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EFFICIENT UTILIZATION OF POULTRY LITTER IN CASH GRAIN ROTATIONS

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Maryland Grain Producers Utilization Board
53 Slama Road
Edgewater, Maryland 21037

Delmarva Poultry Industry, Inc.
16686 County Seat Highway
Georgetown, Delaware 19947

Maryland Center for Agro-Ecology, Inc.
P.O. Box 169
Queenstown, MD 21658

Kenneth W. Staver

College of Agriculture and Natural Resources
Wye Research and Education Center
Box 169
Queenstown, MD 21658
410-827-8056
kstaver@umd.edu

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Ken Staver

University of Maryland, College of Agriculture and Natural Resources
Wye Research and Education Center
P.O. Box 169
Queenstown, MD 21658

Executive Summary

This report includes findings from a four year study that began April 1, 1998. Funding for the first three years of this project was split evenly between the Maryland Grain Producers Utilization Board (MGPUB) and Delmarva Poultry Industry, Inc. (DPI). The fourth year of the project was cofunded by MGPUB and the Maryland Center for Agro-Ecology, Inc.

Little field data currently exists in Maryland regarding the effect of poultry litter applications on nutrient losses, especially with regard to the role of different tillage systems. Reduced erosion achieved through reduced tillage has been credited with reducing phosphorus losses from cropland throughout the Eastern Shore with no consideration given to interactions between tillage and poultry litter applications. The primary objective of this project was to evaluate the effect of nitrogen-based poultry litter applications on phosphorus and nitrogen transport rates in tilled and no-till settings during a three crop/two year rotation of corn/wheat/double-crop soybeans. Two complete cycles of the rotation were completed. Poultry litter was applied in the spring (3 tons/acre) prior to corn planting and also in the fall (2 tons/acre) prior to wheat planning in 1998 and 2000. During the second year of the rotation, no additional poultry litter was applied but nutrient transport patterns were tracked during wheat/double-crop soybean production. To meet the project objectives poultry litter was applied to two fully instrumented field-scale watersheds where detailed studies have been conducted since 1984 of nutrient transport rates from cropping systems utilizing inorganic fertilizers. Substitution of poultry litter for inorganic fertilizer is likely to increase in the mid and upper Eastern Shore if phosphorus-based nutrient management is fully implemented in 2005 as is the current plan. Results from this study will be useful for developing management guidelines that help grain producers take full advantage of the nutrient content of poultry litter while at the same time minimizing nutrient losses associated with more widespread use of poultry litter on Eastern Shore cropland.

The primary findings of this study are:

1. Applying poultry litter (3 tons/acre) during no-till corn production resulted in a greater than fourfold increase in surface runoff phosphorus losses during summer months relative to where the same amount of poultry litter was incorporated prior to corn planting. Annual average dissolved phosphorus concentrations in runoff from the no-till watershed were greater than had been measured in any year since monitoring began in 1984. Although incorporating poultry litter did result in higher runoff sediment losses,

phosphorus losses associated with that sediment were no greater than sediment-bound phosphorus losses from the no-till watershed. The phosphorus content of eroded sediment tends to increase as sediment losses decrease. Incorporating poultry litter resulted in no discernible short-term increase in surface runoff phosphorus losses during summer months relative to past years when inorganic fertilizers were used.

2. Poultry litter applications during no-till corn production also increased summer surface runoff nitrogen losses approximately threefold relative to where poultry litter was incorporated prior to corn planting. The higher nitrogen losses were due in part to higher runoff volumes from the no-till watershed early in the growing season, but were also due to supplemental inorganic sidedress nitrogen applications that were necessary because of the low availability of nitrogen from the surface applied poultry litter.

3. Fall incorporation of poultry litter (2 tons/acre) prior to wheat planting had little apparent effect on short-term surface runoff phosphorus losses beyond those related to tillage. Dissolved phosphorus concentrations in runoff from the no-till watershed were actually reduced as a result of fall tillage in 1998 that brought lower-phosphorus soil to the surface. Due to slow development of the wheat crop erosion potential remained elevated well into the winter and particulate nutrient losses were higher as a result of fall tillage than spring tillage. Surface runoff nitrogen concentrations during wheat production were higher than those in previous years when cover crops were no-till drilled in both watersheds following corn harvest. Wheat nitrogen uptake accounted for a major fraction of nitrogen supplied by fall applied poultry litter as well as some of the residual nitrate from the previous corn crop. However, development of the wheat crop was not rapid enough to fully utilize the pool of available nitrate before winter groundwater recharge began. Water quality degradation associated with wheat production can be minimized by early planting which increases fall nitrate uptake and allows rapid development of sufficient surface cover to minimize winter soil erosion. The most striking effect of wheat production on water quality occurs during the following summer when both erosion and surface runoff nitrogen losses are greatly reduced relative to during corn production.

4. Even though nitrogen was only applied in one of the two years of the crop rotation used in this study, nitrate leaching rates increased relative to the previous decade when corn was grown every year. The increases were greatest where poultry litter was incorporated. Some of the increase in nitrate leaching apparently resulted from high soil nitrate concentrations that develop soon after poultry litter is incorporated prior to corn planting. With relatively low evapotranspiration rates and little crop nitrogen uptake this increases the potential for nitrate leaching. Even though applying poultry during no-till corn production increases the potential for surface runoff nutrient losses, the potential for late spring nitrate leaching is reduced relative to where poultry litter is incorporated. During previous corn production using inorganic fertilizer, most nitrogen was applied as a sidedress application after evapotranspiration rates had increased and just prior to maximum corn nitrogen uptake.

5. Even though no nitrogen was applied during the second year of the rotation, rye cover crops planted following double-crop soybean harvest reduced profile nitrate concentrations and took up significant quantities of

nitrate relative to the quantities necessary to raise groundwater nitrate-N concentrations to the drinking water standard (10 mg/L). It is likely that poultry litter applications during the first year of the rotation resulted in late season nitrate releases during the second year of the rotation that were higher than if only inorganic fertilizers had been applied. This suggests that fields with a history of poultry litter applications should be considered a priority for use of winter cover crops.

6. Ammonia losses resulting from not incorporating poultry litter increased the need for inorganic nitrogen applications and resulted in relatively low uptake efficiency of applied nitrogen. Projected losses of ammonia-N from surface applied poultry litter were approximately 45 lb/acre during the first years of the rotation. Corn responses to supplemental nitrogen suggest that losses may have been even higher. Uncertainty regarding nitrogen availability makes it difficult to determine supplemental nitrogen rates. Even though presidedress soil testing suggested adequate soil nitrogen to meet yield goals, it was apparent in both years of corn production that additional nitrogen would have increased grain yields. Available nitrogen from incorporated poultry litter appeared to be much closer to projected values.

7. Even though tillage can be used to reduce short-term surface runoff nutrient losses due to poultry litter applications, using poultry litter to meet a major fraction of nitrogen needs of both corn and wheat will result in a rapid increase in soil phosphorus levels unless the N:P ratio in poultry litter is increased. The poultry litter application rates used in this study added about 170 lb/acre of phosphorus above what was removed in harvested grain, resulting in an approximately 50 unit increase in the 0-8" soil phosphorus Fertility Index Value (FIV). In both watersheds soil test phosphorus increased from the optimum to excessive range. For the soils used in this study, the 0-8" FIV increased approximately 0.3 units for each lb/acre of phosphorus added to the soil. Although the soil phosphorus levels in the study watersheds are still relatively low compared to areas where there is a long history of poultry litter application, there was some evidence during the final year of this study that increases in soil phosphorus were contributing to higher dissolved phosphorus concentrations in surface runoff. A longer observation period will be needed verify any trend.

8. Results from this study clearly suggest that past projections of reduced phosphorus losses from Eastern Shore cropland as a result of reduced tillage, without consideration of nutrient application practices, has resulted in an overestimate of reductions in phosphorus losses from cropland. Independent of soil phosphorus concentrations, applying poultry litter in a no-till setting can dramatically increase surface runoff phosphorus losses. This study suggests that as implementation of phosphorus-based nutrient management encourages the transport of poultry litter to areas with relatively low soil phosphorus levels, the intended outcome of reduced phosphorus losses from cropland will not be achieved unless the potential for high phosphorus losses in no-till settings is considered.

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University of Maryland, College of Agriculture and Natural Resources
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Background

Water quality problems in the lower Eastern Shore tributaries have drawn attention to the possible effects of poultry production on nutrient transport from cropland. However, little direct evidence exists that establishes the relationship between poultry litter applications and water quality. At present it is not clear whether the primary effect of poultry litter applications on phosphorus transport is due to the resulting long-term buildup of soil phosphorus levels or the direct loss of phosphorus from the applied litter. Widespread adoption of poultry litter storage structures, nutrient management planning and reduced tillage has occurred since the Bay restoration effort began but the effects of these practices on phosphorus transport have not been well documented in settings where poultry litter is used to supply crop needs. Results from other studies suggest that these practices alone are unlikely to reduce phosphorus transport rates, and may even be leading to increased rates of phosphorus loss.

Long-term studies in low-relief agricultural watersheds on the Delmarva Peninsula have indicated that phosphorus losses occur primarily through transport of dissolved phosphorus in surface runoff (Staver and Brinsfield 1995). The potential for dissolved phosphorus transport is strongly correlated with soil phosphorus levels which are a function of long-term phosphorus fertilization rates relative to removal rates in harvested crops (Sharpley 1995). Currently, the majority of agricultural soils tested on the Delmarva Peninsula have soil phosphorus levels higher than needed for crop production, and an increasing trend in soil test phosphorus levels has been observed over the last several decades (Sims 1993). While a build-up of soil phosphorus levels can result from long-term application of inorganic phosphorus at rates higher than crop removal rates, the build-up is accelerated when animal manures, enriched in phosphorus relative to nitrogen, are applied to cropland at rates based on crop nitrogen requirements (Sharpley et al. 1994). Using animal manures to supply crop nitrogen needs can result in phosphorus being applied at rates more than three-fold greater than needed for crop production. Soil phosphorus levels many times greater than needed have been reported for fields with a history of poultry litter application (Mozaffari and Sims 1993). Currently, nutrient management practices being promoted in the Chesapeake Bay region recommend animal manure application at rates sufficient to meet crop nitrogen requirements. This approach has little potential to reduce or even stabilize soil phosphorus levels in the concentrated poultry growing regions on the Delmarva Peninsula. This will change when phosphorus-based nutrient management plans become mandatory in 2005, but currently proposed regulations suggest that, in the near term, much of the cropland on the mid and upper Eastern Shore will still qualify for nitrogen-based application rates of poultry litter.

The most direct strategy for preventing further increases in soil phosphorus levels will require balancing field phosphorus budgets so that phosphorus application rates do not exceed phosphorus removal rates in harvested grain. This will necessitate application of poultry litter based on crop phosphorus requirements. Unless phosphorus levels in poultry litter can be reduced dramatically, the land base needed to accommodate phosphorus-based application will be from three to five times greater than that needed using nitrogen-based application rates. Thus, balancing most poultry farm phosphorus budgets will not be possible without exporting a major fraction of the waste that is generated. Using a regional phosphorus-based nutrient management strategy in the Eastern Shore counties of Maryland will require applying poultry litter to most of the cropland used for grain production and substituting poultry litter phosphorus for almost all of the inorganic phosphorus currently used in the region (Staver and Brinsfield 2001). Although this strategy may stabilize soil phosphorus levels, given the current lack of knowledge regarding phosphorus transport patterns associated with poultry litter applications, it is not clear that applying poultry litter to three to five times more acreage will result in a reduction of nutrient losses from cropland.

A second concern regarding the current nutrient reduction strategy is the universal recommendation of no-till practices. While reduced tillage has proven to be an effective tool for reducing phosphorus transport from agricultural watersheds predisposed to high rates of soil erosion (Forster et al. 1985), the link between soil erosion and phosphorus transport on the Eastern Shore is less clear (Staver and Brinsfield 1995). Surface runoff dissolved nutrient concentrations are determined by the availability of soluble nutrient forms on or near the soil surface (Sharpley et al. 1995). Thus, even though reducing tillage minimizes the transport of particulate phosphorus, allowing phosphorus-rich material such as poultry litter to remain on the soil surface could greatly enhance surface runoff transport of dissolved phosphorus, and more than offset reductions in particulate phosphorus transport. Minimizing water quality impacts from poultry litter applications will require the development of management systems that minimize particulate nutrient transport without enhancing dissolved nutrient transport.

Objectives

The primary objective of this study was to evaluate the effect of poultry litter applications at rates based on crop nitrogen needs on phosphorus and nitrogen transport in tilled and no-till settings during a three crop/two year rotation. A secondary objective was to use findings to develop management recommendations for minimizing both phosphorus and nitrogen losses associated with the use of poultry litter to supply cash grain nutrient requirements.

Methodology

Study site description

This study was conducted at the Wye Research and Education Center in Queen Anne's County Maryland (38E 55' N, 76E 09' W). Soils within the experimental watersheds are classified within the Elkton, Matapeake, and Mattapex Series (Typic Ochraquults, Typic Hapludults, and Aquic Hapludults), which exhibit gentle slopes (0-3 percent) and a range in hydraulic characteristics from poorly- to moderately well-drained (USDA 1966). The soil surface ranges from 4 to 6 m above sea level and the water table is located at a seasonally variable depth of 1 to 4 m below the soil surface.

Agronomic practices

Corn was grown continuously in the experimental watersheds from 1984 through 1998. During this period conventional tillage (CT) practices were used in one watershed and no-till (NT) methods in the other. From 1984 through 1998 chisel plowing was the primary tillage operation in the CT watershed in conjunction with the use of a disk and field cultivator. Herbicides were used to control weeds in both watersheds following planting. Nitrogen in the form of urea-ammonium-nitrate (UAN) was applied at planting at a rate of 34 kg/ha (30 lb/acre) in a banded solution. A surface sidedress application of UAN was applied from 30 to 50 days after planting at an nitrogen (N) rate of approximately 123 kg/ha (110 lb/acre), except in 1989 when the sidedress application was reduced to 92 kg/ha. Generally, corn was planted in mid-May and grain was harvested in September. From 1984 through 1987 both watersheds remained fallow during the non-growing season. Following grain harvest from 1988 through 1997 a rye cover crop was no-till planted [188 kg/ha (3 bu/acre)] in both watersheds. Cover crop planting dates ranged from September 26 to October 16. Spring tillage or herbicide application generally occurred in early April when above-ground cover crop tissue carbon to N ratios (mass basis) were less than 30.

Phosphorus was applied in a solution with nitrogen at planting in both watersheds at a rate of approximately 25 kg/ha in a band 5 cm below and 5 cm to the side of the seed from 1985 through 1992. During the 1993 through 1997 growing seasons no phosphorus was applied. Following corn harvest in 1990, 6 m wide grassed (tall fescue) waterways were installed in both watersheds.

The rye cover crops in both watersheds were sprayed with glyphosate in early April 1998. On April 23-24, poultry litter (floor litter from a broiler house total clean out) was broadcast applied to both watersheds at a rate of 3 ton/acre. Both watersheds were flagged on 20 ft centers to ensure even distribution. The center of the first pass around the grass waterways was set back 16 ft to minimize application to the waterways. Individual samples were collected from every load of litter spread on the watersheds in April 1998 (Table 1). Each sample was analyzed through the manure testing program at the University of Maryland soil testing laboratory in College Park. Moisture content averaged 29.5 percent while total nitrogen and P_2O_5 averaged 3.98 and 3.21 percent, respectively. Overall, the composition of the 30 samples was relatively consistent with coefficients of variation ranging from 7 to 22 percent. Ammonia-N was the most variable constituent, due mostly to a very low reading for one sample (PL-9). Projected nitrogen availability averaged

48.9 lbs/ton for incorporated litter and 30.7 lbs/ton under no-till conditions. The CT watershed was disked the same day that poultry litter was applied and chisel plowed on April 27.

The CT watershed was disked just prior to corn planting on May 18. Corn was planted in the NT watershed on May 19. Starter fertilizer was applied in both watersheds as a liquid banded 5 cm to the side of the row and 5 cm deep at a rate of 15 lb N/ac and 6.5 lb P/ac. A pre-sidedress nitrate test was conducted by Queen Anne's county MCE on June 9. As would be expected due to incorporation of poultry litter, soil nitrate concentrations were higher in the CT watershed (36.9 ppm) versus the NT watershed (24.3 ppm). However, both readings suggested that no additional N was needed. Strips were maintained in each watershed throughout the study where no poultry litter was applied and inorganic fertilizer was used. In 1998, these strips received a starter fertilizer application of 32 lb N/ac and 14 lb P/ac, and a sidedress N application of 120 lb/ac.

Corn was harvested and stalks were chopped in both watersheds in late September. On October 5-6, poultry litter was applied using the same procedures and poultry litter source as in the spring, except that the application rate was 2 ton/ac. Both watersheds were disked the same day that poultry litter was applied. On October 12-16 both watersheds were moldboard plowed and disked. On October 20-22 wheat was planted in the no-till watershed and part of the CT watershed but planting was stopped due to dry soil conditions. Wheat planting was completed in the CT watershed November 13.

Topdress N applications to wheat were based on soil cores taken to a depth of 3 ft in late January 1999. Nitrate-N availability was approximately 34 lb/ac in the NT watershed versus 86 lb/ac in the CT watershed. As a result of the low N availability of N in the NT watershed 40 lb of N was applied on March 9 and again on March 31. A single N application of 20 lb/ac was broadcast sprayed on the CT watershed on March 31. Wheat was harvested June 25-29 and soybeans were no-till drilled in both watersheds July 1-3. Soybeans were harvested November 1-9, and a rye cover crop was no-till drilled in both watersheds November 9-15.

In 2000 this rotation was started again following nearly the same procedures and schedule. The poultry litter used was similar although contained slightly less available N (Table 2). Poultry litter was spread May 8-9, and corn was planted May 10-12. Starter P rates were the same as in 1998 (6.5 lb/ac) but a higher starter N rate was used in the NT (30 lb/ac) versus the CT (15 lb/ac) watershed. As in 1998 a presidedress nitrate test indicated no additional N was needed in the CT watershed, but results did suggest a need for a 40 lb N/ac sidedress N application in the NT watershed. As a result of questions that developed regarding N availability from poultry litter, some additional sidedress rates were applied in adjacent 6 row strips. Corn was harvested September 28 - October 6 and stalks were chopped. Due to wet conditions, poultry litter (2 ton/ac) was not spread until October 25. A different source of poultry litter was used and its N content was slightly higher than that of the litter applied in the spring (Table 3). Both watersheds were disked immediately after poultry litter was applied and chisel plowed the next day. This was a change from 1998 when a moldboard plow was used. Both watersheds were disked again just prior to planting of wheat on

October 30-31.

Due to wet conditions no late winter N applications were possible in the watersheds. Wheat in both watersheds was topdressed with N on April 5-6 at a rate of 60 lb/ac. Inorganic only strips were topdressed at an N rate of 80 lb/ac. Wheat was harvested June 26-29 and soybeans were no-till drilled beginning July 2. Wet field conditions prevented completion of soybean planting until July 17. Soybeans were harvested October 26-29 and a rye cover crop was no-till drilled in both watersheds during the first week of November.

Crop yields and nutrient uptake

Grain yields in the watersheds were estimated each year from combine yields from the same 1 ac blocks. In addition, yield data also were collected from the adjacent strips that were fertilized with poultry litter or exclusively with inorganic fertilizer. Additional fertility treatments were applied in the test strips but not all tissue nutrient parameters were measured in all years. Yield data were collected from three side-by-side blocks (10 ft x 80 ft for corn; 13 ft x 80 ft for wheat and soybeans). Corn residue and grain nutrient concentrations also were evaluated by collecting triplicate samples, each consisting of the above-ground portion of three whole corn plants. Grain was separated from the vegetative material to determine a grain to stover ratio so that combine grain yields could be used to estimate fodder nutrient levels at the time of harvest. Wheat sampling followed a similar procedure to determine nutrients in grain and straw. Because of leaf drop, no whole plant sampling of soybeans was conducted. Rye cover crop nutrient uptake was estimated by collecting six above-ground samples from each watershed just prior to burn down, each sample consisting of three adjacent 1 ft row sections. Plant samples were oven dried, weighed, and ground (0.1 cm; 40 mesh screen), and subsamples were analyzed for nutrient content using acid digestion and an ICP spectrometer.

Surface runoff

Edge-of-field surface runoff volume from the experimental watersheds was measured using calibrated flumes instrumented with flow meters connected to automated samplers. The flow measurement and sample collection systems were operational continuously throughout this project. Discrete samples were collected on specified volumetric intervals. Nutrient and sediment data from individual samples were volumetrically weighted to determine average runoff event concentrations and transport loads. Generally, the elevation of the flumes remained above the water table. Consequently, edge-of-field surface discharge from these watersheds occurs only in close association with precipitation. Samples were transported from the field immediately after each event to the analytical lab at WREC.

Surface runoff samples were analyzed for total suspended solids by filtering subsamples through a pre-weighed glass-fiber filter pad, which was reweighed after drying. Subsamples also were filtered through a 0.45 micron filter for analysis of nitrate, ortho-phosphate, and ammonium. Samples also were analyzed for total, and total dissolved (< 0.45 micron) N and P using a persulfate digestion (Valderamma 1981) followed by colorimetric analysis of phosphate content (Parsons et al. 1984) and nitrate analysis using high pressure liquid chromatography. Ammonium content also was determined colorimetrically.

Soil sampling

Soil sampling was used to track changes in soil phosphorus concentrations as a result of poultry litter applications, tillage, and crop uptake. Six sites in each watershed were identified in April 1998. These sites were in slightly different locations from the five sites that had been used from 1985-1998. These sites were sampled prior to poultry litter applications on April 13, 1998, and resampled October 2, 1998, July 15, 1999, May 8 and October 5, 2000, and October 30, 2001. On each date at each site five 2 cm diameter cores were collected to a depth of 30 cm using a push probe. Each core was divided into five depth intervals (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm). Five additional 5 cm cores were collected to provide sufficient soil in the shallowest two intervals for analysis. Samples were placed in a preweighed sealed polyethylene containers. Samples were stored briefly in coolers for transport to soil processing facilities at WREC where they were weighed and placed in forced air drying ovens at 40 EC. P content of these soils was determined on weighed subsamples extracted (Mehlich-1) and analyzed at the University of Maryland Soil Testing Laboratory in College Park.

Soil sampling to the depth of the water table was used to evaluate nitrate leaching at several points in the rotation. Soil samples were collected in close proximity to the same six sites in each watershed where shallow soil samples were collected. On each sampling date, samples were collected from the soil surface to the depth of the water table in 6 inch increments using a 2 inch diameter bucket auger. Samples were collected in the watersheds prior to poultry litter application in April 1998, and again September 1998, November 1999, April 2000, October 2000, and April 2002 at the end of the study. In addition, the same type of sampling was conducted on selected dates within the adjacent strips with and without rye cover crops.

All deep coring samples were weighed and placed in forced-air ovens immediately after collection. Samples were dried to a constant weight and reweighed to determine gravimetric water content. Nitrate analysis was performed colorimetrically on 2 M KCl extracts. Soil nitrate concentrations were calculated on both a soil (mg/kg dry soil) and pore-water basis ((mg/kg dry soil)/gravimetric water content).

Groundwater nitrate

Groundwater elevation and quality within the experimental watersheds were monitored using a network of 16 wells. All wells had 1.5 m (5 ft) screens centered approximately 2 m (6.5 ft) above sea level, which corresponded to the approximate position of the annual minimum elevation of the water table. The average depth to the top of the screened interval was 2.1 m in the CT watershed and 1.5 m in NT watershed. Elevation in the entire well network was measured weekly using a conductivity probe. Samples were collected from each well spring and fall throughout the study. One day prior to sampling, each well was pumped dry or three bore volumes of water were removed. Groundwater samples were analyzed for nitrate using high-pressure chromatography in the laboratory at WREC.

Results

Hydrology

Precipitation patterns varied widely from long-term averages during the four years of this study (Tables 4-8) resulting in extremes in both crop yields, surface runoff and groundwater recharge. In 1998 the growing season started with near average precipitation rates but from July through December precipitin was well below average every month and the total deficit for the second half of the year was over 32 cm. Precipitation during winter and early spring of 1999 was near average but from April 24 through June 12 rainfall totaled only 1.2 cm. Later in the summer rainfall was well above average, due in part to Hurricane Floyd that produced 16.7 cm of rainfall on September 16. Over 55 cm of rain were recorded in July and August 1999, more than was recorded during the first seven months of the year. In contrast to the first two years of this study, rainfall during the 2000 growing season was above average from May through July, creating near ideal growing conditions for corn. The winter of 2000-2001 was dry with below average precipitation in 6 of 7 months between October 2000 and April 2001. The summer growing season in 2001 also was wet, with May through August precipitation exceeding average levels by more than 23 cm. However, dry conditions returned in September 2001 and persisted through the end of this study in April 2002. For the 12 months from September 2001 through August 2002, precipitation was 41.9 cm below average.

Surface runoff volumes reflected the widely fluctuating precipitation patterns throughout this study. This study began following a high rainfall/high runoff period in late winter/early spring 1998 (Figs. 1 and 2). Rainfall in May and June 1998 following poultry litter application and corn planting was close to the long-term average and generated several runoff events. Similar to the pattern observed in past years, runoff volume from the NT watershed was approximately four times greater than from the CT watershed during May due primarily to the roughness of the soil surface in the CT watershed immediately after tillage. An additional contributing factor is the surface plant residue in the no-till watershed that tends to slow soil drying. As repeated rainfall smooths and seals the exposed soil surface the CT watershed, and corn water uptake rather than direct evaporation becomes the dominant mechanism of soil drying, the situation reverses (Staver and Brinsfield 1995a). During most of the growing season the extra soil surface residue in the no-till watershed helps reduce runoff by preventing direct raindrop impact on the soil surface and by slowing water flowing over the soil surface so that infiltration can occur within the field. In June runoff volume from the tilled watershed was approximately three times greater than from the no-till watershed. From July 1 through November 25, 1998 precipitation at the study site was 5.8 inches, nearly 12 inches below the long-term average for the period. No runoff occurred during this period, the longest period without runoff since monitoring began at this site in 1984. Although precipitation rates early in 1999 were near average, the large soil moisture deficits that had developed due to prolonged drought conditions during the second half of 1998 limited surface runoff from both watersheds. For the first year of this study (May 1, 1998 - April 30 1999) total precipitation was 75.5 cm, and total surface runoff was 4.15 cm and 3.76 cm from the CT and NT watersheds, respectively. Both values were approximately equal to the lowest values observed since monitoring began in 1984, and well below the 1985-2002 average annual precipitation depth (101.4 cm) and surface runoff volumes (CT 14.65 cm;

NT 14.23 cm).

Runoff continued to be limited through wheat maturation and harvest in 1999 but increased dramatically in August and September, the two wettest months in this four year study (Fig. 1). In September, Hurricane Floyd resulted in the single largest daily precipitation and runoff volumes since monitoring began at this site in 1984. Runoff during Floyd from both watersheds (CT 10.06 cm; NT 8.71 cm) was well above the total runoff volumes for the entire first year of this study, and represented approximately half of the total runoff during the second year of this study. Only limited runoff occurred through the end of 1999 and early 2000 but during late winter/early spring 2000 runoff volumes again were above average. March 2000 had the second highest runoff volumes from both watersheds from May 1998 through April 2002. Until tillage in May 2000, runoff volume from the CT watershed was consistently higher than from the NT watershed. The cause for this difference is unclear since management of two watersheds was identical after corn harvest in the fall of 1998 when the NT watershed was tilled for the first time since 1984. One possible explanation is that increased soil organic matter resulting from the long period without tillage enhanced soil structure and infiltration rates. Another possibility is that the tillage in the fall of 1998 reduced some compaction of the soil that had developed after 15 years of continuous no-till corn. For the second year of this study total precipitation was 128.8 cm, and total runoff from the CT watershed was 21.7 cm versus 17.0 cm from the NT watershed.

