grown continuously in the experimental watersheds from 1984 through 1996. Prior to this study, both watersheds had been in corn and soybean production for at least the previous ten years and in agricultural production for many decades. Conventional tillage (CT) practices were used in one watershed throughout the study and no-till (NT) methods in the other. Chisel plowing was the primary tillage operation in the CT watershed in conjunction with the use of a disc and field cultivator. Herbicides were used to control weeds in both watersheds following planting. Nitrogen in the form of urea-ammonium-nitrate (UAN) was applied at planting at a rate of 34 kg/ha (30 lb/a) in a banded solution. A surface sidedress application of UAN was applied from 30 to 50 days after planting at an N rate of approximately 123 kg/ha (110 lb/a). Nitrogen application rates remained the same throughout the study except during the 1989 growing season when the sidedress application was reduced to 92 kg/ha (82 lb/a). Generally, corn was planted in mid-May and grain was harvested in September. From 1984 through 1987 both watersheds remained fallow during the non-growing season. Following grain harvest from 1988 through 1996 a rye cover crop was no-till planted [188 kg/ha (3 bu/a)] in both watersheds. Cover crop planting dates ranged from September 26 to October 16. Spring tillage or herbicide application generally occurred in early April when above-ground cover crop tissue carbon to N ratios (mass basis) were less than 30. In addition, following the 1988 growing season, a grid of plots was established in the CT field adjacent to the gauged watershed to evaluate the effects of different cover crop planting dates and

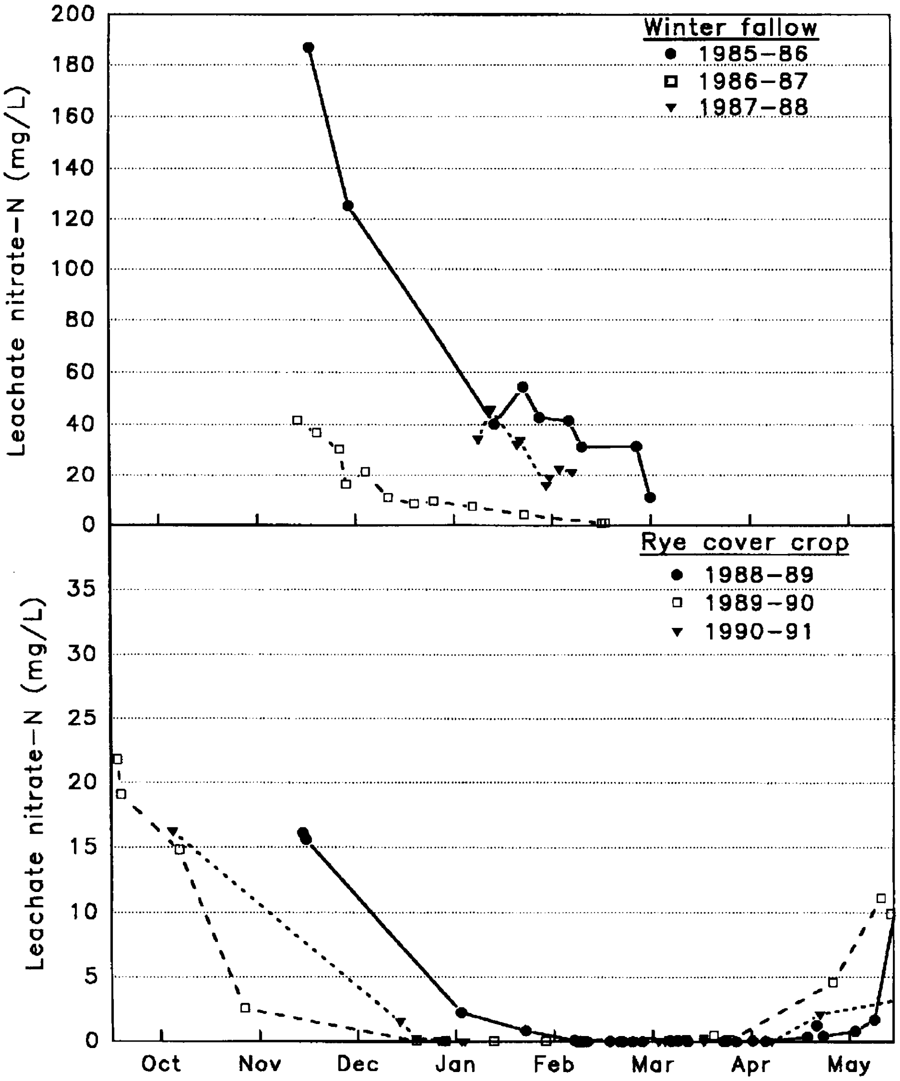

Figure 4. Root zone leachate nitrate-N concentrations in the conventional till watershed under winter-fallow conditions (1985-1988) and with rye winter cover crops (1988-91)

spring tillage/herbicide application dates on nitrate concentrations in the root zone.

In the split-plot studies initiated in 1990, no-till methods were used for corn and cover crop planting. The plots were established at a site that had been in alfalfa hay production for the previous three years. Planting and weed control methods as well as N application rates and schedules were nearly identical to those used in the no-till watershed. Cover crop planting and herbicide application dates also were similar to those used in the experimental watersheds.

Sampling methodology. Surface runoff volume was measured continuously throughout the period and used in conjunction with water table elevation and on-site precipitation data to calculate groundwater recharge volumes. Groundwater elevation and quality within the experimental watersheds were monitored using a network of 16 wells. All wells had 1.5 m (5 ft) screens centered approximately 2 m (6.5 ft) above sea level, which corresponded to the approximate position of the annual minimum elevation of the water table. The average depth to the top of the screened interval was 2.1 m in the CT watershed and 1.5 m in the NT watershed. One day prior to sampling, each well was pumped dry or three bore volumes of water were removed. Groundwater samples were analyzed for nitrate using high-pressure chromatography.

