GROUNDWATER IMPACTS

Effects of cover crops on groundwater quality

J. J. Meisinger, W. L. Hargrove, R. L. Mikkelsen, J. R. Williams, and V. W. Benson

Cover cropping is a practice that can benefit soil-crop systems in several ways: increasing nitrogen (N) supply for the next crop, reducing soil erosion, improving soil physical properties, and conserving nutrients.

Cover cropping dates back to ancient agriculture, reportedly as far back as 3,000 years to the Chou Dynasty in China *(25, 38)*, where cover crops were used to improve soil productivity. In colonial periods, winter cover crops of clover or hairy vetch (*Vicia villosa* L.) were recommended by Thomas Jefferson in Virginia to supply N to the next crop *(4)*. Winter cover crops of rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), and hairy vetch were systematically evaluated as N sources for cotton (*Gossypium hirsutum* L.) in Alabama as early as 1898 *(9)*. A summary of the excellent work of agricultural scientists in the early 1900s is provided in Pieters' compilation of literature *(38)*. This work emphasized the benefits of increasing N availability to the next crop.

Later in this century (1930-1945), the role of cover crops in conserving N against leaching was studied. Reported lysimeter work *(7, 22, 32)* clearly shows that winter cover crops can significantly reduce nitrate (NO_3) losses in water percolating through soil.

Today, NO_3 losses from agricultural land into groundwater are a conern to society, agriculture producers, and farm technical advisors. The agricultural community is being asked to develop N management practices that minimize NO_3 losses to groundwater and improve the sustainability of modern agriculture. Herein, we summarize the relationships between winter cover crops and groundwater quality by identifying and elaborating underlying principles, reviewing relevant literature, estimating percentage reductions in leachate N for the United States, identifying improved management practices, and suggesting future research needs.

J. J. Meisinger is a soil scientist, Environmental Chemistry Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland 20705; W. L. Hargrove is professor of agronomy, University of Georgia, Griffin 30224; R. L. Mikkelsen is soil scientist, Tennessee Valley Authority, Muscle Shoals, Alabama 35660; J. R. Williams is hydrologic engineer, Agricultural Research Service, U.S. Department of Agriculture, Temple, Texas 76502; and V. W. Benson is agricultural economist, Soil Conservation Service, U.S. Department of Agriculture, Temple Texas 76502.

General principles

Our discussion of the effects of cover crops on groundwater quality will focus on NO_3 because it has been shown to be the dominant contaminant in several state and national groundwater quality surveys *(1, 12, 21, 31, 48)*.

Nitrogen is the most difficult nutrient to manage in agriculture. Nitrogen must be supplied in large quantities to meet the nutritional requirements of grasses. Yet NO_3 is the most mobile agricultural nutrient because it forms completely soluble compounds, and it is not retained by the negatively charged soil colloid system *(24, 41)*. Thus, NO_3 within the root zone is free to move with percolating water and could leach into groundwater when two prerequisites are met: the soil contains significant NO_3 and water percolates below the root zone. In humid climates, these conditions occur most frequently during the fall-winter-spring water-recharge season when evapotranspiration is low and precipitation exceeds the soil's water-holding capacity. The fall and winter period often coincides with high soil NO_3 levels resulting from residual fertilizer N or from the fall mineralization of soil organic matter and crop residues. Therefore, in humid and subhumid climates, the primary leaching season usually occurs between November and May.

Winter cover crops can influence NO_3 leaching and groundwater quality by influencing the water budget, affecting the soil NO_3 content, and synchronizing competition with the water-recharge season.

Water budget effects

Evapotranspiration. Winter cover crops directly affect the water budget through evapotranspiration, whereby crops lose water to the atmosphere as dry matter is produced, thus reducing the quantity of soil water available for leaching. Precise water-use values will vary with such factors as type of cover crop, degree of water stress, climate, and soil fertility status. However, for illustration purposes, we can assume that about 300 pounds of water will be used to produce each additional pound of aboveground dry matter *(15, 39, 45)*. A winter cover crop producing 2,000 pounds of dry matter per acre will thus use about 2.5 acre-inches of water. In climates with excess winter precipitation, the savings of 2.5 inches of percolate can significantly reduce the depth of NO_3 movement. In some soils, this could make the difference between leaching NO_3 out of the root zone versus retaining it within the root zone for uptake by the winter cover crop or the next crop.

A disadvantage of water use by winter cover crops is the lowering of soil-water reserves for the next crop. In semiarid climates, this may prevent the use of winter cover crops altogether, unless irrigation is available. In subhumid climates and in humid climates, this may necessitate early spring killing to allow for timely water recharge for germination. There also may be situations where late-spring water use can be a benefit, for example, in reducing the water content of wet soils *(17)*.

Infiltration. Cover crops can also affect the water budget by reducing surface runoff that will increase infiltration and increase the likelihood of leaching. The increased infiltration effect originates as the cover crop leaf area breaks the kinetic energy of falling raindrops and increases the residence time of water at the soil surface. The size of the infiltration effect depends on the rainfall intensity, soil infiltration rate, and the slope at each site. The effect will be largest with high-intensity rains on sloping soils with slow infiltration rates. Conversely, this effect will be of little or no consequence in low-intensity rain events or on level soils with high-infiltration rates.

Net Effects. The net effect of evapotranspiration reducing potential percolation and ground cover increasing potential percolation depends on site-specific factors, such as cover crop dry matter production rate, degree of soil cover, soil infiltration rate, and rainfall intensity. We cannot make overall generalizations at this time due to the complexities and interactions of these factors. But, one way we can integrate and evaluate these factors at each site is to use a simulation model to estimate the components of the water budget for selected cover crops at several areas within the United States. We will discuss this modeling approach in a later section using the EPIC model.

Nitrogen uptake effects

Winter cover crops can directly affect groundwater quality by reducing the quantity of soil NO_3 available for leaching. In most humid areas of the United States, average winter rainfalls ensure percolation events beyond the root zone. In these areas, and on coarse-textured soils in lower rainfall areas, the only practical method to reduce NO_3 leaching is to reduce the size of the soil NO_3 pool entering the winter recharge season. A winter cover crop can be an excellent vehicle to convert mobile soil NO_3 into immobile plant organic N.

Nonlegume N uptake. Nitrogen uptake is the product of N concentration and dry matter production. But total N uptake in nonlegumes is more directly affected by dry matter production than N concentration because nonlegumes have only small ranges in N concentrations among species *(19, 53)*. Thus, a nonlegume that produces the greatest dry matter will usually immobilize the greatest quantity of NO_3.

When considering high dry matter production, we usually focus on aboveground production, but belowground production is equally important. For example, a cereal rye cover crop generally has 20% to 30% of its total dry matter in roots, but annual ryegrass (*Lolium multiflorum* Lam.) can have 30% to 45% of its total dry matter in roots *(28, 30, 38)*. The root system of a cover crop should be given careful consideration because a deep-rooted cover with high-root density will offer the greatest chance for NO_3 capture.

Legume N uptake. Total N uptake for legume cover crops can be related to both dry matter production and N concentration because legume species can vary considerably in N concentration. For example, vetches will commonly contain 3% to 4% N, while crimson clover commonly contains 2% to 3% N *(10, 13, 16)*. Thus, a vetch cover crop can account for 1.5 to 2 times more N with the same dry matter production compared with crimson clover.

We must also remember that legumes will use symbiotic N_2 fixation to meet some, or all, of their N requirement. It has been shown that N_2 fixation will not begin until soil NO_3 is low *(18, 49)*. Thus, legumes offer the potential to reduce NO_3 leaching to the extent that they use soil NO_3 rather than N_2 fixation to meet their N requirements.

Once again we should emphasize that the rooting characteristics of a legume cover crop are very important in recovering the mobile NO_3 ion. An ideal root system possesses both depth and a high-root density.

Timely competition

The final mechanism that winter cover crops utilize to reduce NO_3 leaching is timely competition. This mechanism synchronizes the above water budget and N uptake effects to compete directly with the leaching process and, thus, impact groundwater quality. To illustrate this principle, consider a coarse-textured soil in a humid region where the leaching season begins in the late fall. If a winter cover crop is to improve groundwater quality in this situation, it must become quickly established and grow vigorously in the fall before NO_3 is leached out of the root zone. A cover crop with little fall growth but much spring growth is not likely to effectively reduce NO_3 leaching because it cannot exert the water budget and N uptake effects until after the NO_3 has leached into the groundwater.

To control a natural process like NO_3 leaching, a winter cover crop system (crop species, establishment, etc.) must be devised that maximizes the direct competition between the cover crop N -uptake season versus the NO_3-leaching season. We will discuss several methods of enhancing this timely competition in a later section on managing cover crop systems to improve groundwater quality.

Cover crops and water quality

Nonlegumes are attractive cover crop choices for a variety of reasons, in addition to their potential water quality benefits. For example, they form an excellent mulch for no-till management that can reduce evaporation, increase infiltration, and decrease erosion *(14)*. They can also increase soil organic matter, improve soil structure, and help break-up root-restricting layers *(32, 40)*.

History and species used. The value of nonlegumes in reducing N loss has been recognized for many years. In reviewing the literature, we were quickly impressed with the efforts, resourcefulness, and knowledge gained by earlier generations of agronomists. Our review will include much of this early literature because it is not our intent to "reinvent the wheel" as we seek to devise more efficient N management systems.

Many nonlegumes have demonstrated their ability to recover soluble N. The two major plant families are the Gramineae and the Cruciferae. In the Gramineae family, the majority of research has centered on the use of cereal rye, although many other grasses have been successfully used, such as barley (*Hordeum vulgare* L.) *(19, 33)*, bluegrass (*Poa pratensis* L.) *(23)*, annual ryegrass *(26, 37)*, oats (*Avena sativa* L.) *(22, 30)*, timothy (*Phleum pratense* L.) *(32)*, and wheat (*Triticum aestivum* L.) *(36, 46)*. Most of the remaining nonlegume cover crops are members of the Brassica genus and include species such as mustard (*Brassica* spp.) *(7)*, rape (*Brassica rapa* ssp. *olifera*) *(3, 34)*, radish (*Raphanus sativus* L.) *(34)*, and turnip (*Brassica rapa* L.) *(50)*. The ability of nonlegumes to affect N leaching is related to their ability to rapidly establish root systems and produce dry matter under cool conditions. Some of the above cover crops are more effective than others in this regard.

Grass cover crops. Grasses have been used extensively as cover crops because they are hardy under a wide range of environmental conditions. The field evaluations using grasses to recover residual N are difficult to compare directly due to incomplete reporting of such factors as soil NO_3-N at planting, winter soil/air temperatures, winter precipitation, cover crop dry matter production rate, cover crop N uptake, and N leaching losses. We chose to summarize this divergent literature by comparing the cover crop treatment of a given study with the no-cover control by calculating the percent reduction in N leaching that was attributable to the cover crop. For example, if a lysimeter study measured the mass of N leached as 100 pounds N/acre for the no-cover treatment and 40 pounds N/acre for the cover crop treatment, the percent reduction in N leaching due to the cover crop would be 60%.

Morgan et al. *(32)* in 1942 conducted a classic lysimeter cover crop experiment (Table 1). The cropping system was continuous tobacco fertilized with 200 pounds N/acre from a combination of organic N sources (120 pounds N/acre from cottonseed meal and 40 pounds N/acre from castor pumice) *plus sodium nitrate* ($NaNO_3$) *(at 40 pounds N/acre) that was applied at tobacco planting in late May.* The tobacco was harvested in early August; within 10 days cover crops of oats, rye, or timothy were planted. The average yearly total percolation, mass of N leached, and NO_3-N concentration of the leachate (Table 1) clearly showed that grass cover crops can effectively reduce NO_3 leaching. The rye was the most effective, giving a 66% reduction in the mass of N leached and a 62% reduction in NO_3 concentration. The oat crop was less effective than the rye because it winter-killed in Connecticut. However, the rapid establishment and vigorous fall growth of the annual oat crop enabled it to out-perform the slower growing perennial timothy. The cover crops reduced drainage volumes somewhat in this study, but their primary influence on N leaching was through N uptake, which reduced the mass of N available for leaching. The cover crops also increased the organic matter content of this soil over the 10-year study. Surface soil organic matter levels for no-cover, oats, rye, and timothy were 1.9%, 2.2%, 2.3%, and 2.2%, respectively. This study clearly demonstrates the positive impact cover crops can have on water quality, even in the high N-leaching situation of coarse-textured soils, high-N inputs, a short-season summer crop, and the cool-humid climate of Connecticut.

A recent replicated lysimeter study in France *(26)* used lysimeters filled 18 years before this study, which should have allowed sufficient time for normalization of the silt loam soil. A winter wheat crop was first grown that was fertilized with 178 pounds of NO_3-N/acre, labeled with ^{15}N. Following the wheat, researchers established either a no-cover control or an unfertilized cover of ryegrass. Lysimeter percolate was collected throughout the winter, during which precipitation measured 16 inches. The ryegrass cover crop reduced percolation by 29% (9.0 inches versus 6.4 inches, table 1), reduced the mass of N leached from 98 to 36 pounds N/acre, and reduced NO_3 concentration from 48 to 25 parts per million (ppm). This represents a 63% reduction in the mass of N leached and a 48% reduction in NO_3 concentration. The quantity of labeled N leached without a cover amounted to 19% of the original labeled fertilizer applied to the wheat, compared with 7% leached under the ryegrass cover. The labeled fertilizer N accounted for only about one-third of the total N leached for both treatments, which indicates that native-soil N was the major contributor to NO_3 leaching in this study. The authors concluded that the ryegrass cover crop clearly reduced NO_3 leaching, which demonstrates an ecological advantage to cover crop systems.

Karraker et al. *(23)* reported a lysimeter study in Kentucky using disturbed Maury silt loam soil. Annual seedings of unfertilized Korean lespedeza (*Lespedeza stipulacea* L.) added about 180 to 210 pounds N/acre to each lysimeter through N_2 fixation. Most of the fixed N was removed through harvested crops, but about 60 pounds N/acre was added to the lysimeters annually in October through killed-root plus crown residues. These residues decomposed rapidly and liberated N that was vulnerable to leaching. One pair of lysimeters was not cover-cropped, but rye was grown on another. Table 1 also shows the average drainage, NO_3 concentration, and mass of N leached from these lysimeters during the year. It is apparent that the rye cover crop did an excellent job of reducing both the mass of N leached (from 58 to 15 pounds N/acre) and the NO_3 concentration of the leachate (from 16 to 4 ppm). The rye cover crop achieved these N-leaching reductions primarily through N uptake during the winter and early spring (January-June) when average annual N leachings were 49 pounds N/acre without rye and 7 pounds N/acre with rye. The rye reduced drainage volumes only a little in this study, so the mechanism for rye's improvement on water quality was through direct N uptake.

A field study was conducted on the Atlantic Coastal Plain of Maryland *(29)* in which corn (*Zea mays* L.) was fertilized with 300 pounds N/acre and an unfertilized rye cover crop was planted in early October. The corn was intentionally over-fertilized to ensure a large pool of fall NO_3-N to test the capacity of the rye to use residual N. Shallow groundwater wells (6 feet deep) were installed in replicate plots in November, before the water recharge season, and samples of recent percolate draining into these wells were collected throughout the winter and spring. The average NO_3-N concentration below the no-cover controls was 17 ppm, while the corresponding concentration below the rye cover was 12 ppm (Table 1). Thus, the rye reduced the concentration of NO_3 entering shallow groundwater by 29%. It was not possible to measure drainage volumes in this type of study, but it is clear that the rye cover crop had a beneficial impact on groundwater quality.