Precipitation patterns during the second cycle of the rotation were markedly different than during the first, being much more favorable for corn production in 2000. Approximately 34.5 cm of rain fell in June through August of 2000 versus approximately 19 cm for the same three months in 1998. The additional precipitation resulted in several major runoff events in mid-summer, and total runoff volumes between poultry litter application and corn harvest that were approximately four-fold greater than in 1998 (Fig. 2). As in 1998, runoff from the NT watershed in May (1.77 cm) was much greater than from the CT watershed (0.50 cm), but the case was reversed for the remainder of the growing season (June-September, CT 4.85 cm; NT 4.27 cm). After corn harvest in 2000, monthly precipitation remained below average through February 2001. Runoff through the 2000/2001 winter was consistently higher from the CT versus the NT watershed. During the third year of this study total precipitation was 103.9 cm generating total runoff of 11.0 cm from the CT watershed versus 10.5 cm from the NT watershed.

From May through August 2001 total precipitation (62.7 cm) was 23 cm above average. Major runoff events occurred in all four months, with runoff tending to be greater from the CT (10.30 cm) versus the NT (8.00 cm) watershed. The exception was in July when an intense, but very localized, storm moved through the study site. Even though the watersheds are located within the same field it was apparent from rainfall readings around WREC that as much as in additional 0.5 inches of rain fell on the NT versus the CT watershed. Following the wet period during the summer of 2001, below average precipitation rates prevailed from September 2001 through April 2002, resulting in a total deficit for the 8 month period of 28.6 cm. Despite these extremes precipitation for the fourth year of this study (100.8 cm) was near average (105.7 cm), generating total runoff volumes of 10.5 cm from the tilled watershed versus 8.1 cm from the NT watershed. For the entire four years of this study total precipitation was 408.9 cm generating total runoff volumes of 47.4 cm (11.6 percent) from the CT watershed and 39.3 cm (9.6 percent) from the NT watershed.

Groundwater recharge patterns also varied widely during the study as a result of the extremes in precipitation patterns (Fig. 3). Significant groundwater recharge following the 1998 growing season did not occur until early 1999 and late-winter water table elevations were the lowest observed at this site since monitoring began in 1984. In contrast, Hurricane Floyd was the start of a long period of consistently elevated water table conditions. From September 1999 through September 2001 water table elevations remained above the highest water table elevations recorded during winter 1998/1999. During August 2001 water table elevations actually reached typical late winter maximum elevations. Prolonged drought conditions began again in September 2001 and water table elevations during the winter of 2001/2002 were nearly as low as those in 1998/1999, and well below those in the previous summer.

Surface runoff nutrient transport

Despite consistently lower runoff volumes from the NT watershed on an annual basis, the tendency for tillage to temporarily reduce relative runoff rates in late spring, just after poultry litter application, contributed to markedly higher N and P losses from the NT watershed during corn production in 1998 and 2000 (Figs. 4 and 5). This was due in part to higher runoff volumes from the NT watershed but increased nutrient availability on the soil surface due to poultry litter applications also contributed to higher nutrient losses. The largest differences in runoff concentration were just after poultry litter was applied (Figs. 6 and 7). Volume-averaged P concentrations in runoff from the NT watershed during May through September were 3.85 mg/L versus 0.88 mg/L in runoff from the CT watershed. Average P losses in runoff from May through September in 1998 and 2000 were 1.46 kg/ha from the NT watershed versus 0.28 kg/ha from the CT watershed, even though approximately double the amount of sediment was lost from the CT watershed (36 kg/ha versus 17 kg/ha from the NT watershed) during this period (Fig. 8). Despite the reduction in bulk sediment transport from the NT watershed from May through October, particulate P transport was approximately three times greater from the NT (0.17 kg/ha) versus the CT (0.06 kg/ha) watershed. However, P transport in both watersheds during this period was dominated by the dissolved fraction, which comprised approximately 80 percent and 88 percent of total P transport from the CT and NT watersheds, respectively.

Nitrogen losses in surface runoff also tended to be higher from the NT watershed between spring poultry litter application and fall grain harvest, although the differences were restricted to May and June. In 1998, runoff N concentrations actually were higher from the CT watershed in May (Fig. 6). Poultry litter was applied and disked in on April 24. The CT watershed was then chisel plowed and left in a very rough condition until just before corn planting in mid May. Low intensity rainfall was recorded 11 of the first 12 days in May, but no runoff was generated until May 12 when high water table conditions resulted in near-saturation throughout the entire soil profile (Fig. 3). The dominant N component in runoff from the CT watershed was nitrate, with little loss of particulate N. Apparently, sufficient nitrification had occurred in the root zone to generate high nitrate concentrations in runoff. During May 1998 little nitrate was present in runoff from the NT watershed, but dissolved N concentrations were elevated. The higher runoff volumes from the NT watershed more than offset the higher total N concentrations from the CT watershed in May 1998. In 2000, a presidedress nitrate test indicated that additional N was needed only in the NT watershed. The additional surface application of inorganic N in June resulted in another spike in runoff dissolved N (Fig. 6) shortly after the application that was not observed in the CT watershed.

From May through September in 1998 and 2000 the volume-weighted average total N concentration in runoff from the NT watershed was 7.2 mg/L versus 2.9 mg/L from the CT watershed yielding average runoff total N losses from the NT watershed of 2.7 kg/ha versus 0.9 kg/ha from the CT watershed. Similar to the case for P, surface runoff N losses during the corn production part of the rotation were primarily in dissolved form from both the NT (81 percent) and the CT (75 percent) watersheds.

After both watersheds were tilled following corn harvest, runoff nutrient patterns were similar through the end of the rotation. Sediment loss was higher in the CT watershed following fall tillage than following spring tillage prior to corn planting (Fig. 8). The slow development of the wheat crop due to dry conditions in 1998 and wet conditions in 2000 left the soil exposed well into the winter in both years. Sediment loss from fall tillage through April of the next year averaged 355 kg/ha from the CT watershed versus 224 kg/ha from the NT watershed (Fig. 9), with most of the difference between the watersheds due to the approximately 25 percent lower runoff volumes from the NT watershed during this period.

Despite the higher sediment losses during the establishment phase of wheat production, total N and P concentrations and loads from the NT watershed were lower during this period than during corn production, primarily as a result of much lower dissolved nutrient concentrations (Figs. 10 and 11). The volume-weighted average dissolved P concentration in runoff from the NT watershed from October through April (0.54 mg/L) was less than 20 percent of the average during corn production (3.41 mg/L). The October-April runoff average dissolved N concentration from the NT watershed (3.24 mg/L) was approximately half of the average value during corn production (5.85 mg/L). Total and dissolved N and P concentrations in runoff from the CT watershed during October-April were very similar to those in runoff from the NT watershed. However, unlike the case for the NT watershed, there were not dramatic reductions in dissolved nutrient concentrations in runoff from the CT watershed relative to during corn production. As a result, the increase in particulate nutrient losses in the CT watershed associated with fall tillage contributed to higher total N (4.56 mg/L) and P (1.45 mg/L) concentrations in surface runoff relative to those during corn production (total N 2.93 mg/L; total P 0.88 mg/L). Dissolved P losses during October-April were approximately 40 percent of total P losses from both watersheds.

The absence of tillage and nutrient applications in the second year of the rotation resulted in very low sediment and particulate nutrient concentrations in runoff, and an absence of the spikes in dissolved nutrient concentrations associated with surface applications of soluble nutrient sources (Figs. 12 and 13). Dissolved P, and to a lesser extent N, concentrations peaked in both watersheds in mid-summer and fall in association with senescence of the wheat and soybean crops, but these peaks were minor compared to those associated with surface poultry litter applications or inorganic N sidedress applications to corn. This low potential of nutrient transport during this phase of the rotation is evident in the effect of the large runoff volume associated with Hurricane Floyd in September 1999 on overall nutrient losses (Figs. 14-17). Monthly runoff volume in September 1999 was approximately 22 percent of the total runoff volume during the four years of this study, but generated only about 5 percent of the surface runoff N losses and less than 10 percent of the P losses. In contrast, less than 5 percent of the total runoff volume from the NT watershed during the four years of this study occurred in May 2000 but associated N and P losses were approximately 20 percent of the four year total losses.

On an annual basis, average dissolved P concentrations were similar in both years of the rotation in runoff from the CT watershed, while average particulate P concentrations during the second year of the rotation were less than 20 percent of those in the first year. Dissolved N concentrations in runoff from the CT watershed during year two of the rotation were approximately one third of those in the first year so that both average dissolved and total N losses were approximately 30 percent less than during the first year of the rotation. These lower runoff N losses occurred even though runoff in year two averaged more than double the volumes in the first year of the rotation.

The differences between surface runoff dissolved nutrient transport patterns in year one versus year two of the rotation were even more dramatic in the NT watershed. Volume weighted dissolved P and N concentration in year two were 28 percent and 20 percent of those in year one, respectively. Particulate N and P concentrations also were lower in year two, resulting in annual average total N (1.7 kg/ha) and P (0.88 kg/ha) loads that were less than half of N (4.30 kg/ha) and P (1.92 kg/ha) loads in year one, even though average annual runoff volume in year 2 was 76 percent greater than in year one. In both watersheds approximately two thirds of total N losses and 82 percent of P losses were in dissolved form during the second year of the rotation.

Poultry litter effects on annual surface runoff nutrient losses

Although annual differences in precipitation patterns complicate direct comparisons of inter-annual runoff nutrient losses, the application of poultry litter and the changes in the crop rotation that were part of this study caused major changes in average annual surface runoff nutrient concentrations, particularly in the NT watershed. Apparent changes in runoff nutrient transport from the CT watershed appeared to more linked to tillage effects associated with adding wheat production and no-till double crop soybeans to the rotation. The effects on annual nutrient loads were less apparent due to annual variation in runoff volume. Annual precipitation and runoff volumes in the 1998 cropping year (May 1, 1998 - April 30, 1999) were very close to being the lowest recorded since monitoring of runoff from these two watersheds began in 1984 (Fig. 18). In contrast, precipitation during the 1999 cropping year was the highest recorded in 20 years, and runoff volume was well above the long-term average. During the second cycle of the rotation precipitation and runoff depths were much closer to average, even though there was great intra-annual variability. From 1985-1997 differing tillage practices were maintained in each of the watersheds making it difficult to directly compare the intrinsic runoff potential of the two watersheds. In the second and fourth years of this study when both watersheds were managed identically, the consistently lower runoff volumes from the NT watershed suggest an inherently lower potential to generate runoff, unless the lower runoff volumes were due to latent effects of no-till practices during previous corn production.

Despite the very low runoff volumes in the 1998 cropping year, the additional tillage associated with wheat planting resulted in the highest annual soil losses measured since grassed waterways were installed in both watersheds in the fall of 1990 (Fig. 19). However, as sediment transport rates increased, the nutrient content of eroded particles decreased. Both the N and P concentration of sediment eroded from the NT watershed in 1998 decreased to levels very similar to those in the CT watershed. In contrast, during the second year of the rotation the absence of tillage in the CT watershed reduced sediment losses to the lowest levels recorded in the past two decades, but increased sediment nutrient concentrations to higher levels than had previously been observed. The decrease in the nutrient content of eroded sediment as soil loss rates increased dampened the effect of increased soil losses on particulate nutrient losses. Thus, while fall tillage for wheat production increased sediment transport in surface runoff, the associated increase in particulate nutrient transport was proportionately much less.

While tillage changes associated with adding wheat and double-crop soybeans to the rotation greatly affected sediment transport, the most apparent short-term effect of substituting poultry litter for inorganic fertilizer was on dissolved nutrient transport during no-till corn production. Even though average annual surface runoff dissolved N and P concentrations for 1998 and 2000 (May 1-April 30) included runoff that occurred after fall tillage that had much lower dissolved nutrient concentrations, annual average dissolved N and P concentrations were higher than in any of the previous 13 years of no-till corn production (Figs. 20 and 21). For N, some of the increase in average annual dissolved N concentrations were due to higher runoff N concentrations during wheat production, relative to previous years when no N was applied in the fall following corn production (Figs. 10 and 22). However, for P dissolved concentrations following fall tillage in 1998 and 2000 were similar to those in 1993-1997 when no P was applied to the fields (Figs. 11 and 23). In 1999, the absence of any surface N applications resulted in the lowest average annual surface runoff dissolved N concentrations measured since 1985 in either watershed. For P, average dissolved P concentrations in 1999 in runoff from the NT watershed were the lowest recorded to date, while average concentration for the CT watershed was similar to those in previous years. Apparently the effects of moldboard plowing in the fall of 1998, which buried surface residue and brought soil with a lower P content to the surface in the NT watershed (see soil phosphorus section below, Fig. 29), carried over through the 1999 cropping year. During the second cycle of the rotation annual average runoff P concentrations suggested that increasing surface soil P concentrations were starting to affect runoff P concentrations, especially in the CT watershed where average dissolved P concentrations in 2000 and again in 2001 were the highest measured to date (Fig. 21). In the NT watershed, average dissolved P concentrations in 2001 also were much higher than in 1999. Part of this increase most likely was due to the lower runoff volume in 2001 versus 1999, which tends to increase average nutrient concentrations (large runoff events such as those associated with Hurricane Floyd in 1999 tend to have low nutrient concentrations). However, unlike in 1998 when fall moldboard plowing brought soil with a lower P content to the soil surface, the same effect could not be achieved in the fall of 2000 because of an overall increase in P concentrations through the entire plow layer (see soil phosphorus section below, Fig. 29). While the effects of using poultry litter and changing the rotation are not apparent in total annual surface runoff N or P losses from 1998-2001 (Figs. 20 and 21), the dissolved P losses from the CT watershed in 2001 were nearly as high as any observed previously despite below average runoff volumes and no P applications. Longer-term observation will be necessary to better establish management effects on nutrient loss rates under a full range of weather conditions.

Crop yields and nutrient uptake

Corn yields and nutrient uptake were markedly different during the two cycles of the rotation (Tables 9 and 10). In 1998, drought conditions from mid July through the end of the growing season reduced corn grain yields to approximately half of the yield goal of 140 bu/acre. Despite the apparent effect of limited soil moisture on yield, N availability also appeared to limit corn yield especially in the NT watershed. This yield limitation occurred despite presidedress nitrate test results suggesting that no additional N was needed. Yield, grain N concentration, dry matter production and fodder N concentration all were lower in the NT poultry litter treatment compared to adjacent strips where 158.9 kg/ha of inorganic N was applied and also compared to both inorganic and poultry litter treatments in the CT field. Poultry litter test results indicated that approximately 92 kg/ha of N would be available from the surface application of poultry litter so the evidence of N limitation of yield at such low yield levels is somewhat surprising. Although not as severe, N availability in the tilled field also seemed to be less where poultry litter was used rather than inorganic N, even though N availability was projected to be nearly identical in the inorganic versus poultry litter treatments. Of the approximately 250 kg/ha of N applied in the spring of 1998 to both watersheds only 63.4 kg/ha and 112.7 kg/ha in the NT and CT watersheds, respectively, were accounted for in above-ground corn biomass at harvest. Even less N was removed in harvested grain. The approximately 50 kg/ha difference in above-ground N uptake between the NT and CT treatments is approximately equal to the projected difference in N availability from poultry litter incorporated versus surface applied. Despite this apparent inefficiency in N use, tissue and grain N concentrations did not indicate that soil plant available N levels were excessive. In addition, soil sampling (discussed in later section) also did not suggest excessive leaching or unusually elevated root zone nitrate levels following harvest.

The 2000 growing season was ideal for corn and yields were more than double those in 1998 and well above the yield goal of 140 bu/acre. In the adjacent test strips comparing inorganic and poultry litter, there once again were apparent effects of N availability on yield. As in 1998, grain yields and N concentration, and fodder N concentration were higher in inorganic treatments versus where poultry litter was applied. The poultry litter applied in 2000 was projected to supply somewhat less N than the litter applied in 1998 (Tables 1 and 2). Presidedress nitrate testing again indicated that no additional N was needed but a sidedress N application (44.4 kg/ha) was applied to the no-till watershed to compensate for the lower N availability from the poultry litter and to make total N availability approximately equal to that in the inorganic only test strips. An additional 16.8 kg/ha of starter N also was applied in the NT watershed. Despite the additional N applications to the NT watershed in 2000, total N availability appeared to be less than in the CT watershed. Yields in the inorganic only test strips in both tillage systems were similar and approximately 30 bu/acre greater than in the adjacent poultry litter test strips.

Overall N use efficiencies were much higher in 2000 than in 1998. Total N uptake in both NT (192.7 kg/ha) and CT (204.2 kg/ha) inorganic test strips in 2000 substantially exceeded applied N (156.9 kg/ha). Total N uptake in the watersheds exceeded projected plant available N but was somewhat less than total N applied in the litter. The primary difference in uptake between 1998 and 2000 was in the N content of the grain as fodder N content was only marginally higher. The drought condition in 1998 came late in the growing season during grain development but after the vegetative component of the crop was nearly fully developed. In 2000, N removed in grain exceeded 80 percent of applied N except in the NT poultry litter system (63 percent). However, yield patterns suggest that N availability was over estimated in that system, reducing the calculated removal efficiency. Total N uptake per unit of grain production was much lower in 2000 versus 1998, and again was lowest in the NT poultry litter system, indicative of much lower N availability.

Additional N treatments were added in the test strips in 2000 to determine whether yield differences were N related (Table 11). Where no additional N (other than 33.6 kg/ha of starter N) was applied in the no-till system other than poultry litter, grain yield and N concentration and fodder tissue N all were lower than where supplemental sidedress N was applied. Grain yield and N parameters all increased up to the maximum N rate of 123.2 kg of inorganic N in addition to poultry litter. The highest rate resulted in grain yield and tissue N concentrations that were similar to the inorganic treatment where a total of 156.8 kg/ha of N was applied. This also suggests that considerably less N was available from the surface applied poultry litter than projected. In the CT test strips an additional 44 kg/ha N application increased grain yields and tissue N levels to those in the inorganic only treatment. The projected N supply in the CT poultry litter system (including 16.8 kg/ha of starter N) was approximately 128 kg/ha so it is not surprising that additional N was needed to bring availability up to the same level as in the inorganic treatment. Since the yield goal was exceeded in the CT watershed and nearly achieved in the NT test strips with no sidedress N application, the presidedress test results were accurate for the stated yield goal.

Wheat yields were less variable than corn yields in the two cycles of the rotation (Tables 9). Despite the slow development of the wheat crop in the fall of 1998 due to dry conditions, favorable conditions early in 1999 resulted in yields that exceeded the target yield of 80 bu/acre. Soil sampling was conducted just after corn harvest in 1998 and again in January 1999 to help determine N application rates. The soil sampling prior to fall poultry litter applications indicated higher nitrate-N availability in the top 30 cm of the profile in the CT (43.1 kg/ha) versus the NT watershed (20.6 kg/ha), and relatively little nitrate in the 30-90 cm depth interval in the NT watershed that could be used by the following wheat crop (Fig. 24). Sampling in late January 1999 indicated adequate nitrate-N availability in the CT system (96.7 kg/ha in the upper 90 cm) but lower availability persisted in the

NT system (38.3 kg/ha) even though poultry litter applications and tillage were identical in both systems in the fall of 1998. To compensate for the limited N availability in the NT watershed, N was applied on March 9 (44.8 kg/ha) and again on March 31 (44.8 kg/ha) while N was applied to the CT watershed (22.4 kg/ha) on the later date.

Yield and tissue N parameters were similar in the 1999 wheat harvest in both watersheds as well as in the inorganic test strips (Table 9) suggesting that N availability was similar and adequate in all treatments. The N content of harvested grain was approximately equal to N applications in the inorganic only treatments. Total N uptake in the CT inorganic only treatment (126.5 kg/ha) was nearly double the applied N while in the NT poultry litter treatment projected N availability from the fall poultry litter application (97.8 kg/ha) in combination with the supplemental inorganic N (89.6 kg/ha) was well in excess of above-ground N content at harvest (149.8 kg/ha). Grain yields were approximately 10 percent higher in the poultry litter versus the inorganic only treatments, probably as a result of additional N availability in the fall and early winter. Additional N treatments were included in the test strips although tissue N parameters were not measured (Table 11). Grain yield where poultry litter had been applied, but no supplemental inorganic N, was only slightly less (86.1 bu/ac) than where an additional 89.6 kg/ha of inorganic N had been applied (92.4 bu/ac). Apparently, much of the N supplied by the poultry litter was mineralized in the spring and was not evident in the January soil testing. Yields in the NT inorganic treatments where no N was applied (50.1 bu/ac) were well below yields in all other treatments, but did indicate significant soil nitrate availability following corn production under drought conditions in 1998. Wheat yield in the CT inorganic only treatment without additional N (73.2 bu/ac) also indicated elevated soil nitrate following corn production in 1998, and the overall higher N status of the CT system during the first cycle of this rotation.

Grain N concentrations in 2001 were approximately 10 percent higher than in 1999 but total N uptake was less due to lower grain yields and straw production (Table 9). Both watersheds were fertilized the same, receiving a single supplemental N application (67.2 kg/ha) on April 5. As in 1999, yields in the inorganic fertilizer only test strips were lower than where poultry litter had been fall applied. Both grain and straw N concentrations also were higher in the poultry litter treatments. Additional N treatments (Table 11) suggested overall lower N availability relative to 1998/1999, probably as a result of much higher soil N removal rates by corn in 2000 versus 1998. The poultry litter used in 2000 also had a lower N content than did that used in 1998 so that approximately 75 kg/ha more N was applied in 1998 versus 2000. The NT inorganic only test strip with no additional N yielded only 34.1 bu/acre and the poultry litter treatment with no supplemental N yielded 57.5 bu/acre versus 86.1 bu/ac in 1999. The CT poultry litter test strip where no additional N was applied yielded 51.5 bu/ac suggesting that there was little difference in N availability between the two tillage systems. Grain and fodder N concentrations, and calculated total above-ground N content at harvest values (CT 1.43 lb/bu; NT 1.46 lb/bu) were highest in the treatments receiving the greatest N inputs.

No major differences in double-crop soybean yields were apparent between the two tillage systems or nutrient sources (Table 9). Due to the high N content of soybeans (approximately 6 percent), N removal in harvested soybeans was the primary N removal term in both cycles of the rotation. During the first cycle when corn yields were limited by drought, the N content of harvested soybeans exceeded combined N removal of the preceding corn and wheat harvests. Even in the second cycle of the rotation when corn yields were well above yield goals, soybean N content was well in excess of that removed in corn harvest. Although soybean N fodder data was not collected, previous studies at the site (Staver and Brinsfield 1998) have indicated an above-ground soybean fodder N content at leaf drop of approximately 1 kg/bu of harvested soybeans. This suggests above-ground N content of the soybean crop in excess of 200 kg/ha in both watersheds during both cycles of the rotation.

A total of 806 kg/ha of N was applied to the watersheds in poultry litter. Additional inorganic N applications totaled 123 kg/ha in the CT watershed and 252 kg/ha in the NT watershed, giving combined N applications of 929 kg/ha in the CT watershed and 1058 kg/ha in the NT watershed. Projected reductions in N availability from the unincorporated poultry litter applied for corn production in the NT watershed indicate N volatilization of approximately 95 kg/ha, or approximately 15 lb/ton from the 6 tons/acre that were applied prior to corn planting in 1998 and 2000. Plant available N (inorganic plus available from poultry litter) totaled 565 kg/ha in the CT system and 598 kg/ha in the NT system. Total N applications to the inorganic only test strips were 471 kg/ha in the CT system and 493 kg/ha in the NT system.

Nitrogen removal in harvested grain totaled 671 kg/ha in the CT watershed and 656 kg/ha in the NT watershed of which approximately half was in corn/wheat and half in soybeans. N removal in grain harvested in the inorganic only treatments totaled 712 kg/ha in the CT system and 684 kg/ha in the NT system. Calculating rotational N use efficiency depends on how soybean N parameters and poultry litter N availability are handled. The most straightforward case is for the corn/wheat part of the rotation in the inorganic only treatments. In 1998, N removal in corn grain harvest accounted for 47 percent and 35 percent of the applied N in the inorganic only treatments in the CT and NT systems, respectively. For wheat, N removal in grain harvest actually exceeded applied N in the CT system and was 93 percent of applied in the NT system. Combined N uptake efficiency for the corn/wheat part of the rotation was 70 percent in the CT system and 56 percent in the NT system. Higher corn yields in 2000 increased the fraction of applied N accounted for in grain harvest to 90 percent in the CT system and 82 percent in the NT system but for wheat the values were slightly lower than in 1999 (CT 75 percent; NT 72 percent). Combined corn/wheat efficiency in the second cycle of the rotation was 85 percent in the CT system and 78 percent in the NT system. For both cycles of the rotation corn/wheat harvest accounted for 78 percent of the applied N in the CT system and 67 percent of the N applied to the NT system.

Since poultry litter application rates were intended to supply quantities of plant available N similar to those in the inorganic only treatments, uptake of estimated plant available N was similar to that in the inorganic only treatments. Overall N uptake efficiency in the corn/wheat parts of the rotation were much lower when total poultry litter N inputs were considered, especially in the NT system were additional inorganic N was applied to compensate for volatilization losses. Corn/wheat grain harvest accounted for

36 percent of the total N applied in the CT watershed and only 30 percent of the N applied to the NT watershed. Including N removal in harvested soybeans increases the overall N use efficiency but it is difficult to determine the exact fraction of total removal that should be considered net removal. Other studies at the site have shown that soybeans readily use most of the soil nitrate that is available during the growing season (Staver 2001). Since the N contained in the fodder is returned to the soil, net removal can be estimated as the difference between nitrate uptake and total fodder N content. Although neither were measured directly in the CT and NT systems, intense soil sampling in 1998, 2000 and 2002 in a nearby field with a similar soil type indicated total nitrate supply from the soil during the summer growing season of approximately 120 kg/ha (Fig. 25). Since approximately 5 ton/acre of poultry litter were applied to both watersheds in the year prior to soybean production it is likely that soil nitrate availability was at least as great as indicated by the fallow soil sampling. Using previously estimated soybean fodder N values of 1 kg/bu of harvested grain indicates that net removal of soil N in soybean harvests in 1999 and 2001 was approximately 80 kg/ha, or approximately half of the N content of the harvested beans. Including soybean net N removal estimates increases net recovery of applied N in harvested crops to approximately 53 percent in the CT watershed and 45 percent in the NT watershed for the entire four years of the study. Using similar estimates for soybean N removal in the inorganic only treatments suggests net recovery of nearly all the applied N in harvested grain during the four years of the study.

In the watersheds the net addition of N to the system was approximately 400 kg/ha. Assuming constancy of soil C:N at 10:1 (Brady 1984), this additional N would be sufficient to support an increase in soil organic matter of approximately 8000 kg/ha or a 0.2 percent increase in soil organic matter expressed on a whole soil basis (2.0 to 2.2 percent). Since other losses of N occurred (volatilization and leaching), net N accrual and organic matter increases were likely somewhat less than estimated as possible. However, given that poultry litter is sawdust based, and over 22,000 kg/ha were applied during the study, increases in soil organic matter would be expected, especially since tillage was limited to two of the four years of the study and winter cover crops were planted in two of the four years.

Tracking net P accrual is much more straightforward since atmospheric exchanges and hydrologic losses are negligible relative to total inputs (Fig. 26). Poultry litter dominated P inputs, totaling 300 kg/ha in both watersheds (Table 9). An additional 15 kg/ha of inorganic P was added as a starter at corn planting. P removal in crop grain harvest totaled 105.6 kg/ha in the CT watershed and 103.4 kg/ha in the NT watershed during the four years of the study. Removal rates were slightly higher in the second cycle of the rotation due to the exceptional corn yields. Annual removal rates were slightly higher in the second year of the rotation due to the double harvest and higher P content of soybeans. Since runoff losses totaled around 5 kg/ha for the entire study, approximately 205 kg/ha P were added to the soil in the watersheds. Average annual P removal rates in grain harvest were slightly less than the P content of 1 ton of poultry litter.