From 1988 through 1995, vadose zone nitrate storage was evaluated following corn harvest by collecting soil samples (four replicates in CT and three replicates in NT) from the soil surface to the water table using a 5 cm (2 in) diameter bucket auger. This sampling also was conducted prior to corn planting from 1989 through 1994. Winter-fallow plots were maintained throughout the study in close proximity to each of the sampling sites within the area planted with winter cover crops. This permitted side-by-side comparisons of upper vadose zone (0 to 90 cm) nitrate storage with and without a winter cover crop. Limited vadose zone coring also was conducted in the split-plot studies. The greater depth to the water table in these plots (≈ 3 m) allowed evaluation of cover crop effects to a greater depth without interference due to lateral groundwater flow. All soil samples were weighed and placed in forced-air ovens immediately after collection. Samples were dried to a constant weight and reweighed to determine gravimetric water content. Nitrate analysis was performed colorimetrically on 2 M KCl extracts. Soil nitrate concentrations were calculated on both a soil (mg/kg dry soil) and pore-water basis [(mg/kg dry soil)/gravimetric water content].

Root zone leachate was monitored in the watershed and split-plot studies using gravity lysimeters installed approximately 60 cm (2 ft) below the soil surface. Lysimeters were constructed from 1.8 m (6 ft) sections of 5 cm (2 in) diameter PVC well casing slotted on one side for a distance of approximately 80 cm (50 cm in the watersheds). Lysimeters were installed parallel to the soil surface by auguring horizontally through the wall of a 1.2 m (4 ft) deep pit, and then driving the lysimeters into place. A single pit with three lysimeters was maintained in the CT watershed from 1985 through 1991. Two additional pits were installed in 1991 in the center of plots split into winter-fallow and cover crop treatment areas. In these pits three lysimeters were installed 60 cm (2 ft) apart in two opposing walls. The installation procedure required no disruption of the soil profile above the lysimeter collection area and allowed execution of agronomic activities over the collection area using commercial-scale equipment. Flow into the lysimeters drained into a carboy within the lysimeter pit. Samples were collected immediately after lysimeter flow ceased, which generally occurred within 24 hr of the end of the precipitation event. Leachate nitrate concentrations also were determined using high-pressure chromatography.

Corn grain yields in the watersheds were estimated each year from combine yields from the same 0.5 ha plots. Triplicate four row × 15 m strips were harvested in each of the split-plot treatments to estimate grain yield. Corn stover was estimated by oven-drying nine whole plant samples at harvest and determining the grain to stover ratio. Rye dry matter and N uptake were determined by collecting in triplicate all above-ground plant tissue

Table 1. Corn grain yield and stover, post-harvest soil nitrate-N, and cover crop dry matter and N accumulation in the conventionally tilled (CT) and no-till (NT) watersheds from 1987 through 1995

Cover crop biomass data were collected just prior to spring tillage/herbicide application

Year	Tillage	Corn grain yield	Corn stover	Post-harvest soil NO_3-N 0-30 cm	Post-harvest soil NO_3-N 30-90 cm	Cover crop dry matter	Cover crop N accumulation
		kg/ha					
1987	CT	2750	-	58.9	-	0	0.0
	NT	3350	-	44.2	-	0	0.0
1988	CT	3830	4238	110.0	63.5	10098	180.7
	NT	4480	4564	32.2	-	3400	49.7
1989	CT	6120	4643	23.8	9.5	2750	46.6
	NT	6620	5324	17.4	12.0	2940	34.1
1990	CT	7590	6117	21.9	17.5	3007	48.2
	NT	7830	6108	34.4	6.8	2868	47.5
1991	CT	7480	7220	16.8	17.0	2640	32.9
	NT	7860	7393	28.9	9.3	1973	28.8
1992	CT	9120	7211	9.9	5.0	950	15.5
	NT	9130	7850	13.0	3.0	1239	21.8
1993	CT	5250	5804	12.2	2.3	1511	23.7
	NT	5930	6495	13.6	1.6	1391	25.8
1994	CT	9960	8516	9.8	3.4	1330	19.9
	NT	8160	7106	14.7	2.0	2078	30.9
1995	CT	6380	6506	35.5	6.9	2308	34.1
	NT	7190	7677	31.0	4.0	2533	

from randomly selected 90 cm (3 ft) row sections just prior to spring tillage/herbicide application. Plant tissue N and carbon content were determined by grinding (0.1 cm; 40 mesh screen) oven-dried whole samples and analyzing subsamples using a carbon-hydrogen-N analyzer.

Results

Watershed studies. Although variations in precipitation resulted in year-to-year variability in leaching and groundwater recharge patterns, strongly seasonal patterns of evapotranspiration consistently resulted in a concentrated period of groundwater recharge during winter months (Figure 1). High evapotranspiration rates tended to limit water movement from the root zone from May through September as indicated by the steady decline in water table elevation during the growing season. The surface (0 to 60 cm) soils within the study site have a gravimetric moisture content at field capacity of approximately 0.22 gm/gm and can store approximately 0.14 gm/gm of plant available water. This potential to store from 10 to 15 cm of water in the top 60 cm of soil minimizes leaching losses from the root zone during summer and early autumn months. Although corn water uptake generally ceased by early September, water table elevation continued to decline in many years well into November as a result of the soil moisture deficits established within the root zone during the growing season. For the 1986 through 1995 water years (October to September), groundwater recharge in the CT watershed averaged 33.0 cm (13.0 in) or 34.4% of the average annual precipitation depth of 95.8 cm (37.7 in). Average annual recharge volume was approximately 2.6 times greater than average annual surface runoff discharge [12.7 cm (5.0 in)], although this relationship varied widely (1.4 to 4.4) as a function of precipitation patterns (Figure 2). Although less intensive water table monitoring was conducted in the NT water-