Other investigators have monitored the soil NO_3-N content below field-grown cover crops during fall and winter *(37, 44)*. In these studies, researchers have observed marked reductions in the size of the mobile NO_3-N pool below grass cover crops (Table 1). For example, in Maryland *(44)*, a rye cover reduced the NO_3-N content in the surface 12 inches of soil from 52 to 12 pounds N/acre during the winter. In Denmark (37), an annual ryegrass cover crop reduced the NO_3-N pool in 39 inches of soil by 33 pounds N/acre, which represented a 62% reduction in potentially leachable N.

In the above studies, researchers have shown that grass cover crops are effective in reducing the mass of N leached (average percent reduction of about 60%) and the NO_3 concentration of the leachate (average percent reduction of 50%). The somewhat smaller percent reduction in NO_3 concentration stems from the fact that as crops take up N, the mass of N available for leaching decreases, but the NO_3 concentration in the soil solution does not decrease as fast due to the simultaneous use of NO_3 and water by the cover crop. Thus, larger percentage reductions would be expected in the mass of N lost compared with the concentration of N lost. Among the grass cover crops studied thus far, it seems that cereal rye is better suited to improve water quality than the others, although the number of studies with direct comparisons between grasses are few. The evaluation of cover crop species to achieve improved water quality across a range of climates is an important research need.

Brassica cover crops. The brassicas are known for their rapid establishment and cool-season growth. They have a wide

Table 1. Literature summary of effect of grasses on water quality.

Reference and Brief Description of Study	Cover Crop	Percolation (inches)	Soil Nitrate-N	N Leached: Mass of N	N Leached: Nitrate-N Conc. (ppm)	Percentage Reduction due to Cover Crop: Mass of N	Percentage Reduction due to Cover Crop: Nitrate-N Conc.
			— pounds N/acre —				
Morgan et al. 1942 (32); filled lysimeters sandy loam, soil; 20" diameter by 30" deep; tobacco with 200 pounds N/acre then cover crops; 10-year study in Connecticut	None	15.3		74	21	-	-
	Oats	12.8		32	11	57	48
	Rye	14.2		25	8	66	62
	Timothy	16.1		51	14	31	33
Martinez and Guirard, 1990 (26); filled lysimeters silt loam soil; 39" square lysimeters 39" deep; winter wheat with 178 pounds N/acre then cover crop; 1-year study in France	None	9.0		98	48	-	-
	Perennial Ryegrass	6.4		36	25	63	48
Karraker et al. 1950 (23); filled lysimeters silt loam soil; 22" diameter by 26" deep, unfertilized Korean lespedeza then rye cover crop; 11-year study in Kentucky	None	16.1		58	16	-	-
	Rye	15.2		15	4	74	72
Meisinger et al. 1990 (29); shallow groundwater below field plots on silt loam soil; corn fertilized with 300 pounds N/acre followed by rye cover crop; 1-year study in Maryland	None				17	-	
	Rye				12		29
Staver and Brinsfield, 1990 (44); Soil samples to 12" from field plots on silt loam soil; corn fertilized with about 150 pounds N/acre then rye cover crop; 1-year data (November-June) in Maryland	None		52			-	
	Rye		12			77	
Nielsen and Jensen, 1985 (37); Soil samples to 39" from field plots on sandy loam soil; spring barley fertilized with 80 pounds N/acre then annual ryegrass; two years of data samples taken about 60 days after planting in Denmark	None		53			-	
	Annual Ryegrass		20			62	

Table 2. Literature summary of effect of brassicas on water quality.

Reference and Brief Description of Study	Cover Crop	Percolation (inches)	Soil Nitrate-N	N Leached: Mass of N	N Leached: Nitrate-N Conc. (ppm)	Percentage Reduction due to Cover Crop: Mass of N	Percentage Reduction due to Cover Crop: Nitrate-N Conc.
			— pounds N/acre —				
Chapman et al. 1949 (*7*); filled lysimeters with loam soil; 10' diameter by 4' deep; unfertilized summer sudangrass followed by fertilized (100 pounds N/acre) cover crop treatments; 5-year study in California	None (straw)			46	75	-	-
	Mustard			9	15	80	80
Bertilsson, 1988 (*3*); filled lysimeters with two soil textures, one sandy soil, one clay soil; 14" diameter by 31" deep; 335 pounds manure N/acre in fall containing 175 pounds ammonium N/acre then cover crop; 1 year data in Sweden	None	20.7		176	37	-	-
	Rape	18.9		62	14	66	62
Volk and Bell, 1945 (*50*); filled lysimeters with loamy sand; 63" diameter by 48" deep; 100 pounds N in fall then cover crop; 1 year of winter data in Florida	None	15.6		113	32	-	-
	Turnips	11.6		14	5	87	84
Muller et al., 1989 (*34*); soil samples to 39" from field plots; winter wheat followed by unfertilized cover crops; 1 year of data samples taken before and after winter leaching season in France	None		86			-	
	Rape		56			35	
	Radish		48			44	
	Rye		35			59	

range of adaptability, as evidenced by their use from Scandinavia to Florida and from semiarid areas of California to the Mediterranean climate of France.

Chapman et al. in 1949 *(7)* reported an excellent lysimeter experiment with a brassica cover crop, using large-filled lysimeters in Riverside, California. The data summarized in table 2 are from the 1939-1944 period because the investigators considered these years to be most representative of the treatment effects. Average annual rainfall amounted to only 14.3 inches, but the lysimeters received supplemental irrigation as needed to ensure crop growth. The unfertilized summer crop of sudangrass (*Sorghum vulgare* ssp. sudanensis L.) was followed by a fall cover crop that was fertilized with 100 pounds NO_3-N/acre. The no-cover treatment received 4,700 pounds/acre of straw annually in the fall, but this was not considered to be an important factor because the N addition reduced the carbon (C)/N ratio to about 18:1, which is favorable for mineralization. The no-cover treatment lost an average of 46 pounds N/acre and had high NO_3-N concentrations in the leachate (75 ppm) due to the small percolation volumes (2.7 inches annually) in this dry climate (Table 2). The mustard cover crop, however, reduced the mass of N leached to only 9 pounds N/acre and reduced the NO_3-N concentration to 15 ppm. Percolation under the mustard averaged 2.8 inches annually. Overall, the mustard reduced both the mass of N leached and the NO_3-N concentration 80% compared with the no-cover treatment.

Bertilsson conducted lysimeter experiments in Sweden *(3)* that demonstrated the effectiveness of rape in reducing N losses from a fall manure application. He used small lysimeters filled with two contrasting soil textures that received 335 pounds N/acre as manure in August and were either left bare or were cropped to rape (Table 2). On the sandy soil, the rape cover crop reduced NO_3 leaching losses from 213 to 79 pounds N/acre, and on the clay soil corresponding losses were reduced from 139 to 45 pounds N/acre. The rape was plowed down in November but the N sequestered by the crop was remineralized the following spring. Controlling N leaching under these high mineralization conditions thus requires the presence of a continuously growing crop. Cover cropping, of course, is one way to move toward more continuous cropping.

Researchers evaluated turnips as a winter cover crop in Florida *(50)* by using large-filled lysimeters containing Norfolk loamy sand. The data summarized in table 2 is from the first 16 weeks of 1944, which represents the winter-leaching season in Florida. The sandy soil was fertilized with 100 pounds N/acre in the fall. The percolation with turnips was about 4 inches less than the control due to the production of 1,900 pounds/acre of turnip dry matter. The turnips took up 58 pounds N/acre in main-root plus aboveground dry matter. These data show that turnips sharply reduced the mass of N leached (87% reduction) and the NO_3 concentration in the leachate (84% reduction) for this sandy soil under high (22 inches) winter-rainfall conditions.

In a field-plot study in France *(34)*, Muller et al. evaluated rape, radish, and rye cover crops that were planted in October after a wheat crop. They sampled the soil to 39 inches and analyzed it for NO_3-N at the beginning of the winter-leaching season and at the end of cover crop growth (early March). The total N uptake values (tops plus roots) for rape, radish, and rye were 23, 43, and 120 pounds N/acre, respectively. These crop N accumulations were the primary reason for the reductions in soil NO_3-N listed in table 2. The nongrass covers in this study were damaged by the cold winter weather, which accounts for the superiority of rye in taking up N and in reducing the soil NO_3-N pool. These authors also noted a rapid remineralization of N with rape and radish covers during the following spring. They concluded that the choice of cover crop will depend mainly on the cropping system and climate.

The above studies have shown that brassica cover crops have a beneficial impact on water quality that can amount to an average reduction of 60% to 75% in N transported through leaching. These crops deserve more research study and should be given careful consideration in cover crop water quality studies. The brassicas are easy to establish over a broad range of climates, but they are not as winter hardy as the grasses, and they release their N rapidly after killing. These characteristics must be taken into account when selecting a cover crop for a given crop-climate situation.

Legumes versus nonlegumes. Two major attributes of an ideal winter cover crop would be the ability to significantly reduce NO_3 leaching and the ability to supply N to the next crop. The preceding sections have shown that grasses can significantly reduce N leaching, but they generally make little or no N contribution to the next crop *(10, 16, 19)*. The legumes, on the other hand, have repeatedly demonstrated their value as N sources, but their impact on N leaching is uncertain. In order to accurately determine the relative merits of legumes versus nonlegumes, it is essential to make direct comparisons under the same growing conditions, i.e., in the same research study.

We have already described the details of Chapman's large lysimeter experiment *(7)* in the brassica section. In addition to evaluating mustard, cover crops of sweet clover (*Melilotus indica* L.) and purple vetch (*Vicia atropurpurea* L.) were also included, receiving 100 pounds N/acre each fall, the same as the other treatments. The impact of these covers on N leaching (Table 3) clearly shows that mustard reduced N leaching more than the legumes. For example, the legumes reduced the mass of N leached by 24% compared with an 80% reduction for mustard. Moreover, the legumes reduced the NO_3 concentration only 6% compared with an 80% reduction for mustard. The total N accumulated by these covers (Table 3) shows that the legume growth was good (140 to 160 pounds N/acre), but apparently the legumes were relying more on N_2 fixation than on soil N uptake to meet their N requirements. This view is supported by the N uptake values on unfertilized lysimeters where sweet clover, vetch, and mustard accumulated 113, 142, and 16 pounds N/acre/year, respectively. By assuming similar N_2 fixation levels in unfertilized and fertilized lysimeters, we can calculate that the legumes' apparent use of the 100 pounds of fall N/acre was only about 20 pounds N/acre, while the corresponding figure for mustard was 84 pounds N/acre. The legumes, however, did have a beneficial effect on the succeeding summer sudangrass crop. The sudangrass N uptake averaged 175 pounds N/acre after legumes, 125 pounds N/acre after mustard, and 126 pounds N/acre after no cover.

Nielsen and Jensen *(37)* compared annual ryegrass with legume covers in Denmark after a spring barley crop by collecting soil samples to 39 inches and determining NO_3-N. The legumes studied were red clover (*Trifolium pratense* L.) in 1982 and black medic (*Medicago lupulma* L.) in 1983. The soil NO_3 levels were lower below the legumes (33 pounds N/acre) than under fallow plots (60 pounds N/acre). But the annual ryegrass lowered the soil NO_3 pool the most (to 22 pounds N/acre, table 3). The authors concluded that the annual ryegrass was more efficient than the legumes in reducing soil-mineral N levels during autumn and winter.

In Alabama, Jones *(22)* conducted a 4-year lysimeter study using three soil types: Norfolk sandy loam, Hartsells fine-sandy loam, and Decatur clay loam. Soybean [*Glycine max* (L.) Merr.] residues were spaded into each lysimeter in October; they decomposed rapidly producing NO_3-N. The average annual N leachings were determined without a cover crop and with cover crops of either hairy vetch or oats. The N-leaching results, averaged across soils (Table 3), showed that hairy vetch reduced the mass of N leached by only 6%, while oats reduced it by 81%. Oats reduced N leaching more than hairy vetch on all three soils studied, although leaching losses were highest on the sandy loam soils and were very small on the clay loam soil.

Table 3. Literature summary of effect of non-legumes versus legumes on water quality.

Reference and Brief Description of Study	Cover Crop	Cover Crop N Uptake (inches)	Soil Nitrate-N	N Leached: Mass of N	N Leached: Nitrate-N Conc. (ppm)	Percentage Reduction due to Cover Crop: Mass of N	Percentage Reduction due to Cover Crop: Nitrate-N Conc.
			pounds N/acre				
Chapman et al. 1949 (7); filled lysimeters loam soil; 10' diameter by 4' deep; unfertilized summer sudangrass followed by fertilized (100 pounds N/acre) cover crop treatments; 5-year study in California; supplemental irrigation as needed	None (straw)			46	75	-	-
	Sweet Clover	137		38	74	17	1
	Purple Vetch	159		32	67	30	10
	Mustard	100		9	15	80	89
Neilsen and Jensen, 1985 (37); soil samples to 39" from field plots on sandy loam; spring barley with 80 pounds N/acre then covers; 2 years of data from samples taken 60 days after planting in Denmark	None		60			-	
	Legumes		33			45	
	Annual Ryegrass		22			63	
Jones, 1942 (22); filled lysimeters averaged over 3 soil textures; 30" diameter by 30" deep; sudangrass in summer followed by soybean residues (75 pounds N/acre) then covers; 4-year study in Alabama	None			32		-	
	Hairy Vetch			30		6	
	Oats			6		81	
Meisinger et al., 1990 (29); shallow groundwater below field plots on silt loam soil; corn fertilized with 300 pounds N/acre followed by rye or hairy vetch; 1-year study in Maryland	None	-			17		-
	Hairy Vetch	150			18		−6
	Rye	80			12		29

The summer sudangrass crop benefited little from the N conservation of the oats, as shown by its N uptake, which averaged 23 pounds N/acre after no cover, 20 pounds N/acre after oats, and 63 pounds N/acre after hairy vetch. The author concluded that oat crop was more effective than hairy vetch in preventing leaching losses, but yields of sudangrass were much greater after hairy vetch.

The replicated field experiment with shallow wells in Maryland has been described in the grass cover crop section *(29)*; but, in addition to rye, a hairy vetch cover crop was also studied. The NO_3-N concentrations in shallow groundwater show that the vetch made no impact, while the rye reduced the NO_3 concentrations by 29% (Table 3). In addition to the groundwater NO_3 data, these investigators also directly measured cover crop N conservation by use of ^{15}N. This was accomplished by growing corn and adding isotopically labeled fertilizer N, allowing the tagged fertilizer to distribute throughout the corn root zone during summer, and then planting fall cover crops. A direct field measurement of the cover crop fertilizer N conservation was made by measuring the uptake of tagged fertilizer in the aboveground dry matter of the various cover crops during the following spring. Allowances were also made for tagged N in the root system by reviewing the scientific literature. An intentionally high rate of fertilizer N was applied to the corn (300 pounds N/acre) to ensure an adequate pool of labeled N in the fall and to assess the N conservation capacity of the various cover crops. The average recovery of corn fertilizer N by the various cover crops is shown in figure 1, expressed as a percentage of the labeled mineral N present in 32 inches of soil at the time the cover crops were planted. The data of figure 1 clearly show that grasses are superior to legumes in recovering corn fertilizer N. Cereal rye accumulated about 60% of the left-over corn fertilizer N at mid-April, which is its normal kill date in Maryland. Annual ryegrass was less aggressive than rye in its early spring growth, but by mid-May had recovered about 53% of the corn fertilizer N. Hairy vetch, crimson clover, and the native weeds (chickweed) recovered not more than 10% of the corn fertilizer N. Nonetheless, legumes contained an average of 150 lbs of total N/acre compared with an average of 80 pounds N/acre in the grasses (Table 3). Legume covers were, therefore, vigorous and healthy, but did not rely on recycling fertilizer N.