P leaching from crop residue after harvest contributes to P losses in runoff. Both corn and wheat fodder were consistently higher in P where poultry litter was applied in comparison to the inorganic only test strips (Fig. 27). Fodder P content at harvest in the 1999 wheat crop and the 2000 corn crop was more than double that in the inorganic only treatments. The P content of wheat grain in 1999 was approximately 50 percent higher than in the inorganic test strips but this pattern was not apparent in any other harvest.

Even though rye cover crops were not planted until early November after double-crop soybean harvest in 1999 and 2001, nitrate uptake was significant relative to the quantity of nitrate-N needed to raise groundwater concentrations to 10 mg/L (approximately 20 to 30 kg/ha/yr). At the time of glyphosate application in early April 2000, average cover crop biomass was approximately 3100 kg/ha in the CT watershed and 3500 kg/ha in the NT watershed (Table 12). The average tissue N content was approximately 1.4 percent, yielding a total above-ground N content of approximately 42 kg/ha in the CT watershed and 50 kg/ha in the NT watershed. The cover crop C:N ratio was approximately 30:1 at the time of herbicide application. Tissue P content was 0.34 percent in both watersheds, yielding a total above-ground P content of 10.5 kg/ha and 12.0 kg/ha in the CT and NT watersheds, respectively. Where only inorganic fertilizer had been applied, above-ground biomass and N and P uptake were approximately 20 percent less in the CT system and 30 percent less in the NT system. Cover crop biomass and total N and P uptake were less in all treatments in the second cycle of the rotation, but cover crop nitrate content in April 2002 was, nevertheless, significant relative to the root zone nitrate pool measured in soil cores taken following soybean harvest (see nitrate leaching section below). Biomass and tissue N and P concentration were very similar in both watersheds. Total above-ground N content just prior to herbicide application was approximately 37 kg/ha in the CT watershed and 40 kg/ha in the NT watershed while total P uptake was approximately 7 kg/ha in both watersheds. Average above-ground cover crop N content in the inorganic only treatment areas was 27 kg/ha in the CT system and 19 kg/ha in the NT system. As was the case for vegetative tissue P concentration in corn and wheat, cover crop tissue P was consistently lower (approximately 30 percent) in the inorganic fertilizer only treatments.

Soil phosphorus

During the five years prior to the beginning of this study in April 1998 no phosphorus had been applied to either watershed. From 1992 through just prior to poultry litter applications in April 1998 rootzone soil phosphorus levels decreased gradually in both watersheds as soil phosphorus removed in harvested corn was not replaced (Figs. 28 and 29). The five sites that were sampled from 1992 through 1997 were moved in April 1998 and a sixth sampling site was added. Both sets of sites were sampled in April 1998. Soil phosphorus concentrations were similar at both sets of sites with the biggest difference being in the 20-30 cm depth interval. Average soil P concentrations in the 0-20 cm depth interval were 31.2 ppm in the NT watershed and 37.7 ppm in the CT watershed. Expressed in terms of the Fertility Index Value (FIV), for a sampling depth of 8" both watersheds were in the optimum range in April 1998 (Figs. 30 and 31). Soil phosphorus levels in the tilled watershed were more consistent with depth, probably due to annual mixing of the plow layer.

The effects of the first application of poultry litter (3 tons/acre) on soil P concentrations were evident when the watersheds were resampled just before fall poultry litter application and tillage in preparation for planting of wheat (Figs. 28 and 29). In the NT watershed, surface poultry litter applications sharply increased soil P levels in the 0-2.5 cm (0-1") layer, while the increase was similar in all layers in the tilled watershed. Both watersheds were again sampled in July 1999 following wheat harvest. The additional application of poultry litter in the fall of 1998 again increased soil P concentrations uniformly in all layers in the tilled watershed. However, in the no-till watershed (which was moldboard plowed in the fall of 1998 prior to wheat planting), soil P levels decreased dramatically in 0-2.5 cm layer and increased in the 10-20 cm (4-8") layer. As a result of tillage, P levels in the top soil layer in the NT watershed actually were lower than before poultry litter had been applied, even though during the same period the 0-8" FIV had increased from 69 to 98 (Fig. 31). Minor decreases in soil P occurred in both watersheds from July 1999 through May 2000, just prior to the start of the second cycle of the rotation. For the first cycle of the rotation the 0-8" FIV increased from 83.8 to 120.9 in the CT watershed and from 69.0 to 98.2 in the NT watershed. The smaller increase in the NT watershed most likely was related to higher soil organic matter levels resulting from the long-term use of no-till methods.

The spring poultry litter application in 2000 again resulted in a sharp increase in soil P concentrations in the 0-2.5 cm depth interval in the NT watershed. Both watersheds were chisel plowed in the fall of 2000 rather than moldboard plowed as had been done in the fall of 1998. This tillage resulted in uniform soil P concentrations in the 0-10 cm depth interval but the 10-20 cm interval was much less affected than in 1998. The final soil sampling was conducted following soybean harvest in November 2001. Even though the fall 2000 poultry litter application added approximately twice as much P to the soil as was removed by wheat and soybean harvest in 2001, the 0-8" FIV was little changed from fall 2000 levels. For the second cycle of the rotation, increases in the 0-8" FIV were less than in the first cycle of the rotation. This likely was due in part to the lower rates of net P additions to both watersheds during the second (approximately 95 kg/ha) versus the first cycle of the rotation (approximately 115 kg/ha). However, the 0-8" FIV increase per unit of net excess P during the second cycle of the rotation (CT 0.24; NT 0.15) also was lower than during the first cycle of the rotation (CT 0.32; NT 0.25). For this entire study the 0-8" FIV increased from 83.8 to 143.5 in the CT watershed and from 69.0 to 112.3 in the NT watershed. The increase in the FIV per pound/acre of P added to the soil above what was removed in harvested grain was approximately 0.33 in the CT watershed and 0.24 in the NT watershed. For the five growing seasons prior to the beginning of this study when corn was grown and harvested but no P was applied to either watershed, the decrease in the 0-8" FIV per pound of P/acre removed from the soil was approximately 0.31 in the CT watershed and 0.40 in the NT watershed.

Nitrate leaching

Continuous use of cover crops during the ten years before this project started resulted in relatively low groundwater nitrate concentrations in both watersheds (Fig. 32). The average groundwater nitrate-N concentration on April 21, 1998 was 5.1 mg/L in the no-till watershed and 3.9 mg/L in the tilled watershed. Soil sampling in April 1998 indicated soil profile pore-water nitrate-N concentrations in the 1-2 ppm range in both watersheds (Fig. 24).

Due to the lack of precipitation, only minor amounts of groundwater recharge occurred between the two sampling dates and groundwater nitrate concentrations were little changed. On October 27, the average groundwater nitrate-N concentration in the no-till watershed was 3.6 mg/L versus 4.2 mg/L in the tilled watershed. Although groundwater recharge was limited during the 1998 summer growing season, the brief period of wet conditions early in the growing season most likely caused the increases in soil profile nitrate concentrations in the CT watershed that were evident in samples collected following corn harvest (Fig. 24). As was discussed in the surface runoff section, the incorporated poultry litter in the CT watershed increased soil nitrate concentrations early in the growing season, while the surface applied poultry litter in the NT watershed had much less effect on root zone nitrate availability. Consequently, the brief period of leaching early in the growing season moved much more nitrate downward in the soil profile in the CT versus the NT watershed (Fig. 24). Both root zone (0-60 cm) and intermediate vadose zone (60-240 cm) nitrate concentrations in the CT watershed were more than double those in the NT watershed.

The overall reduced nitrate availability in the NT watershed also was evident in 150 cm soil cores collected in January 1999 to assess N needs of the wheat crop (Fig. 33). Since both watersheds received equal poultry litter applications and were tilled identically in the fall of 1998, the differences in nitrate availability were most likely carry over effects from management differences during the summer of 1998. Total nitrate-N availability in late January 1999 in the top 90 cm of the soil profile averaged 86 lb/ac in at the CT sampling sites versus 34 lb/ac at the NT sampling sites. Due to below average precipitation throughout the winter of 1998-99, groundwater recharge during this period was the lowest recorded since monitoring of the watersheds began in 1984 (Fig. 3). Given the small volume of recharge it is not surprising that average groundwater nitrate concentrations were little changed from October 1998 to April 1999 (Fig. 32). During this interval average groundwater nitrate-N concentration increased from 4.2 mg/l to 5.6 mg/L in the CT watershed and from 3.5 mg/L to 5.5 mg/L in the NT watershed. The large volume of precipitation from July through September 1999 resulted in a significant volume of groundwater recharge and an increase in groundwater nitrate concentrations in both watersheds. The average groundwater nitrate-N concentration on November 9, 1999 was 6.1 mg/L in the CT watershed and 11.6 mg/L in the NT watershed. Several of the wells in the NT watershed are highly responsive to root zone leaching rates and the higher nitrate concentrations in the NT watershed in the fall of 1999 reflect the quick response of these wells, rather than overall higher nitrate leaching rates in the NT watershed. Soil cores collected in November 1999 continued to indicate the generally higher nitrate leaching rates in the CT versus the NT watershed (Fig. 34). Average intermediate vadose zone (60-240) pore-water nitrate-N concentrations immediately following soybean harvest were 5.6 mg/L in the CT watershed versus 2.7 mg/L in the NT watershed. Despite the lack of any N applications since early spring and the high precipitation volumes in late summer, the root zone nitrate-N content was approximately 36 lb/ac in the CT watershed and 27 lb/ac in the NT watershed following soybean harvest in mid-November 1999. Spring 2000 soil cores showed the effects of the rye cover crops planted in both watersheds (Fig. 34). In addition to the cores collected from the watersheds, side-by-side cores also were collected from adjacent strips with a cover crop and left fallow during the winter (Fig. 35). Pore-water nitrate-N concentrations were consistently higher to a depth of 120 cm in the winter-fallow versus the cover crop strips. By the end of the first cycle of the rotation in spring 2000 groundwater nitrate concentrations were similar in both watersheds (Fig. 34).

Soil profile nitrate-N concentrations following corn harvest in 2000 were similar in both watersheds (Fig. 36). Unlike in 1998 when leaching early in the growing season moved significant quantities of nitrate downward in the profile in the CT watershed (Fig. 24), post-harvest profile nitrate concentrations in 2000 were similar in the upper part of the profile to those prior to corn planting (Fig. 34). Below a depth of 120 cm, nitrate concentrations were consistently higher in the CT watershed. Cores were collected to a depth of 120 cm in early March 2001 to determine N needs of the wheat crop. Unlike in 1999 when nitrate availability was much greater in the CT versus the NT watershed, approximately 30 lb/ac of nitrate-N was available in both watersheds. Corn N uptake was much greater in 2000 versus 1998 (Table 9), reducing some of the surplus nitrate in root zone that was present in the CT watershed in 1998. Soil cores at the end of the study in April 2002 again indicated the effect of cover crops in the upper region of the soil profile, and the overall higher nitrate leaching losses in the CT watershed (Fig. 36). Side-by-side sampling in cover crop/winter fallow strips also again indicated the effect of rye nitrate uptake on profile nitrate concentrations (Fig. 37). Groundwater nitrate concentrations at the end of the study also indicated the higher nitrate leaching losses in the CT watershed (Fig. 32). Ending groundwater nitrate-N concentrations suggested an approximate doubling of nitrate leaching rates in the CT watershed during this study relative to those during the previous decade when corn was grown every year using 140 lb/ac of inorganic N and rye cover crops were planted after harvest every fall. In the no-till watershed the increase in nitrate leaching was less even though total N applications were approximately 130 kg/ha greater as a result of supplemental inorganic N applications. Apparently, ammonia volatilization more than offset the extra N applications.

Conclusions and Management Implications

Isolating the effects of poultry litter on nutrient transport rates was made more difficult in this study by the extreme variability in precipitation patterns during the four years of this study. In addition, switching from a continuous corn system to a rotation including fall tillage followed by a full year without any tillage or nutrient applications also made direct comparison of annual nutrient transport patterns with historical patterns in the study watersheds more complicated. Nevertheless, several effects of switching from an inorganic based fertility system to one utilizing N-based rates of poultry litter were discernible.

The most apparent and immediate water quality effect of applying poultry litter to cropland was the high losses of dissolved nutrients in surface runoff during no-till corn production. Summer runoff dissolved P concentrations were increased dramatically relative to historical levels at the site, and also relative to concentrations during this study in the adjacent watershed where poultry litter was incorporated into the soil. Incorporating poultry litter caused no apparent short-term increase in surface runoff P losses other than those associated with tillage. The increase in particulate P losses associated with tillage was minor compared to the increase in dissolved P transport resulting from not incorporating poultry litter into the soil. It should be noted that the erosion potential in the study watersheds is relatively low, especially since grassed waterways were installed. At sites with higher erosion potential the particulate P losses due to tillage may be much greater than at this site. However, it is clear that allowing poultry litter to remain on the soil surface in fields with runoff potential will greatly increase dissolved P losses, and in many Coastal Plain settings, total P losses. Clearly, the practice of projecting reduced P losses from cropland in association with reduced tillage, independent of nutrient application practices, has resulted in an overestimate of reductions in P transport from Eastern Shore cropland.

The effects of surface applications of poultry litter on surface runoff N transport are more complicated since inorganic sidedress N applications to corn often are surface applied, and also create a period of high potential losses. Summer runoff N losses in this study were much greater in the no-till versus the tilled setting, but unlike the case for P, runoff N concentrations were not noticeably higher than in past years when inorganic surface sidedress N applications were used to meet corn N needs. The potential for summer runoff N losses from the no-till watershed in this study was actually increased by the low availability of N from unincorporated poultry litter. As a result of this low N availability, it was necessary to apply supplemental inorganic N in the no-till system, but not in the tilled system, leading to an additional period of elevated surface runoff N concentrations. Summer surface runoff N losses will likely be lower where sufficient quantities of poultry litter are incorporated prior to planting to eliminate the need for later surface sidedress N applications. The water quality drawback of this approach, and it was apparent in the first year of this study, is that incorporating poultry litter early in the growing season when evapotranspiration rates are still low increases soil nitrate concentrations when there is little plant demand, thereby increasing the potential for nitrate leaching or nitrate transport in surface runoff under high water table conditions. Thus, no-till poultry litter applications increase the potential for surface runoff nutrient losses, but decrease the potential for late spring nitrate leaching since most of the ammonia is volatilized rather than nitrified.

The water quality effects of using poultry litter for wheat production were much less apparent since all fall applied poultry litter was incorporated, and since there was no history of wheat production at the site for comparison. In addition, October through December in both 1998 and 2000 was a relatively dry period, minimizing both surface runoff and nitrate leaching during a period when the potential for losses through both pathways would be expected to be elevated. However, the minimal effect of incorporated poultry litter on surface runoff nutrient losses during corn production suggests that the primary risk of fall poultry litter applications is the increased potential for nitrate leaching. Nitrate leaching rates increased during the study period, relative to the previous decade when corn was grown continuously, as indicated by increases in soil profile and shallow groundwater nitrate concentrations. However, since both watersheds were managed identically in the fall, and the increase in subsurface nitrate concentrations was most apparent in the tilled system, it is likely that much of the increase in nitrate leaching was due to elevated soil nitrate concentrations early in the growing season after poultry litter incorporation.

In addition, fall root zone nitrate availability was higher in the tilled system, especially in 1998 when drought reduced corn N use and shortened the period of corn N uptake.

Although nitrate leaching rates did increase, the increases were not extreme given the high rates of N application to the watersheds (approximately 250 kg/ha annually) and that some was fall applied. Total N uptake suggests that wheat was highly efficient in using fall and winter applied N, as well as some of the nitrate remaining in the soil following corn production, especially in the tilled system. Although planting winter cover crops after double-crop soybean harvest is generally considered a low priority for water quality benefits, both soil coring and cover crop N uptake indicated that cover crops helped minimize overall nitrate leaching losses in this study.

The most challenging agronomic aspect of switching from inorganic fertilizer to poultry litter also emerged in no-till corn production. Although the stated objective of this study was to evaluate the use of poultry litter at N-based rates, under no-till conditions supplying corn N needs with the poultry litter used in this study would require an application of approximately 5 tons/acre. This study was not designed to do detailed evaluations of N availability from poultry litter, but it was apparent that estimating supplemental N requirements in no-till settings is problematic. In both years of this study, presidedress soil nitrate testing indicated adequate soil N supplies to achieve corn yield goals in the NT watershed, but in both years it was apparent that additional supplemental N would have increased grain yield. The reverse situation occurred for incorporated poultry litter during wheat production. January soil testing suggested the need for a large inorganic N application to wheat in the NT watershed in 1999, but the additional N had little effect on yields. Apparently early spring N mineralization was adequate to meet crop needs. Most current mineralization projection methods are for spring applications. Overall better diagnostic techniques will be needed to effectively use poultry litter as a major N source for wheat production.

Although, tillage management can be used to minimize short-term increases in P transport associated with poultry litter applications, in the long-term the potential for increases in P losses due to increasing soil P concentrations also must be considered. Use of poultry litter to supply even the partial N needs of both corn and wheat will increase soil P levels rapidly, unless the P content of poultry litter is reduced. Although increases in soil test P results for a given increase in soil P content will vary for differing soil types, the soil types in the study watersheds are widely used for grain production on the mid and upper Eastern Shore. The increase in soil test P in the study watersheds suggests that the 0-8" FIV value will increase approximately 0.3 units per every pound/acre of P added to the soil. Since every ton of poultry litter supplies the approximate amount of P removed by grain harvest annually, every ton of poultry litter applied above a rate of 1 ton/acre annually will increase the 0-8" FIV approximately 10 units. Using poultry litter at a rate of 3 ton/acre for corn production every other year with no additional P applications would increase the 0-8" FIV approximately 5 units per year for soils similar to those used for this study. It is unclear from this study how soon increasing soil P levels will significantly increase runoff P losses but unprecedented dissolved P concentrations in runoff from the tilled watershed and increases in the P content of crop residues suggest even modest increases can lead to increased runoff losses.

Much of the effort in Maryland to reduce nutrient losses from cropland has focused on improved nutrient management and minimizing soil erosion by reducing tillage. The inherent characteristics of poultry litter necessitate making some tradeoffs in pursuing this dual strategy. The central premise of nutrient management is that by more closely matching nutrient availability to crop needs, both in terms of rate and timing, the quantity of nutrients available for transport will be reduced. Since N availability from poultry litter is much more variable than from inorganic sources, it will be difficult to ever achieve the same level of precision that can be achieved with inorganic fertilizers in terms of matching N supply to crop needs. This lack of precision is compounded by the lack of options for applying poultry litter to established crops closer to the time of maximum N uptake as in the case of sidedressing corn or topdressing wheat. During this study a no-till subsoiler was modified and successfully used to sidedress corn with pelletized poultry litter. Although currently not economically feasible, no-till options for subsurface application of poultry litter would help solve most of the short-term water quality problems.

Results from this study suggest that given current poultry litter characteristics and application technology, the best option for taking full advantage of the nutrient content of poultry litter while minimizing the potential for nutrient losses is to incorporate poultry litter as close to crop planting dates as possible. For fall applications, earlier applications will increase fall mineralization, but also will give winter cereals time to utilize available N and quickly establish enough soil cover to reduce winter soil erosion. Incorporation will increase the potential for soil erosion but will reduce ammonia volatilization, the need for inorganic N applications, surface runoff losses of dissolved P, and in most Coastal Plain settings, total P losses. As with all organic N sources, incorporated poultry litter will tend to increase late summer mineralization rates and the potential for nitrate leaching. Aggressive use of winter cereal cover crops in the fall following spring poultry litter applications, and in following years will help reduce overall nitrate leaching rates.

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Appendix A (Figures)

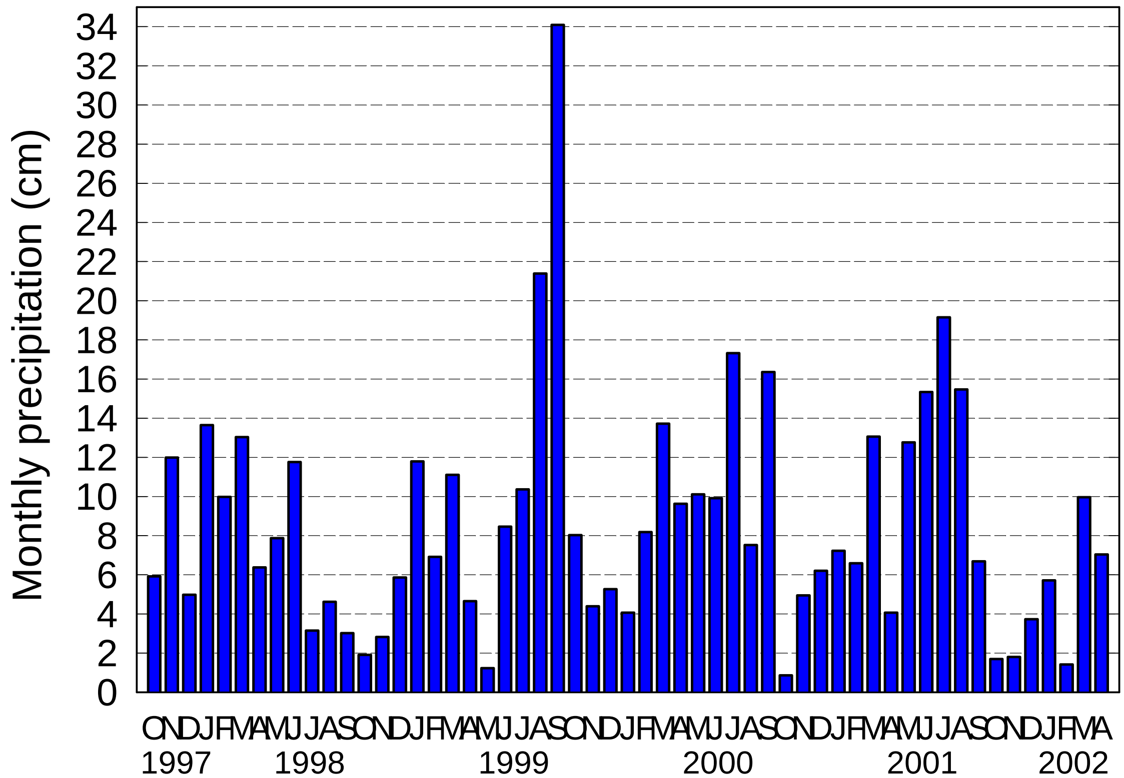

Figure 1. Total monthly precipitation at WREC weather station from October 1997 to April 2002. Measurements were made using a weighing bucket gauge.

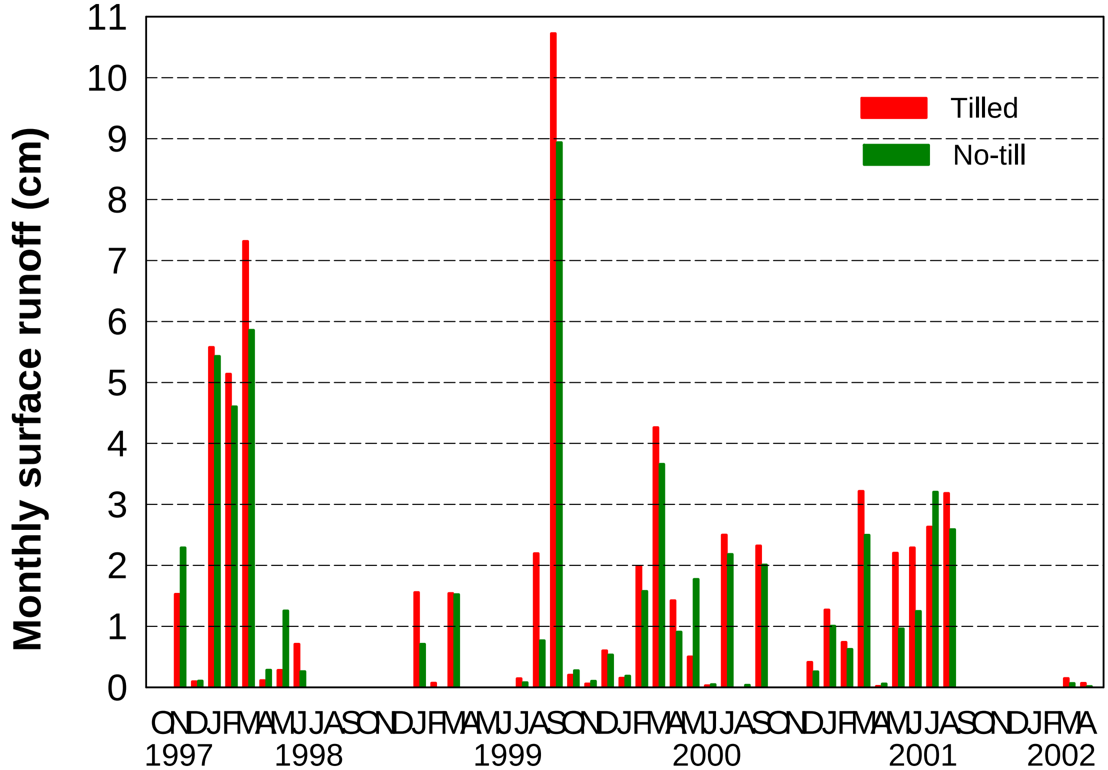

Figure 2. Monthly area-normalized surface runoff volume from the tilled (CT) and no-till (NT) watersheds from October 1997 to April 2002.

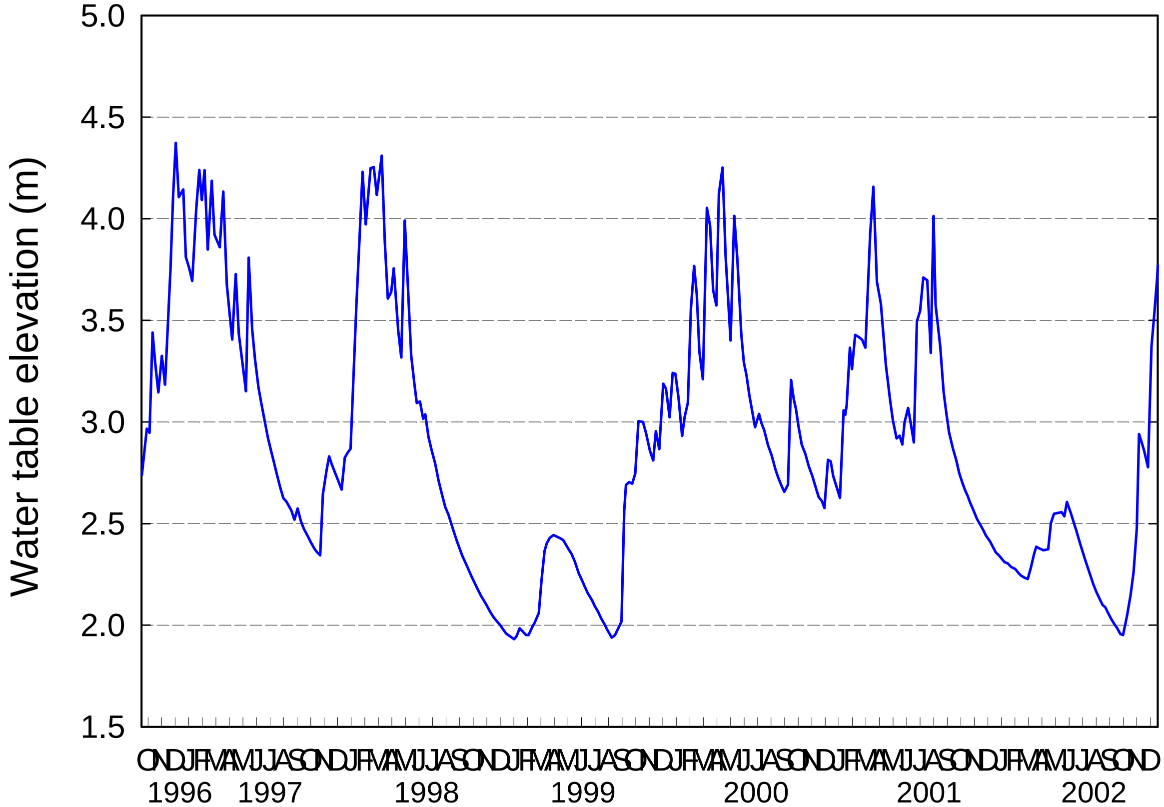

Figure 3. Average (nine wells) water table elevation relative to sea level in the tilled (CT) watershed from October 1996 to December 2002.