Table 2. Growing season rainfall, corn grain yield, grain N content and stover, and cover crop above-ground dry matter and N accumulation in continuous no-till corn split-plot treatments from 1990 through 1995

Cover crop biomass data were collected just prior to spring herbicide application

Year	Treatment	May-August rainfall (cm)	grain yield*	Corn† grain N	stover	Cover crop dry matter	Cover crop N uptake
			(kg/ha)				
1990	rye cover	48.9	10049	130.4	9447	4048	85.0
	winter-fallow		9483	137.8	8809	-	-
1991	rye cover	34.1	9104	129.2	8171	1793	25.9
	winter-fallow		9096	126.5	7462	-	-
1992	rye cover	35.2	9920	115.7	7689	2053	40.5
	winter-fallow		10898	146.5	8245	-	-
1993	rye cover	29.5	8586	130.4	8732	1873	37.3
	winter-fallow		7421	120.2	7455	- -	
1994	rye cover	43.0	10042	148.2	9261	3645	59.2
	winter-fallow		10036	143.3	9114	-	-
1995	rye cover	32.9	8372	109.1	7822	-	-
	winter-fallow		8978	117.4	8474	-	-

* @ 15.5 percent moisture
† all years fertilized at 156 kg N/ha

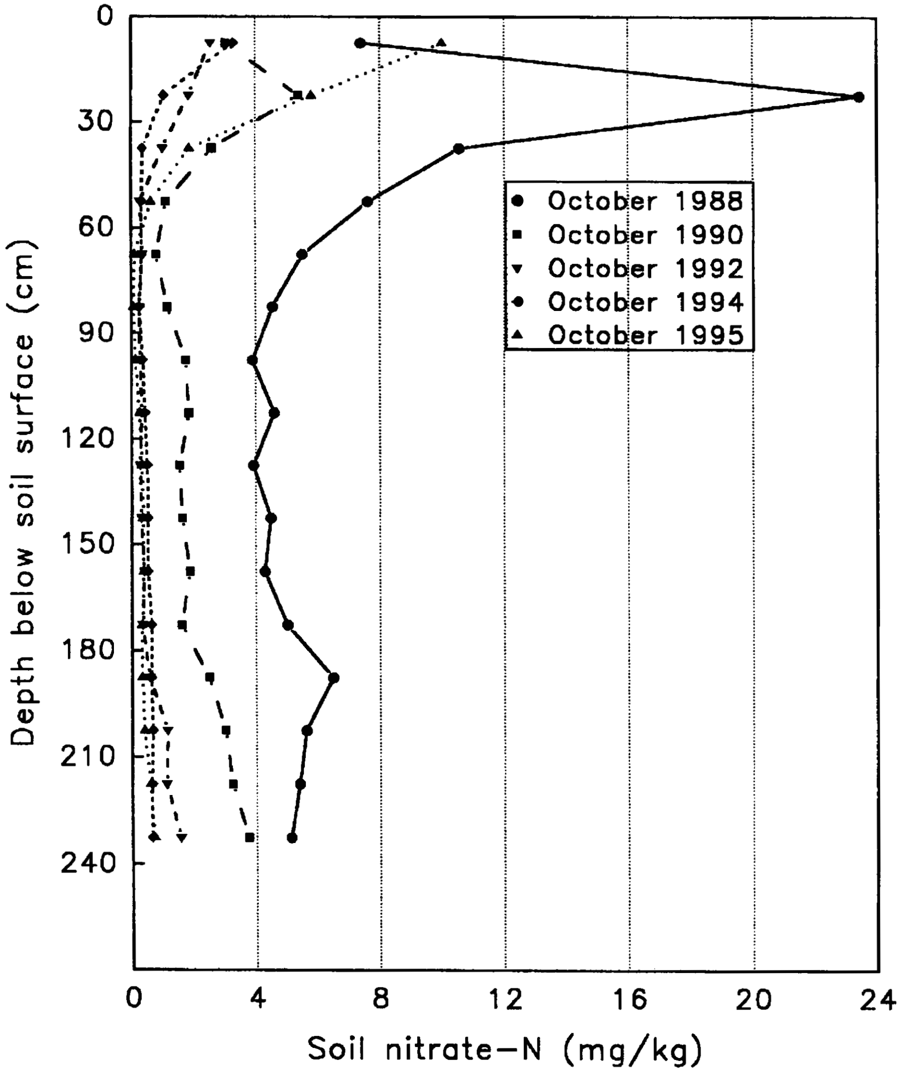

Figure 5. Post-harvest vadose zone nitrate-N concentrations (mg/kg dry soil) in the conventional till watershed from 1988-1995

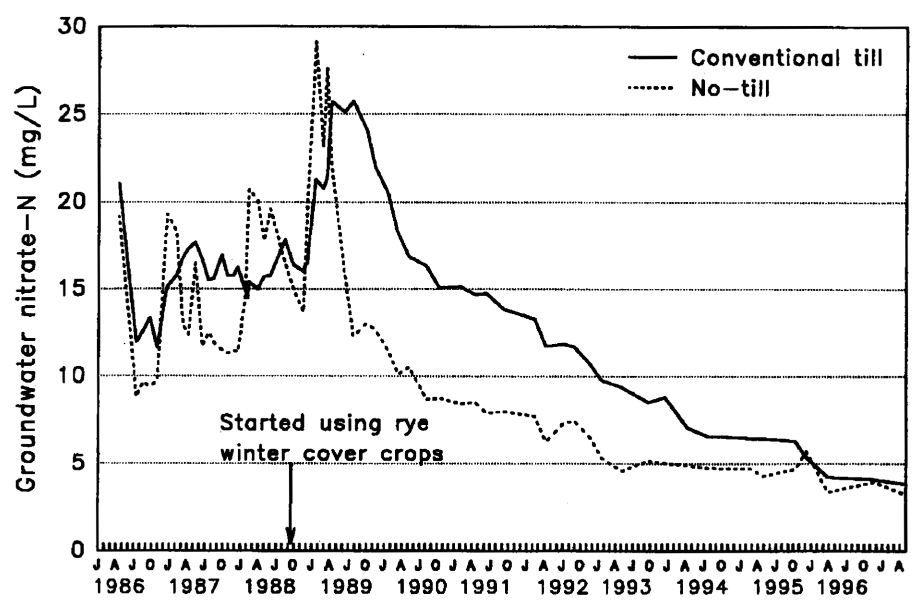

Figure 6. Average nitrate-N concentration in shallow groundwater in the conventional till and no-till watersheds from 1986-1996

shed, similarities in surface runoff volumes (104% of CT runoff), especially during the primary period of groundwater recharge, suggest that recharge rates were similar.