A 1989 preliminary report summarized 2 years of data from a lysimeter trial in Kentucky, which compared hairy vetch and rye cover crops on a Maury silt loam *(27)*. The cover crops were established after no-till corn, and both years produced similar dry matter yields and similar percolation volumes. The hairy vetch gave a 46% reduction in the mass of N leached, but the corresponding value for rye was 98%, that is, the rye virtually eliminated N leaching in this study.

The above data consistently show that nonlegumes are superior to legumes in reducing N leaching, with average percent reductions being 70% for nonlegumes and 23% for legumes. Thus, nonlegumes are about three times more efficient than legumes at reducing N leaching. The exact underlying reason for this difference remains as a future research need but informal field observations indicate that it is probably related to fall growth rates. The legumes are usually slow to establish and exhibit little fall growth, which allows N to leach

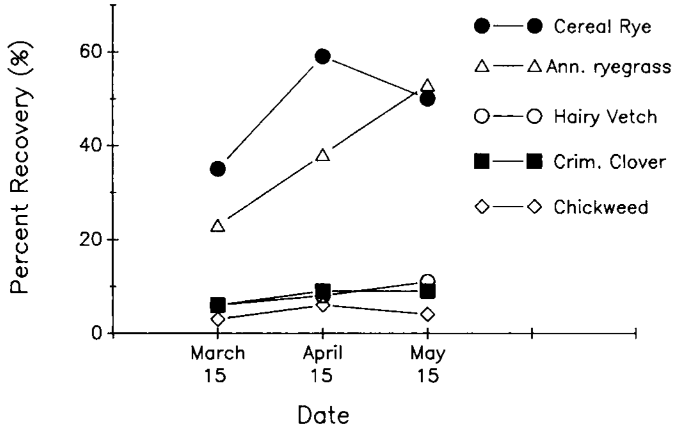

Figure 1. Average (over 2 years) percent recovery of corn fertilizer N (^{15}N labled) by winter cover crops in Maryland *(29)*.

below their root zones before they resume active spring growth. Nonlegumes, on the other hand, are quick to establish and exhibit rapid fall growth that allows them to compete in a timely manner with N leaching. The above studies also have confirmed the positive effect of legumes on the next crop and the neutral (or negative) effect of nonlegumes.

The observations in this section lead us to conclude that at this time a single cover crop that possesses attributes of both high reductions in winter N leaching and high N contributions to the next crop has not been found. Therefore, it remains as a high-priority research need to find such a species or to devise cover crop management systems that will encourage both N conservation and N supply. We will discuss such cover crop management systems in a later section.

National potential of cover crops

The research summarized above has primarily been conducted in humid climates or with irrigated systems. A major remaining question is the value of winter cover crops in other climatic regions. The impact of winter cover crops on water quality will be site-specific and will depend on the site's winter rainfall and temperature, the water-holding capacity and hydraulic properties of the soil, the soil organic matter content and crop residues, and the application time and rate of previous N additions. A national assessment of the relations between cover crops and groundwater quality is a complex problem considering the range in climates, agronomic practices, and soils across the United States. Simulation models offer the most direct estimates to such complex problems on a national scale. The EPIC (Erosion-Productivity Impact Calculator) model, developed by Williams et al. *(55)*, was used to produce a first estimate of the relative comparisons among no cover versus grass cover versus legume cover crop systems.

EPIC evaluation. A validation of the EPIC model was conducted with a 3-year data set from Coshocton, Ohio, representing a humid eastern climate. The predicted monthly percolation and evapotranspiration were compared with measured values obtained from a large monolith-weighing lysimeter *(8)*. The seasonal percolation pattern predicted by EPIC was in good agreement with the observed values; the average monthly difference between observed and predicted percolation was only 0.1 inches (Figure 2). The regression comparison of observed monthly percolation with predicted percolation for the 3-year period (36 data points) had an R^2 of 0.86, a slope of 0.86 (not statistically different from 1.0), and an intercept of 0.1 inches (not statistically different from zero). The regression comparison of observed monthly evapotranspiration values with EPIC's predicted values over the 3 years had an R^2 of 0.87, a slope of 1.0, and an intercept of 0.1 inches. Other validations of the EPIC model have been conducted with subhumid climatic data *(47)*.

This data indicates that the EPIC model can be used to provide a first estimate of relations between winter cover crops and water quality. Other EPIC evaluations show that accurate simulation of plant N uptake, crop water use, and organic matter mineralization are important in predicting percolation and N leaching. Simulated NO_3 leaching seems quite sensitive to the size of the soil NO_3 pool when percolation begins.

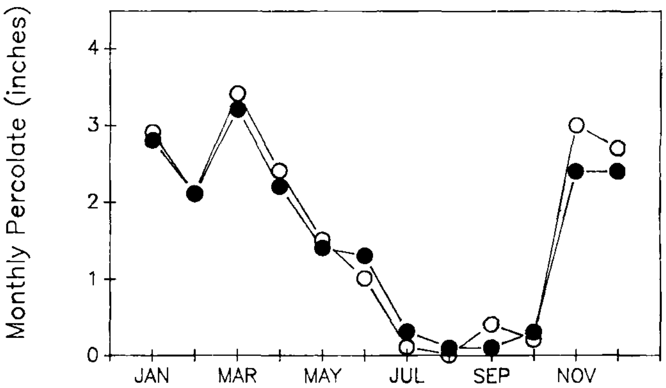

Figure 2. Average monthly percolation over 3 years from Coshocton, Ohio lysimeters (●) and predicted percolation (○) from EPIC simulations.

EPIC simulations. We accomplished the regional assessment of the effect of winter cover crops on leachate water quality by running EPIC simulations at 10 representative U.S. sites. To most accurately compare climatic regions, we assumed two generic soils to be present at each site. One soil was a coarse-textured low organic matter soil, which represents a worst-case scenario for N leaching. The other was a fine-textured high organic matter soil, which represents a high N mineralizing agricultural soil. Table 4 provides a summary of specific properties assumed for these two generic soils. Three cropping systems were simulated for each soil at each site: continuous corn without a winter cover crop, continuous corn with a barley cover, and continuous corn with a clover cover crop. Fertilizer N inputs were allowed to vary between soils, among sites, and among cropping systems to simulate common production practices. The fertilizer management strategy was to apply 45 pounds N/acre and 35 pounds phosphorus (P)/acre to the corn at planting. Additional corn fertilizer N (up to a total of 225 pounds N/acre) was added as 1- or 2-simulated side-dressings whenever the corn nutritional status indicated an N deficiency. Investigators intentionally kept the total rate of N applied close to optimal rates based on potential yield and the legume-N credits for the clover cover crop system. This simulated fertilizer N management system was devised for efficiency in terms of grain production per unit of fertilizer N; it represents minimum potential N losses in runoff and leaching. Other less-efficient fertilizer strategies (over-optimistic yield goals, excessive manure inputs, poor timing) would likely lead to higher potential N losses. The EPIC simulations were carried out at each location over 20 years.

The EPIC simulations of the continuous corn winter cover crop system (Table 5) show improved leachate water quality with winter cover cropping. For example, in the humid Southeast on the sandy soil, the barley cover crop reduced percolation 3.5 inches compared with the no-cover control. The predicted mass of N leached in this example was 30 pounds N/acre for no cover compared with 7 pounds N/acre for the barley cover (N data not shown), which translates into a 77% reduction that is attributable to the barley cover crop. These predictions show that the greatest potential for cover crops to improve water quality is in the Southeast and in the irrigated areas of the semiarid West because of the good fall and winter growing conditions. In the northern locations, the predicted benefits are less, but winter cover cropping is still a beneficial practice in the Midwest. The EPIC simulations forecast a greater benefit from grass cover crops than legumes; this agrees with the literature summary of previous sections. Notice also that EPIC forecasts a positive cover crop effect on both the highly leachable sandy soil, and on the high organic matter soil where N mineralization presents a difficult N management problem because N release rates are not controllable.

Table 4. Summary of soil properties used with EPIC simulations at each location to simulate a sandy, low-organic matter soil and a clay loam, high-organic matter soil.

Soil Property	*Sandy, Low-Organic Matter Soil*				*Clay Loam, High-Organic Matter Soil*			
Depth (inches)	0-12	12-24	24-40	40-80	0-15	15-26	26-42	42-80
Sand (%)	95	94	95	96	36	33	25	34
Silt (%)	3	5	4	3	37	41	43	44
Clay (%)	2	2	2	1	27	26	32	22
Organic C (%)	1.4	0.8	0.6	0.1	3.4	2.1	1.1	0.3
Total Porosity (%)	43	43	42	37	45	45	43	43
Water (Volumetric)								
Field Capacity (%)	10	10	9	8	35	27	32	28
Wilt point (%)	3	3	3	2	23	14	21	13
Saturation conductivity (in/hr)	0.5	0.5	0.5	0.5	0.3	0.3	0.2	0.3
Bulk density (g/cm^3)	1.50	1.52	1.55	1.67	1.45	1.45	1.50	1.50

Table 5. Average annual results of 20-year EPIC simulations to estimate the effect of winter cover crops in a continuous corn system on leachate water quality at 10 U.S. locations.

State, Location, and Precipitation	Soil Texture	Cover Crop	Irrigation	Evapotranspiration	Runoff	Percolation	Corn Grain Yield (bushels/acre)	Fertilizer N Added (pounds N/acre)	% Reduction due to Cover Crop: Mass of N	% Reduction due to Cover Crop: Nitrate N Concentration
			inches						(%)	
Humid, Southeast										
Watkinsville, Georgia;	Sand	None	0	22.6	0.1	22.0	143	119	-	-
46 inches		Barley	0	26.2	0.1	18.5	143	103	77	67
		Clover	0	25.7	0.1	18.9	145	62	47	33
	CL	None	0	27.4	3.2	14.3	185	112	-	-
		Barley	0	32.2	3.1	9.8	187	89	90	83
		Clover	0	31.2	3.1	10.7	192	56	64	50
Gainsville, Florida;	Sand	None	0	25.4	0.4	20.1	149	120	-	-
47 inches		Barley	0	26.3	0.4	19.2	155	110	67	67
		Clover	0	26.9	0.4	18.7	156	70	62	56
	CL	None	0	31.2	4.6	10.3	196	92	-	-
		Barley	0	32.1	4.5	9.7	185	80	76	73
		Clover	0	33.7	4.4	8.2	194	54	71	67
Humid, Mid-Atlantic										
Hagerstown, Maryland;	Sand	None	0	18.3	0	16.2	132	116	-	-
36 inches		Barley	0	19.5	0	15.0	134	112	41	40
		Clover	0	19.6	0	14.9	134	87	29	40
	CL	None	0	21.6	1.5	11.4	164	107	-	-
		Barley	0	23.1	1.5	9.9	164	98	50	43
		Clover	0	23.2	1.5	9.9	166	76	33	29
Raleigh, North Carolina;	Sand	None	0	19.8	0.1	18.4	138	107	-	-
40 inches		Barley	0	22.3	0.1	15.9	139	98	83	83
		Clover	0	21.9	0.1	16.3	139	74	58	50
	CL	None	0	23.9	2.1	12.3	175	96	-	-
		Barley	0	27.2	2.1	9.1	177	89	89	90
		Clover	0	27.4	2.1	8.9	183	49	71	60
Humid, Midwest										
Ames, Iowa;	Sand	None	0	19.6	0	11.5	121	107	-	-
32 inches		Barley	0	20.3	0	10.8	124	105	64	50
		Clover	0	20.3	0	10.8	124	96	45	50
	CL	None	0	23.0	1.8	6.5	151	98	-	-
		Barley	0	23.9	1.7	5.7	153	96	67	50
		Clover	0	23.9	1.7	5.7	153	87	33	25
Jackson, Illinois;	Sand	None	0	18.9	0	12.0	115	101	-	-
32 inches		Barley	0	20.1	0	10.9	117	96	69	67
		Clover	0	20.1	0	10.9	117	62	25	17
	CL	None	0	23.1	1.3	6.5	160	94	-	-
		Barley	0	24.5	1.2	5.2	158	89	73	70
		Clover	0	24.4	1.2	5.3	164	58	47	30
Sub-Humid, Great Plains										
Grand Island, Nebraska;	Sand	None	15.7	25.0	0	11.2	155	132	-	-
22 inches		Barley	14.7	25.6	0	9.5	160	132	36	33
		Clover	14.9	25.9	0	9.7	160	119	29	33
	CL	None	10.2	26.6	1.0	3.3	164	101	-	-
		Barley	10.2	27.5	0.9	2.4	168	98	50	38
		Clover	10.2	27.4	0.9	2.6	168	87	33	25
Temple, Texas;	Sand	None	0	22.1	0.1	10.3	107	107	-	-
33 inches		Barley	0	26.4	0.1	6.1	102	101	76	61
		Clover	0	27.3	0.1	5.2	102	58	57	20
	CL	None	0	27.5	2.2	2.8	155	80	-	-
		Barley	0	31.0	1.8	0	126	61	100	100
		Clover	0	31.3	1.7	0	113	45	100	100
Semiarid, West										
Davis, California;	Sand	None	20.7	24.5	0	10.6	183	143	-	-
16 inches		Barley	20.3	29.5	0	5.4	179	152	92	83
		Clover	20.3	31.1	0	3.8	194	52	69	33
	CL	None	14.8	25.8	0.5	3.1	198	112	-	-
		Barley	16.3	30.6	0.4	0.3	185	116	100	100
		Clover	16.9	31.7	0.3	0	181	52	100	100
Lubbock, Texas;	Sand	None	23.8	30.4	0	9.1	170	138	-	-
17 inches		Barley	23.9	32.2	0	7.5	172	136	56	38
		Clover	23.9	32.2	0	7.4	172	132	50	38
	CL	None	16.7	31.5	0.7	0.5	179	89	-	-
		Barley	17.5	32.9	0.6	0.2	173	87	100	100
		Clover	17.2	32.6	0.6	0.3	172	83	100	100

The above EPIC simulations predict that winter cover cropping will have a broadly beneficial impact on leachate water quality across much of the United States. This benefit will likely be greatest with grass cover crops and in warmer regions that encourage rapid fall growth.

Cover crop management

Cover crop management strategies, to date, have focused primarily on optimizing N supply for the next crop or soil erosion control. In this section, we will suggest management approaches for cover crops to improve groundwater quality.

Selection. If the primary objective of the cover crop is groundwater quality, then species selection focuses on selecting a grass or brassica species that is adapted to the climate and adapted to the cropping system and equipment of the farm. Cereal rye is usually one of the top candidates among the grasses. On Maryland's eastern shore, researchers have reported *(43)* average fall cover crop N uptakes in early December for rye, wheat, oats, and barley of 71, 29, 32, and 42 pounds N/acre, respectively. Similarly, in Georgia, N uptake for several winter annuals was in the order: rye > wheat > triticale > ryegrass > oats > rapeseed > barley (Unpublished data, W. L. Hargrove, Department of Agronomy, Univsersity of Georgia, Griffin). In this and many other studies, researchers have shown cereal rye to be a good overall choice due to its cold tolerance, wide adaptability, and ease of establishment.

However, other grasses and brassicas offer unique advantages for specific situations. For example, oats can be rapidly established in the fall and will naturally winter-kill in cold regions, which could eliminate a knock-down herbicide application. Brassica species offer rapid growth and a larger N uptake capacity than most grasses, if planted early, which is useful for immobilizing large quantities of NO_3.

It is also important to note the possibility of mixing species to obtain some of the benefits of both. For example, mixtures of cereal rye and hairy vetch could provide some N conservation, and some added N supply. Researchers have evaluated mixtures for N supply *(30)* and for residue production *(33)*, but there is little or no data on the ability of mixtures to affect groundwater quality. This remains a future research need.

Establishment. Planting time, method, and seeding rate are management options that have major impacts on fall growth and N uptake.