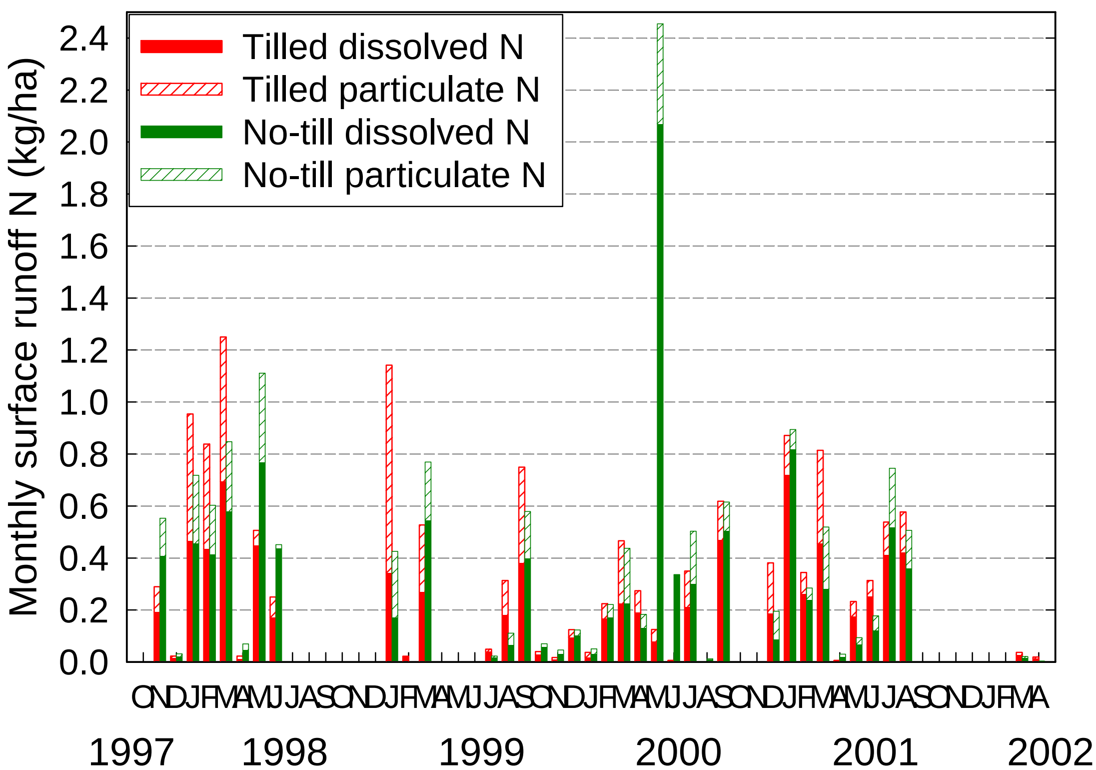

Figure 4. Monthly dissolved and particulate nitrogen (N) losses in surface runoff from the tilled and no-till watersheds from October 1997 to April 2002.

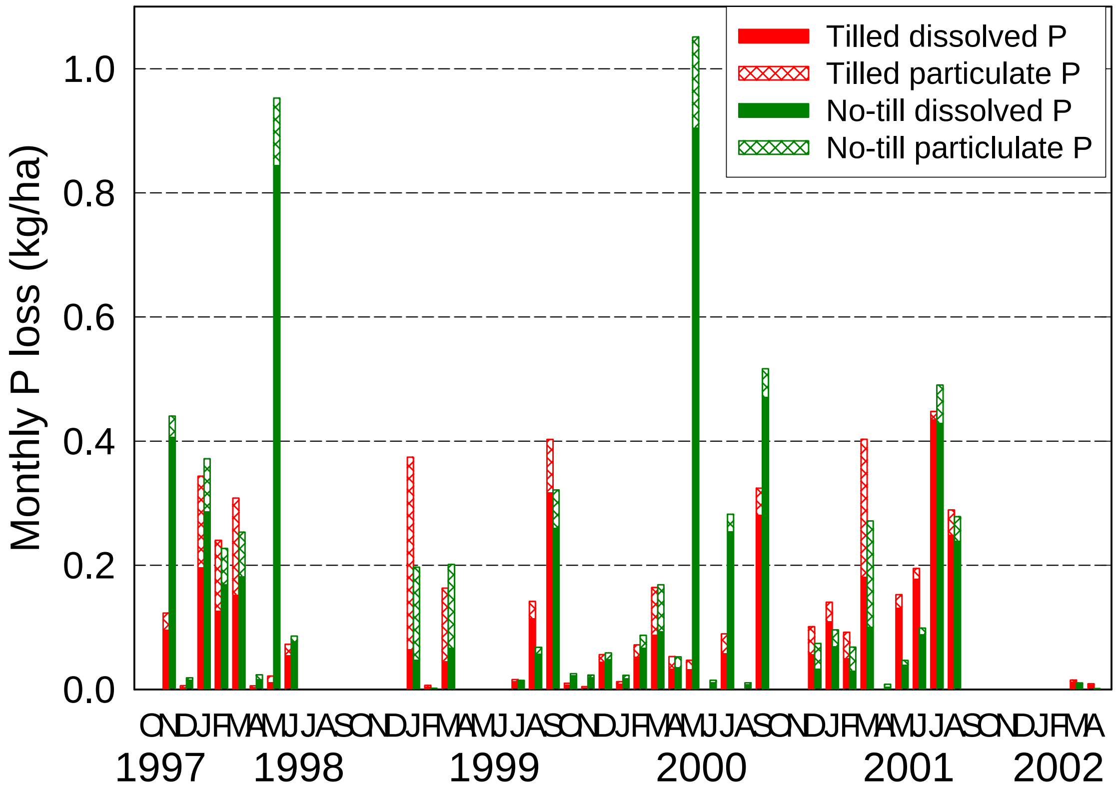

Figure 5. Monthly dissolved and particulate phosphorus (P) losses in surface runoff from the tilled and no-till watershed from October 1997 to April 2002.

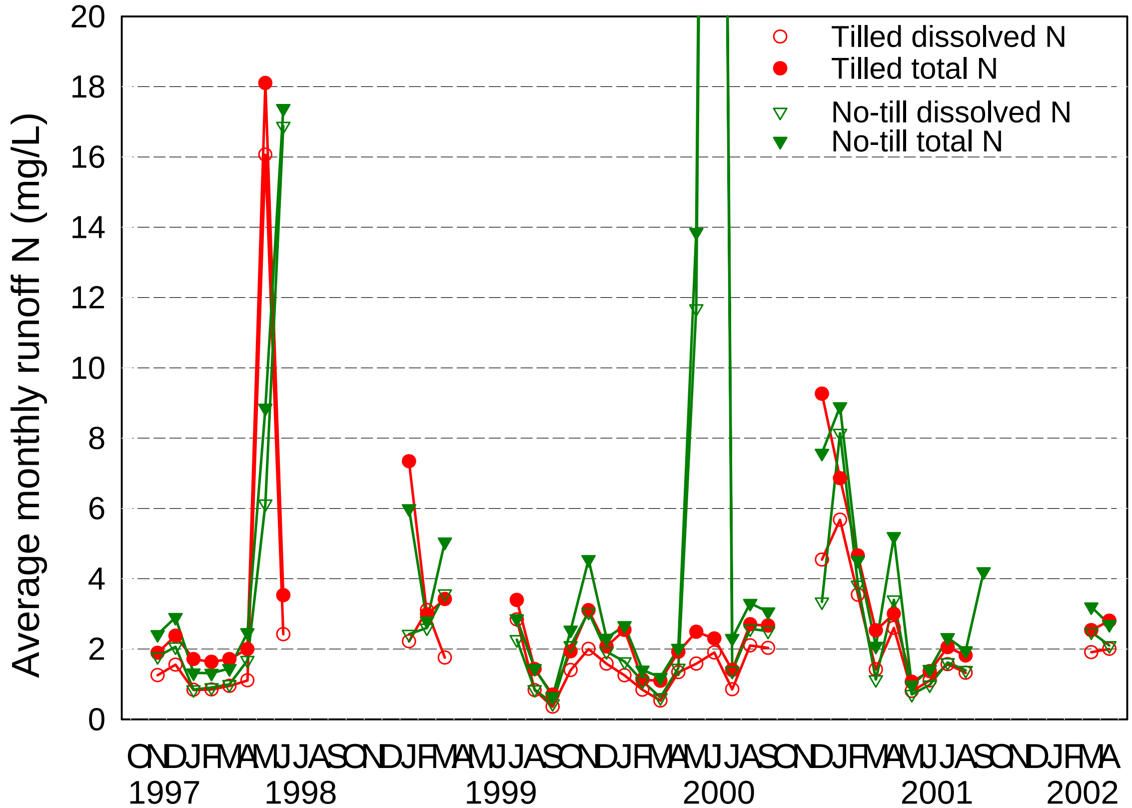

Figure 6. Monthly volume-weighted average dissolved and total nitrogen (N) concentrations in surface runoff from the tilled and no-till watersheds from October 1997 to April 2002.

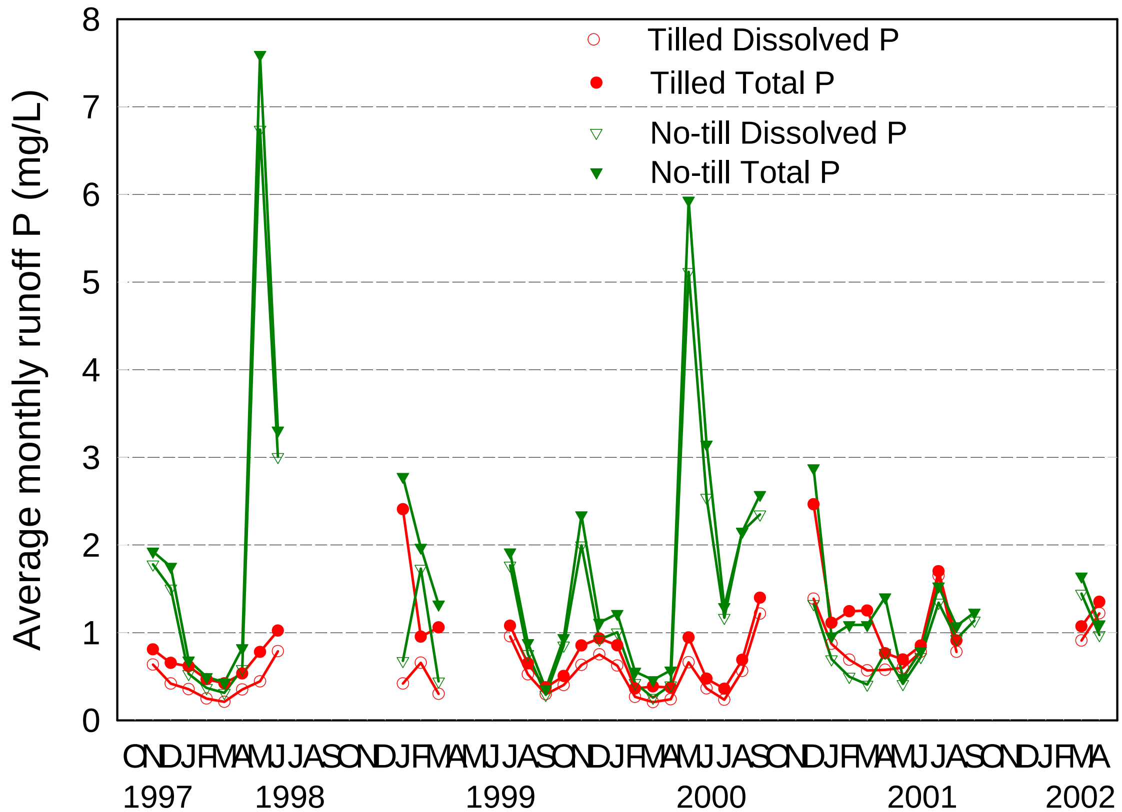

Figure 7. Monthly volume-weighted average dissolved and total phosphorus (P) concentrations in surface runoff from tilled and no-till watersheds from October 1997 to April 2002.

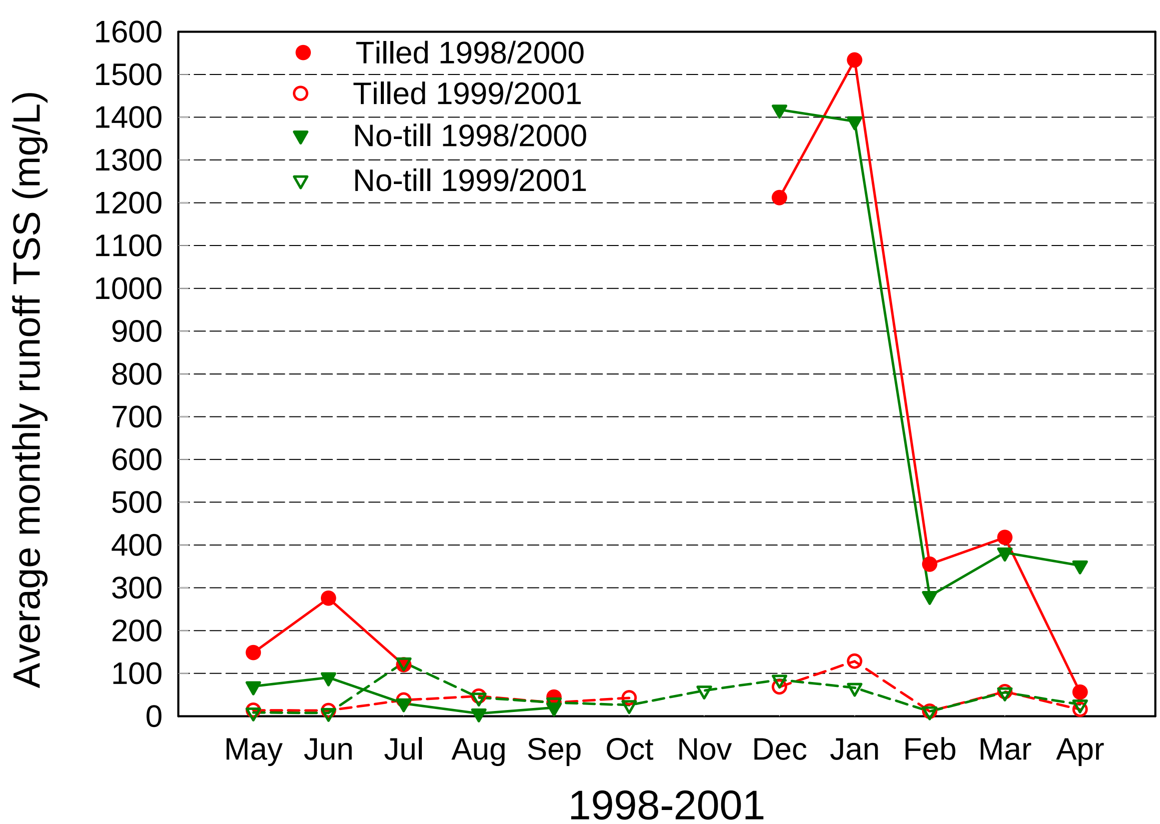

Figure 8. Volume-weighted monthly average total suspended solids (TSS) concentrations in surface runoff from the tilled and no-till watersheds for the first and second years of the rotation.

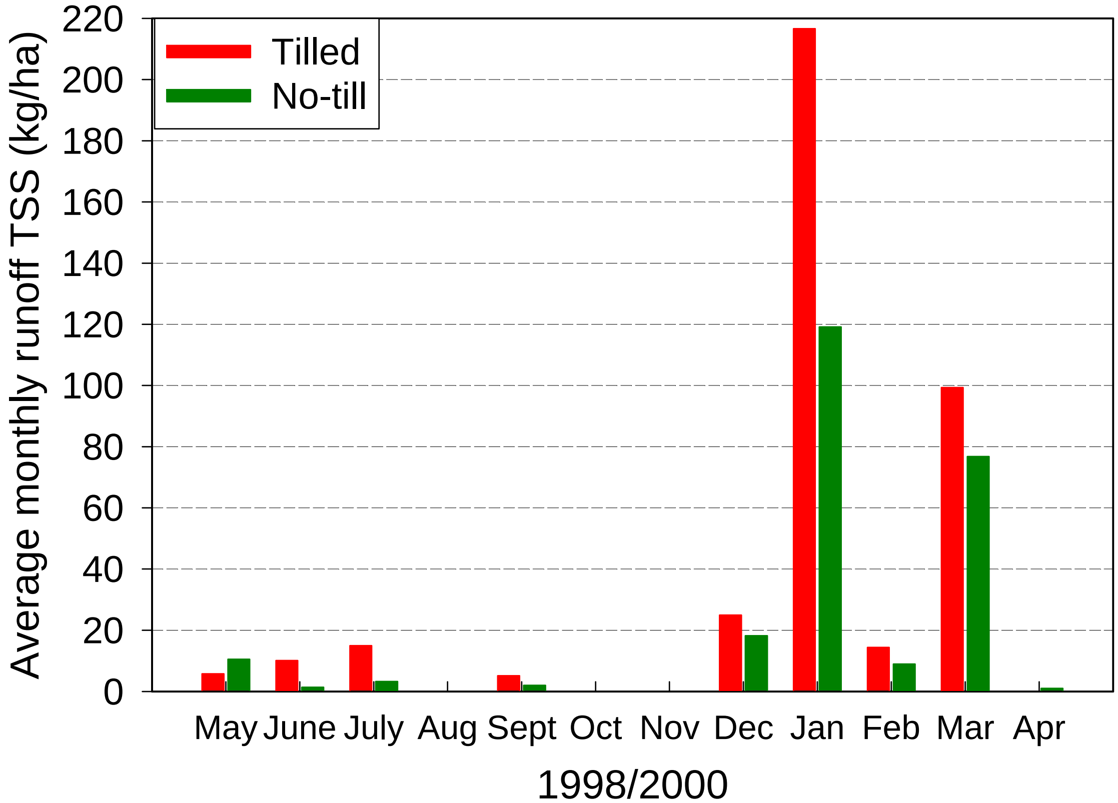

Figure 9. Average monthly total suspended solids (TSS) losses in surface runoff from the tilled and no-till watersheds during the first year (1998 and 2000) of the rotation.

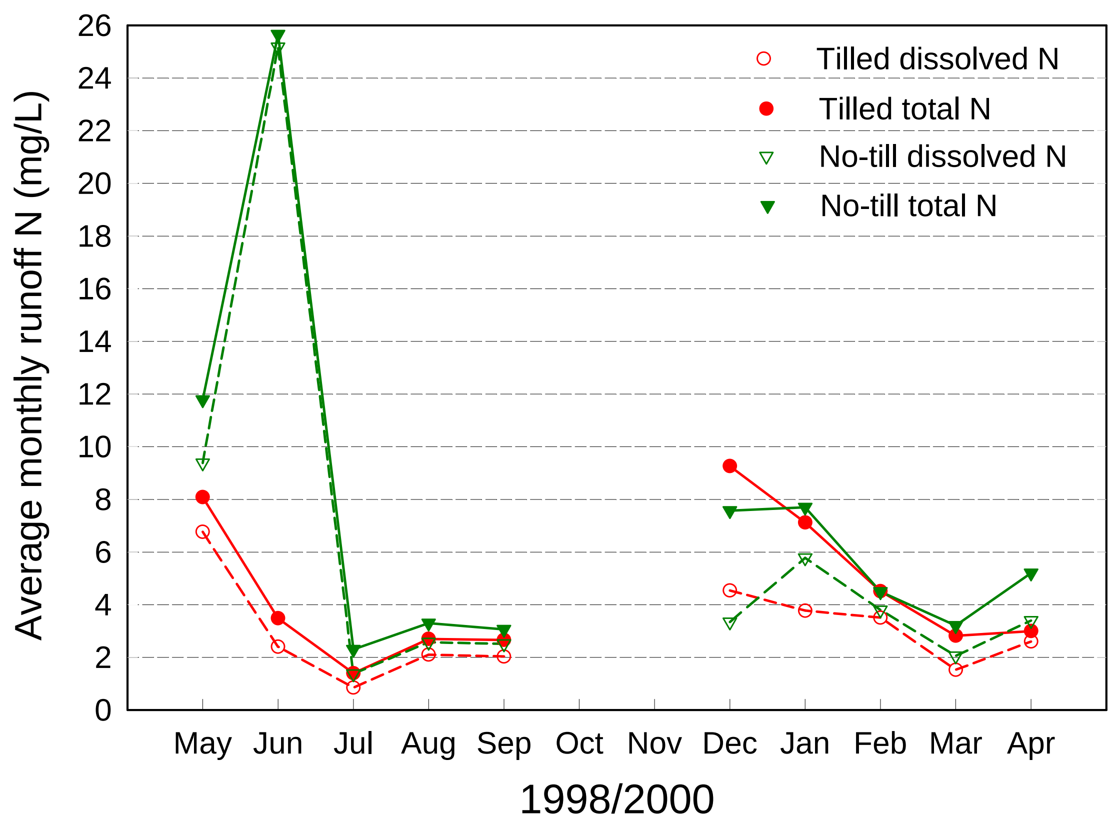

Figure 10. Volume-weighted monthly average dissolved total nitrogen (N) concentrations in surface runoff from the tilled and no-till watersheds during the first year (1998 and 2000) of the rotation.

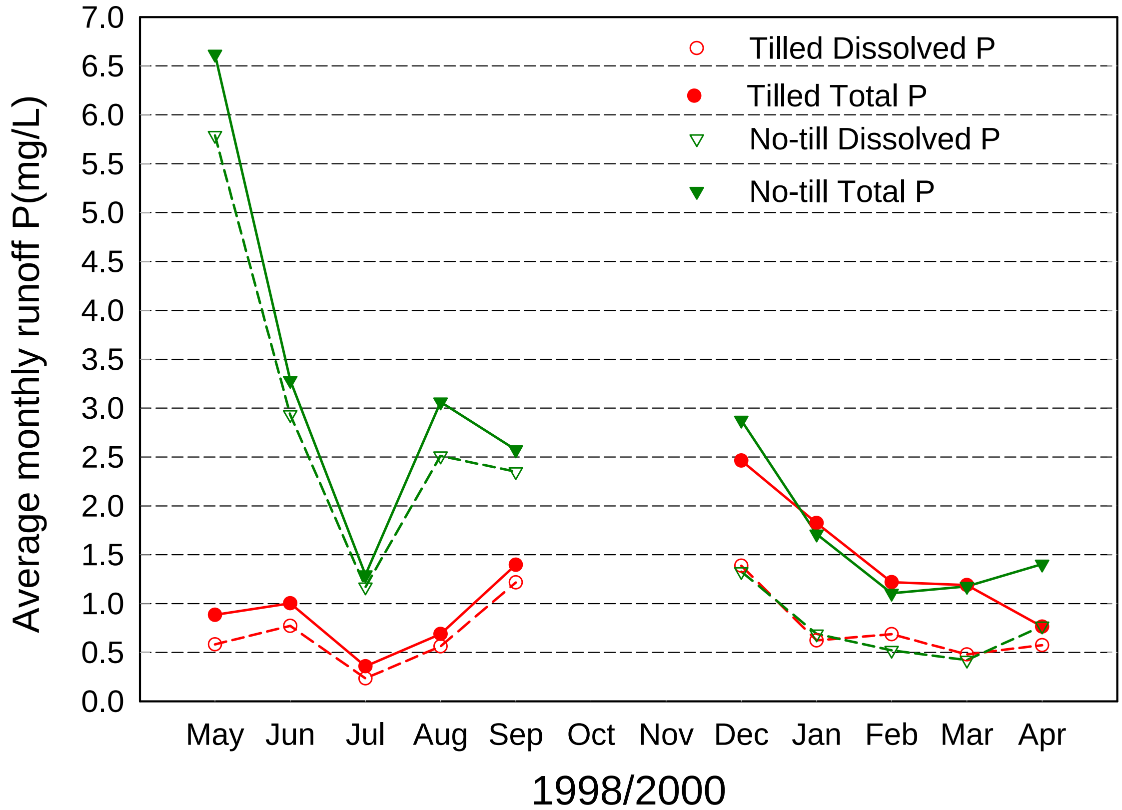

Figure 11. Volume-weighted monthly average dissolved and total phosphorus (P) concentrations in surface runoff from the tilled and no-till watersheds during the first year (1998 and 2000) of the rotation.

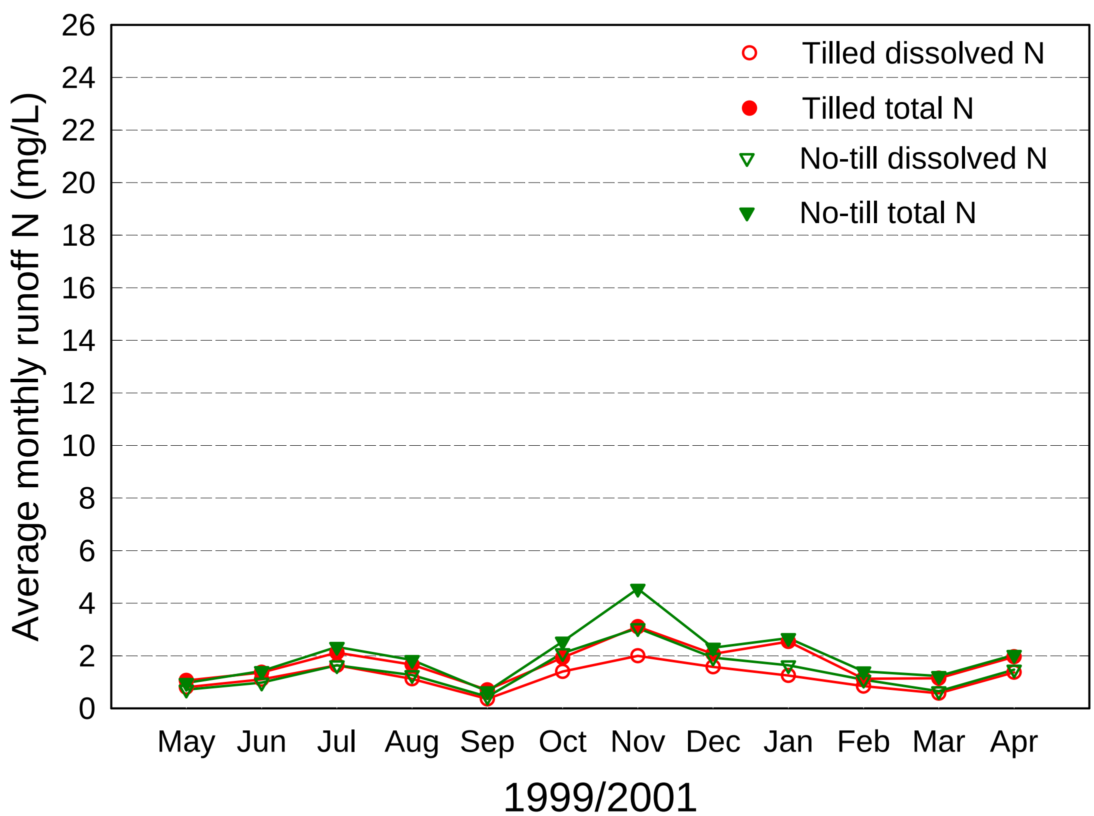

Figure12. Volume-weighted monthly average dissolved and total nitrogen (N) concentrations in surface runoff from the tilled and no-tilled watersheds during the second year (1999 and 2001) of the rotation.