The effects of cover crop N uptake on root zone nitrate were intensively measured in the CT watershed following the 1988 growing season (Figure 3). The limited number of leaching events in early autumn made it possible for cover crops planted immediately after corn harvest to utilize a large fraction of the root zone nitrate pool prior to the onset of the mid-winter period of concentrated groundwater recharge. Drought conditions during the 1987 and 1988 growing seasons limited corn N uptake, particularly in the CT watershed. This, combined with below average leachate volumes during the winter of 1987-88, resulted in a root zone nitrate pool in early October 1988 of more than 100 kg/ha (90 lb/a) in the CT watershed. Cover crop growth responded to the high level of root zone nitrate and cover crop N uptake by late December accounted for most of the nitrate that had been present in the top 30 cm (12 in) of the soil profile in early autumn. Cover crop growth reduced soil nitrate levels compared to winter-fallow areas, but this effect was greatly diminished when cover crop planting was delayed 30 days. In response to these findings, cover crops were planted as soon as possible following harvest in subsequent years. The absence of severe drought conditions during the growing season from 1989 through 1995 greatly reduced post-harvest root zone nitrate availability in comparison to 1988 (Table 1). From 1989 through 1995, N accumulation in above ground biomass of rye cover crops planted in early October averaged only 31.5 kg/ha (28 lb/a) in the CT watershed and 32.8 kg/ha (29.3 lb/a) in the NT watershed.

During the recharge periods from 1985 through 1987, when fallow conditions existed during winter months, leachate nitrate-N concentrations generally remained above 10 mg/L. Below average precipitation during March and April of these three years resulted in abbreviated groundwater recharge periods. In contrast, despite high levels of nitrate in the root zone following the 1988 corn harvest, nitrate-N concentrations in leachate collected at a depth of 60 cm (2 ft) in the CT watershed remained below 1 mg/L throughout much of the winter groundwater recharge period (Figure 4). Similar leaching patterns were observed following the 1989 and 1990 growing season, although elevated nitrate concentrations were observed when leaching events occurred early in the fall. Leachate nitrate concentrations increased again in late spring after tillage.

The reduction in root zone nitrate leaching losses due to the use of winter cover crops was first apparent in the soil profile between the root zone and the water table (intermediate vadose zone), and eventually affected nitrate concentrations in the underlying unconfined aquifer. In the CT watershed, the thickness of the intermediate vadose zone (IVZ) in early autumn varied with surface topography from approximately 1.5 to 3 m (5 to 10 ft). In the fall of 1988 when the use of cover crops was initiated, approximately 140 kg/ha (125 lb/a) of nitrate-N were stored in the IVZ in the CT watershed (Figure 5) and the average nitrate-N concentration was higher in IVZ (60-240 cm) pore-water (27.9 mg/L) than in shallow groundwater (Figure 6). Consequently, groundwater nitrate concentrations increased during 1989 as nitrate-rich IVZ pore-water reached the water table. From 1988 through 1995, nitrate-rich pore-water was gradually displaced from the IVZ and screened interval of the unconfined aquifer. After approximately four years of cover crop use, IVZ pore-water nitrate-N concentrations stabilized in the 2 to 3 mg/L range, while groundwater nitrate-N concentrations were still declining slowly. The IVZ was not sampled in the NT watershed until 1989 (Figure 7), but during subsequent years subsurface nitrate-N concentrations followed a pattern of decline similar to that observed in the CT watershed. The thinner vadose zone in the NT watershed accelerated the response of groundwater nitrate concentrations to changes in root zone leaching patterns. Although soil data are not available beyond 1995, groundwater monitoring was continued through another corn/cover crop cycle. By early 1997 groundwater nitrate-N concentrations had decreased to approximately 4 mg/L in both watersheds (Figure 6).

Split-plot studies. Side-by-side comparisons of leachate nitrate-N concentrations (Figure 8) indicated cover crop effects similar to those seen in the before-and-after studies conducted in the watersheds (Figure 4). The lack of severe drought conditions during the growing season from 1990 through 1995 resulted in relatively consistent corn yields in the split-plot studies, with associated N removal rates in harvested grain averaging 80% of the inorganic N inputs (Table 2).