In general, a winter cover crop for water quality should be planted as early as possible. Researchers in England *(2)* studied the benefit of early seeding of winter wheat by measuring root growth throughout the growing season. Their data show that September-sown wheat made substantial root growth throughout the winter. In March, the roots under the September-sown crop measured 4.8 miles/cubic yard of soil, while October-sown wheat had only 1.1 miles of roots/cubic yard. Furthermore, the early planted wheat roots reached the 39-inch depth by early December, while late-sown wheat roots did not reach this depth until April. Other scientists *(54)* summarized winter wheat N uptake at several locations in England and reported that September-planted wheat took up 1.7 pounds N/acre/week, while October-planted wheat had weekly N accumulations of 0.6 pound N/acre. Researchers in the United States *(43)* reported average December N uptakes of mid-September-sown covers of 72 pounds N/acre, while mid-October-sown covers accumulated only 15 pounds N/acre. These data show the importance of early planting, which allows more extensive rooting and permits more efficient uptake of the mobile NO_3 ion.

Planting time will, of course, depend on the maturity of the summer crop, but it is often possible to hasten cover crop planting by a few weeks by selecting earlier-maturing cultivars, planting summer crops early, and using interseeding techniques. All of these approaches require more timely management, but this is a price that must be paid if agriculture is to reduce NO_3 losses.

The method of establishment will depend on equipment capabilities, moisture regime, and length of growing season. The two basic methods are seeding into a standing crop and seeding after harvest. Seeding into a standing crop usually involves overseeding before leaf drop so crop residues will conserve moisture *(5, 10, 13)* or seeding into the summer row crop at last cultivation *(35, 42)*. These interseeding practices allow early establishment of cover crops and virtual year-round crop growth that is important in minimizing NO_3 movement into groundwater. The drilling methods require planting after harvest of the summer crop. They are not as timely as interseeding, but they are more reliable in stand establishment under intermittent moisture conditions because of the better soil-seed contact. The drilling equipment should use conservation tillage techniques to preserve crop residue cover. English researchers *(11)* have documented deeper root penetration with no-till wheat compared with plow-tillage establishment. In sprinkler irrigation systems, it may also be feasible to establish small seeded covers (e.g., brassicas) by injecting seed into the irrigation water and applying a light irrigation just before summer crop maturity.

The seeding rates and fertilizer practices could also be adjusted to improve the fall N uptake. For example, the conventional seeding rate of 1 to 2 bushels/acre for cereals is based on grain yield practices. Why not seed at 2 to 4 bushels/acre and with narrow rows (4-inch spacing) to increase competition for fall NO_3-N? English scientists have reported *(54)* a direct linear relation between December N accumulations with winter wheat and plant density. One should also be aware that most cover crops require P and fairly high levels of potassium (K). In fact, cover crops take up a little more K than N during their growth *(20)*. Thus, if a soil tests medium or low in P or K, these elements should be added to ensure rapid fall growth.

Limitations. Grass or brassica cover crops are not without some limitations, such as cost of establishment, water use, and N immobilization for the next crop.

Establishment costs are generally \$10 to \$20/acre, depending on equipment needs. Cover crop water use can be a limitation if covers are allowed to grow so late that their water use exceeds rainfall, thus depleting soil-water reserves needed by the summer crop *(10, 19)*. Several researchers *(6, 53)* have reported examples of cover crop water use delaying germination and reducing early season growth of the summer crop. This limitation can be minimized by timely killing of the cover, for example, killing the crop 2 weeks before planting *(6)*. Other researchers have pointed out that this practice should move the kill date up rather than delay corn planting *(52)*.

The limitation of greater N immobilization is an inherent characteristic of cool-season grasses because of their low-N concentrations (wide C/N ratios), which results in a greater fertilizer N need *(17, 19, 53)*. This limitation is commonly met with increased fertilizer-N additions. It can also be minimized by early killing *(51)*, using grass-legume mixtures to raise the percentage N of the mixed stand *(30)*, harvesting the grass for forage or straw, or following the grass cover with a legume, such as soybeans, that will fix its own N. A final option would be to use a brassica cover in place of the grass because the brassicas generally have higher N concentrations and, therefore, lower N immobilization tendencies.

Research needs

There is a need for more screening and evaluation of plant materials that are suited for use as cover crops to recover residual NO_3 and recently mineralized N. Although there have been comparisons among some legume, brassica, and grass species, there are several possibilities that have not been evaluated, for example, forage turnip and spring oats. Also, genetic variation in rooting depth and N uptake within species needs to be evaluated. Research in Georgia, for example, has shown considerable variation in root growth among winter wheat cultivars (Personal communication, Jim Box, Agricultural Research Service, U.S. Department of Agriculture). In this regard, the potential benefit of genetic engineering, resulting in superior plant materials is obvious.

Applied research also is needed to develop establishment methods for earlier seeding, identify optimum mixtures of species, and develop spring management practices that minimize adverse affects on the summer crop.

More direct field measurements of NO_3 leaching for cover crop and no-cover crop conditions are needed for a variety of soil and climatic conditions across the United States.

A limitaion in assessing the importance of cover crops in prevention of NO_3 leaching is the inability to predict the amount of NO_3 in the soil profile. An improved understanding of the N cycle in general, and N mineralization in particular, is a prerequisite to the development of predictive models for NO_3 concentrations in the soil.

Finally, we need studies of the fate of N taken up by cover crops. If cover crop decomposition and N mineralization are not synchronized with N demand by a subsequent crop, the N could still be leached to groundwater.

With improved predictive models of the N cycle and better knowledge of cover crop characteristics, including N demand, we can develop cropping systems for reduced NO_3 leaching.

Summary and conclusions

Winter cover crops can influence NO_3 leaching and groundwater quality by influencing the water budget, affecting the soil NO_3 concentration, and synchronizing competition during the water-recharge season.

Experimental results from the literature clearly show that cover crops can reduce both the mass of N leached, and the NO_3 concentration of the leachate 20% to 80% compared with no cover crop. The grasses and brassicas are two to three times more efficient than legumes in reducing N leaching. Management factors that improve N conservation include selection of a species with vigorous fall growth and early establishment.

Using the EPIC model, it was estimated that a winter cover crop will have the greatest impact on NO_3 leaching in the humid Southeast and in irrigated agricultural areas, but cover crops had a positive effect for all scenarios evaluated.

Additional research needs include more direct field measurements of NO_3 leaching for a range of soils, cover crops, and climates; improved understanding and modeling of the N cycle; and improved plant germplasm for use as cover crops.

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Impact of annual cropping on shallow groundwater quality in the Northern Great Plains

G. J. Beke

Establishment of agriculture in the Northern Great Plains has dramatically impacted the salinity status of soil resources *(10)*. Prior to agricultural development around the turn of the century, 3.7% of the soil in a 37,000-square-mile area of southern Alberta was believed to be saline. Presently, 10.7% of the land area consists of saline soils. This increase in extent of salt-affected land has been attributed to the development or rise and salinization of shallow groundwater, in part as a result of farming practices *(3, 7)*.

The shorter period of water use by annual crops compared with native vegetation was partly responsible for the increasing water content in the subsoil and rising groundwater levels. Other contributing practices included post-1940 cultivation of marginal land and increasing effectiveness of weed control due to enhanced tractor power, improved tillage tools, chemicals, or a combination of these factors. The impact of these practices on increased water storage has been dependent on cropping system, which is greatest with the conventional crop-fallow systems of dryland farming.

Crop-fallow systems produce one crop every other year. The fallow year is intended to conserve water for the following year's crop. Research has shown, however, that about 75% of the precipitation in the Lethbridge region is lost during the 21-month fallow period due to runoff, evaporation, or deep percolation *(4)*. The resulting increased water storage in the subsoil and the incidence of saline groundwater-discharge (seep) areas has been reduced agronomically by annual cropping, flexible cropping, or growing high water-use crops *(3, 7)*. Whether or not such cropping strategies also result in improved groundwater quality has not been evaluated.

In the early 1980s, increasing soil salinization prompted several dryland farmers in southern Alberta to change from the traditional crop-fallow rotation to annual cropping. Concurrently, a detailed examination of groundwater conditions was undertaken. Herein, I present results of a study of the groundwater properties in a shallow farm well, taken primarily after the change in cropping system; also discussed are the contributions of annual small-grain cropping to improved well-water quality.

Methodology

I chose a farm well, located about 20 miles north of the Montana-Alberta border, to evaluate the impact of the change in cropping systems that took place in 1981. This well was selected because the farmland was bounded on the south or upslope side by the north flank of the Milk River Ridge with native grassland vegetation. Also, there were no major roads upslope of the well site to restrict the generally northeastward surface and subsurface drainage, and a side-hill saline seep was located about 0.5 mile upslope of the well. The land had been glaciated and its stratigraphy consisted of up to 35 feet of till over non-marine, dominantly shale bedrock. A layer of sorted sediments or reworked bedrock and till of variable thickness may be present between the till and bedrock. The farm well was located near the north-center of the cultivated section of land at an elevation of 3,504 feet. It was installed in 1917 and completed in a 14-foot-thick layer of sand and gravel. Total depth of the well was 25 feet, with dimensions of 3 sqaure feet and a wooden casing.

The well water was evaluated in 1917, 1936, 1970, 1974, and 1980, with analytical results available for the three latter years. Monthly monitoring was initiated in the fall of 1983. Samples were taken with a bailer, placed in clean, 16.9-ounce polyethylene bottles, measured for temperature, and kept refrigerated at 39°F. Within 24 hours after sampling, the samples were filtered and half of each sample was acidified with 1 N HNO_3 in preparation for determination of zinc (Zn), copper (Cu), and fluoride by atomic absorption spectrophotometry *(9)*. The unacidified samples were analyzed for pH, electrical conductivity, and major cations and anions as outlined by Beke and Hironaka *(1)*. Total dissolved salts content was calculated by summation of ion contents *(5)*. It will be referred to as salinity.

Results and Discussion

The water quality of the shallow, unconfined aquifer deteriorated over time under the crop-fallow system. It was hard, alkaline, and useable at the time of well installation *(6)*, but, by 1936, the water had become too bitter for livestock use. However, development of the upslope saline seep did not occur until the early 1950s. During the last 11 years of the crop-fallow rotation period (1970-1980), midsummer salinity of the water was around 7,400 ppm total dissolved salts (Table 1). Sodium and sulfate were the dominant ions.

The quality of the well water improved after the introduction of annual cropping in 1981. Salinity, sodium, and sulfate contents decreased over time as did electrical conductivity, sodium adsorption ratio, and the content of calcium, magnesium, and chloride. Conversely, the amount of potassium, carbonate, and bicarbonate increased since 1980. The content of nitrate-nitrogen, fluoride, Cu, and Zn did not change appreciably under annual cropping (Table 1).

During the 1970s, the water graded as marginally suitable for livestock use, but only for older ruminants *(8)*. This, coupled with occurrences of sulfur-toxicity symptoms in the beef cattle *(1)*, prompted the farmer to dilute the well water with surface water of low salinity for livestock watering. Deleting the data of these dilution-periods showed that well-water salinity decreased quite rapidly in the first few years and then more gradually (Figure 1). This apparent nonlinear

G. J. Beke is a hydrologist with the Agriculture Canada Research Station, P.O. Box 3000, Main, Lethbridge, Alberta T1J 4B1. *The author thanks William Norris for his cooperation and encouragement throughout the study and T. Entz for his assistance with statistical data analyses.*

relationship was evaluated by using the 1980 data as the starting point, as groundwater conditions tend to relate to the annual rainfall in the preceding year *(2)*. The curve of best fit for the salinity data was estimated by the equation:

$$TDS = 607.79 + 6724.94\ e^{(-0.199*time)} \qquad (R^2 = 0.95)$$

Equations derived for sodium (Na) and sulfate (SO_4) , respectively, were

$$Na = 243.19 + 1162.80\ e^{(-0.224*time)} \qquad (R^2 = 0.92)$$

$$SO_4 = -557.34 + 5176.61\ e^{(-0.150*time} \qquad (R^2 = 0.93)$$

Similar results, but with slightly slower rates of improvement in water quality, were obtained for a shallow well located 0.5 mile north of the study site.

Improvements in well-water quality since 1980 were mainly attributable to use of an annual cropping system and the generally below-average precipitation during the 1980s. These two conditions ensured that part of the water stored in the subsoil was used up each year, which caused the soil to dry out and shallow water tables to decline. This was supported by the lowering of the water table in the upslope saline seep from less than 2 feet below the surface in 1981 to more than 7 feet in 1984. As a result, the continuum between water stored in the surface soil and in the subsoil/groundwater was broken. Direct recharge of groundwater supplies by incoming precipitation was, therefore, greatly reduced or eliminated.

The wood cribbing of the well allowed visual verification ofseepage along the well wall. The last major seepage event occurred after an 8.8-inch rainfall between August 9 and September 22, 1985. According to the water quality data of a piezometer that was completed in aquifer material located about 5 yards upslope of the well, seepage had comparable effects on the water quality of the well and the aquifer.

Table 1. Well-water quality characteristics at selected dates during the crop-fallow and annual-cropping periods of dryland farming.

	Crop-fallow Rotation		*Annual Cropping*	
Determinant	*July 1970*	*August 1980*	*May 1984*	*May 1988*
Temperature (°F)	-	-	45.5	44.6
EC* (mmho/cm)	7.8	8.0	5.1	2.9
pH	7.9	8.2	8.5	8.0
Sodium adsorption ratio	12.8	12.6	10.0	8.6
Calcium (ppm)	-	-	200	88
Magnesium (ppm)	-	-	210	88
Calcium + magnesium (ppm)	749	752	410	176
Sodium (ppm)	1,426	1,403	849	476
Potassium (ppm)	-	4	7	13
Carbonate (ppm)	0	0	20	36
Bicarbonate (ppm)	335	354	593	610
Chloride (ppm)	82	92	48	25
Sulfate (ppm)	4,848	4,733	2,496	1,046
Nitrate-nitrogen (ppm)	-	16	2.0	2.5
Fluoride (ppm)	-	0.20	0.16	0.18
Copper (ppm)	-	-	0.03	0.01
Zinc (ppm)	--	-	0.04	0.03
Total dissolved salts (ppm)	7,440	7,411	4,130	2,059

*Electrical conductivity

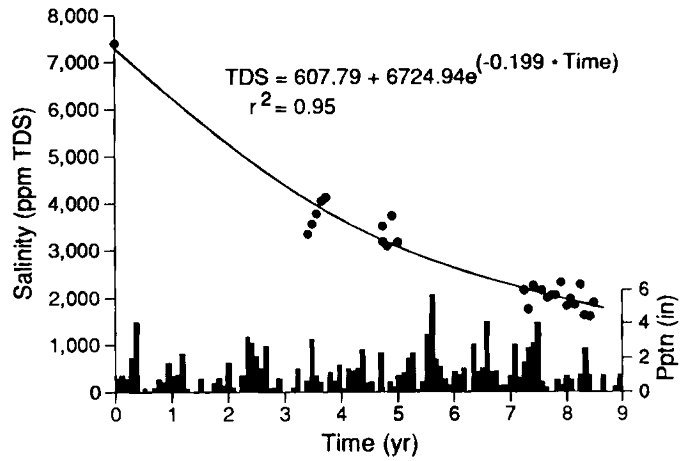

Figure 1. Well water salinity trend and monthly precipitation from 1980 to 1988.

Conclusion

The crop-fallow system of dryland farming had a more rapid negative impact on groundwater quality than on soil quality. Assuming that this cropping system was introduced at the time of well installation, salinization of the unconfined aquifer water had occurred within 20 years as opposed to about 40 years for soil salinization and saline-seep development. The salinity of the well water remained relatively constant at 7,400 ppm total dissolved salts during the growing season of the last 10 years of the crop-fallow rotation.