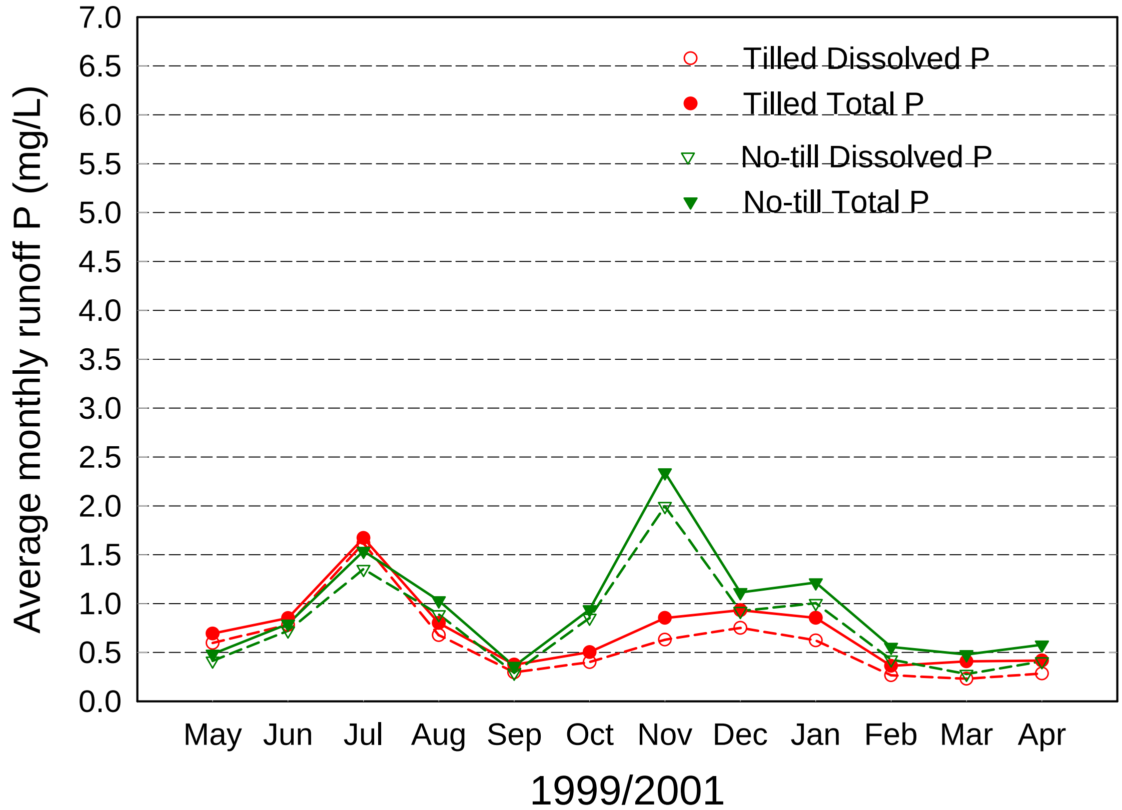

Figure 13. Volume-weighted monthly average dissolved and total phosphorus (P) concentrations in surface runoff from the tilled and no-till watersheds during the second year (1999 and 2001) of the rotation.

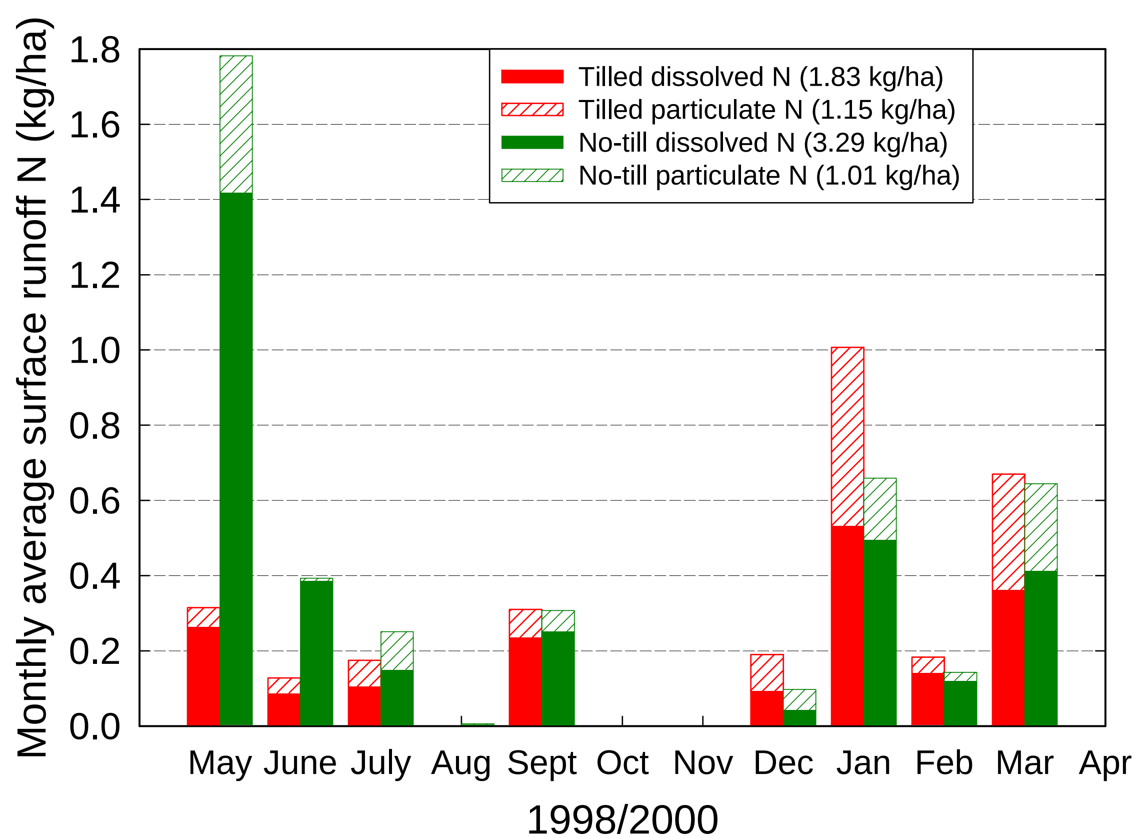

Figure 14. Average monthly total and particulate nitrogen (N) losses in surface runoff from the tilled and no-till watersheds during the first year (1998 and 2000) of the rotation. Values in parentheses are average annual totals for the two years.

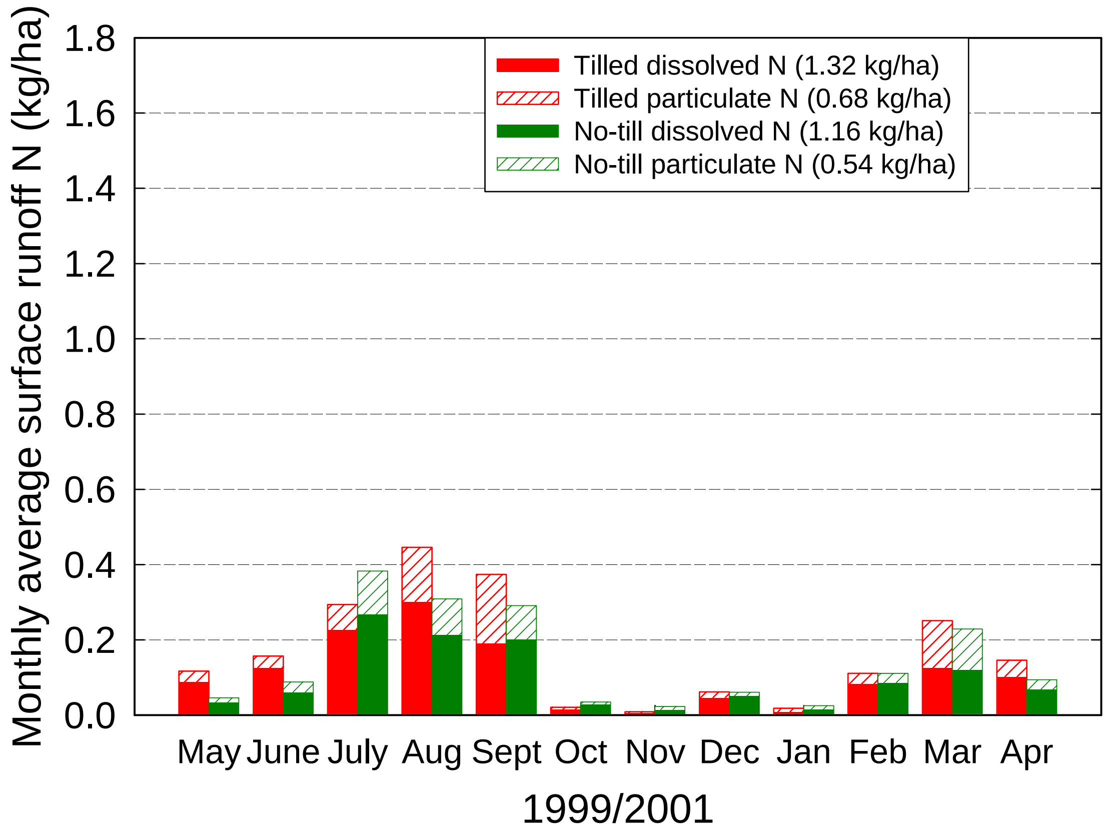

Figure 15. Average monthly total and particulate nitrogen (N) losses in surface runoff from the tilled and no-till watersheds during the second year (1999 and 2001) of the rotation. Values in parentheses are average annual totals for the two years.

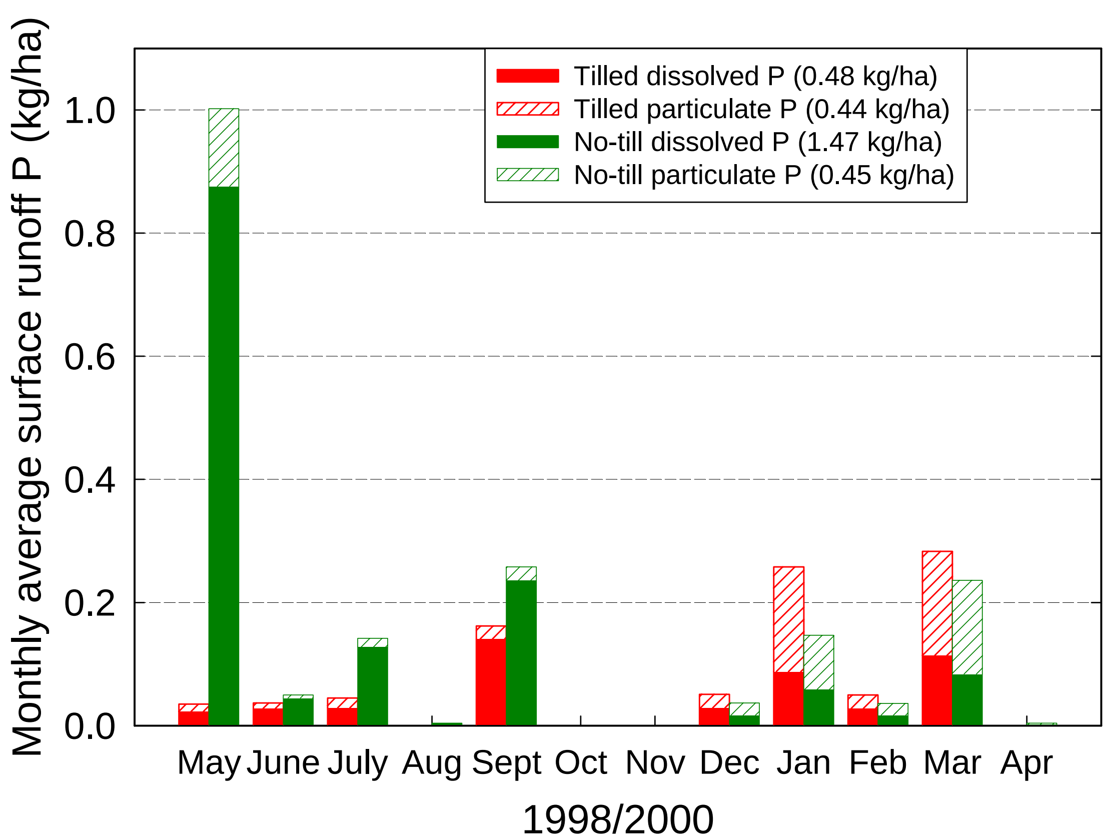

Figure 16. Average monthly total and particulate phosphorus (P) losses in surface runoff from the tilled and no-till watersheds during the first year (1998 and 2000) of the rotation. Values in parentheses are average annual totals for the two years.

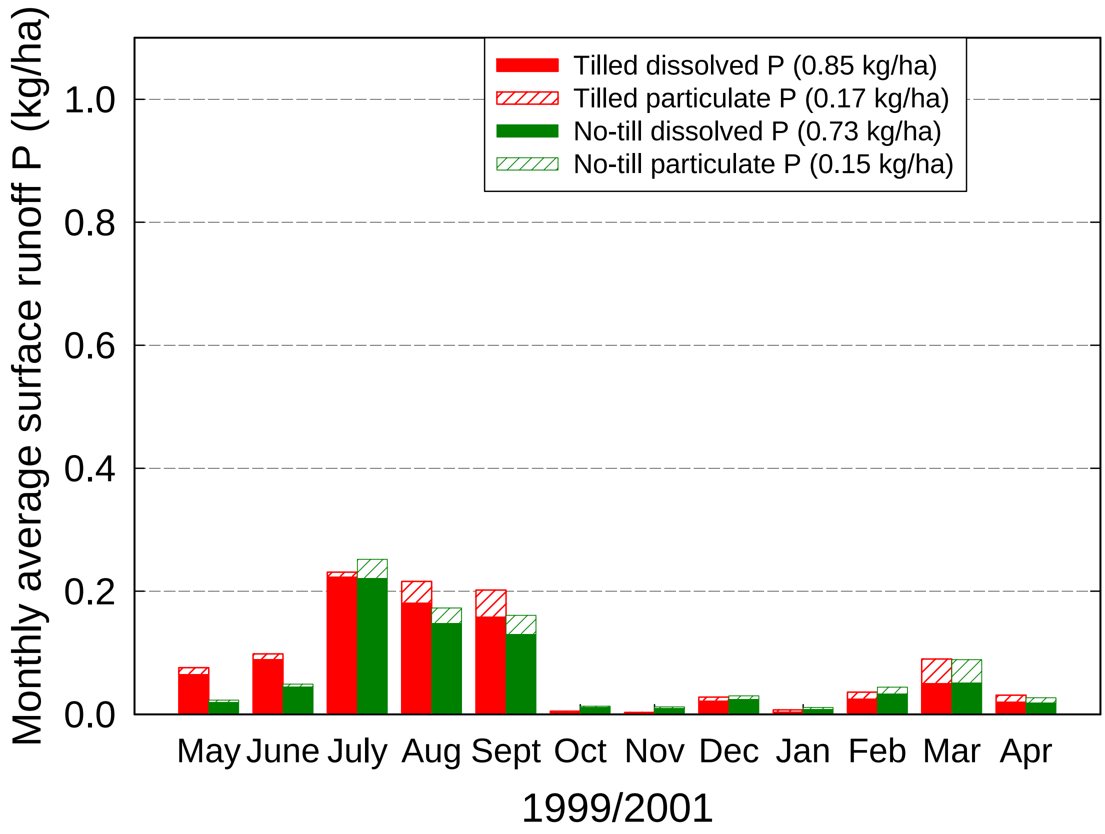

Figure 17. Average monthly total and particulate phosphorus (P) losses in surface runoff from the tilled and no-till watersheds during the second year (1999 and 2001) of the rotation. Values in parentheses are average annual totals for the two years.

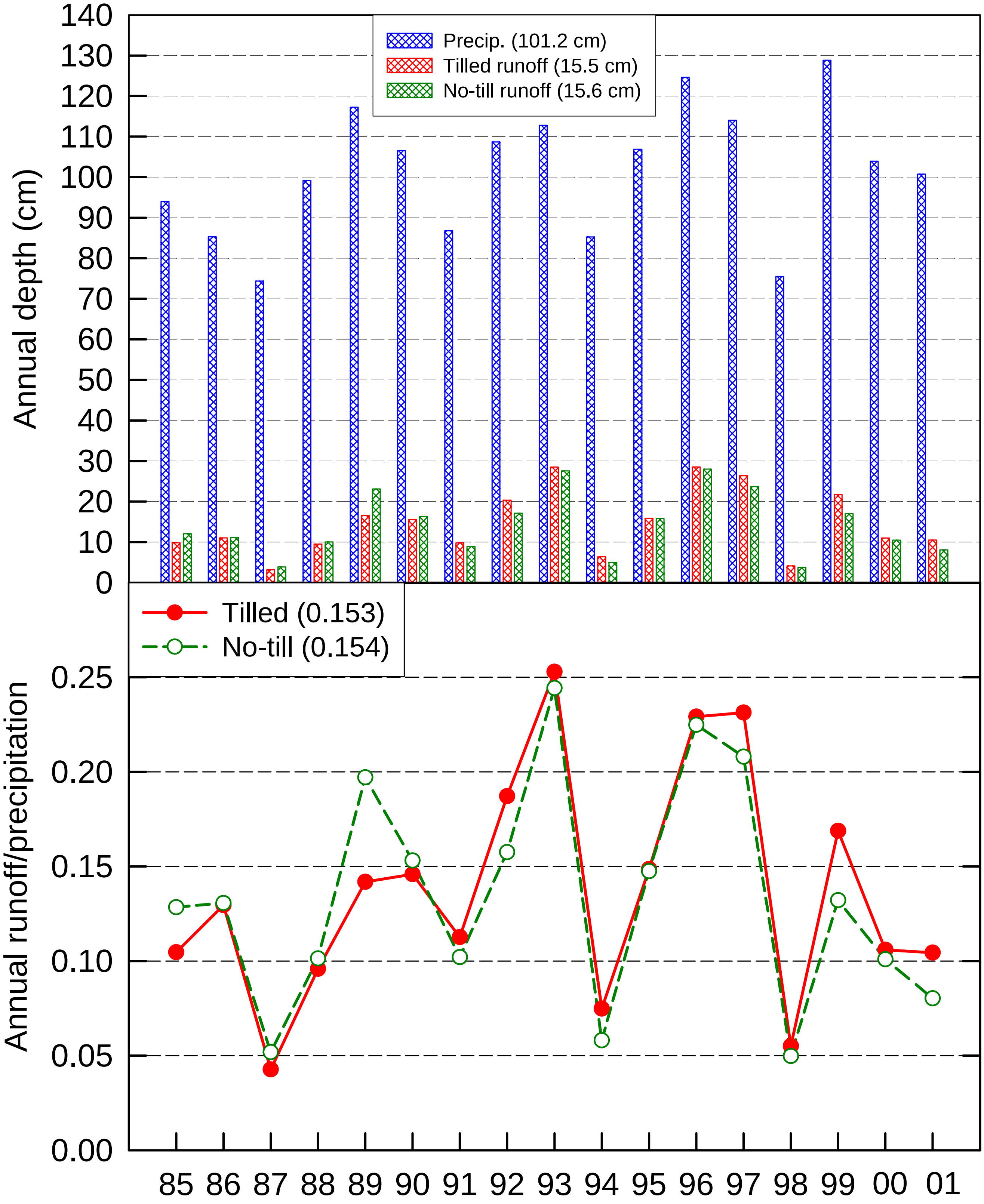

Figure 18. Total annual precipitation and surface runoff and fraction of precipitation discharged as runoff from the tilled and no-till watersheds from 1985 to 2001. Values in parentheses are average annual values for May 1985 to April 1998.

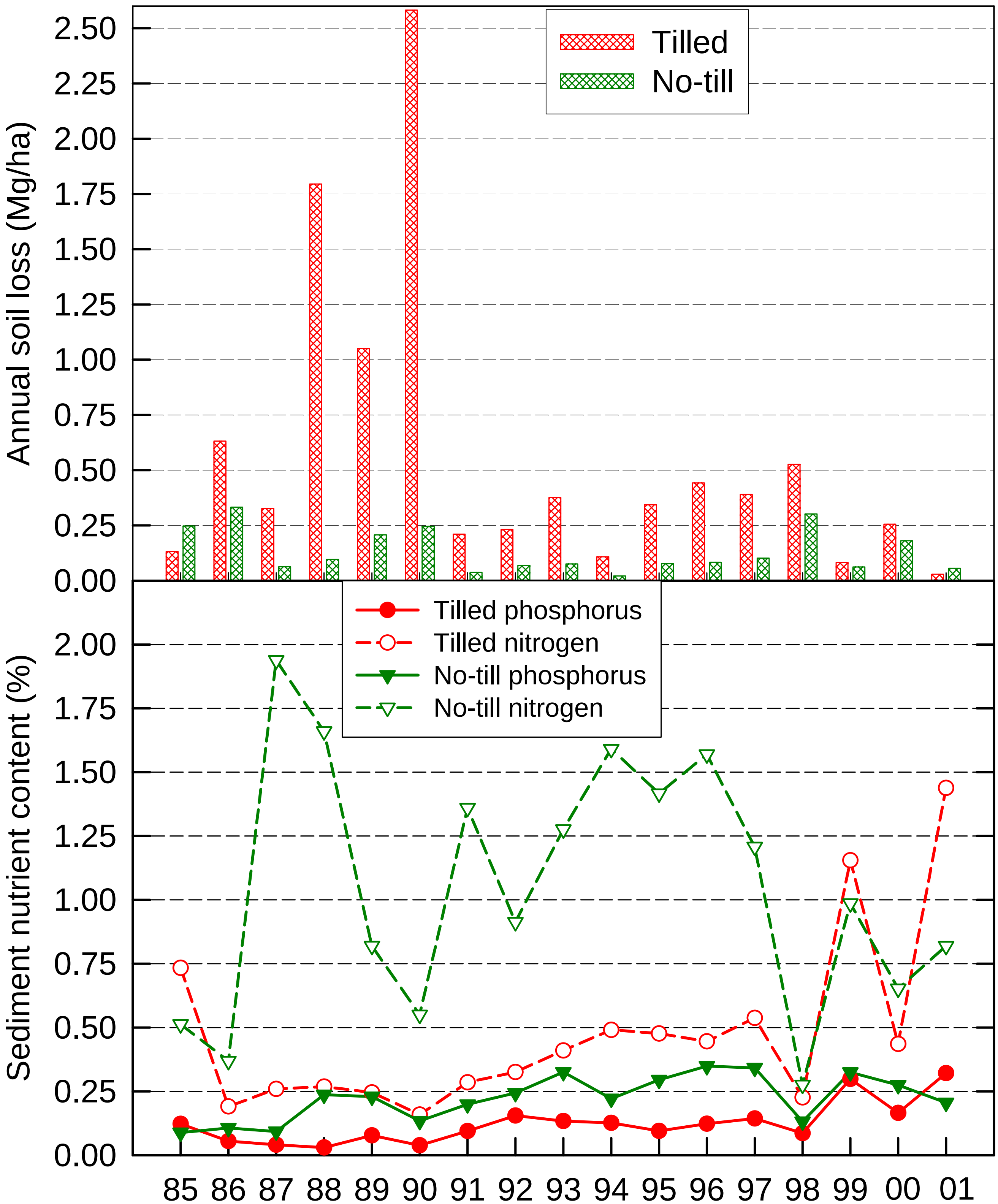

Figure 19. Total annual edge-of-field soil loss in surface runoff and annual average nutrient content of eroded particles in runoff from the tilled and no-till watersheds from 1985 to 2001.

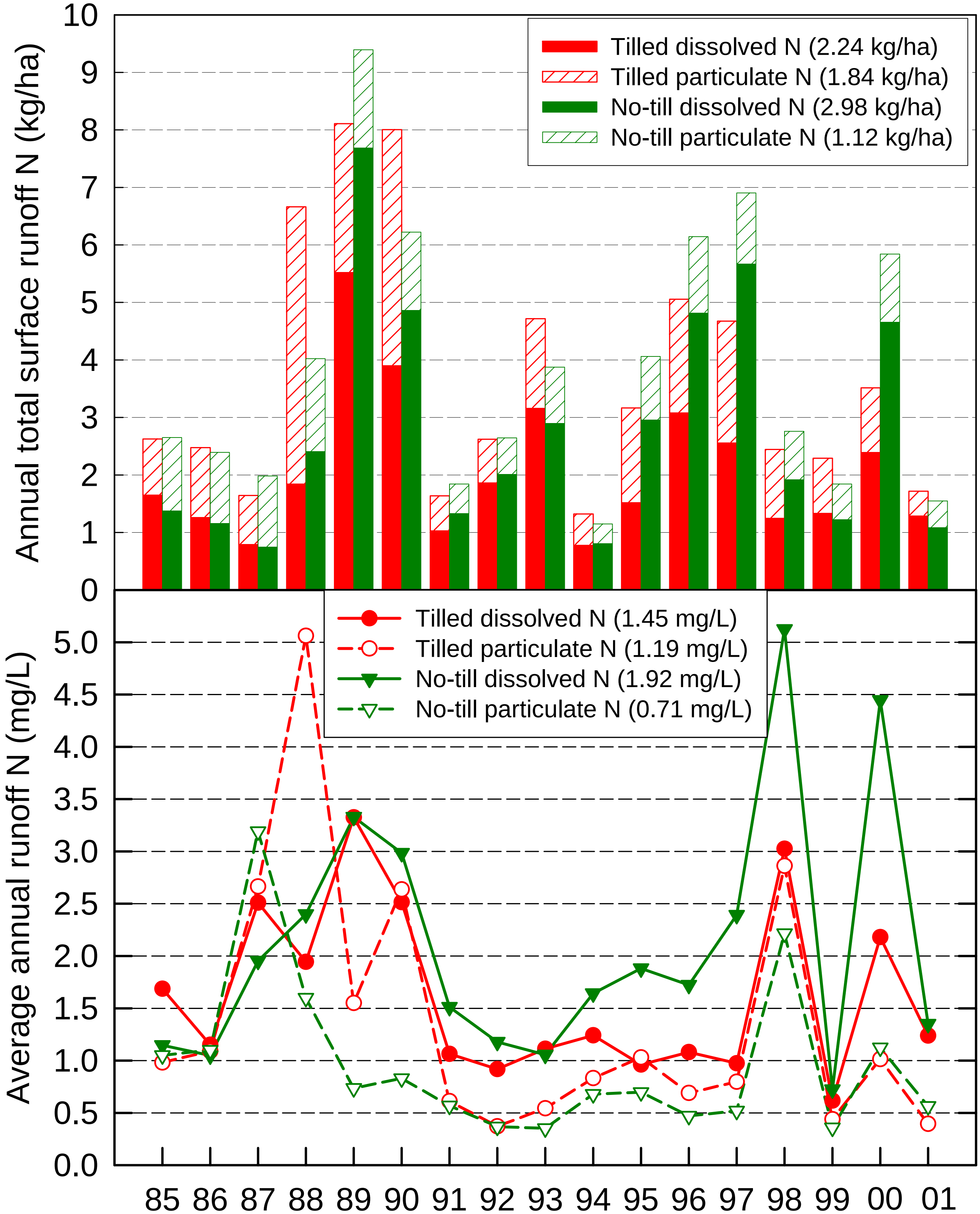

Figure 20. Annual edge-of-field surface runoff dissolved and particulate nitrogen (N) losses and annual average runoff N concentration for the tilled and no-till watersheds from 1985-2001. Values in parentheses are average annual values for May 1985 to April 1998.