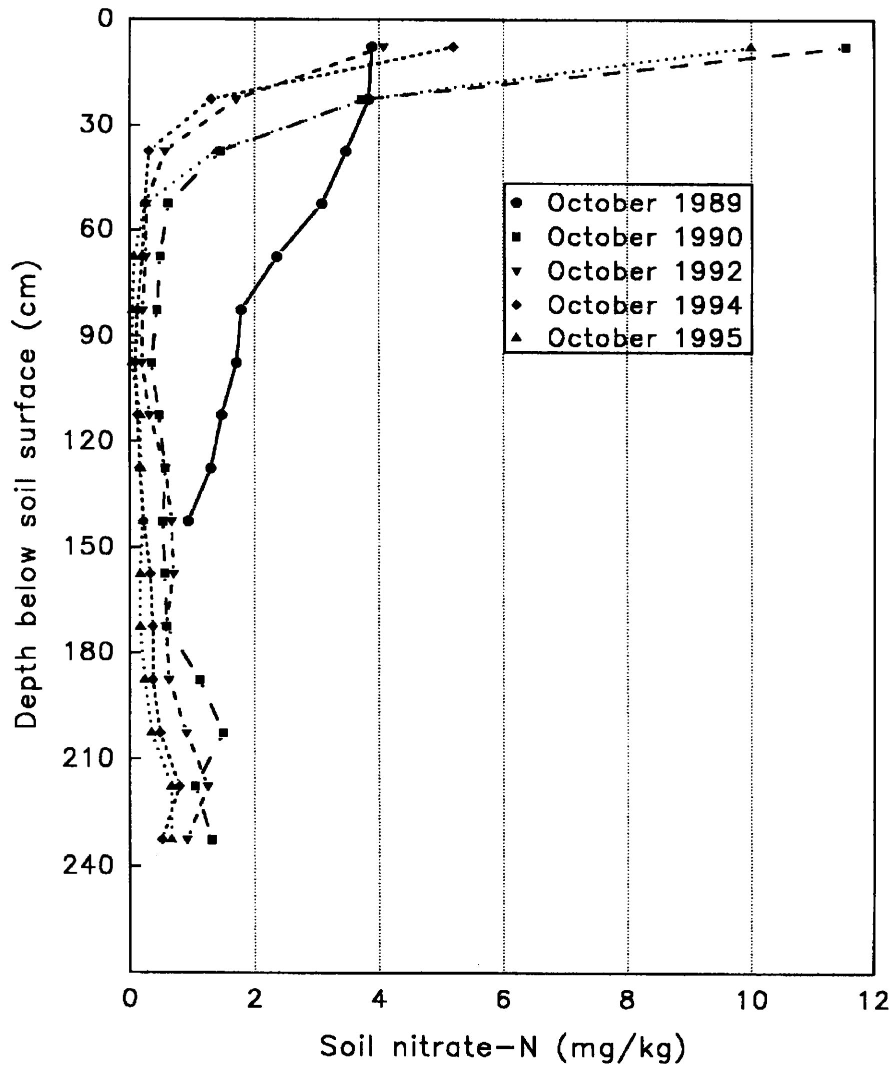

Figure 7. Post-harvest vadose zone nitrate-N concentrations (mg/kg dry soil) in the no-till watershed from 1988-1995

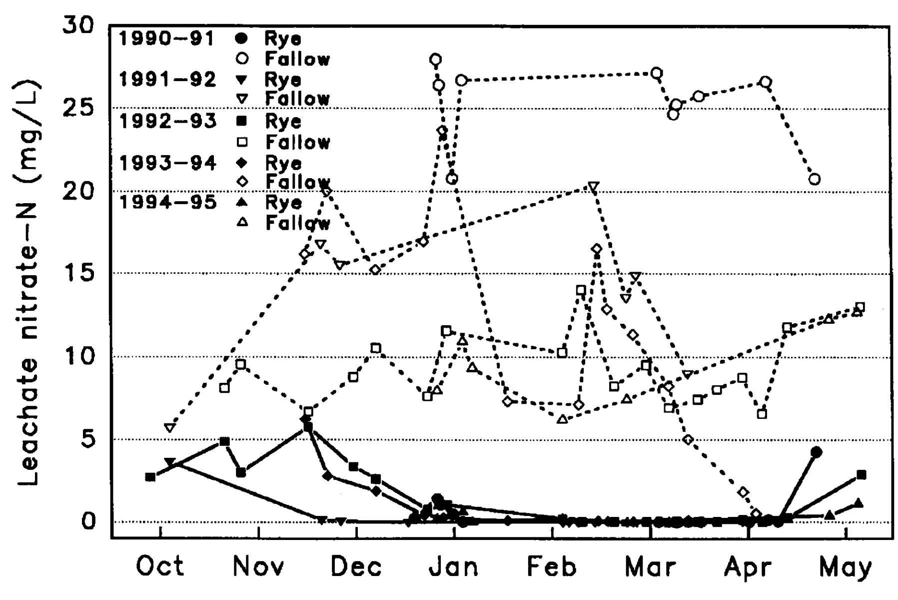

Figure 8. Event-average (n = 6) root zone leachate nitrate-N concentrations in continuous no-till corn plots with and without a rye cover crop from 1990-1995