The annual cropping farming system, in combination with below-average precipitation, resulted in a considerable improvement of the well-water quality over an 8-year period. The content of salinity, Na, and SO_4 in the water was reduced by one-half about every 4 years.

Pertinent equations were presented to estimate these nonlinear relationships. Only the carbonate and bicarbonate content of the water increased during this time period.

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Tillage and cover crop effects on nitrate leaching

G. V. Wilson, D. D. Tyler, J. Logan, K. Turnage

Despite the extensive research demonstrating nitrate (NO_3) transport, research on the effect of tillage practices under field-scale conditions is seriously lacking *(2)*. Research by Thomas and associates *(5, 6, 7)* in Kentucky demonstrated greater NO_3 leaching with no-till than conventional tillage. They concluded that no-till enhanced the preferential leaching of NO_3 through macropores. The timing and intensity of rainfall events following fertilizer applications plays a significant role in nitrogen (N) leaching. A light rainfall following fertilizer applications promotes movement into soil micropores, thereby immobilizing NO_3 for subsequent events. Heavy to moderate rainfalls generally result in macropore flow that may enhance or reduce NO_3 leaching. Kanwar et al. *(3)* concluded that increased macroporosity under no-till results in decreased N leaching when the N source is within soil micropores. Under this scenario, macropores facilitate the bypassing of water-filled micropores, thereby reducing NO_3 leaching relative to displacement of the N-rich micropore water.

The significance of cover crops on NO_3 leaching is less quantified than tillage effects. Winter annual legumes generally supply the equivalent of 100 pounds/acre of N for the subsequent crop *(1, 4)*. Anderson et al. *(1)* found that hairy vetch provided the greatest (159 pounds/acre) N production of the four legumes (hairy vetch, Cahaba white vetch, Austrian winter pea, crimson clover) they tested. While this is advantageous for summer row-crop production, it may increase NO_3 leaching if fertilizer applications are not properly managed. In contrast, grass cover crops supply a minimal amount of N and may reduce NO_3 leaching. Meisinger et al. *(4)* reported that the ability of grass cover crops to retain N resulted in lower NO_3 concentrations of percolating water and reduced leaching.

We initiated a project in 1990 to study the effects of various combinations of cover crops, tillage, and cropping systems on the leaching of NO_3 using pan lysimeters. Our secondary objective was to evaluate the effect of lysimeter size on leachate measurements.

Procedures

We used three sizes of tension-free pan lysimeters (24- by 30-inch, 18- by 14-inch, and 5- by 12-inch) to collect water draining from the soil profile of three experimental designs. No-till versus conventional tillage (chisel-plowed followed by disking) cotton plots with four cover treatments were estab-

G. V. Wilson is an assistant professor, D. D. Tyler is a professor, J. Logan is an assistant professor, and K. Turnage is a graduate assistant, University of Tennessee, Department of Plant and Soil Science, Knoxville, Tennessee 37901-1071.

lished on a Lexington silt loam. These plots have been consistently maintained, with 90 pounds N/acre/year, since 1981. We instrumented four of the no-cover plots (two no-till and two conventional tillage) with a single, large lysimeter per plot. Soybean plots were established in 1979 under no-till and conventional tillage (chisel-plowed) on a Lexington silt loam. Beginning in 1990, these plots were converted to soybeans, double-cropped with wheat that received 80 pounds N/acre and with corn that received 150 pounds N/acre. Eight of the soybean-wheat-corn rotation plots (four no-till and four conventional tillage) were instrumented with a single, large lysimeter per plot. The third design has been consistently maintained since 1984 on a Memphis-Grenada silt loam intergrade and consists of no-till corn with three cover treatments, each receiving 100 pounds N/acre/year. Two plots each of wheat, hairy vetch, and no-cover treatments have been instrumented with a single, large lysimeter per plot. In addition, a medium and four small lysimeters were installed in each of the hairy vetch plots.

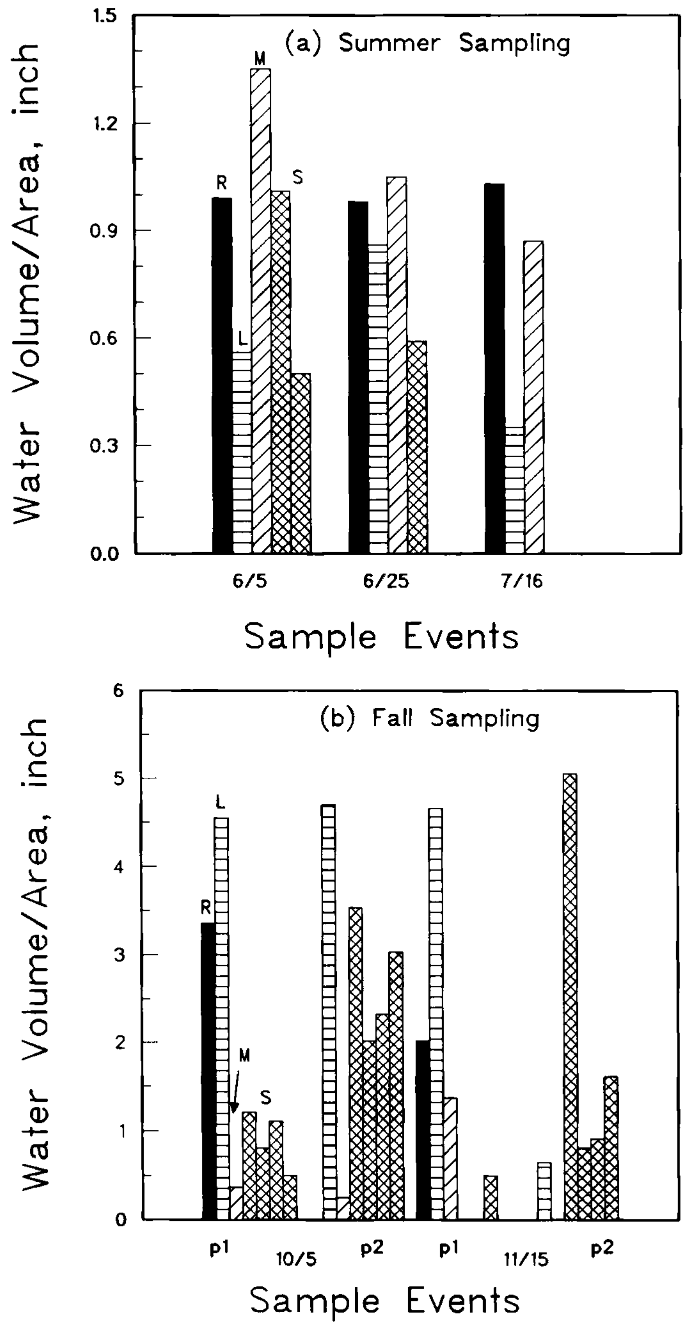

Figure 1. Rainfall (solid) accumulated between samplings and percolate from large (horizontal), medium (diagonal), and small (hatch) lysimeters under the no-till corn with hairy vetch cover crop. p1 and p2 are replicate plots.

We placed the lysimeter pans by excavating laterally from a trench adjacent to each plot at a 36-inch depth. We inserted a lysimeter into the excavated area such that the pan's outer edge was about 6 inches from the trench face. We filled each lysimeter with sterilized sand and crushed granite to establish continuity with the soil profile. We connected tubing to route water collected into a buried 16-gallon polypropylene carboy. Following rainfall events, we siphoned out all water in each carboy for analysis of NO_3 concentration by ion chromatograph, then we recorded the volume of subsurface flow.

Preliminary results and discussion

We have collected only a small number of events to date, so results are preliminary. We observed extreme variability in volume of percolate collected with the different size lysimeters (Figure 1a and 1b). The larger the lysimeter, the greater the probability of obtaining a representative sample of macropore flow paths. We observed an inconsistent response for all three lysimeter sizes. For the three sampling times during the summer (Figure 1a), we obtained only three samples of the 24 possible from the small lysimeters, and three of the possible six samples were obtained from the medium and large lysimeters. The remaining lysimeters yielded no subsurface flow. Those that did collect flow, produced volumes approximating the rainfall accumulated between samplings, with the medium lysimeters collecting the greatest volume. During the fall, a greater proportion of lysimeters collected subsurface flow, and flow volumes were considerably greater than during the summer. However, percolate volumes again were extremely variable, and we observed an inconsistent response to lysimeter size (Figure 1b). Percolate volumes from several lysimeters exceeded rainfall, yet in contrast to the summer, the medium pans collected the smallest volume.

The corn with wheat, hairy vetch, and no cover each received a single, 100-pound/acre N fertilizer application. Prior to fertilizer application, the hairy vetch plots had the lowest NO_3-N concentration and no-cover plots had the highest (Figure 2). Six days after fertilizer application, we detected peak concentrations of 36.0, 49.4, and 12.6 parts per million (ppm) N for wheat, hairy vetch, and no cover, respectively. The average NO_3-N concentrations of all samples was 13.8, 11.6, 4.9 ppm N for wheat, hairy vetch, and no-cover, respectively. We combined NO_3-N concentrations in percolate from the corn with wheat, hairy vetch, and no-cover treatments and constructed a frequency distribution (Figure 3). We observed a skewed distribution with about 50% of the samples containing NO_3-N concentrations exceeding the U.S.

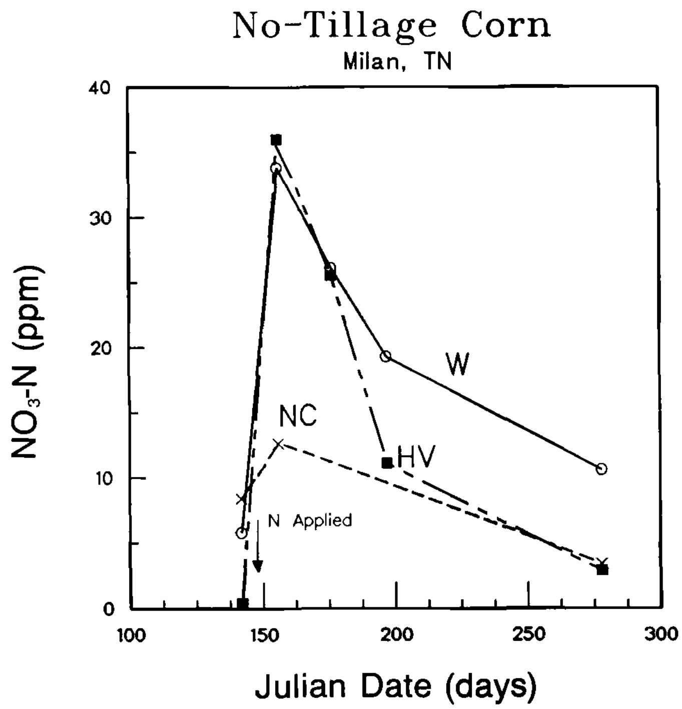

Figure 2. Breakthrough of NO_3-N following fertilizer application on Julian day 149.

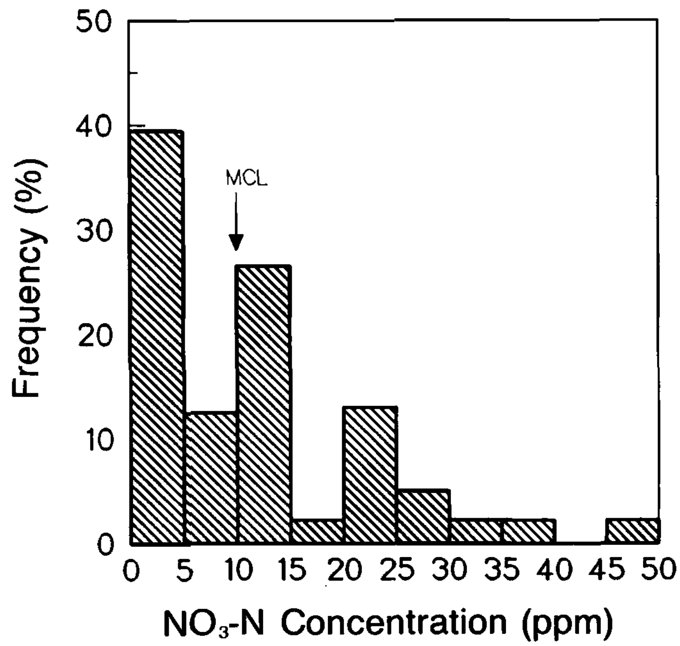

Figure 3. Frequency distribution of NO_3-N concentrations of all samples from no-till corn with wheat, hairy vetch, and no-cover.

Environmental Protection Agency primary maximum concentration level of 10 ppm N.

Conclusions

Leaching was variable, probably due to heterogeneity in preferential flow paths. Our analysis of the appropriate-size lysimeter for obtaining a representative elemental value of leachate was inconclusive. We found the breakthrough of NO_3-N from fertilizer application to be rapid. The wheat cover crop did not appear to reduce NO_3-N concentrations of leachate relative to the hairy vetch legume.

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Evapotranspiration and nitrogen accumulation in a winter rye cover crop in the Northern Corn Belt

D. C. Reicosky and D. D. Warnes

The net effect of winter cover crops on the movement of water through the soil depends on the contrasting influences of increased infiltration and water use by the growing crop *(4)*. Because nitrogen (N)-leaching losses depend on the quantity of water flow and the nitrate (NO_3) concentration, cover crop water use may be important in limiting N losses. Wagger and Mengel *(4)*, and Hooke and Gascho *(1)* concluded that the recovery of inorganic N in shoots of nonleguminous plants is usually in the range of 10 to 75 pounds N/acre and is related positively to the interval of active growth. Cover crops in the Northern Corn Belt have not been readily used because they generally leave the soils cooler in the spring, compete for water, and tend to shorten the growing season *(4, 5)*. The objectives of our study were to measure evapotranspiration of early and late-fall-planted winter rye (*Secale cereale* L.), used for weed control by interference in soybeans [*Glycine max* (L.) Merr.], and to measure the N accumulation by winter rye that we planted in early fall into corn (*Zea mays* L.) and soybeans.

Methods and materials

We conducted the time-of-planting study on a Doland silt loam [Udic Haploborolls, fine-loamy, mixed (fine-silty)] on the West Central Experiment Station near Morris, Minnesota *(6)*. We used four replicates of border plots to follow the spring regrowth of the rye early-fall planted (September 9, 1987) and late-fall planted (October 2, 1987) at 1 bushel/acre. The 1988 spring regrowth measurements included biomass, leaf area index, and surface-soil moisture. We made portable chamber measurements of midday evapotranspiration as described by Reicosky *(2)* and Reicosky et al. *(3)* and compared those results with those from a bare soil (weed-free) plot. Because of the severe drought of 1988 in the late-spring regrowth period, one-half of the early fall-planted plots were watered with 1.6 inches on May 13, 1989, (Day 134) and May 16, 1989, (Day 137) to establish differences in growth and evapotranspiration.

We evaluated N uptake of a winter rye cover crop on a Sioux sandy loam (Udorthentic Haploborolls, sandy-skeletal, mixed) with the objective of comparing conventional tillage and no-till with and without irrigation using a corn and soybean rotation. We interseeded the winter rye using a fertilizer spreader on August 18, 1988, calibrated at 2 bushels/acre. We applied 1 inch of water to the irrigated plots the following day to enhance germination. We measured leaf area index and biomass on October 3, 1988, and after spring regrowth only on the no-till plots on May 9, 1989, before we applied herbicide for the next crop. We analyzed tissue samples for total Kjeldahl N using standard analytical techniques.