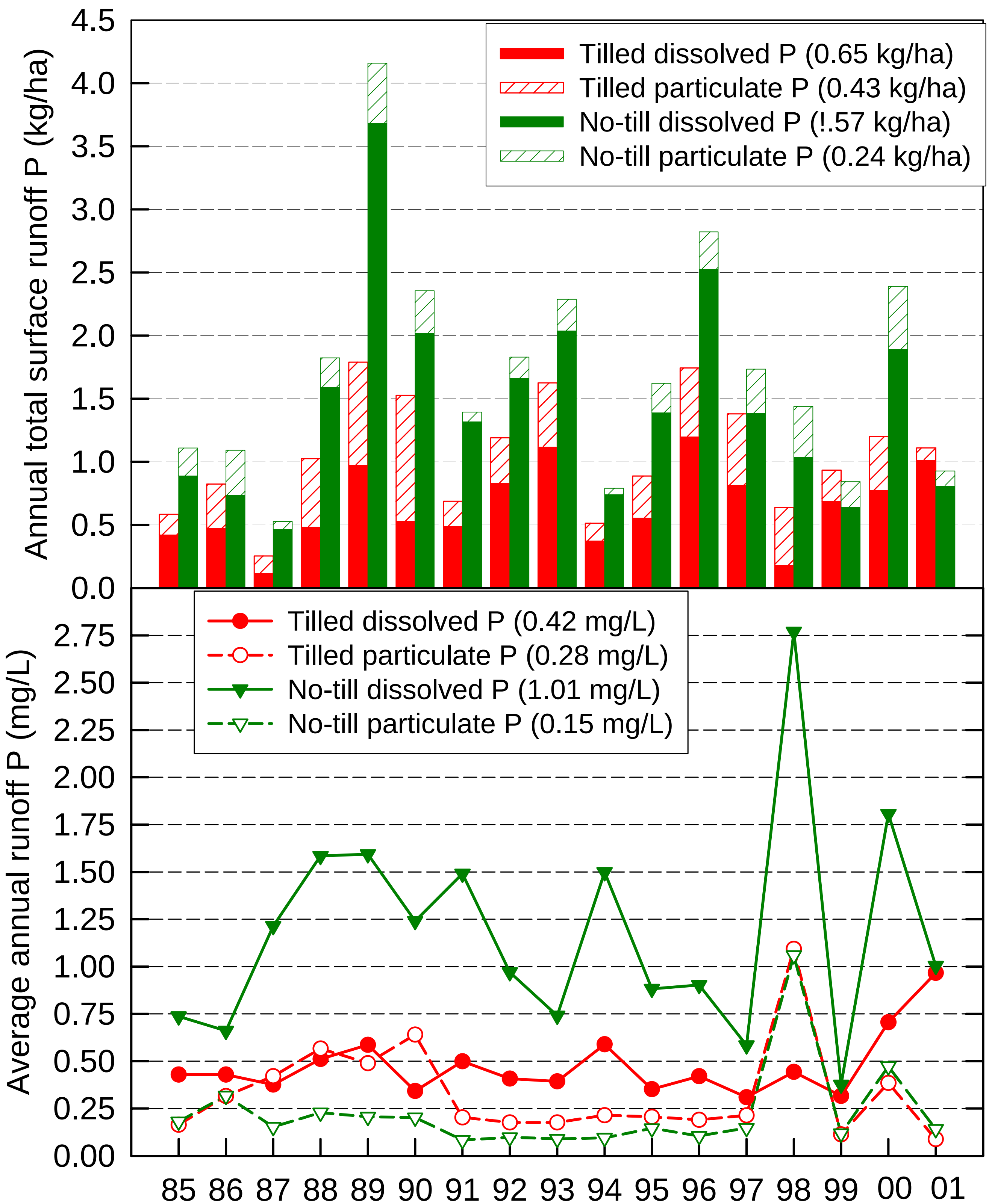

Figure 21. Annual edge-of-field surface runoff dissolved and particulate phosphorus (P) losses and annual average runoff P concentrations for the tilled and no-till watersheds from 1985-2001. Values in parentheses are average annual values for May 1985 to April 1998.

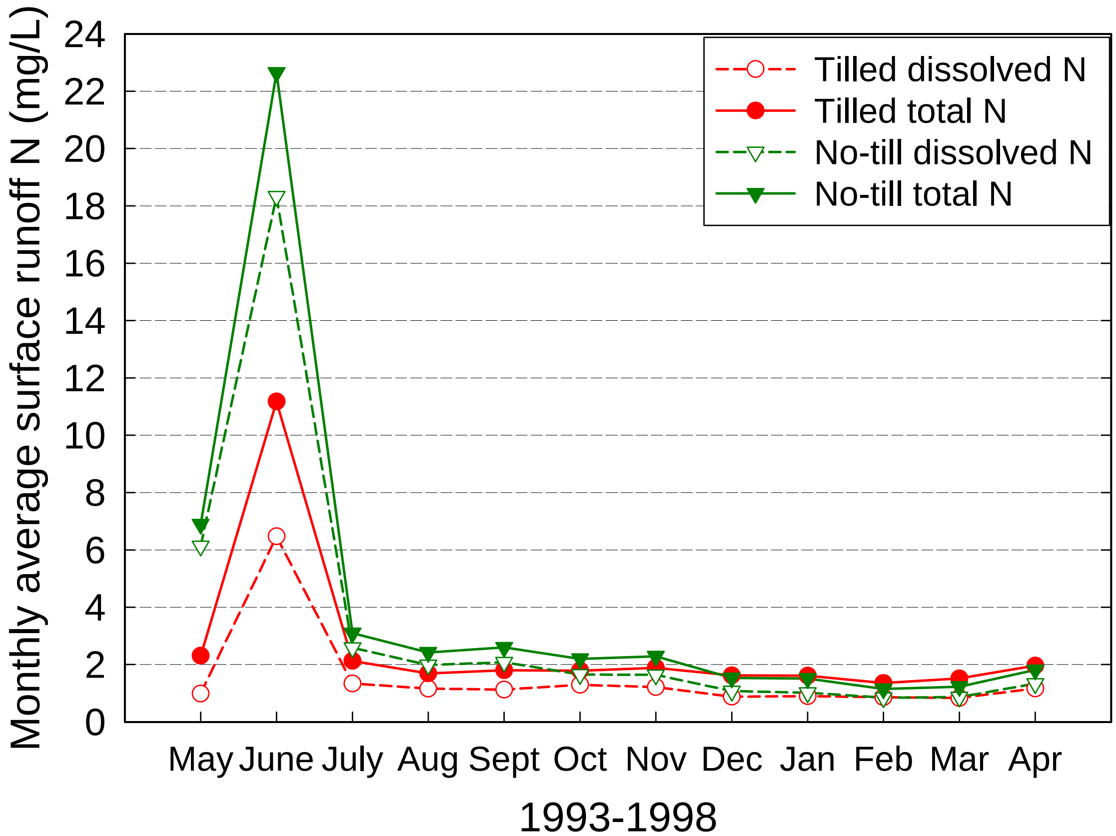

Figure 22. Volume-weighted monthly average dissolved and total nitrogen (N) concentrations in surface runoff from the tilled and no-till watersheds from May 1993 through April 1998. Both watersheds were in continuous corn production during the entire period.

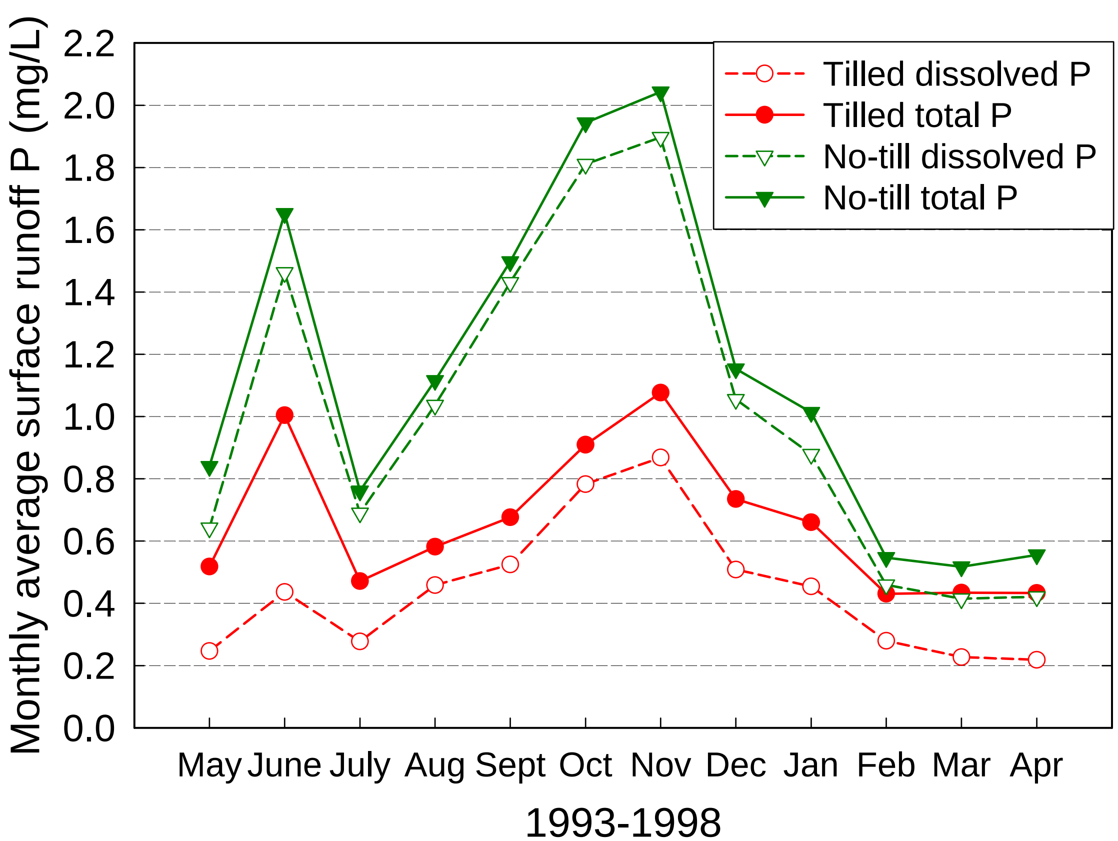

Figure 23.Volume-weighted monthly average dissolved and total phosphorus (P) concentrations in surface and runoff from the tilled and no-till watersheds from May 1993 through April 1998. Both watersheds were in continuous corn production during the entire period.

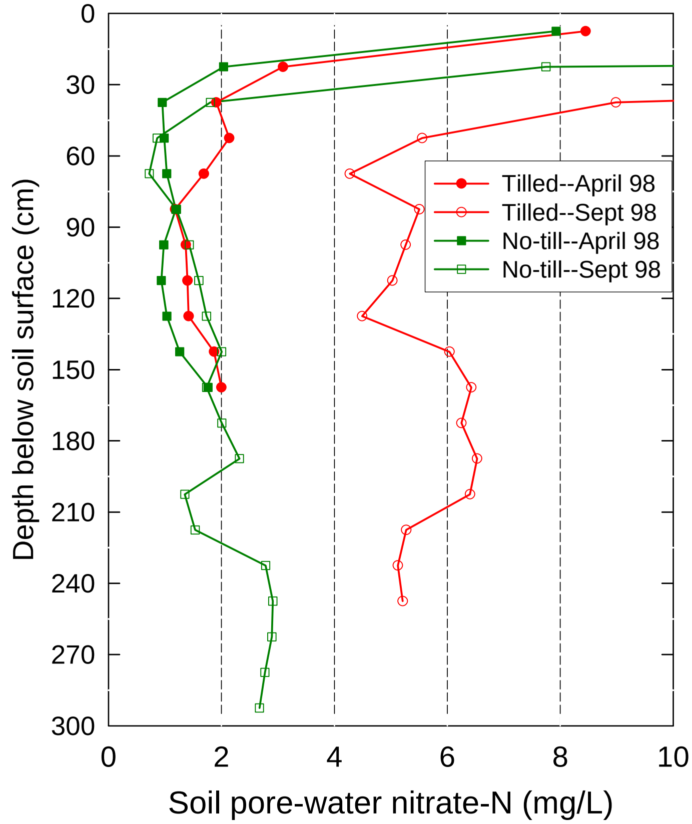

Figure 24. Average (n=6) soil pore-water nitrate-N concentrations to the depth of the water table in the study watersheds prior to poultry litter applications and following corn harvest in 1998.

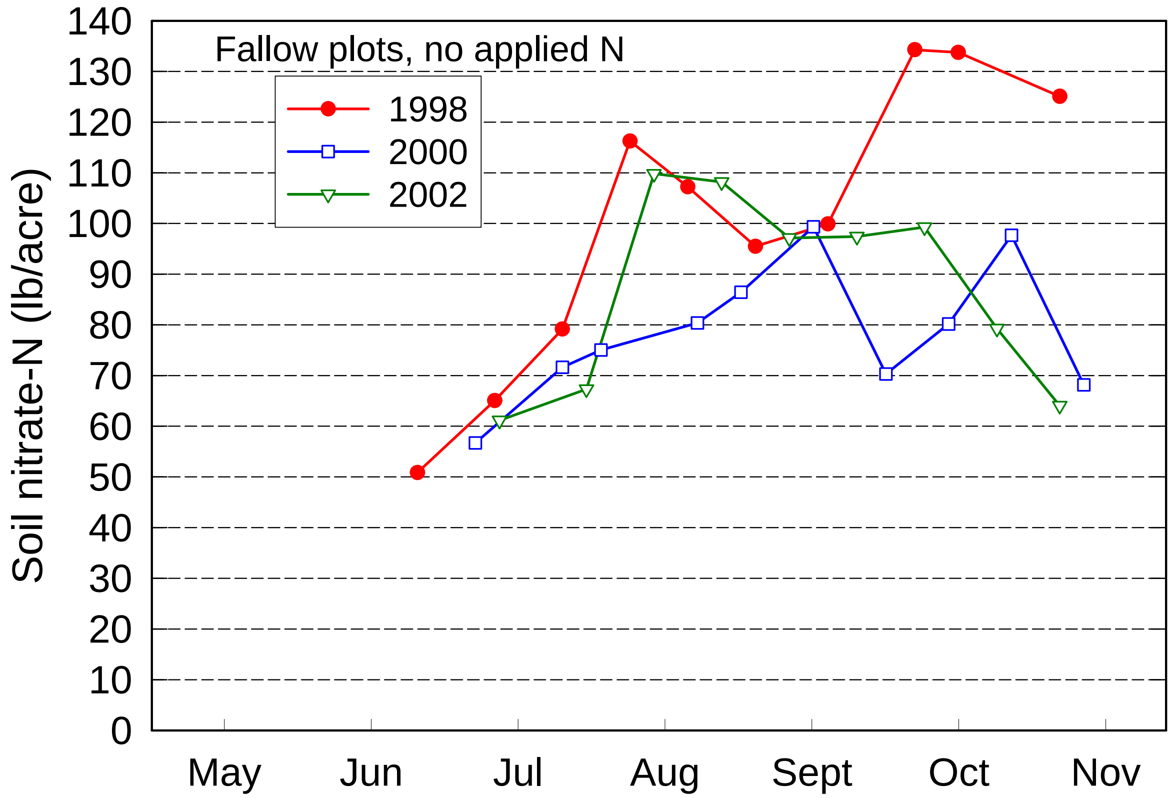

Figure 25. Average (n=3) nitrate-N content of the root zone (0-1 ft) during the summer growing season in unfertilized fallow plots with soil types similar to those in the study watersheds.

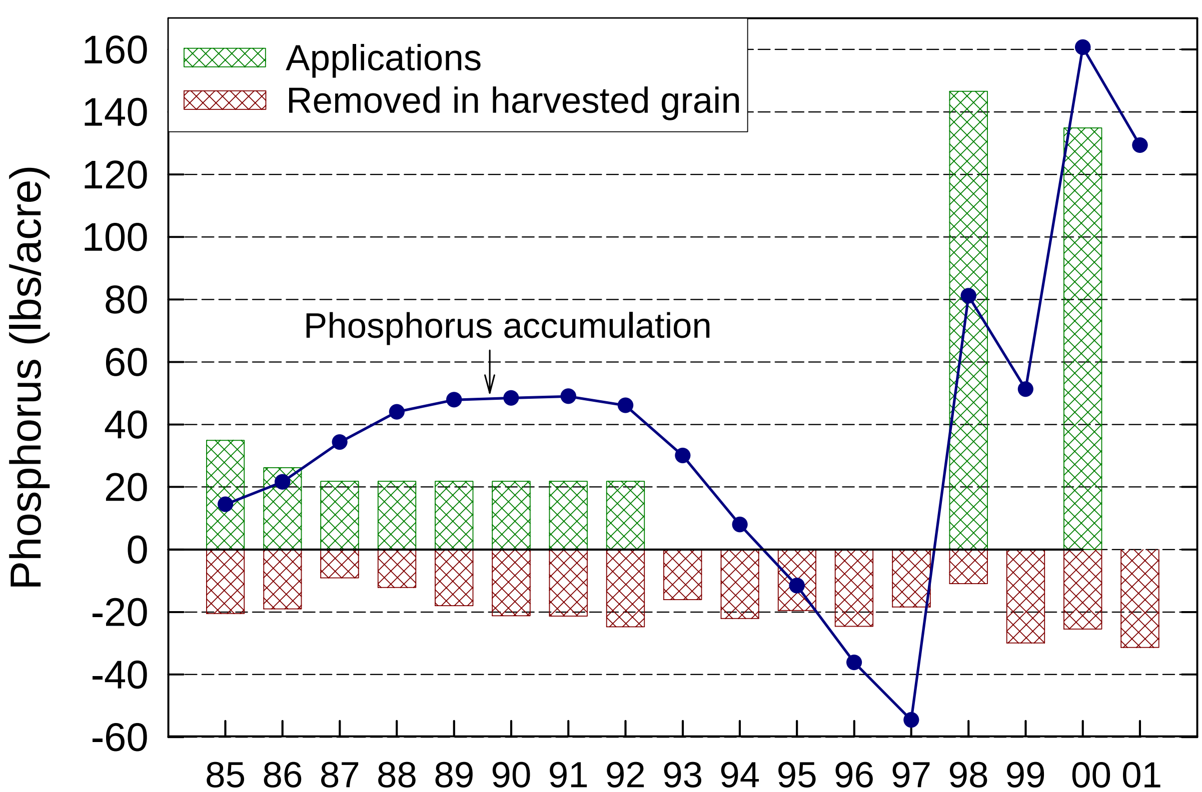

Figure 26. Phosphorus inputs (inorganic fertilizer and poultry litter) and removal in harvested grain in the no-till watershed from 1985 to 2001.

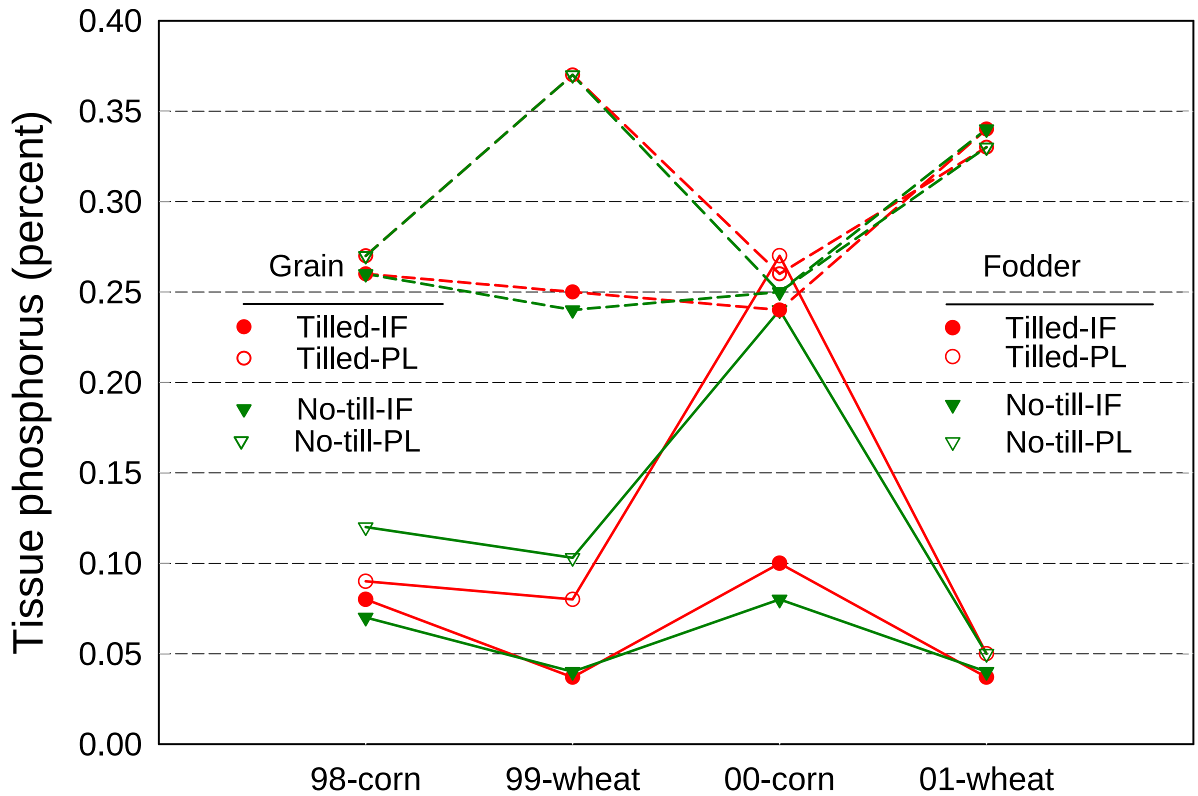

Figure 27. Average (n=3) grain and fodder phosphorus concentrations at harvest in side-by-side plots fertilized with poultry litter (PL) plus supplemental inorganic nitrogen or inorganic fertilizer (IF) only.

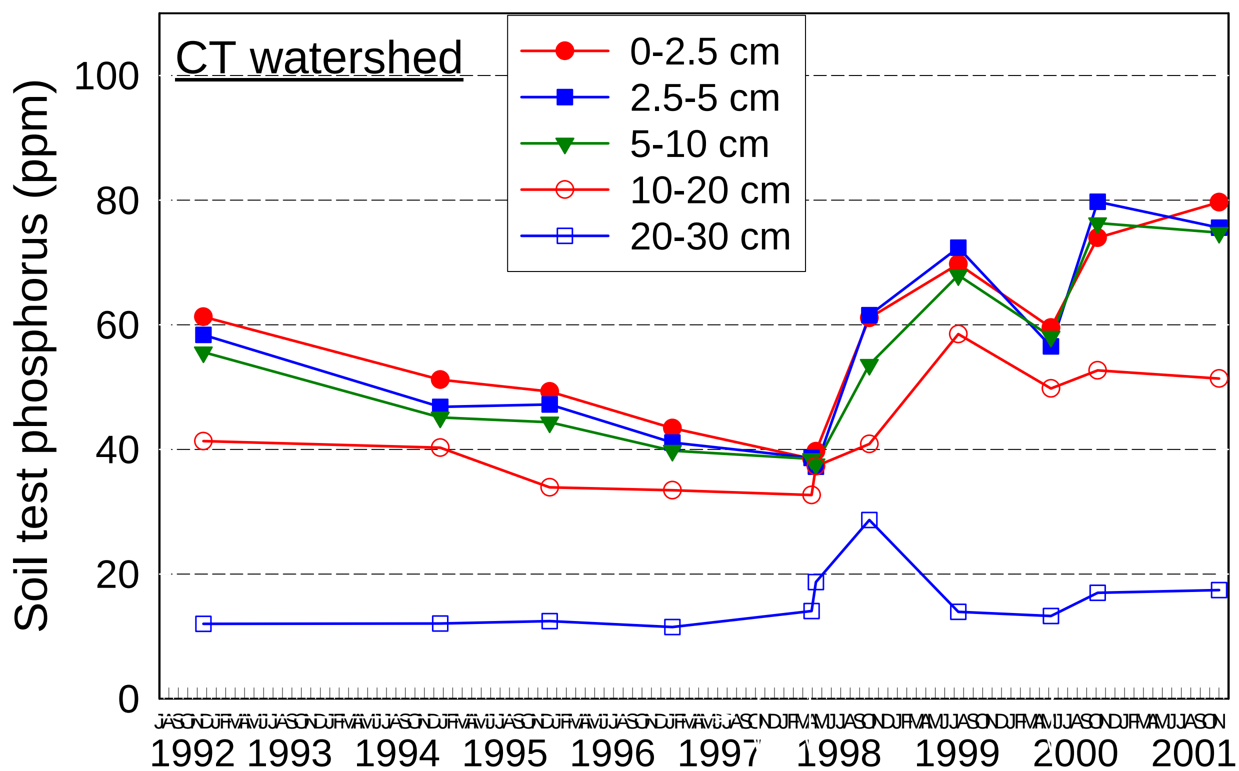

Figure 28. Average soil test (Mehlich-1) phosphorus concentrations in the tilled (CT) watershed from 1992 to November 2001.

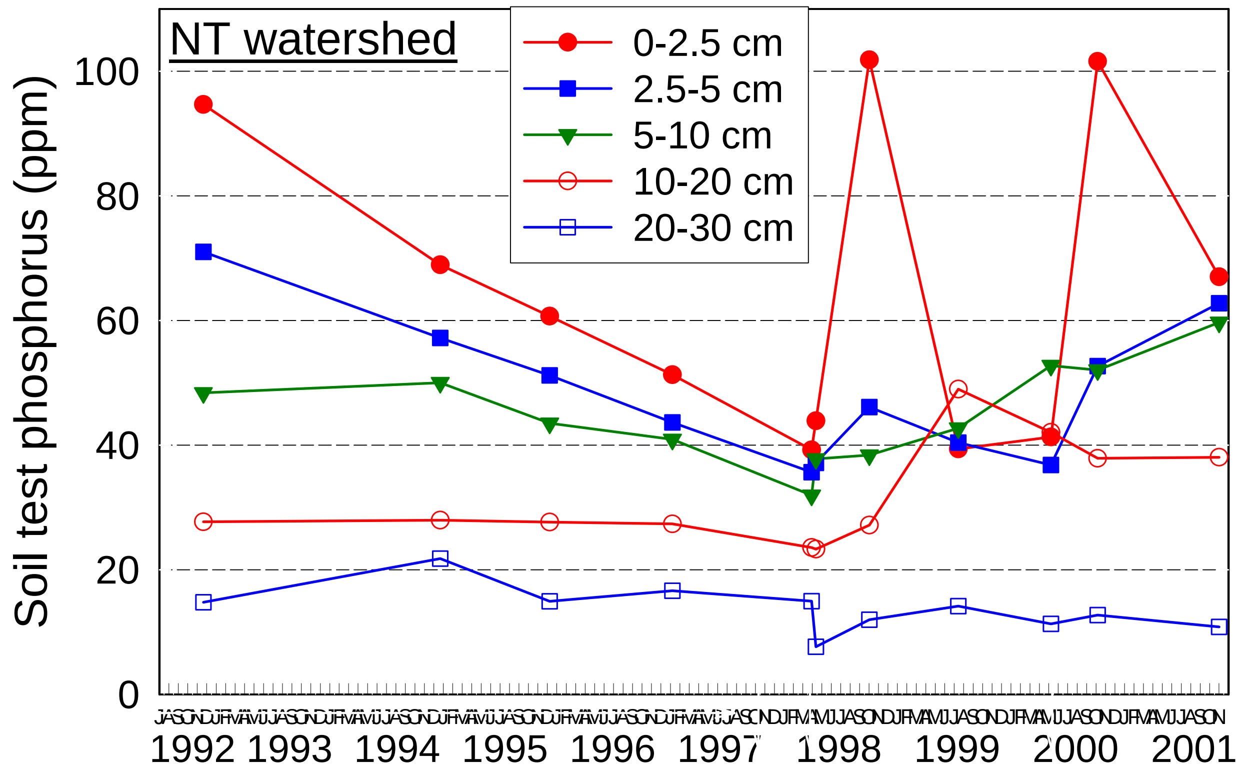

Figure 29. Average soil test (Mehlich-1) phosphorus concentrations in the no-till (NT) watershed from 1992 to November 2001.