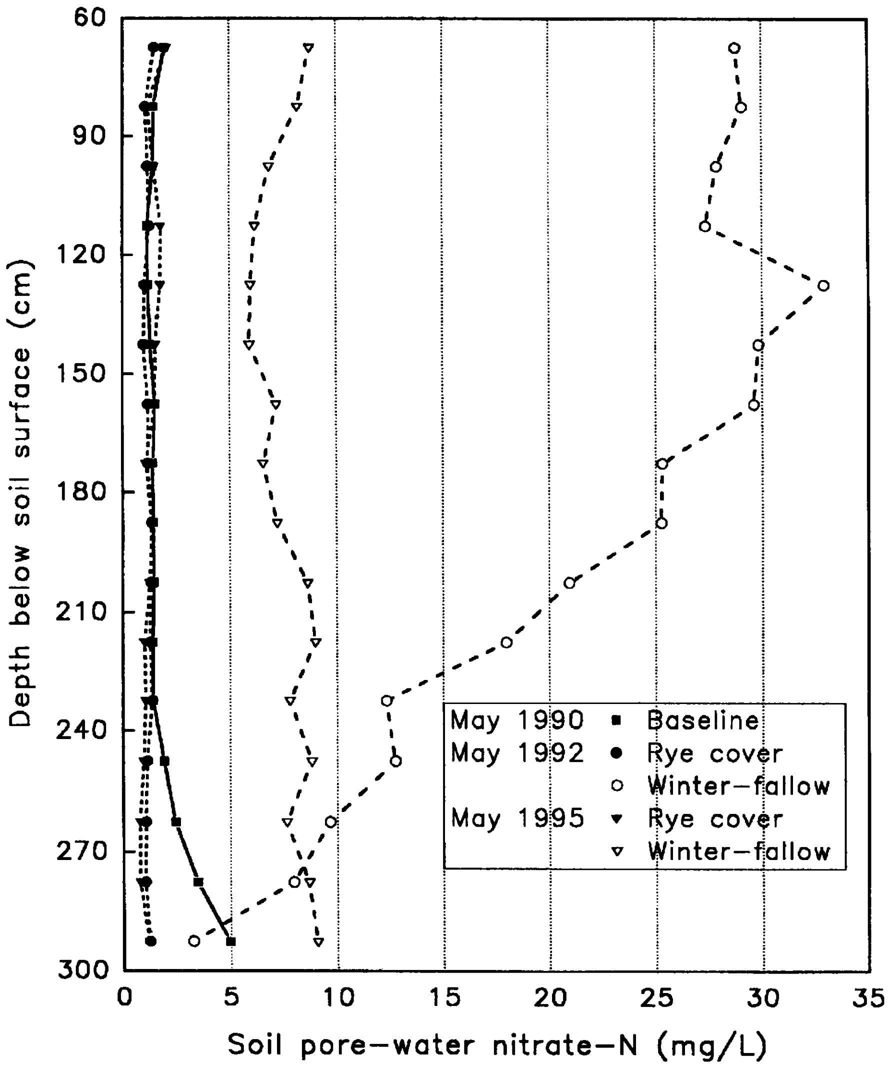

Figure 9. Pre-plant IVZ (60-300 cm) soil pore-water nitrate-N concentrations in May 1990 (baseline), May 1992, and May 1995 in continuous no-till corn plots as affected by a rye cover crop

Consequently, leachate nitrate concentrations collected under winter-fallow conditions following the 1990 through 1994 growing seasons were somewhat lower and less variable than the concentrations observed under similar N fertilization rates in the CT watershed from 1985 through 1987 (Figure 8). The highest nitrate leaching potential in the split-plot studies followed the 1990 growing season. Even though corn grain yield indicated N uptake in excess of N fertilizer applications, the failure to adjust N application rates downward to account for additional soil N mineralization due to the preceding alfalfa crop led to a large post-harvest root zone nitrate pool. However, below-average precipitation in the fall of 1990 minimized leaching until January 1991, by which time the root zone nitrate pool had been largely immobilized in the cover crop treatment (Figure 8). Both cover crop N accumulation (Table 2) and winter-fallow leaching patterns indicated lower post-harvest nitrate pools following the 1991 through 1994 growing seasons. Generally, nitrate leaching patterns in the cover crop treatment were similar to those in the CT watershed from 1988 through 1991, with significant nitrate concentrations during infrequent autumn leaching events, but consistently low nitrate concentrations during the major groundwater recharge period from January through April. In both the watershed and the split-plot studies, leachate nitrate-N concentrations under rye were consistently less than 0.1 mg/L from mid-February through spring tillage/herbicide application (Figure 8).

Changes in IVZ (60 to 300 cm) pore-water nitrate concentrations generally reflected the differences that were observed in nitrate leaching patterns between cover crop and winter-fallow treatments. Baseline IVZ cores obtained in May of 1990 when the split-plot treatments were established indicated pore-water nitrate-N concentrations consistently below 2 mg/L to a depth of 200 cm, with a gradual increase to approximately 5 mg/L in the 240 to 300 cm depth interval (Figure 9). By May 1992, upper IVZ pore-water nitrate-N concentrations had increased by more than an order of magnitude in the winter-fallow treatments while decreasing slightly in the cover crop treatments. By May 1995, after five growing season/groundwater recharge cycles, IVZ pore-water nitrate concentrations were relatively consistent with depth in both treatments. Above-average groundwater recharge volume (Figure 2) combined with lower root zone leachate nitrate concentrations (Figure 8) reduced IVZ pore-water nitrate concentrations more than 50% in the winter-fallow treatment from May 1992 to May 1995 (Figure 9). During the same period, pore-water nitrate-N concentrations in the cover crop treatment remained in the 1 to 2 mg/L range.

In May 1995, total nitrate-N storage in 60 to 300 cm depth interval was 8.7 kg/ha in the cover crop treatment versus 45.1 kg/ha in the winter-fallow treatment. The volume-averaged pore-water nitrate-N concentrations in the same depth interval were 1.3 mg/L under the cover crop and 7.3 mg/L in the winter-fallow treatment. Area-normalized water storage within the IVZ was approximately 60 cm, nearly equivalent to two times the average annual recharge volume (33 cm) estimated for the CT watershed (Figure 2). Since changes in IVZ nitrate levels indicated that percolation occurred predominantly as piston flow, IVZ pore-water nitrate concentrations should represent an integrated average of root zone leachate nitrate concentrations during the previous two years. Applying the estimated groundwater recharge volume from the CT watershed from October 1993 through May 1995 (61.3 cm) to May 1995 IVZ average pore-water nitrate concentrations indicates that average annual root zone nitrate-N leaching losses following the 1993 and 1994 growing seasons were 4.0 kg/ha with a cover crop versus 22.4 kg/ha under winter-fallow conditions. Pore-water nitrate concentrations in May 1992 indicated similar leaching losses in the cover crop treatment following the 1990 and 1991 growing seasons, but much higher losses in the winter-fallow treatment.

Production implications

Although assessment of the effect of cover crops on corn yield was not possible in the watershed studies, grain yields from 1989 through 1995 averaged 7414 kg/ha in the CT watershed and 7531 kg/ha in the NT watershed, close to the yield goal of 7526 kg/ha (120 bu/a). Generally, yield was determined by rainfall patterns during the growing season. Grain yields under the favorable conditions in 1992, 1994, and 1996 indicated that sufficient N was available to support yields approximately 20% higher than the yield goal.