D. C. Reicosky is a soil scientist, North Central Soil Conservation Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Morris, Minnesota 56267; and D. D. Warnes is an agronomist, West Central Agricultural Experiment Station, University of Minnesota, Morris, 56267.
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Results and discussion

Table 1 summarizes the date-of-planting study comparing early fall- and late-fall-planted spring water use. The midday evapotranspiration of the early fall-planted rye crop was consistently larger than the late-fall-planted rye through the early part of the season. Apparently, the additional time to establish the stand based on biomass and leaf area index data resulted in better carryover through the winter and more regrowth in the spring. However, due to the severe drought in 1988, early fall-planted rye ran out of water and had final evapotranspiration lower than late-fall-planted rye. These midday estimates of evapotranspiration compared with the bare soil measurements showed that rye could transpire a substantial amount of water. While there was a relatively high-evaporative demand, the changes in the soil-water content and visible wilt suggested substantial water stress. There was a difference in evapotranspiration between early fall-planted and late-fall-planted until the severe drought overrode the effects of water extraction. The beneficial effect of the rye cover crop for weed control was directly related to the amount of rye biomass generated *(5)*. Even on the final measurement day, the additional irrigation was not sufficient to enable adequate regrowth. The maximum evapotranspiration was 0.016 inches/hour.

Table 2 summarizes N uptake, leaf area index, and biomass of the winter rye cover crop in the tillage irrigation study. Noteworthy is the small rye biomass and leaf area that developed under the irrigated corn canopy as a result of shading. Some rye growth occurred in the nonirrigated plots with low crop-leaf-area index that enabled sunlight to penetrate. The largest amount of fall rye growth was in the irrigated soybeans that defoliated in early September, resulting in dry rye biomass of 740 pounds/acre and the largest total N content in the aboveground biomass of 27 pounds N/acre. Irrigation was the greatest factor in the fall rye N content, which ranged from 3% to 3.8% for irrigated plots and 5.1% to 5.7% for the nonirrigated plots.

The spring regrowth in 1989 showed a slightly different trend, with the maximum N uptake from the nonirrigated plots attributed to N not used by the previous crop when both irrigated and nonirrigated plots were fertilized the same. Rye on the irrigated treatments had N contents from 2.4% to 2.6%, while the nonirrigated treatments ranged from 4.7% to 4.8% N. The largest amount of N that accumulated, 33 pounds N/acre, in the spring regrowth was on the no-till, nonirrigated corn plot. The total amount of N was more directly related to the total aboveground biomass, which was larger in irrigated soybeans in the fall because of less light competition. However, in the spring regrowth, the largest amount of N was taken

Table 1. Summary of midday evapotranspiration, biomass, and leaf area index during spring regrowth of early and late fall-planted winter rye at Morris, Minnesota. Each value is the average of four replicates.

		Early Fall-Planted Winter Rye			*Late Fall-Planted Winter Rye*			*Bare Soil Evaporation*	
Date 1988	*Day*	*Evapotranspiration (inches/hour)*	*Biomass (pounds/acre)*	*Leaf Area Index*	*Evapotranspiration (inches/hour)*	*Biomass (lbs/acre)*	*Leaf Area Index*	*Smooth (inches/hour)*	*Cracked (inches/hour)*
April 15	106	0.004	730	0.93	0.002	146	0.26	0.0009	0.0048
April 20	111	0.003	689	0.80	0.002	160	0.26	0.0006	0.0027
April 29	120	0.008	968	1.08	0.006	323	0.53	0.0016	0.0035
May 5	126	0.010	1,206	1.24	0.008	414	0.63	0.0017	0.0040
May 12	133	0.014	1,436	0.86	0.013	896	0.98	0.0031	0.0047
May 19	140	0.006	1,829	1.07	0.010	1,175	1.12	0.0008	0.0023
May 19	140	0.016*	2,376*	1.17*					
May 19	140	0.015†	-	-					

*Early fall-planted winter rye irrigated 3 days previous. See text.
†Largest canopy of winter rye adjacent to study area that apparently experienced little stress.

Table 2. Summary of winter rye cover crop data in the tillage-irrigation study for 1988 and 1989, Morris, Minnesota. Each value is the mean of four replicates.

		Irrigated				*Nonirrigated*			
		Corn		*Soybean*		*Corn*		*Soybean*	
Date		*Conventional Till*	*No-Till*	*Conventional Till*	*No-Till*	*Conventional Till*	*No-Till*	*Conventional Till*	*No-Till*
August 18, 1988 (Day 231)		Broadcast Rye							
October 3, 1988 (Day 277)	Leaf Area Index	0.16	0.12	1.58	1.12	0.33	0.39	0.28	0.38
	N Content (%)	3.22	3.06	3.69	3.81	5.32	5.14	5.68	5.57
	Biomass (pounds/acre)	94	73	740	541	203	255	203	268
	Total N (pounds/acre)	3.0	2.2	27.2	20.7	10.7	12.9	11.7	14.9
		Winter							
May 9, 1989 (Day 129)	Leaf Area Index	-	0.38	-	0.54	-	0.91	-	0.63
	N Content (%)	-	2.55	-	2.37	-	4.68	-	4.81
	Biomass (pounds/acre)	-	287	-	430	-	705	-	451
	Total N (pounds/acre)	-	7.1	-	10.1	-	32.6	-	21.5
May 10, 1989 (Day 130)		Planted Next Crop							

up in the no-till, nonirrigated plots as a result of fertilizer carryover from the previous crop.

These limited data indicate less N accumulation under rainfed conditions and the limited potential of winter rye cover crops in the Northern Corn Belt. A winter rye cover crop can absorb about 30 pounds N/acre. A short growing season restricts rye biomass growth and N uptake; however, the practicality of using a rye cover crop will depend on other costs or regulations to maintain groundwater quality.

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Influence of fall tillage and cover crops on soil water and nitrogen use efficiency of corn grown on a Coastal Plain soil

D. W. Reeves and J. T. Touchton

The development of cropping systems that more effectively utilize N means that less N becomes available to degrade the quality of water resources. In the Southeast, coarse-textured coastal plain soils are subject to compaction by tillage, traffic, and natural consolidation by rainfall. This compaction limits crop productivity and consequently limits N use. Deep tillage has been reported to result in greater N recovery by corn (*Zea mays* L.) than conventional tillage on these soils *(1, 2)*. The authors attributed this effect to roots being able to access N that had leached below root-restricting hardpans.

Researchers also have used plants themselves to modify soil structure so that subsequent crops can more easily penetrate compacted zones, thereby increasing rooting depth and utilization of soil water and nutrients. Bahiagrass (*Paspalum notatum* Fluegge) sod grown prior to cotton (*Gossypium hirsutum* L.) increased seed cotton yields 179% in Alabama *(6)*. In Australia, lupin (*Lupinus angustifolius* L.) has been shown to act as a biological plow by leaving root channels through hardpans, enabling subsequent grain crops to more readily penetrate the compacted soil *(5)*.

The objectives of our study were to determine if cover crops adapted to the Southeast could by themselves or in combination with fall deep tillage (paraplowing), reduce soil compaction, increase crop growth and yield potential and thereby improve nitrogen (N)-use efficiency.

Methodology

We conducted the study for 3 years (1988-1990) on a Norfolk sandy loam (Typic Paleudults) in east-central Alabama. The site has a well-developed hardpan 7 to 13 inches below the surface.

Treatments consisted of fall tillage (disking or disking plus paraplowing) prior to planting winter cover crops of crimson clover (*Trifolium incarnatum* L.), rye (*Secale cereale* L.), 'Tifwhite-78' lupin (*Lupinus albus* L.) *(7)*, or fallow. Paraplow depth was 17 inches. We killed cover crops with a burndown herbicide 11 to 14 days before planting corn each spring. Planting dates were May 17, May 4, and April 10, respectively, for 1988, 1989, and 1990. Prior to planting corn, we disked the plots to a 4- to 5-inch depth. We subdivided cover crop plots and randomly assigned fertilizer treatments of 0, 50, 100, or 150 pounds N/acre. In addition to grain yield, we collected ear-leaf samples at midsilk for N analyses. We measured soil strength at the end of the corn growing season 4 inches from the row with a recording penetrometer. We measured soil-water content for a 2-week period, both prior to killing the cover crop and during tasseling-silking. These measurements were taken from the 0- to 8-inch, 8- to 16-inch, and 16- to 32-inch depths.

D. W. Reeves is a research agronomist, National Soil Dynamics Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Auburn, Alabama 36831-0792, and J. T. Touchton is head of the Agronomy and Soils Department, Auburn University, Auburn University, Alabama 36849.

Results

Rye and clover resulted in soil-strength increases in the 3- to 7-inch depth of from 3 to 5 bars compared with lupin and fallow (data not shown). The beneficial effect of paraplowing in reducing soil compaction in the 7- to 17-inch depth was still evident at corn harvest (data not shown). Paraplowing increased rye rooting depth, as evidenced by an average 47% decrease in soil-water content measured prior to burndown in the 8- to 16-inch depth compared with disking (data not shown). Both fall tillage and the cover crop affected soil-water content at tasseling; however, the effects varied with year and were inconsistent.

Although paraplowing the cover crop in the fall had a strong residual effect in decreasing soil strength, grain yields tended to be lower with paraplowing (Table 1). This was likely due to increased infiltration and leaching of N, as evidenced by reductions in ear-leaf N with paraplowing compared with disking (Table 1). The effect was greatest in 1989, with an extremely wet growing season. The fact that in 1990, following 9.8 inches of rain in a 48-hour period, soil-water content in the 8- to 16-inch depth increased from 20.1% to 27.1% in disked plots compared with an increase of from 19.7% to 28.9% in paraplowed plots demonstrates further evidence of increased infiltration in paraplowed plots. Other studies have demonstrated that paraplowing increases infiltration *(3, 4)*.

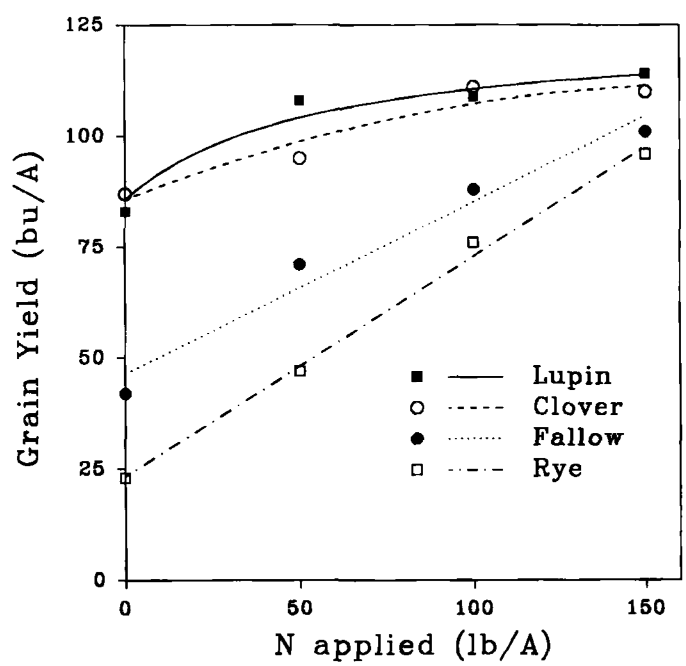

Figure 1. Three-year average (1988-1990) corn grain yield response to applied N, as affected by cover crop.

Table 1. Influence of cover crop tillage on corn ear-leaf N and grain yield.

	Ear-Leaf N (%)			*Grain Yield (bushels/acre)*		
Tillage	*1988*	*1989*	*1990*	*1988*	*1989*	*1990*
Disk	2.87	2.19	2.62	87	86	94
Paraplow	2.78	2.14	2.59	80	76	93
$P \leq$ *	0.09	0.01	0.57	0.36	0.13	0.60

*Probability that treatment differences are significant.

The two legume cover crops increased yields (Figure 1). Regression curves indicate that yield levels were optimized at between 50 and 100 pounds N/acre for clover and lupin and 150 pounds N/acre for rye and fallow. Based on grain yields and ear-leaf N data (data not shown), lupin compared favorably to crimson clover in N production. There was no tillage x cover crop interaction effect on grain yield.

Summary

The beneficial effect of paraplowing prior to planting a fall cover crop in reducing soil strength for a subsequent corn crop did not increase corn yield. Data suggest that increased water infiltration and N leaching from paraplowing offset any yield response from reducing soil strength. White lupin compared favorably to crimson clover in N production and resultant benefit to a corn crop. Nitrogen response and penetrometer and soil-water data, however, indicated that none of the cover crops acted as a biological plow.

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Relating nitrogen uptake by cereal grain winter cover crops to changes in groundwater nitrate concentration

K. W. Staver, R. B. Brinsfield, and W. L. Magette

Nitrate (NO_3) contamination of groundwater has been documented in most regions of the United States and Europe where nitrogen (N) fertilizers are applied *(4)*. In the Coastal Plain region of the Chesapeake Bay watershed, NO_3-N concentrations in shallow groundwater underlying agricultural areas often exceed 10 parts per million (ppm) *(5)*, resulting in elevated NO_3 loads in baseflow streams draining the region *(8)* and raising the potential for eventual contamination of deeper groundwater resources.

Researchers have identified reducing NO_3 transport into the Chesapeake Bay through groundwater-flow paths as essential to the restoration of bay water quality *(3)*, and this will require the development and implementation of practices that prevent NO_3 from entering subsurface flow systems. With cereal grain winter cover crops, researchers have demonstrated the ability to reduce NO_3 concentrations in upper-soil horizons *(1)*. However, relating this NO_3 uptake potential to changes in groundwater NO_3 concentrations requires consideration of water and solute storage in the vadose zone and unconfined groundwater, as well as separation of cover crop effects from other factors that influence groundwater NO_3 concentrations. In this study, we investigate changes in NO_3 transport through the vadose zone into shallow groundwater in response to a winter cover crop and the sampling considerations necessary to accurately assess winter cover crop effects on groundwater quality.

Methodology

Our research is an extension of a 5-year study investigating nutrient transport from corn production systems in the mid-Atlantic Coastal Plain *(7)*. Its primary objective is to evaluate the potential of cereal grain winter cover crops for reducing NO_3 leaching to groundwater *(2)*. Following the 1988 corn harvest, we planted a rye (*Secale cereale* L.) cover crop in an area that had been planted with corn for grain production since 1983. Soils in the study area belong to the Mattapex series of silty, moderately well-drained, and nearly level soils (0% to 3% slopes). The soil surface ranges from 13 to 20 feet above mean sea level. An unconfined aquifer underlies the research area at a seasonally variable depth of 3 to 13 feet below the soil surface.

We conducted stratified soil and groundwater sampling in and out of cover crop treatment areas during the 1988-1989

K. W. Staver and R. B. Brinsfield are researchers with the Department of Agricultural Engineering and Maryland Agricultural Experiment Station, and W. L. Magette is with the Department of Agricultural Engineering, University of Maryland System, Box 169, Queenstown, Maryland 21658.

recharge cycle. We compared results with those obtained from monitoring wells and lysimeters sampled since 1984.

Results and discussion

Growth of the rye cover crop during the fall and winter following the 1988 corn harvest removed more than 134 pounds N/acre from the soil profile, substantially reducing the soil NO_3 pool. Lysimeter samples collected at a 24-inch depth below the soil surface showed reduced NO_3 levels in the soil profile. However, NO_3 concentrations in samples from a network of shallow wells (5-foot screens centered 3 feet above sea level) actually increased during the 1988-1989 recharge cycle *(2)*. This lag time between changes in leaching rates and changes in groundwater NO_3 concentrations results from water and solute storage between the primary crop-rooting zone, where management practices, such as cover crops, have their immediate effect and the point at which groundwater samples are collected. Even in Coastal Plain systems, where the water table is relatively close to the soil surface, this storage can greatly exceed annual inputs.