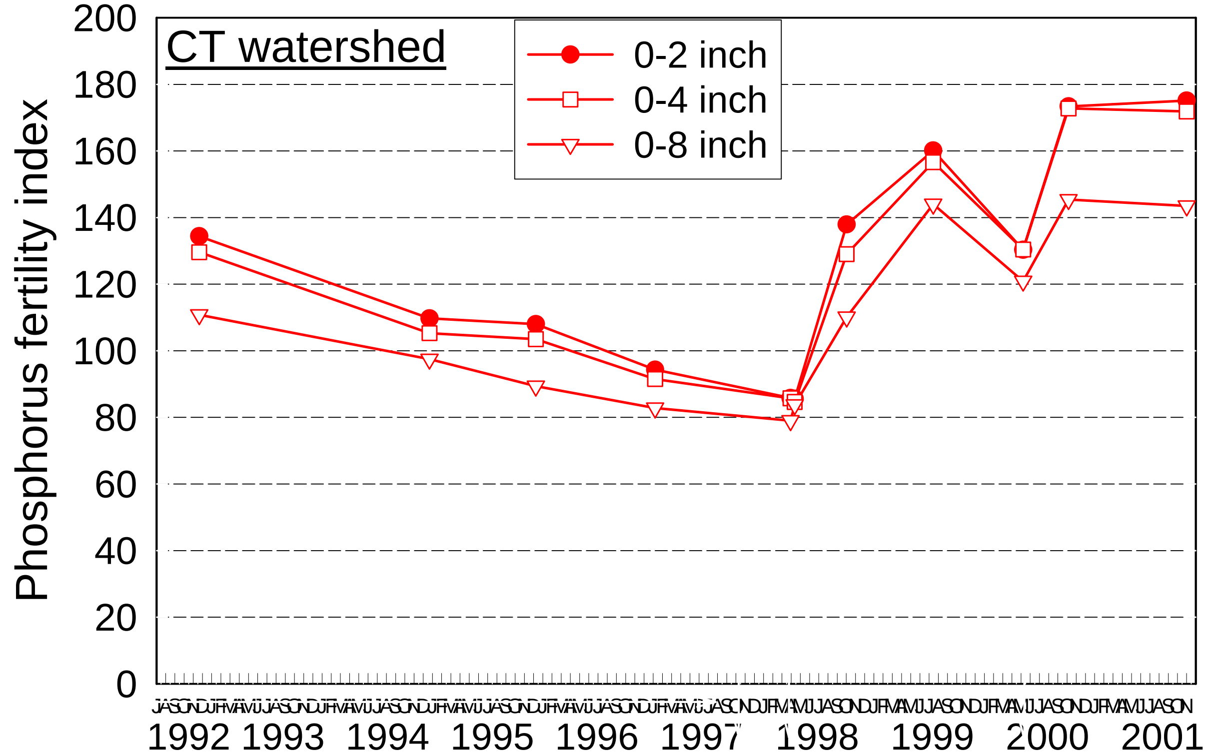

Figure 30. Average soil test (Mehlich-1) phosphorus Fertility Index Values (FIV) for differing sampling depths in the tilled (CT) watershed from 1992 to November 2001.

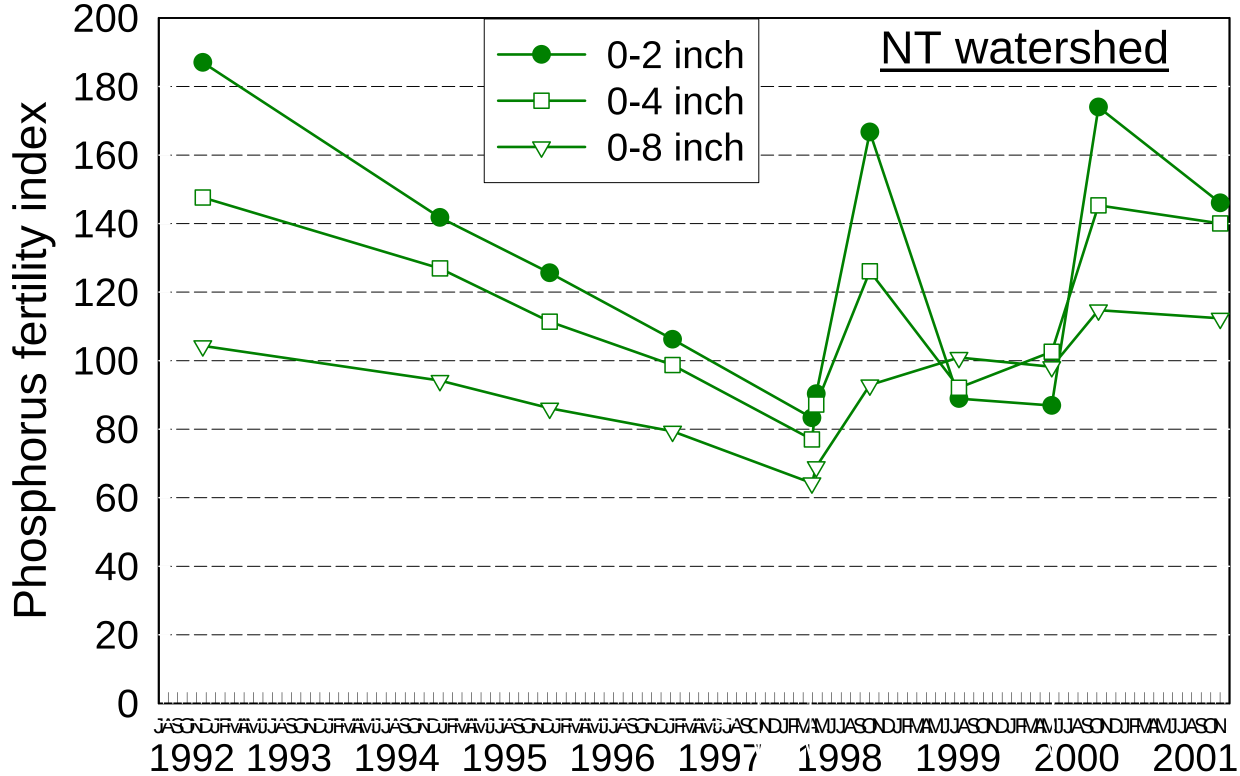

Figure 31. Average soil test (Mehlich-1) phosphorus Fertility Index Values (FIV) for differing sampling depths in the no-till (NT) watershed from 1992 to November 2001.

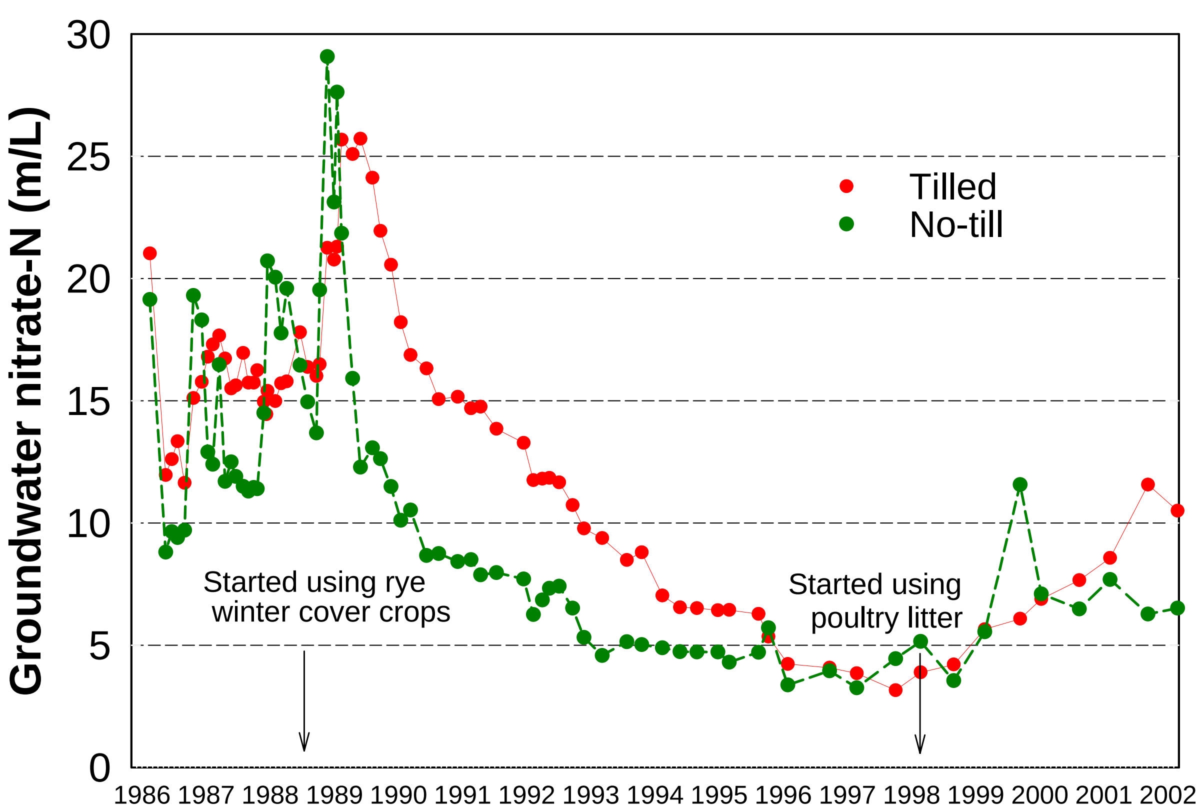

Figure 32. Average nitrate-N concentration in shallow groundwater in the tilled and no-till watersheds from 1986 through 2002.

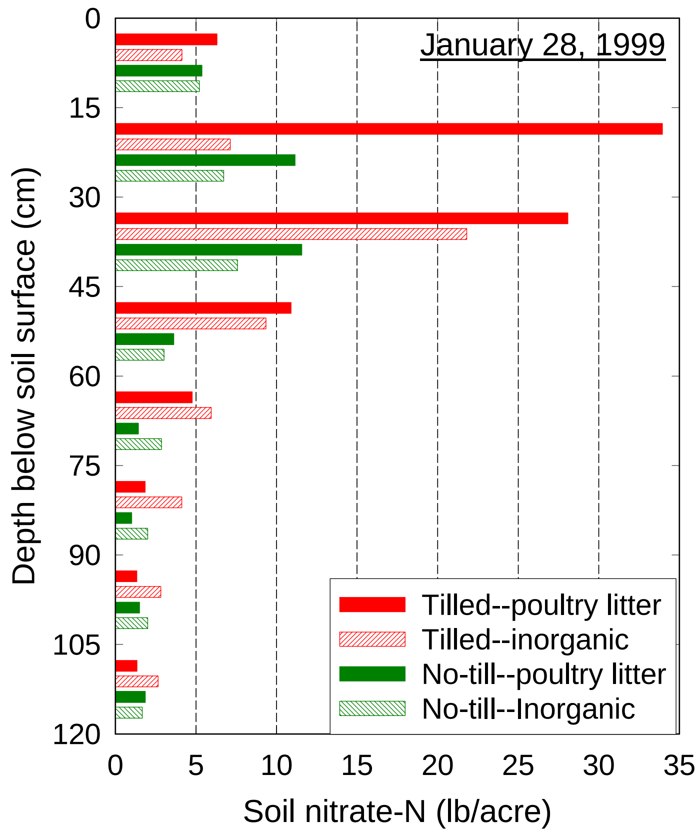

Figure 33. Average (n=3) soil nitrate-N content in 120 cm cores collected in January 1999 to determine nitrogen application rates for wheat.

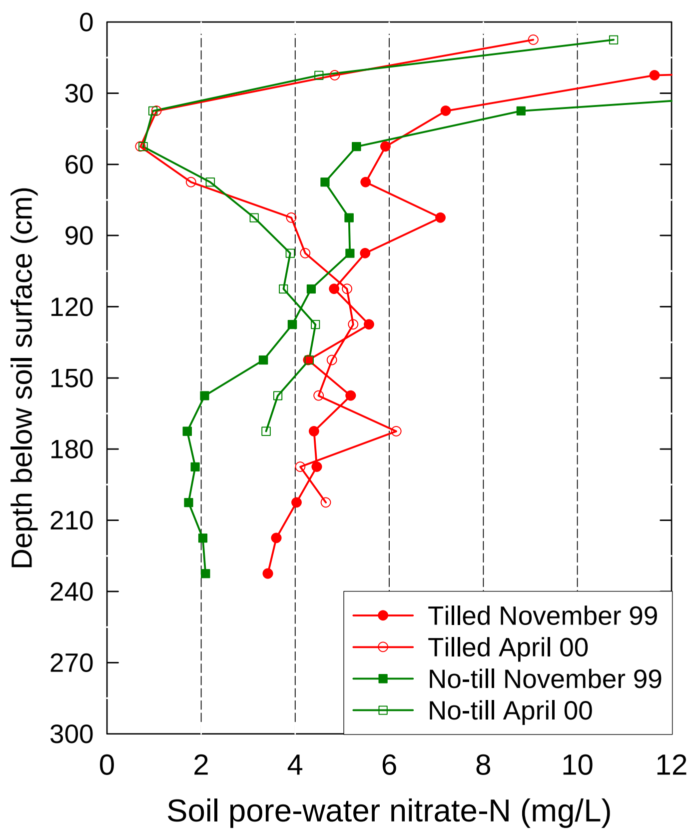

Figure 34. Average (n=6) soil pore-water nitrate-N concentrations to the depth of the water table in the study watersheds following soybean harvest in November 1999 and prior to the beginning of the second cycle of the rotation in April 2000.

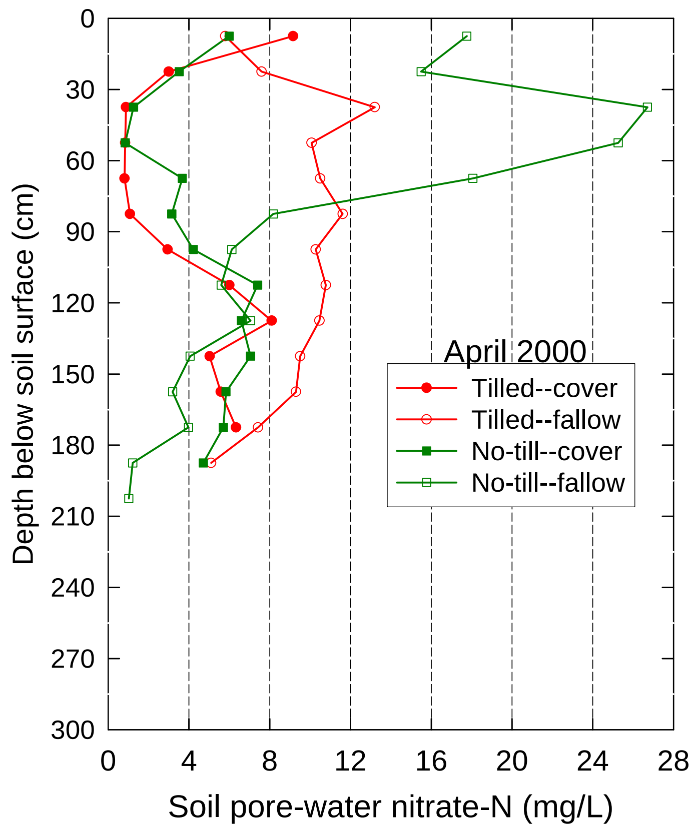

Figure 35. Average (n=3) soil pore-water nitrate-N concentrations to the depth of the water table in adjacent strips with and without rye cover crops just prior to herbicide application in April 2000.

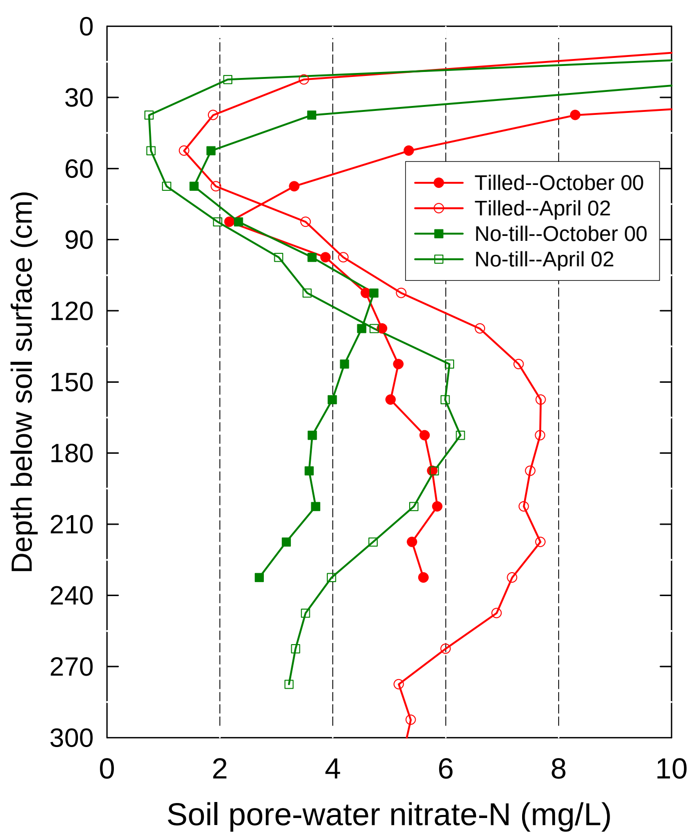

Figure 36. Average (n=6) soil pore-water nitrate-N concentrations to the depth of the water table in the study watersheds following corn harvest in 2000 at the conclusion of the study in April 2002.

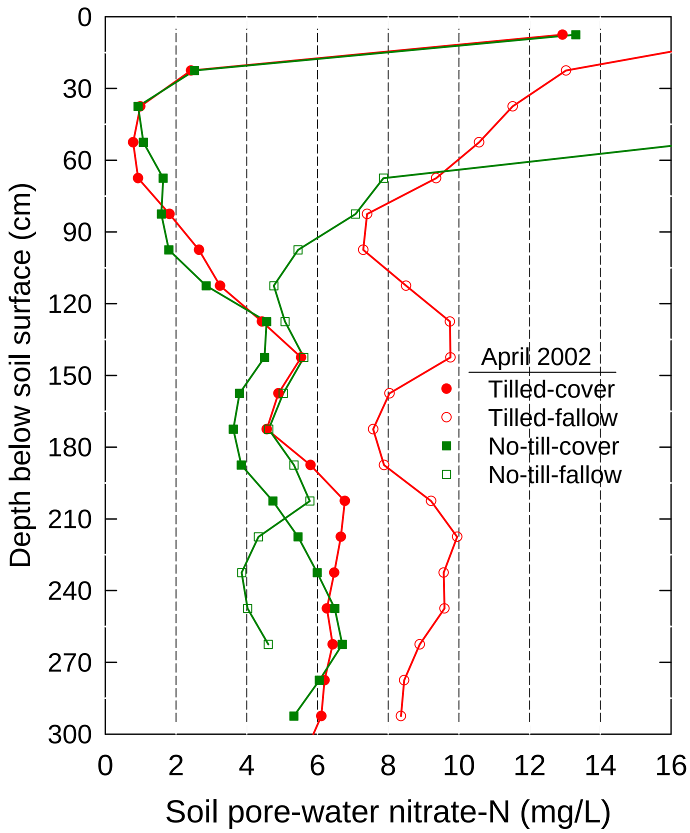

Figure 37. Average (n=3) soil pore-water nitrate-N concentrations to the depth of the water table in adjacent strips with and without rye cover crops just prior to herbicide application in April 2002.

Appendix B (Tables)

Table 1. Nutrient analysis of poultry litter samples collected from each spreader load applied to the study watersheds in April 1998. Analysis was performed by the University of Maryland Soil Testing Lab in College Park.

Sample	Moisture (%)	Total N (%)	NH4-N (%)	P2O5 (%)	K2O (%)	Ca (%)	Mg (%)	S (%)	Mn (ppm)	Zn (ppm)	Cu (ppm)	Available N incorp. (lbs/ton)	Available N not incorp. (lbs/ton)
PL-1	28.7	3.98	1.06	3.47	2.63	1.77	1.16	0.85	591.7	673.0	490.5	50.4	29.2
PL-2	31.8	4.13	1.15	3.80	2.78	1.77	1.03	1.04	608.0	766.1	526.2	52.9	29.8
PL-3	40.0	2.72	0.46	3.02	2.37	1.56	0.75	1.05	523.1	575.9	386.3	31.8	22.7
PL-4	27.7	3.78	1.01	3.13	2.35	1.62	0.76	0.97	558.2	679.6	483.0	47.8	27.7
PL-5	30.9	4.17	1.20	2.78	2.26	1.33	0.73	1.01	544.4	690.8	433.8	53.8	29.7
PL-6	33.2	3.90	0.91	3.32	2.53	1.63	0.90	0.90	570.1	630.2	470.0	48.1	29.9
PL-7	31.0	3.96	0.94	3.36	2.58	1.62	0.97	0.85	553.9	769.8	496.7	49.1	30.2
PL-8	29.8	4.28	1.06	2.95	2.51	1.54	0.71	1.19	558.1	800.3	471.7	53.4	32.2
PL-9	25.5	3.30	0.10	2.92	2.65	2.65	0.67	0.77	539.0	644.1	477.1	34.0	32.1
PL-10	25.8	4.33	0.98	3.21	2.65	1.72	0.86	0.84	548.9	685.3	486.6	53.2	33.5
PL-11	27.4	4.09	0.93	3.26	2.60	1.60	0.76	0.94	611.5	705.9	511.2	50.1	31.6
PL-12	30.3	3.69	0.86	3.37	2.40	1.81	0.73	0.89	566.6	632.8	540.8	45.5	28.2
PL-13	26.6	4.07	0.92	3.12	2.64	1.59	0.68	1.07	581.7	713.9	505.3	50.0	31.5
PL-14	30.0	4.00	0.94	3.69	2.69	1.74	1.11	1.06	592.6	724.9	520.6	49.4	30.6
PL-15	28.3	4.12	0.87	3.13	2.38	1.61	0.74	0.90	562.9	656.9	481.9	49.9	32.6
PL-16	33.5	3.89	0.90	3.15	2.47	1.46	0.69	1.04	518.5	590.3	430.7	48.0	29.9
PL-17	31.0	4.16	0.97	3.44	1.66	1.57	0.80	0.93	553.4	618.2	438.8	51.4	31.9
PL-18	29.1	4.23	0.89	3.32	1.91	1.73	0.66	1.13	582.5	701.0	476.8	51.3	33.4
PL-19	31.3	3.93	0.84	3.19	1.86	1.62	0.71	0.94	505.3	576.7	409.2	47.7	30.9
PL-20	33.8	3.94	1.17	3.18	1.60	1.54	0.64	1.11	623.8	664.8	460.9	51.1	27.7
PL-21	31.0	3.92	0.88	3.19	2.48	1.52	0.72	1.02	505.6	573.8	413.8	48.0	30.4
PL-22	27.9	4.18	0.91	2.64	1.82	1.24	0.61	0.90	529.8	622.8	438.2	50.9	32.7
PL-23	30.1	4.09	1.02	3.34	2.69	1.51	0.79	0.97	523.1	657.3	419.6	51.1	30.7
PL-24	29.8	3.96	0.90	3.21	2.56	1.40	0.78	0.82	465.9	544.5	409.8	48.6	30.7
PL-25	26.8	3.81	0.93	2.83	1.55	0.62	0.77	0.81	462.2	416.1	376.5	47.4	28.9
PL-26	29.6	4.04	0.91	3.21	2.54	1.38	0.72	0.90	498.7	583.2	417.0	49.5	31.3
PL-27	19.4	4.16	0.97	3.45	2.62	1.64	0.88	0.85	518.8	583.3	428.6	51.3	31.9
PL-28	27.7	4.10	0.86	3.22	1.79	1.56	0.82	0.94	483.6	575.4	404.8	49.5	32.4
PL-29	26.0	4.41	0.93	3.44	1.97	1.54	0.84	0.94	555.2	615.9	456.0	53.4	34.7
PL-30	30.3	4.02	0.85	3.00	2.48	1.34	0.63	0.93	515.6	621.5	432.0	48.7	31.6
average	29.5	3.98	0.91	3.21	2.33	1.57	0.79	0.95	545.1	643.1	456.5	48.9	30.7
maximum	40.0	4.41	1.20	3.80	2.78	2.65	1.16	1.19	623.8	800.3	540.8	53.8	34.7
minimum	19.4	2.72	0.10	2.64	1.55	0.62	0.61	0.77	462.2	416.1	376.5	31.8	22.7
standard deviation	3.4	0.31	0.20	0.25	0.36	0.29	0.13	0.10	40.6	76.2	42.5	4.7	2.2
coefficient of variation	11.6	7.84	21.66	7.66	15.62	18.73	16.85	10.56	7.4	11.8	9.3	9.6	7.2

Table 2. Nutrient analysis of poultry litter samples collected form each spreader load applied to the study watersheds in May 2000. Analysis was performed by the University of Maryland Soil Testing Lab in College Park.

Sample	Moisture (%)	Total N (%)	NH4-N (%)	P2O5 (%)	K2O (%)	Ca (%)	Mg (%)	S (%)	Mn (ppm)	Zn (ppm)	Cu (ppm)	PAN incorp. (lbs/ton)	PAN no-till (lbs/ton)
PL-1	29.6	2.79	0.78	2.74	2.11	1.66	0.74	0.90	328.3	295.8	312.0	35.7	20.1
PL-2	33.4	3.08	0.72	2.72	1.28	1.25	0.67	0.92	319.3	271.9	292.6	38.0	23.6
PL-3	33.7	2.99	0.70	3.04	1.57	1.33	0.78	0.84	325.0	289.2	319.0	36.8	22.9
PL-4	33.4	3.09	0.69	3.05	1.54	2.03	0.72	0.97	361.2	306.5	325.9	37.8	23.9
PL-5	29.8	2.71	0.61	2.67	2.05	3.46	0.72	0.93	366.6	286.5	334.3	33.1	21.0
PL-6	33.9	2.85	0.65	3.39	1.54	1.64	0.84	0.89	350.9	322.5	306.0	35.0	22.1
PL-7	33.2	3.02	0.67	2.87	2.28	2.97	0.70	1.11	369.6	323.5	324.1	37.0	23.5
PL-8	32.1	3.18	0.75	3.24	2.00	1.47	0.74	1.02	368.6	317.7	323.1	39.2	24.3
PL-9	34.3	2.59	0.66	2.47	2.10	2.02	0.79	0.80	293.8	241.9	299.7	34.3	32.1
PL-10	32.3	2.91	0.69	2.83	2.48	1.44	0.79	0.74	298.4	273.4	303.2	36.0	22.2
PL-11	35.4	3.30	0.76	2.98	1.63	1.27	0.74	0.78	283.6	240.3	270.6	40.5	25.4
PL-12	34.3	2.86	0.74	2.67	2.15	1.39	0.66	0.99	314.8	320.7	292.5	36.0	21.2
PL-13	32.3	2.84	0.64	2.74	1.59	1.22	0.95	0.87	325.0	316.9	304.7	34.8	22.0
PL-14	29.3	3.04	0.71	3.04	1.63	1.78	0.81	0.92	372.6	336.6	336.6	37.5	23.3
PL-15	30.1	3.09	0.71	3.04	2.12	1.54	0.79	0.94	365.6	349.6	330.0	38.0	23.8
PL-16	28.5	2.90	0.83	3.00	1.46	2.93	0.88	0.99	373.2	394.6	336.7	37.4	20.7
PL-17	36.4	2.92	0.79	2.85	1.66	1.25	0.68	0.73	327.4	312.8	328.0	37.1	21.3
PL-18	36.4	2.76	0.81	2.87	1.63	1.30	0.71	0.89	309.9	328.4	289.6	36.4	33.4
PL-19	34.8	3.07	0.78	2.80	2.41	1.23	0.67	0.86	301.3	281.8	300.7	38.5	22.9
PL-20	28.3	3.25	0.78	3.28	2.54	1.55	0.69	0.91	374.9	384.3	347.0	40.3	24.7
PL-21	33.4	3.03	0.72	2.65	1.43	1.20	0.69	1.00	337.9	325.3	315.3	37.5	23.1
PL-22	32.5	2.91	0.72	2.93	1.59	1.41	0.73	0.99	358.6	321.4	326.2	36.3	21.8
PL-23	29.6	2.67	0.77	2.30	1.78	1.52	1.57	0.64	343.5	309.7	299.8	34.4	19.0
PL-24	33.7	2.99	0.70	2.97	1.57	1.41	0.76	0.84	332.0	307.4	301.5	36.9	22.9
PL-25	35.8	3.20	0.78	2.95	2.53	1.28	0.69	0.85	331.4	300.6	288.3	39.9	24.2
PL-26	36.6	2.95	0.72	2.68	1.45	1.19	0.65	0.79	277.7	263.8	281.5	36.7	22.3
average	32.8	2.96	0.73	2.88	1.85	1.64	0.78	0.89	335.0	308.6	311.1	37.0	23.4
maximum	36.6	3.30	0.83	3.39	2.54	3.46	1.57	1.11	374.9	394.6	347.0	40.5	33.4
minimum	28.3	2.59	0.61	2.3	1.28	1.19	0.65	0.64	277.7	240.3	270.6	33.1	19.0
standard deviation	2.5	0.17	0.05	0.24	0.38	0.58	0.17	0.10	29.1	35.5	19.0	1.8	3.1
coefficient of variation	7.5	5.86	7.46	8.23	20.31	35.50	22.38	11.44	8.7	11.5	6.1	4.9	13.1

Table 3. Nutrient analysis of poultry litter samples collected from each spreader load applied to the study watersheds in October 2000. Analysis was performed by University of Maryland Soil Testing Lab in College Park.