In the split-plot studies, average annual grain yields were very similar in cover crop (9205 kg/ha) and winter-fallow treatments (9285 kg/ha) during the five years after cover crops were first planted (1990-95). However, annual yield differences indicated both negative and positive cover crop effects. When sub-optimal weather conditions prevailed during the growing season, most notably 1993, moisture conservation due to cover crop residues was the probable cause of higher grain yields in cover crop versus winter-fallow treatments (Table 2). When favorable growing conditions raised yield potential, higher yields in the winter-fallow treatment suggested lower N availability in the cover crop treatments. Soil nitrate patterns in the watersheds also suggested a negative effect of cover crops on N availability to the following corn crop. This effect often has been linked to microbial sequestering of nitrate during the decomposition of high-carbon cover crop residues. However, this cause should have been minimized by the early tillage/herbicide application dates that were used throughout this study and the application of inorganic N at recommended rates (Wagger and Mengel 1988). More likely, the reduced N availability resulted from the absence of a significant residual nitrate pool in the lower corn rooting zone. This pool of nitrate only appeared to be a factor when growing conditions favored yields well above the long-term average. Pre-plant nitrate-N pools in the 30 to 90 cm depth interval in both the CT and NT watersheds were consistently higher in winter-fallow versus cover crop areas (Figure 10). From 1989 through 1991 this pool of nitrate apparently was not utilized by the corn crop, as indicated by only minor changes between pre-plant and post-harvest sampling dates. However, the ideal growing conditions in 1992 resulted in above-average yields in both the watersheds and the split-plot studies (Tables 1 and 2). The 30 to 90 cm nitrate-N pool decreased approximately 30 kg/ha in both watersheds between May and October in the winter-fallow areas, while remaining below 5 kg/ha in the cover crop areas. Approximately 10% (15.6 bu/a) higher yields in winter-fallow versus cover crop treatments in the split-plot studies during 1992 suggest that corn yields were N limited in the cover crop treatments. Although no post-harvest soil samples were collected in the split-plot studies following the 1992 growing season, pre-plant sampling (Figure 9) indicated a 30 to 90 cm nitrate-N pool of 50.2 kg/ha in the winter-fallow treatment versus 1.9 kg/ha in the cover crop treatment.

Although a fraction of N in cereal grain cover crop residues may become available to the following corn crop if spring growth is terminated while carbon:N ratios are still low (Evanylo 1991), in this study any enhancement of N mineralization appeared to be offset by cover crop elimination of residual nitrate from the lower rooting zone. In many years, the difference in lower root zone nitrate levels between cover crop and winter-fallow areas carried over to the fall due to an absence of leaching during summer months (Figure 10). Thus, less residual nitrate may be available to a winter cereal grain planted if a cover crop had been present the previous winter rather than winter-fallow conditions.

The long-term role of cover crops in improving soil quality and productivity has generally been associated with their potential for maintaining or increasing soil organic matter (Bruce et al. 1991; National Research Council 1993). In this experiment, the contribution of rye cover crops to total annual above-ground residue production varied widely, depending on corn stover production and post-harvest root zone nitrate availability. When drought conditions during the

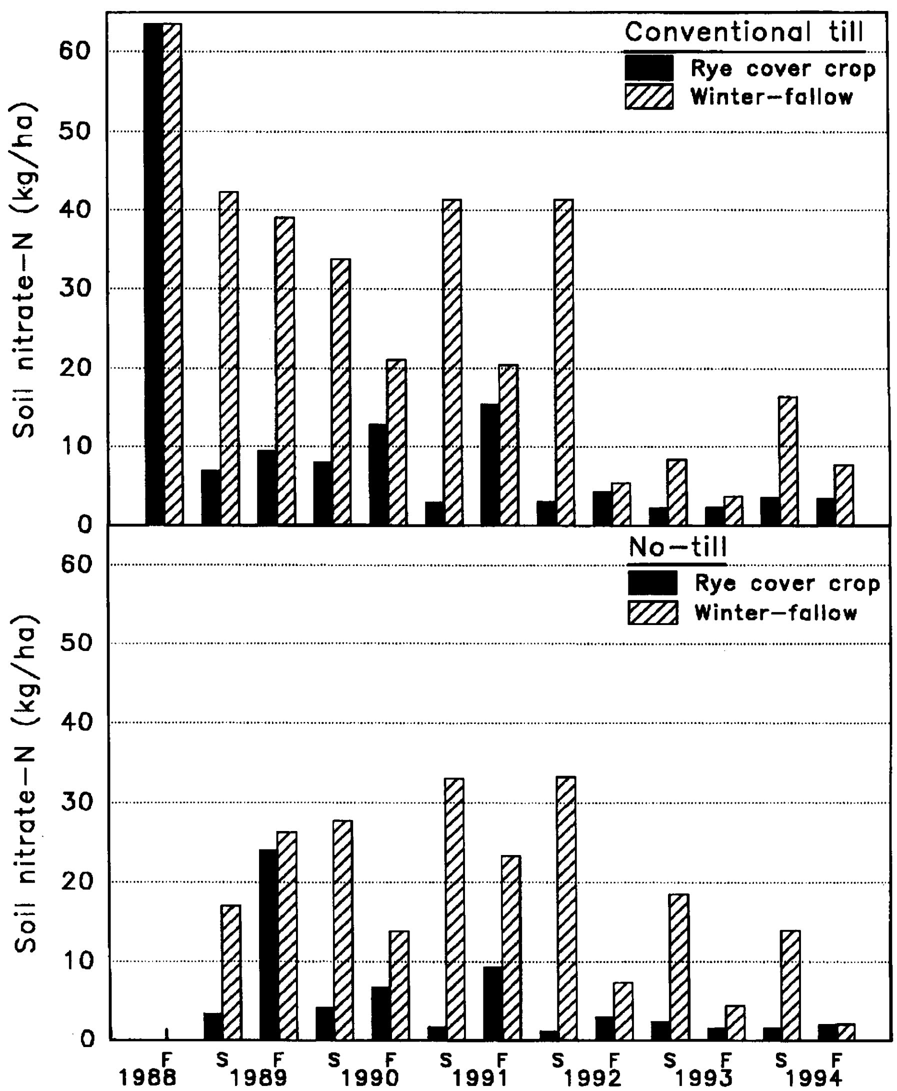

Figure 10. Pre-plant (S) and post-harvest (F) nitrate-N storage in the lower rooting zone (30 to 90 cm) in the conventional and no-till watersheds (rye cover crop) and adjacent winter-fallow plots from 1988-1994