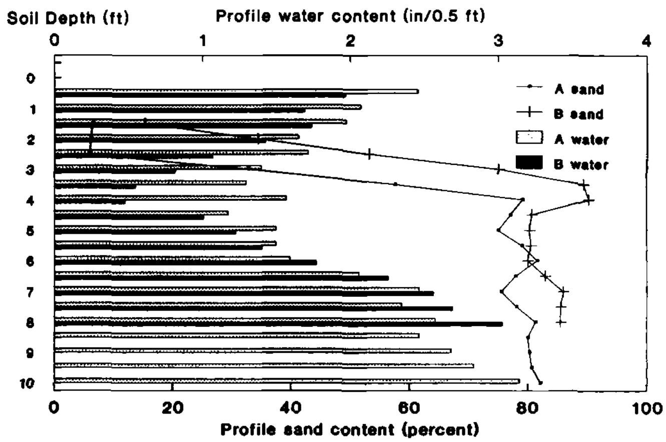

Figure 1. Profile sand (>63 microns) content and water volume in 6-inch increments to the water table at adjacent sites, 11-30-1988.

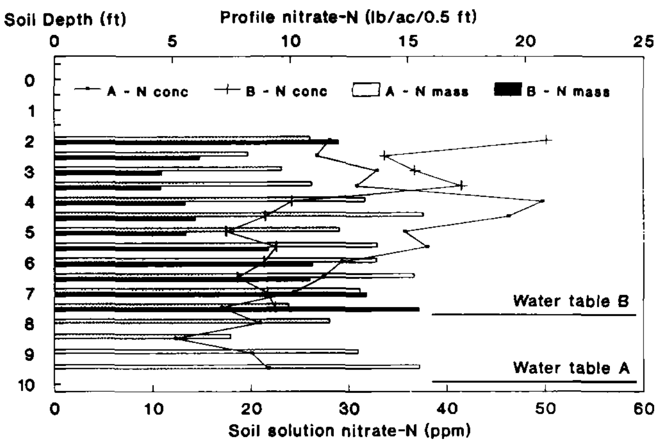

Figure 2. Soil pore-water NO_3 concentration and mass in 6-inch increments to the water table at adjacent sites, 11-30-1988.

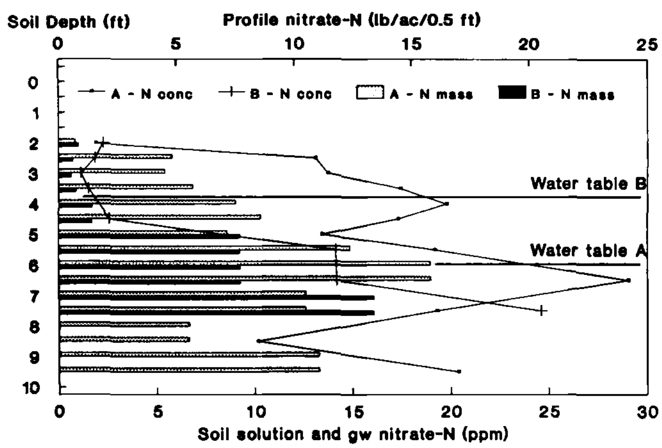

Figure 3. Nitrate concentration and mass in soil pore-water and groundwater in 6-inch increments at adjacent sites, 4-18-1989.

The thickness and water-holding capacity of the vadose matrix will determine total water storage and the potential for solute storage. For example, total water storage in the soil profile between 2 and 5 feet below the soil surface at adjacent sampling sites (site A located 109 yards up-grade of site B) differed by more than 3 inches as a result of textural differences (Figure 1). Although volume-weighted NO_3-N concentrations in the soil solution in this region of the soil profile were similar at the two sites (35.0 and 33.4 ppm at A and B, respectively), total NO_3 storage differed by 29.3 pounds/acre as a result of the difference in water-holding capacity (Figure 2). The additional 2 feet of unsaturated thickness at the up-gradient site held 10.9 inches of water and 46.8 pounds/acre of N. Total water and NO_3-N storage from 2 feet below the soil surface to the water table (10 feet at site A, 8 feet at site B) shortly after the cover crop planting date were 31.8 inches and 190.8 pounds/acre, respectively, at the up-gradient site and 18.5 inches and 102.3 pounds/acre at the down-gradient site. Thus, even if cover crop NO_3 uptake is capable of reducing NO_3 concentrations in leachate, leaving the root zone to low levels, mixing this leachate with NO_3-laden soil pore-water in the intermediate vadose zone will mask or delay the impact of reduced NO_3 leaching rates on groundwater NO_3 concentrations.

The buffering effect of NO_3 storage in the vadose zone on groundwater NO_3 concentrations was evident following the 1988-1989 recharge cycle, during which the water table elevation increased about 4 feet (Figure 3). At the up-gradient site, the total NO_3-N content between 2 and 10 feet below the soil surface on April 18 was 135.1 pounds/acre, a decrease of 55.7 pounds/acre from the November 30 sampling date. However, groundwater NO_3 levels showed little response, even just below the water table. At the down-gradient site on April 18, the NO_3 present between 2 and 8 feet below the soil surface was 62.2 pounds/acre, a decrease of 40 pounds/acre from the prerecharge sampling date. However, at this site groundwater NO_3 levels were highly stratified, being greatly reduced within 1 foot of the water table. Even at this site, where the water table is never deeper than 8 feet below the soil surface, it is clear that wells screened below the water table annual minimum elevation, or across a long vertical distance, would exhibit little response to changes in NO_3 leaching rates during a single-recharge cycle. The long-term groundwater monitoring network at this site consists of wells with 5-foot screens, centered about at the depth of the annual water table minimum depth. Thus, it is not surprising that samples from these wells exhibited no response to dramatic NO_3 uptake by a rye cover crop planted in the fall of 1988 during the ensuing recharge cycle *(2)*.

As the volume of water stored between the soil surface and the point of groundwater sampling increases, so to, will the time required to detect changes in leaching rates using groundwater sampling. This is apparent where the unsaturated region is thick *(6)*. But even in Coastal Plain systems, a water volume several times greater than the annual recharge volume can be stored in a relatively thin vadose zone. In addition, even minor topographical differences, or differences in the water-holding capacity of the unsaturated matrix, can significantly alter the total water and solute storage between the soil surface and the water table, thereby affecting how rapidly groundwater solute levels reflect events in the root zone. Tailoring sampling strategies in both time and space to water-storage patterns in the soil profile is essential to correctly relate groundwater quality data to specific conditions and events at the soil surface.

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Use of cereal grain cover crops for reducing groundwater nitrate contamination in the Chesapeake Bay region

R. B. Brinsfield and K. W. Staver

Since 1984, researchers at the University of Maryland Wye Research and Education Center *(1, 2, 3, 4)* have studied the influence of agricultural practices on nitrogen (N) loading to surface water and groundwater in the Chesapeake Bay region from agricultural watersheds planted to continuous corn. For surface waters, results indicate that although precipitation patterns can create orders of magnitude differences in surface runoff volume, annual loading rates for N are generally less than 4 pounds/acre for both conventional and no-till systems.

Results also show that leaching of N from the root zone to the unconfined aquifer is driven by hydrologic processes. During the growing season, high rates of water removal by the corn crop minimize percolation below the root zone, resulting in a declining water table and negligible N leaching rates. As crop uptake and evaporation rates decline following harvest, soil moisture levels increase, resulting in water moving through the root zone and eventually into groundwater (Figure 1).

Leachate samples collected from gravity-fed lysimeters located just below the root zone show high nitrate (NO_3) levels early in the recharge period followed by a steady decline as the available soil NO_3 pool decreases (Figure 2). As the water table rises, NO_3 concentrations increase to levels that routinely are greater than 10 parts per million (ppm) (Figure 3). Using mean-weighted-averaged concentrations of NO_3 entering the shallow groundwater, we calculated an average annual loading rate of NO_3-N of 18 to 27 and 16 to 24 pounds/acre for the conventional and no-till systems, respectively, for the 1986-1987 recharge period *(3)*.

Collectively, these results indicate that despite the use of best management practices, including no-till, splitting N applications, and fertilizing for realistic yields, N losses to groundwater result in groundwater NO_3 concentrations that consistently exceed the U.S. Environmental Protection Agency recommended maximum drinking water level. In addition, for the Chesapeake Bay region, where unconfined aquifers often intersect surface water bodies, lateral subsurface transport of NO_3 can make significant N contributions to surface streams adjacent to the bay *(5)*. Therefore, in addition to current best management practices, we need to develop other management practices that immobilize residual NO_3 left in the root zone following corn harvest.

A preliminary study reported by Brinsfield and Staver *(1)* showed that cereal grain cover crops planted in the fall following corn harvest can immobilize a large percentage of root-zone NO_3, thereby reducing the potential for NO_3 leach-

R. B. Brinsfield and K. W. Staver are researchers with the Department of Agricultural Engineering, Agricultural Experiment Station, University of Maryland System, Box 169, Queenstown, MD 21658.

ing to groundwater during the ensuing winter recharge period. Based on these preliminary results, a study was initiated in the fall of 1988 using the watersheds described by Brinsfield et al. *(2)* to (a) determine if NO_3 leaching from the root zone to shallow groundwater could be reduced using cereal grain cover crops, (b) evaluate the relative effectiveness of various small grain cultivars for N assimilation at different planting dates, and (c) determine the impact of cover crops on subsequent corn grain yields.

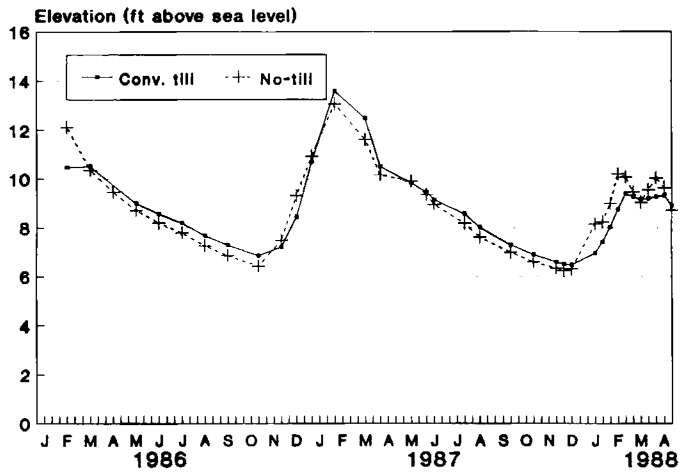

Figure 1. Average water table elevation.

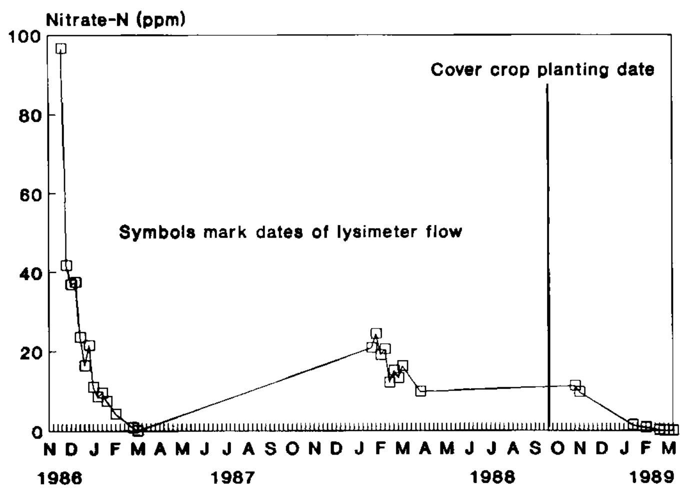

Figure 2. Average lysimeter NO_3-N concentration.

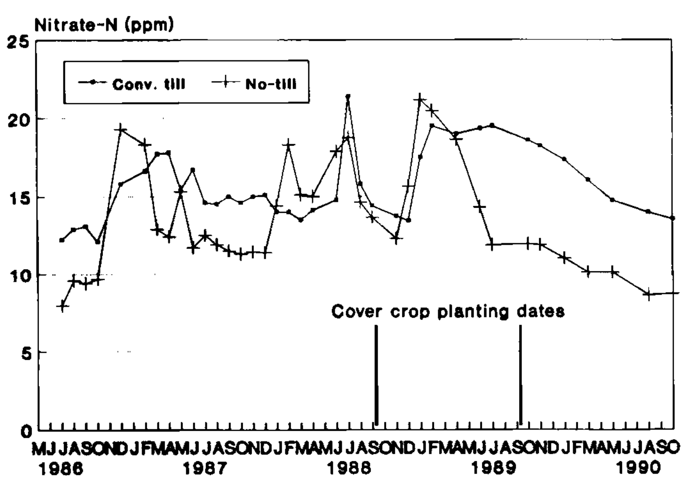

Figure 3. Average groundwater NO_3-N concentration.

Methodology

We no-till planted rye (*Secale cereale* L.) following continuous conventional and no-till corn harvest in 1988 and 1989 using the instrumented watersheds described by Brinsfield and associates *(2)*. Rye biomass production and N uptake, as well as soil-NO_3 levels to the water table, leachate from the root zone, and groundwater NO_3 concentrations, were routinely monitored through two corn production and groundwater recharge cycles. In addition, the relative effectiveness of the small grain cultivars, rye, wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), and barley (*Hordeum vulgare* L.) to assimilate residual root-zone N for two planting dates (mid-September and mid-October) was evaluated periodically by monitoring biomass production and tissue N content. Finally, we evaluated the impact of cover crop management on subsequent corn grain yields for both tillage systems.

Following corn harvest in the fall of 1988 and 1989, we no-till drilled a rye cover crop on 8-inch centers at a rate of 150 pounds/acre on October 1 into both the conventional and no-till watersheds. In addition, on October 1, October 15, and October 30, 1988, we no-till drilled rye at the same rate into 10-foot-wide strips within both the conventional and no-till watersheds to evaluate the effect of planting date on N assimilation and changes in root-zone soil NO_3 concentrations.

Results and discussion

For the conventionally tilled watershed, we observed total N assimilation by the rye cover crop of 161, 134, and 71 pounds/acre about 175, 160, and 145 days, respectively, after planting (Figure 4). For all three planting dates, soil NO_3 levels declined in a pattern that reflected N assimilation (Figure 5). However, changes in soil-NO_3 levels for the October 30 cover crop planting date were not significantly different than for the no-cover area, indicating the importance of planting cover crops immediately following corn harvest. Thus, for early planting dates, rye was able to remove substantial quantities of soluble N from the root zone before the onset of groundwater recharge.

Leachate samples collected prior to the onset of groundwater recharge in November 1988 were significantly lower in NO_3-N concentrations than for samples collected prior to recharge for the previous 2 years without cover crops (Figure 2). However, NO_3-N concentrations in groundwater did not decline significantly until the 1989-1990 recharge cycle (Figure 3). Beginning in January 1990, NO_3-N concentrations in shallow groundwater declined about 1 ppm each month through August. By October 1990, NO_3-N concentrations had declined from a maximum of about 20 ppm in January 1989 for both watersheds to 12 and 8 ppm, respectively, for the conventional and no-till watersheds. Deep soil cores taken periodi-

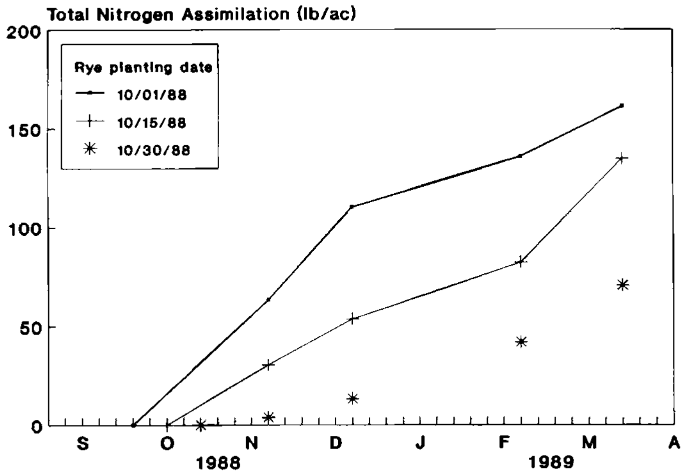

Figure 4. Rye cover crop nitrogen assimilation.