Sample	Moisture (%)	Total N (%)	NH4-N (%)	P2O5 (%)	K2O (%)	Ca (%)	Mg (%)	S (%)	Mn (ppm)	Zn (ppm)	Cu (ppm)	Available N incorp. (lbs/ton)	Available N not incorp. (lbs/ton)
PL-1	23.3	3.17	0.68	2.59	2.22	1.75	0.90	0.76	391.7	315.8	312.0	38.5	24.9
PL-2	24.4	3.32	0.70	2.84	2.23	2.18	0.87	0.65	430.9	344.7	344.7	40.2	26.2
PL-3	26.6	3.43	0.73	3.51	2.56	1.79	0.92	0.90	437.6	334.8	343.7	41.6	27.0
PL-4	26.2	3.67	0.84	3.34	2.66	1.62	0.98	0.89	454.6	425.1	398.5	45.1	28.3
PL-5	25.4	3.45	0.67	2.95	2.57	1.70	0.91	0.64	405.8	361.1	402.8	41.2	27.8
PL-6	28.1	3.62	0.88	2.93	2.42	1.78	0.75	0.94	448.2	305.1	346.8	45.1	27.4
PL-7	25.3	3.62	0.78	3.01	2.60	1.88	0.88	0.61	424.8	340.5	333.0	44.0	28.4
PL-8	27.3	3.74	0.85	3.21	2.66	1.46	0.81	0.95	453.2	483.1	430.7	45.9	29.0
PL-9	26.8	3.65	0.82	3.10	2.42	1.26	0.80	1.08	444.4	442.2	383.6	44.7	28.3
PL-10	23.1	3.70	0.67	3.17	2.43	1.51	1.17	0.76	403.1	353.9	322.3	43.7	30.3
PL-11	25.6	3.70	0.79	3.08	2.45	1.64	0.81	0.85	437.0	378.2	503.3	44.9	29.1
PL-12	23.8	3.65	0.53	3.09	2.32	1.53	0.82	0.84	446.7	396.4	336.9	41.7	31.2
PL-13	23.5	3.54	0.52	2.85	2.26	1.38	0.81	0.83	455.7	367.0	357.8	40.5	30.2
PL-14	24.7	3.62	0.78	2.78	2.43	1.42	0.81	0.95	452.1	409.9	351.1	43.9	28.4
PL-15	23.4	4.00	0.67	3.15	2.30	1.44	0.86	0.69	418.1	340.0	332.3	46.7	33.3
PL-16	24.9	3.64	0.75	3.07	2.40	1.47	0.84	0.86	461.6	486.4	381.3	44.0	28.9
PL-17	23.1	3.93	0.71	2.89	2.33	1.45	0.81	0.25	445.0	427.3	362.8	46.4	32.2
PL-18	27.4	3.33	0.69	2.69	2.23	1.25	0.75	0.58	409.6	886.0	323.2	40.2	26.4
average	25.2	3.60	0.73	3.01	2.42	1.58	0.86	0.78	434.5	411.0	364.8	43.2	28.7
maximum	28.1	4.00	0.88	3.51	2.66	2.18	1.17	1.08	461.6	886.0	503.3	46.7	33.3
minimum	23.1	3.17	0.52	2.59	2.22	1.25	0.75	0.25	391.7	305.1	312.0	38.5	24.9
standard deviation	1.6	0.20	0.10	0.22	0.14	0.23	0.09	0.18	20.3	126.4	45.5	2.3	2.1
coefficient of variation	6.3	5.53	13.24	7.33	5.86	14.35	10.98	23.67	4.7	30.7	12.5	5.4	7.2

Table 4. Daily precipitation depth (cm) at WREC during 1998.

Day	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	-	-	0.08	0.08	0.36	1.02	-	-	-	0.03	-	-
2	-	-	1.98	-	0.15	0.46	-	-	-	-	-	-
3	-	-	1.04	-	1.02	0.08	-	-	-	0.03	0.23	-
4	-	2.49	-	1.07	0.13	-	0.03	-	1.17	0.13	-	-
5	-	1.35	-	-	0.53	-	-	-	-	-	-	-
6	-	0.66	-	-	-	-	-	-	-	-	-	-
7	0.36	-	0.28	-	0.41	-	-	-	0.46	-	-	0.18
8	0.61	-	1.32	-	1.45	-	2.67	-	0.10	1.12	-	1.85
9	-	-	0.84	1.88	0.08	0.36	-	-	-	0.18	-	0.76
10	-	-	-	-	0.05	-	-	3.53	-	0.25	-	-
11	-	0.76	-	-	0.97	0.76	-	0.10	-	-	1.45	-
12	-	0.18	-	-	2.64	0.81	-	-	-	-	-	-
13	-	-	-	-	-	1.02	-	-	-	0.13	-	2.03
14	-	-	-	-	-	-	-	-	-	-	-	-
15	2.36	-	-	-	-	1.91	-	-	-	-	-	-
16	0.13	-	-	-	-	1.35	-	0.03	-	-	-	-
17	0.15	0.99	-	2.11	-	-	-	0.89	-	-	-	0.13
18	-	0.08	2.03	-	-	-	0.18	-	-	-	-	-
19	-	-	3.30	0.74	-	0.15	-	-	-	0.03	-	-
20	0.20	0.08	0.38	0.10	-	-	-	-	-	-	0.30	-
21	-	-	1.78	-	-	-	-	-	0.03	-	-	-
22	0.10	-	-	-	-	-	-	-	1.07	-	-	0.25
23	4.52	2.79	-	-	-	0.08	0.03	-	-	-	-	0.25
24	0.53	0.61	-	-	0.05	-	-	-	-	-	-	0.10
25	-	-	-	-	0.05	-	-	-	0.05	-	-	-
26	-	-	-	0.13	-	3.78	-	-	-	-	0.84	-
27	0.28	-	-	0.28	-	-	-	-	-	-	-	-
28	4.39	-	-	-	-	-	-	0.08	-	0.03	-	0.13
29	-	-	-	-	-	-	-	-	-	-	-	0.05
30	-		-	-	-	-	-	-	0.15	-	-	0.13
31	-		-		-		0.25	-		-		-
Total	13.64	9.98	13.03	6.38	7.87	11.76	3.15	4.62	3.02	1.91	2.82	5.86
Ave. (41-02)	8.45	7.04	9.74	7.72	9.87	8.96	9.88	10.25	9.15	7.68	8.19	8.73
+/-	+5.19	-2.94	+3.29	-1.34	-2.00	+2.80	-6.73	-5.63	-6.13	-5.77	-5.37	-2.87

Table 5. Daily precipitation depth (cm) at WREC during 1999.

Day	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	-	-	-	0.91	-	-	2.29	3.38	-	-	-	-
2	-	1.02	-	-	-	-	1.50	0.05	-	-	1.09	-
3	3.99	-	0.56	-	0.15	-	0.03	-	-	-	-	-
4	-	0.10	0.08	0.97	-	-	-	-	1.22	1.50	-	-
5	-	-	-	-	-	-	-	-	4.42	-	-	-
6	-	0.10	1.30	-	-	-	-	-	0.25	-	-	0.76
7	-	0.10	-	-	-	-	-	-	1.22	-	-	-
8	0.56	0.08	-	-	0.13	-	-	0.20	-	-	-	-
9	0.10	-	1.09	0.46	-	-	-	-	0.23	0.08	-	-
10	-	-	0.05	-	-	-	0.10	-	1.02	1.35	-	1.14
11	-	-	-	0.76	-	-	-	-	-	0.53	-	-
12	-	1.19	-	-	-	-	0.69	-	-	-	-	-
13	-	-	-	-	-	0.51	0.08	-	-	-	-	0.23
14	0.28	-	3.56	-	-	2.92	-	1.65	-	-	-	2.64
15	2.41	-	0.64	0.36	-	-	-	0.58	3.58	-	-	-
16	-	-	-	-	-	0.03	-	-	16.69	-	-	-
17	-	0.30	-	-	-	0.61	-	-	-	1.04	-	-
18	1.47	2.11	-	-	-	0.05	-	-	-	0.36	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	0.05	-	2.51	0.05	2.08	-	2.39	-	0.33
21	0.15	-	3.25	0.30	-	0.30	-	-	2.39	-	-	0.10
22	-	-	0.38	0.13	0.03	-	5.41	-	0.46	0.79	-	0.05
23	-	-	-	0.71	0.56	-	-	-	-	-	0.56	-
24	2.79	-	-	-	0.36	-	-	4.19	-	-	-	-
25	-	-	-	-	-	-	0.08	3.56	-	-	0.13	-
26	0.03	-	-	-	-	-	-	5.69	-	-	1.47	-
27	-	0.03	0.05	-	-	-	-	-	-	-	1.14	-
28	-	1.88	0.15	-	-	0.05	0.13	-	-	-	-	-
29	-	-	-	-	-	1.30	0.03	-	0.10	-	-	-
30	-		-	-	-	0.18	-	-	2.51	-	-	-
31	-		-		-		-	-		-		-
Total	11.79	6.91	11.10	4.65	1.23	8.46	10.36	21.39	34.09	8.03	4.39	5.26
Ave. (41-02)	8.45	7.04	9.74	7.72	9.87	8.96	9.88	10.25	9.15	7.68	8.19	8.73
+/-	+3.34	-0.13	+1.36	-3.07	-8.64	-0.50	+0.48	+11.14	+24.94	+0.35	-3.80	-3.47

Table 6. Daily precipitation depth (cm) at WREC during 2000.

Day	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	-	-	-	-	-	0.03	-	-	-	-	-	-
2	-	-	-	-	0.13	0.94	-	0.15	0.43	-	-	-
3	-	-	-	-	-	-	0.51	0.30	1.42	-	-	-
4	2.62	0.10	-	1.02	-	-	0.08	0.71	0.86	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	1.17	-	0.41	-	0.86	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	1.30	-	-	-	-	-	-	-	-
9	-	-	-	1.14	-	-	-	-	-	-	0.33	-
10	0.69	-	-	-	0.38	-	1.17	-	-	-	0.64	0.13
11	-	-	0.46	-	-	-	-	-	-	-	-	-
12	-	-	0.51	-	-	0.10	-	-	-	-	-	-
13	-	0.20	-	-	0.41	-	0.10	0.36	-	-	-	0.03
14	-	1.07	-	-	-	0.25	0.58	3.61	-	-	0.91	2.06
15	-	-	-	0.74	-	2.97	5.21	-	4.11	-	-	-
16	-	-	1.88	0.03	-	-	4.78	-	-	-	0.10	0.76
17	-	-	0.38	1.70	0.08	0.43	-	-	-	-	-	2.84
18	-	1.65	-	0.86	-	0.84	-	0.33	-	-	-	-
19	-	0.43	-	0.18	0.13	-	1.65	-	2.39	-	-	0.13
20	0.76	-	0.10	-	0.08	-	0.41	-	-	-	-	0.08
21	-	-	7.04	0.53	0.61	0.03	-	-	-	-	-	-
22	-	-	0.30	0.48	5.89	1.14	-	-	-	-	-	0.18
23	-	-	-	-	-	-	-	-	-	-	-	-
24	-	-	-	-	0.43	-	0.08	-	-	-	-	-
25	1.70	-	0.74	1.57	0.10	-	-	-	5.72	-	1.09	-
26	-	-	-	-	-	0.05	2.08	-	1.42	-	1.60	-
27	-	0.33	2.18	0.08	0.84	0.86	0.08	1.35	-	-	-	-
28	-	0.33	0.13	-	0.91	0.81	0.48	0.03	-	-	-	-
29	2.36	-	-	-	0.13	0.28	0.03	-	-	-	0.28	-
30	-		-	-	-	-	-	-	-	-	-	-
31	-		-		-		0.08	-		-		-
Total	8.13	4.11	13.72	9.63	10.11	9.91	17.32	7.25	16.36	0.86	4.95	6.21
Ave. 41-02	8.45	7.04	9.74	7.72	9.87	8.96	9.88	10.25	9.15	7.68	8.19	8.73
+/-	-0.32	-2.93	+3.98	+1.91	+0.24	+0.95	+7.44	-3.00	+7.21	-6.82	-3.24	-2.52

Table 7. Daily precipitation depth (cm) at WREC during 2001.

Day	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
1	-	-	-	-	-	2.01	0.25	-	-	0.38	-	-
2	-	0.05	-	-	-	0.20	0.05	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	0.05	-
4	-	-	1.37	-	-	-	5.59	-	-	-	-	-
5	0.15	2.67	0.38	-	-	0.30	2.92	-	-	-	-	-
6	-	-	-	0.03	-	0.38	-	-	-	0.38	-	-
7	0.56	-	-	-	-	4.62	-	-	-	-	-	0.10
8	-	-	-	-	-	0.08	0.56	-	-	-	-	1.09
9	-	-	0.13	0.30	-	-	0.13	-	-	-	-	0.03
10	-	0.05	-	-	-	-	2.36	1.50	0.86	-	-	0.05
11	-	-	-	1.78	-	-	-	6.73	-	-	-	0.76
12	-	0.25	0.97	-	-	-	-	0.41	-	-	-	-
13	-	0.18	0.38	0.13	-	-	-	0.76	-	-	-	-
14	0.03	0.03	-	-	-	-	-	-	-	0.74	-	0.05
15	0.03	0.13	0.69	0.38	-	-	-	-	-	0.13	-	-
16	0.03	1.75	-	0.25	-	3.05	-	-	-	0.05	-	-
17	-	0.18	0.10	0.53	-	3.66	0.08	-	-	-	-	0.38
18	0.03	-	-	0.51	-	-	3.18	-	-	-	-	0.13
19	2.92	-	-	-	0.25	-	-	-	-	-	-	-
20	2.16	-	0.28	-	0.08	-	-	-	2.57	-	0.10	-
21	0.13	-	4.95	-	0.76	-	-	-	0.58	-	-	-
22	-	0.89	-	-	1.63	-	-	-	-	-	-	-
23	-	-	-	-	-	0.43	-	5.18	-	-	-	0.38
24	-	-	-	0.15	-	-	-	-	1.47	-	0.13	0.76
25	-	0.36	-	-	0.51	-	-	-	0.89	-	1.47	-
26	-	-	0.13	-	8.89	-	2.46	-	-	-	-	-
27	-	-	-	-	0.64	-	-	-	0.15	0.03	-	-
28	-	0.05	-	-	-	-	-	-	-	-	-	-
29	-	-	2.41	-	-	-	1.52	-	-	-	0.05	-
30	1.19		1.27	-	-	0.61	0.05	0.89	0.15	-	-	-
31	-		-		-		-	-		-		-
Total	7.21	6.58	13.06	4.06	12.75	15.34	19.15	15.47	6.68	1.70	1.80	3.73
Ave. (41-02)	8.45	7.04	9.74	7.72	9.87	8.96	9.88	10.25	9.15	7.68	8.19	8.73
+/-	-1.24	-0.46	+3.32	-3.66	+2.88	+6.38	+9.27	+5.22	-2.47	-5.98	-6.39	-5.00

Table 8. Daily precipitation depth (cm) at WREC during 2002.

Day	Month J	F	M	A	M	J	J	A	S	O	N	D
1	-	0.33	-	-	-	-	-	0.30	10.06	-	-	-
2	-	-	2.34	-	4.06	-	-	-	-	-	-	-
3	-	-	0.15	0.13	-	-	-	-	-	-	-	-
4	-	0.05	-	-	0.51	-	-	-	-	-	-	-
5	-	-	-	-	-	1.78	-	-	-	-	1.45	2.41
6	2.36	-	-	-	-	4.52	-	0.43	-	-	0.53	-
7	0.30	0.79	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	0.46	-	-	-	-	-	0.05	-	-
10	-	0.25	-	0.36	-	-	0.10	-	0.13	4.39	-	-
11	0.84	-	-	-	-	-	-	-	-	2.77	1.40	3.66
12	-	-	0.25	0.36	0.13	-	-	-	-	-	2.26	-
13	-	-	0.76	-	0.64	0.76	-	-	-	-	0.46	1.24
14	-	-	-	-	-	0.28	0.91	-	0.08	-	-	-
15	-	-	-	-	-	0.13	-	-	0.25	0.13	-	-
16	-	-	-	-	-	-	-	-	0.74	3.53	3.94	-
17	-	-	0.51	-	0.13	-	-	-	-	0.10	1.91	-
18	-	-	1.27	0.51	3.05	-	-	-	-	-	-	-
19	1.52	-	0.08	0.05	-	-	-	-	-	-	-	-
20	-	-	2.01	-	-	-	-	-	-	0.10	-	1.60
21	0.20	-	-	0.10	-	-	-	-	-	-	0.05	-
22	-	-	-	0.60	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	2.95	-	0.38	-	-	-
24	0.25	-	-	-	-	-	0.33	0.03	-	-	-	0.51
25	0.23	-	-	0.36	-	-	0.41	-	-	1.07	-	2.41
26	-	-	1.63	-	-	-	0.13	-	1.60	1.35	-	-
27	-	-	0.18	0.10	-	0.38	-	-	0.38	-	0.25	-
28	-	-	-	3.96	-	0.03	0.15	1.78	0.20	0.10	-	-
29	-	-	-	-	-	-	-	1.75	-	1.85	-	-
30	-		-	-	-	-	-	-	-	0.94	0.20	-
31	-		0.79		-		-	0.03		0.13		-
Total	5.72	1.42	9.96	7.04	8.51	7.87	4.98	4.32	13.82	16.51	12.45	11.84
Ave. (41-02)	8.45	7.04	9.74	7.72	9.87	8.96	9.88	10.25	9.15	7.68	8.19	8.73
+/-	-2.73	-5.62	+0.22	-0.68	-1.36	-1.09	-4.90	-5.93	+4.67	+8.83	+4.26	+3.11

Table 9. Summary of crop yields and nitrogen (N) applications and crop uptake and removal where poultry litter (PL) and only inorganic fertilizer (IF) were applied.

	N Applied (kg/ha)		Grain			Fodder			Total N Uptake	
	PL	Inorganic	Yield (kg/ha)	N content (percent)	N removal (kg/ha)	Biomass (kg/ha)	N content (percent)	N uptake (kg/ha)	(kg/ha)	lb /bu
1998										
Corn										
CT-IF	0	156.8	5357	1.39	74.4	6771	1.04	70.4	144.8	1.52
CT-PL	267.4	16.8	4804	1.29	62.0	6312	0.80	50.6	112.7	1.32
NT-IF	0	156.8	4224	1.29	54.4	5335	0.85	45.4	99.8	1.33
NT-PL	267.4	16.8	3207	1.02	32.8	4874	0.63	30.6	63.4	1.11
1999										
Wheat										
CT-IF	0	67.2	5434	1.51	81.8	8122	0.55	44.8	126.5	1.40
CT-PL	178.3	22.4	5824	1.50	87.3	8543	0.48	41.1	128.4	1.32
NT-IF	0	89.6	5462	1.52	83.2	8383	0.53	44.2	127.3	1.40
NT-PL	178.3	89.6	6210	1.53	95.0	9748	0.56	54.8	149.8	1.45
Soybeans										
CT-IF	-	-	3010	-	180.6*	-	-	-	-	-
CT-PL	-	-	2879	-	172.7*	-	-	-	-	-
NT-IF	-	-	3096	-	185.8*	-	-	-	-	-
NT-PL	-	-	3103	-	186.2*	-	-	-	-	-
2000										
Corn										
CT-IF	0	156.8	12286	1.16	142.0	8072	0.77	62.2	204.2	0.93
CT-PL	198.9	16.8	10202	1.07	108.8	7115	0.74	52.5	161.3	0.89
NT-IF	0	156.8	11557	1.11	127.9	7745	0.84	64.8	192.7	0.93
NT-PL	198.9	78.4	9727	1.01	94.9	7744	0.69	53.4	148.8	0.88
2001										
Wheat										
CT-IF	0	89.6	4060	1.65	67.3	4481	0.53	23.8	91.1	1.34
CT-PL	161.3	67.2	4486	1.74	78.0	4936	0.58	28.6	106.6	1.43
NT-IF	0	89.6	3837	1.68	64.2	4258	0.55	23.5	87.7	1.37
NT-PL	161.3	67.2	5201	1.74	90.5	6011	0.60	36.2	126.7	1.46
Soybeans										
CT-IF	-	-	2672	6.23	166.4	-	-	-	-	-
CT-PL	-	-	2667	6.10	162.5	-	-	-	-	-
NT-IF	-	-	2767	6.23	168.3	-	-	-	-	-
NT-PL	-	-	2578	6.09	157.1	-	-	-	-	-

*Calculated using soybean N content of 6 percent.

Table 10. Summary of crop yields and phosphorus (P) applications and crop uptake where poultry litter (PL) and only inorganic fertilizer (IF) were applied.

	P Applied (kg/ha)		Grain			Fodder			Total P uptake	
	PL	Inorganic	Yield (kg/ha)	P content (percent)	P removal (kg/ha)	Biomass (kg/ha)	P content (percent)	P uptake (kg/ha)	(kg/ha)	lb /bu
1998										
Corn										
CT-IF	0	15.6	5357	0.26	13.9	6771	0.08	5.3	19.3	0.20
CT-PL	94.2	7.5	4804	0.27	13.1	6312	0.09	5.9	19.0	0.22
NT-IF	0	15.6	4224	0.26	11.1	5335	0.07	3.9	15.0	0.20
NT-PL	94.2	7.5	3207	0.27	8.6	4874	0.12	6.1	14.7	0.25
1999										
Wheat										
CT-IF	0	0	5434	0.25	13.4	8122	0.037	3.1	16.5	0.18
CT-PL	62.8	0	5824	0.37	21.6	8543	0.08	7.2	28.8	0.30
NT-IF	0	0	5462	0.24	13.4	8383	0.04	3.4	16.8	0.18
NT-PL	62.8	0	6210	0.37	23.2	9748	0.103	10.1	33.2	0.32
Soybeans										
CT-IF	-	-	3010	-	16.2*	-	-	-	-	-
CT-PL	-	-	2879	-	15.5*	-	-	-	-	-
NT-IF	-	-	3096	-	16.7*	-	-	-	-	-
NT-PL	-	-	3103	-	16.7*	-	-	-	-	-
2000										
Corn										
CT-IF	0	7.5	12286	0.24	29.1	8072	0.10	7.8	37.0	0.17
CT-PL	84.4	7.5	10202	0.26	26.8	7115	0.27	16.2	46.0	0.25
NT-IF	0	7.5	11557	0.25	28.5	7745	0.08	6.4	35.0	0.17
NT-PL	84.4	7.5	9727	0.25	23.3	7744	0.24	18.7	42.0	0.25
2001										
Wheat										
CT-IF	0	0	4060	0.34	13.8	4481	0.037	1.6	15.4	0.23
CT-PL	58.9	0	4486	0.33	14.9	4936	0.05	2.5	17.4	0.23
NT-IF	0	0	3837	0.34	12.8	4258	0.04	1.8	14.7	0.23
NT-PL	58.9	0	5201	0.33	17.3	6011	0.05	3.0	20.3	0.23
Soybeans										
CT-IF	-	-	2672	0.54	14.5	-	-	-	-	-
CT-PL	-	-	2667	0.53	13.7	-	-	-	-	-
NT-IF	-	-	2767	0.54	14.5	-	-	-	-	-
NT-PL	-	-	2578	0.56	14.4	-	-	-	-	-

*Calculated using the 2001 average soybean P concentration (0.54%).

Table 11. Summary of corn and wheat yields and nitrogen (N) uptake and removal where poultry litter (PL) and differing rates of inorganic fertilizer (IF) were applied.

	N Applied (kg/ha)		Grain			Fodder			Total N Uptake	
	PL	Inorganic	Yield (kg/ha)	N content (percent)	N removal (kg/ha)	Biomass (kg/ha)	N content (percent)	N uptake (kg/ha)	(kg/ha)	lb /bu
1998										
Corn										
CT-IF	0	156.8	5357	1.39	74.4	6771	1.04	70.4	144.8	1.52
CT-PL*	267.4	16.8	4804	1.29	62.0	6312	0.80	50.6	112.7	1.32
NT-IF	0	156.8	4224	1.29	54.4	5335	0.85	45.4	99.8	1.33
NT-PL*	267.4	16.8	3207	1.02	32.8	4874	0.63	30.6	63.4	1.11
1999										
Wheat										
CT-IF	0	67.2	5434	1.51	81.8	8122	0.55	44.8	126.5	1.40
CT-IF0	0	0	5114	-	-	-	-	-	-	-
CT-PL*	178.3	22.4	5824	1.50	87.3	8543	0.48	41.1	128.4	1.32
NT-IF	0	89.6	5462	1.52	83.2	8383	0.53	44.2	127.3	1.40
NT-IF0	0	0	3262	-	-	-	-	-	-	-
NT-PL0	178.3	0	5860	-	-	-	-	-	-	-
NT-PL*	178.3	89.6	6210	1.53	95.0	9748	0.56	54.8	149.8	1.45
NT-PL40	178.3	44.8	5929	-	-	-	-	-	-	-
2000										
Corn										
CT-IF	0	156.8	12286	1.16	142.0	8072	0.77	62.2	204.2	0.93
CT-PL*	198.9	16.8	10202	1.07	108.8	7115	0.74	52.5	161.3	0.89
CT-PL40	198.9	61.6	12144	1.22	147.5	8713	0.80	69.5	217.0	1.00
NT-IF	0	156.8	11557	1.11	127.9	7745	0.84	64.8	192.7	0.93
NT-PL0	198.9	33.6	8638	0.96	83.4	6792	0.65	44.4	127.9	0.83
NT-PL*	198.9	78.4	9727	1.01	94.9	7744	0.69	53.4	148.8	0.88
NT-PL80	198.9	123.2	10915	1.15	126.5	7492	0.73	55.0	181.5	0.93
2001										
Wheat										
CT-IF	0	89.6	4060	1.65	67.3	4481	0.53	23.8	91.1	1.34
CT-PL0	161.3	0	3404	1.52	52.3	3827	0.48	17.9	70.2	1.22
CT-PL*	161.3	67.2	4486	1.74	78.0	4936	0.58	28.6	106.6	1.43
NT-IF0	0	0	2293	1.50	34.5	2501	0.48	11.9	46.3	1.21
NT-IF	0	89.6	3837	1.68	64.2	4258	0.55	23.5	87.7	1.37
NT-PL0	161.3	0	3868	1.59	61.5	4363	0.48	21.1	82.6	1.28
NT-PL*	161.3	67.2	5201	1.74	90.5	6011	0.60	36.2	126.7	1.46

*Nutrient applications used in study watersheds.

Table 12. Summary of rye cover crop biomass and nutrient content at the time of herbicide application in April 2000 and 2002.

	Biomass (kg/ha)	N content (percent)	N uptake (kg/ha)	P content (percent)	P uptake (kg/ha)	C:N (kg/kg)
April 7, 2000						
CT-IF	2285	1.46	33.3	0.32	7.2	29.7
CT-PL	3089	1.37	42.3	0.34	10.5	31.4
NT-IF	2347	1.47	34.5	0.32	7.4	29.3
NT-PL	3504	1.43	50.4	0.34	12.0	30.1
April 15, 2002						
CT-IF	1638	1.65	27.0	0.23	3.7	26.1
CT-PL	2272	1.63	36.8	0.31	6.9	26.4
NT-IF	1002	1.92	18.6	0.20	2.1	22.7
NT-PL	2580	1.53	39.6	0.29	7.3	28.2