1988 growing season limited corn growth and N uptake, dry matter production by the following cover crop at the time of 1989 spring tillage in the CT watershed was more than double the 1988 corn stover production (Table 1). Conversely, cover crop above-ground biomass production was only 13.2% of corn stover production following the 1992 growing season when unusually favorable conditions during the growing season minimized post-harvest root zone nitrate availability. Excluding the 1988 growing season, cover crop above-ground dry matter production averaged approximately 31% of corn stover production in both watersheds. In the split-plot studies, cover crop dry matter production from 1990 through 1994 was approximately 28.1% of corn stover production (Table 2). Cover crop biomass contributions to total annual inputs were highest on both a mass and percentage basis (42%) following the 1990 growing season, apparently due to a large post-harvest root zone nitrate pool.

In both the watershed and split-plot studies, highest annual biomass returns to the soil were achieved in years when cover crop dry matter production was the greatest. Since cover crop dry matter production was limited in most years by root zone N availability, the value of cover crops for augmenting soil organic matter was largely determined by how closely N availability matched corn N requirements. Cover crops, as managed in this study, appeared capable of reducing nitrate leaching to similarly low levels across a wide range of post-harvest nitrate availability. Thus, while the efficiency of corn utilization of root zone N was critical in determining nitrate leaching losses under winter-fallow conditions, it had little effect on actual nitrate leaching where a cover crop was planted. Instead, its primary effect was in determining the quantity of cover crop biomass produced.

Summary and conclusions

Nitrate leaching from non-irrigated cropland in the mid-Atlantic region is primarily limited to winter and early spring, particularly where soil types have a high moisture holding capacity. Interactions between growing season conditions and N application rates determine post-harvest root zone nitrate concentrations, which in-turn define the potential for nitrate leaching losses during the winter/spring groundwater recharge period. Rye cover crops planted immediately following corn harvest can immobilize a large fraction of the root zone nitrate pool, thereby reducing annual nitrate leaching rates to approximately 20% of those in winter-fallow settings.

The reductions in nitrate leaching rates that can be achieved through continual use of cereal grain winter cover crops will eventually translate into lower nitrate concentrations in shallow groundwater. The time required to achieve reductions in groundwater nitrate concentrations will depend on IVZ thickness and water holding capacity. Likewise, the time needed for reductions in groundwater nitrate concentrations to change nonpoint source N loads will depend on groundwater residence time within the local subsurface flow system. Thus, although cover crops were shown to be capable of reducing nitrate concentrations in shallow groundwater in excess of 60%, many years may be required for these reductions to become evident in surface water quality. Nevertheless, cover crops do offer a means to eventually reduce nonpoint source N loads from Coastal Plain cropland by more than the 40% goal set forth in the Chesapeake Bay restoration effort. In addition, consistent use of cereal grain winter cover crops can also reduce groundwater nitrate-N concentrations to well below the 10 mg/L EPA maximum concentration limit for drinking water.

The reductions in groundwater nitrate concentrations that eventually can be achieved through the use of winter cover crops will depend on post-harvest soil nitrate concentrations, cover crop type and planting date, and the timing of groundwater recharge. Although rye was used in this study, it is likely that other less cold tolerant winter annuals would be nearly as effective in settings where early planting dates are possible and post-harvest soil nitrate levels are moderate to low. Conversely, as cover crop planting date is delayed or post-harvest nitrate levels increase, the risk of nitrate leaching increases as the cool-season N uptake capacity of the cover crop decreases. The greatest potential for reducing nitrate leaching rates with the use of cereal grain winter cover crops will be in settings where root zone nitrate availability greatly exceeds crop utilization. This can occur when inputs are properly matched to projected crop needs, but N utilization is limited by drought conditions, or when N containing wastes are applied to cropland at rates or times that are not matched with crop N needs. Cover crops also offer a means to control nitrate leaching losses following summer annual legume crops such as soybeans, a setting where there is little opportunity for reducing leaching losses by fine-tuning of N inputs.

Early spring tillage/herbicide application dates combined with innovations in planting technology minimize the potential for reduced grain yields following cereal grain cover crops. Cereal grain cover crops can enhance grain yields when moisture is limiting during the growing season, but may reduce growing season N availability relative to a winter-fallow system. Even though cereal grain cover crops retain N in the root zone that otherwise would have been leached into shallow groundwater, the retained N does not present any short-term opportunities for reducing N fertilization rates. The virtual elimination of residual nitrate from the root zone by a cereal grain cover crop more than offsets any increases in N mineralization due to additions to the root zone organic N pool from cover crop biomass. In this light, cereal grain cover crops offer an advantage in removing uncertainty regarding the residual nitrate pool. To maintain optimum N availability during the growing season, minor increases in N inputs may be necessary to offset reductions in residual root zone nitrate. This poses little apparent threat of increasing nitrate leaching as long as rigorous cover cropping practices are used. Any resulting increases in post-harvest root zone nitrate concentrations will likely enhance cover crop N uptake and biomass production. In soils where additional organic matter or surface residue will increase crop yields, it may be cost-effective in the long-term to increase N inputs to promote cover crop contributions to soil carbon pools.

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