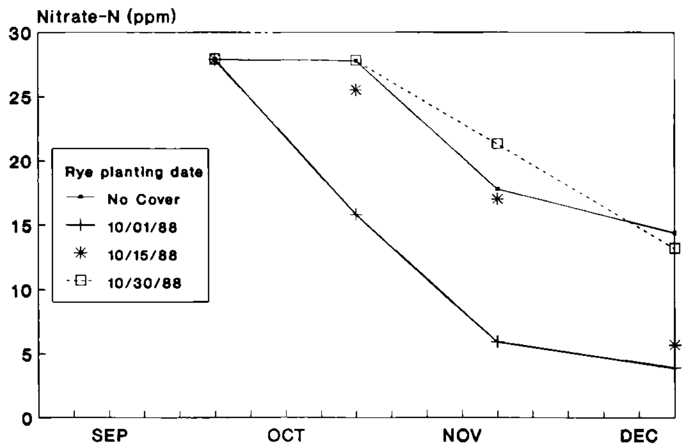

Figure 5. Average NO_3-N concentration (top 12 inches).

cally during the 1988-1989 recharge cycle provided further evidence of the ability of cover crops to immobilize the pool of soluble N left following corn harvest prior to the onset of recharge (Figure 6). We observed similar trends for the no-till watershed . However, residual root-zone N and consequently N assimilation by the cover crop were somewhat lower while corn grain yields were somewhat higher.

The relative ability of various cereals to assimilate root-zone N is highly influenced by planting date. Eighty-five days after the first planting date, N assimilation by the rye cover crop was about 116 pounds/acre compared with 27 pounds/acre for the second planting date, representing over a fourfold decrease in N uptake. We observed similar trends for the other cover crops considered, although N uptake for all other cereals was considerably lower than that observed for rye on both planting dates.

Ongoing studies of the impact of cereal winter cover crops on corn grain yields indicate that for currently recommended N fertilization rates, similar grain yields can be achieved in cover and no-cover treatments for both tillage systems, although spring management of the cover crop is critical.

In summary, our studies indicate that if managed properly, cereal grain cover crop (rye being most effective) incorporated into continuous corn production systems in the mid-Atlantic region can rapidly reduce soil and root-zone leachate NO_3 levels following corn grain harvest. The result is a downward trend in NO_3 concentrations in shallow groundwater.

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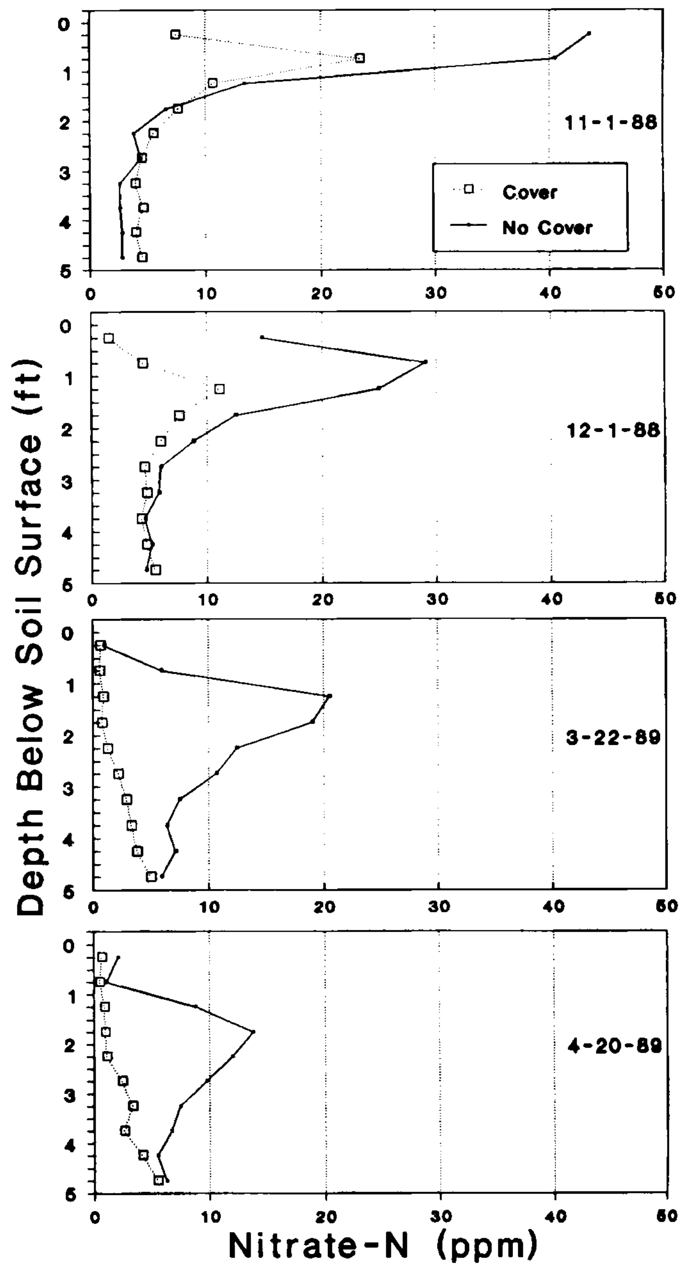

Figure 6. Average depth soil-core NO_3-N concentration.

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Cultivation of cover crops to control nitrate leaching

M. Smukalski, Jutta Rogasik, and Susanne Obenauf

For soil use that aims at minimizing environmental hazards, it is necessary that, in addition to well-balanced, soil-conserving rotational cropping and adequate arable management systems, fertilizer rates do not exceed real nutrient requirements of the crops and that the use of plant protection chemicals is radically restricted. Despite the progress made in computerized fertilization recommendations, marked differences occur in many years between the calculated and the actual nutrient quantities taken up by crops. The nitrate-nitrogen (NO_3-N) that cannot be accumulated in the soil is especially harmful.

Methodology

On the experimental field at Muncheberg, we grew oil radish, white mustard, phacelia, and yellow lupin to obtain experience in freeze-dying cover crops *(5)*. We used a loamy sand with a 6.1 pH, 60% organic carbon (C), and 5.4% total N. We applied 50-30-80 (N-P-K) fertilizer to the spring barley. Annual rainfall measured 21 inches and mean annual air temperature was 47^0 F.

Results and discussion

There can be several reasons why NO_3 is present in the soil after harvest of main crops: excessive amounts of N because of unreasonably high fertilizer rates; lower harvest yields than expected due to unfavorable environmental conditions and microbial mineralization of organic matter that is stimulated after harvest; and stubble breaking of cereal crops (Figure 1).

Growing catch crops is one way we can reduce the hardly predictable risk of excessive nutrient supply, and hence,nutrient leaching from the main root zone, and simultaneously minimize the need for herbicides, favoring biological weed control.

Catch crops counteract nutrient leaching directly by nutrient uptake and indirectly by increased water uptake as compared with evaporation of the bare soil. Thus, the soil is characterized by a relative water deficit that reduces water mobility (Figures 1 and 2).

A certain systemic effect of regular catch-crop growing in rotations is reached by stimulating soil biological activity and improving soil structure, leading to higher yields and, hence, a better nutrient use.

Catch crops that produce great shoot and root matter in a short period are especially suitable to protect the soil from nutrient leaching and weed infestation. With the view to nutrient uptake capacity, the following rank order has been established

M. Smukalski, Jutta Rogasik, and Susanne Obenauf are researchers at the Research Centre of Soil Fertility, Wilhelm-Pieck-Strasse 72, 0-1278 Muncheberg, Germany.

for catch crops *(4)*: cruciferae>gramineae>leguminosae.

In view of the ecological and economic constraints, arable farming today requires new approaches toward reducing tillage operations and herbicide use *(3)*. We must avoid operations that are not necessary. Thus, catch crops that are of importance are those that do not involve additional work and costs for clearing before sowing the succeeding main crop species. We met this demand by growing freeze-dying stubble crops together with conservation tillage, i.e., no-plow growing of the successive crop with and without mulching *(2)*.

Additional tillage operations and herbicide applications are required, however, when wintering catch crops are grown (stubble crops and underseeds).

Belowground and aboveground weight growth in juvenile oil radish plants is markedly higher than in mustard and phacelia plants (Figure 3). Hence, oil radish takes up NO_3-N much quicker and at much greater amounts, protected from leaching into the subsoil. Five weeks after sowing, we found the roots of oil radish and mustard to have grown down to a 16-inch depth, while that of phacelia and lupin were 12 inches deep (Figure 4). More than 50% of the total root mass is found in the 0- to 4-inch layer belowground. Weed suppression is directly dependent on the development of shoots and the completion of the plant cover and on the rate of water uptake from the topsoil (Table 1).

Analogously to the juvenile development, we found differences in root distribution, dry matter production, and nutrient uptake rate between the stubble crops also at the end of the growing season (Figure 4, Table 2). Oil radish shows highest

Table 1. Plant height and weed suppression of selected cover crops after 5 weeks of growth on loamy sand.

Cover Crop	*Plant Height*	*Weed Suppression Potential*
Oil radish	Medium-tall	Good
White mustard	Medium	Good
Phacelia	Medium	Medium-good
Yellow lupin	Moderate	Moderate

Table 2. Dry matter and N-uptake rate of selected cover crops at the end of October on loamy sand following spring barley.

	Dry Matter			*N-Uptake Rate*		
Cover Crop	*Shoot*	*Root*	*Total*	*Shoot*	*Root*	*Total*
	tons/acre			*pounds/acre*		
Oil radish	1.74	.54	2.28	113.8	20.8	134.5
Phacelia	1.07	.51	1.58	67.6	12.6	80.2
Yellow lupin	.98	.33	1.31	76.4	9.2	85.6

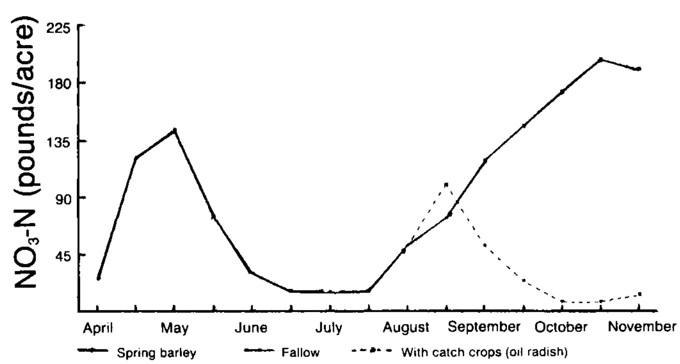

Figure 1. Nitrate contents (pounds/acre NO_3-N) of a loamy sand (0- to 24-inch depth) at and after spring barley cropping (1988).

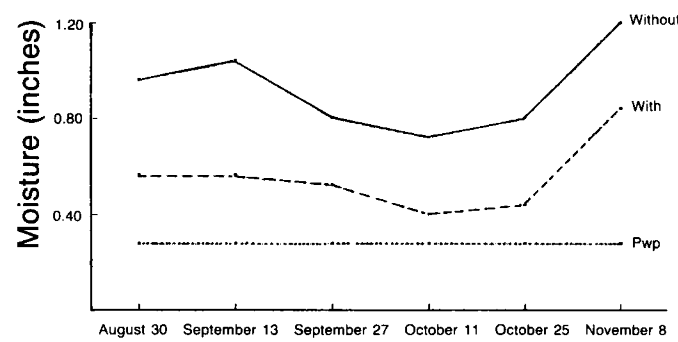

Figure 2. Soil moisture (inches) of a loamy sand after spring barley cropping with and without oil radish (0- to 12-inch soil depth). pwp = permanent wilting point.

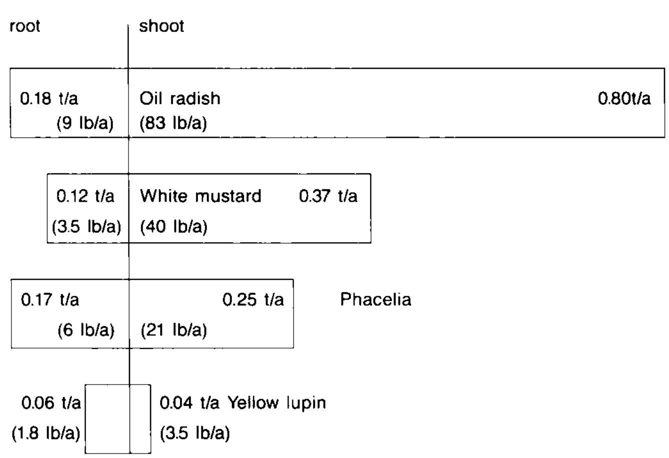

Figure 3. Dry matter production (tons/acre) and nutrient uptake rate (in parentheses in pounds/acre) of selected cover crops after a 5-week growing period on loamy sand with spring barley as the preceding crop.

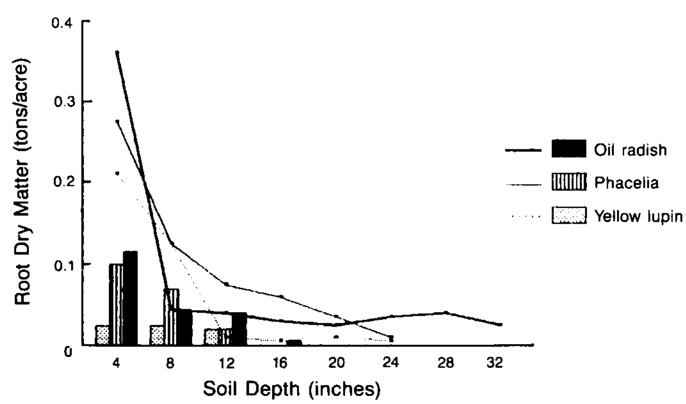

Figure 4. Root dry matter (ton/acre) in the soil profile of selected cover crops after a 5-week growing period (column) and at the end of October (line) on loamy sand.

N uptake rates due to the greater dry matter production and higher N contents of the plant dry matter. The N content is higher in the shoot than in the root mass; and the N content decreases in the roots with increasing rooting depth. In oil radish and phacelia, 85% of the total amount of N taken up is accumulated in the shoots, and the major proportion of the root N content (73% to 76%) is found in the upper part of the roots (0 to 8 inches belowground). Because mineralization processes are largely reduced at dormancy, the nutrients accumulated in the stubbles are mostly prevented from leaching in the winter season *(1)*.

As far as the costs are concerned (equipment and fertilizer prices), oil radish cropping is cheapest, followed by yellow mustard, phacelia, and yellow lupin.

Conclusions

Of the freeze-dying cover crops tested, we found oil radish and white mustard to be superior over phacelia in terms of growth vigor, dry matter production (root and shoot mass), N uptake potential, and suppression of weeds. Oil radish and white mustard can stand late-sowing dates and are easily grown on moderate and even poor soils.

Prerequisites for environmentally compatible stubble cropping of oil radish (adequate matter production and nutrient uptake potential) are a medium-plow furrow, or at least a shallow stubble furrow down to about a 6-inch depth *(5)*. Sowing deadline must be August 20.

Phacelia puts higher demands on seedbed preparation and soil-moisture content at plant emergence than the previously mentioned species. It is regarded as neutral plant species to soil-borne diseases and pests that are specific for the respective crop rotations. Phacelia produces less dry matter and takes up less nutrients than oil radish, whereas sowing costs are higher.

For weed suppression, complete stubble covers are required, which has to be considered in seed rating.

Yellow lupin is characterized by a good drought resistance after plant emergence. The weed suppression potential of that species is low due to its slow juvenile development. The high sowing costs justify its cultivation only as a fodder crop after early main crops. The self-sufficiency of lupin in N is the reason for its low nutrient-accumulation potential.

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