Sediment and nutrient concentrations in surface water in agricultural regions are strongly influenced by agricultural activities. In the Corn Belt, recent changes in farm management practices are likely to affect water quality, yet there are few data on these linkages at the landscape scale. We report on trends in concentrations of N as ammonium (NH₄) and nitrate (NO₃), soluble reactive phosphorus (SRP), and suspended sediment (SS) in three Corn Belt streams with drainage areas of 12 to 129 km² for 1994 through 2006. During this period, there has been an increase in conservation tillage, a decline in fertilizer use, and consolidation of animal feeding operations in our study watersheds and throughout the Corn Belt. We use an autoregressive moving average model to include the effects of discharge and season on concentrations, LOWESS plots, and analyses of changes in the relation between discharge and concentration. We found significant declines in mean monthly concentrations of NH₄ at all three streams over the 13-yr period, declines in SRP and SS in two of the three streams, and a decline in NO₃ in one stream. When trend coefficients are converted to percent per year and weighted by drainage, area changes in concentration are −8.5% for NH₄, −5.9% for SRP, −6.8% for SS, and −0.8% for NO₃. Trends in total N and P are strongly tied to trends in NO₃, SRP, and SS and indicate that total P is declining, whereas total N is not.

Throughout much of the USA, runoff from agricultural land use is the dominant factor affecting the quality of streams and lakes (Turner and Rabelais, 2004; U.S. Geological Survey, 1999). Sediment, nitrogen, and phosphorus are most significant with regard to ecological and economic impacts (Carpenter et al., 1998; Dodds and Whiles, 2004; Pimentel et al., 1995; Lal, 2001; Uri, 1998). Although numerous studies have examined the relations between specific agricultural practices and sediment/nutrient fluxes at the field scale, few have documented the cumulative impacts of changing agricultural management across landscapes. Identification of such trends in ambient stream quality is particularly difficult because of the interacting effects of diverse factors, especially stream discharge variability, and the paucity of high-resolution water quality records.

The Corn Belt of the Midwestern USA is an area of particularly high loadings of agricultural nutrients to streams. Agricultural practices in the Corn Belt have changed significantly in recent decades (Baylis et al., 2002). Three changes are especially relevant to water quality in the region: adoption of conservation tillage, more intensive nutrient management, and restructuring of the meat production industry.

Conservation tillage (defined as tillage practices that leave a minimum of 30% of the soil surface covered with crop residue) is effective in reducing mobilization of soil and associated pollutants, including sediment-associated nutrients. It is less effective in controlling loss of soluble nutrients, most notably nitrate (NO₃) (Rhoton et al., 2002).

In the Corn Belt, the use of conservation tillage systems in soybean production grew rapidly during the 1990s, with the portion of US cropland under conservation tillage increasing from 26.1 to 40.7% between 1990 and 2004 (Peterson, 2005). Intensive management of nutrients has been a focus of agricultural innovation and watershed management efforts (Daniel et al., 1998; Shuyler, 1994; Sims et al., 1999). Intensive nutrient management takes many forms, all with the objective of matching nutrient applications to crop needs to reduce nutrient losses caused by excessive...
fertilizer applications (e.g., Hatfield et al., 1998). In addition to the environmental benefits of improved water quality, cost reductions are a major driver of the trend toward improved nutrient management (USDA-Economic Research Service, 2007). Finally, the region has seen significant consolidation of meat production, accompanied by increased specialization in grain production (Herath et al., 2005; Horowitz, 2006). In Illinois, Indiana, Iowa, Michigan, Missouri, Ohio, and Wisconsin, the total number of farms with hogs or pigs decreased from 109,000 to 49,000 between 1987 and 1997, whereas the total population of hogs and pigs increased slightly from 30.2 million to 30.3 million (USDA-National Agricultural Statistics Service, 2007); thus, the mean number of animals per farm more than doubled. Formerly ubiquitous small feedlots are disappearing, replaced by large indoor feeding operations in which waste products are collected and actively managed rather than deposited on the ground in high concentrations in feedlots where they can be readily transported by overland flow to streams. In some cases, this has resulted in large, episodic increases in waste loads to streams in the vicinity of feeding operations (Mallin and Cahoon, 2003; Rowe et al., 2004), but frequent and widespread feedlot runoff has been reduced. Much of the manure from concentrated feeding operations is being spread on fields, but many of those fields are now in conservation tillage and likely have higher infiltration rates and ability to absorb nutrients than the feedlots of past years. Parallel changes have occurred in the cattle industry. In Ohio, the total population of cattle declined about 20% between 1989 and 2006, whereas the numbers of farms with cattle declined 38% in that period. Beef cattle are primarily raised outdoors, so the impact on reduction of feedlot runoff may be less than for hogs.

Decreased ambient concentrations of sediments and nutrients in streams have been documented in many areas. There is strong evidence for decreasing sediment and phosphorus concentrations in many areas, especially the Great Lakes and the Midwest. For phosphorus, decreasing concentrations in streams during the 1980s seem to be mostly attributable to reductions in point sources, although nonpoint source reductions may be significant (Smith et al., 1994; Zipper et al., 2002). Decreasing suspended sediment concentrations occurred during the 1980s at several stations in the Corn Belt region, and Smith et al. (1994) argued that decreases in sediment concentrations during that period likely resulted from soil conservation efforts that have substantially reduced sheet and rill erosion (USDA-Natural Resources Conservation Service, 2007). Trends for nitrogen are less consistent, with increases in some areas and decreases in others (McIsaac and Libra, 2003; Reutter, 2003).

The Lake Erie Agricultural Systems for Environmental Quality Project (Richards and Baker, 2002) is probably the most detailed study of water quality trends in the Corn Belt. They found substantial decreases in concentrations of total phosphorus (29–46% decrease), total suspended solids (2–37%), and total Kjeldahl nitrogen (14–41%) over the study period and changes in NO₃ concentrations ranging from −46% to +21%. These changes are attributed to changes in agricultural practices, principally increased conservation tillage and reduced fertilizer inputs. Myers et al. (2000) compared the periods 1970 through 1974 with 1996 through 1998 in the Maumee River and one of its tributaries, the Auglaize River, and found significant decreases in suspended sediment concentrations. In both of these cases, the decreases are correlated with the adoption of conservation tillage, although the decreases may have begun before the period of rapid expansion of conservation tillage.

Here we report on changes in water quality in three Corn Belt streams for 13 yr of data covering the period 1994 through 2006. We previously described 5-yr data from these watersheds (1994–1998), focusing on differences in nutrient loads among the three watersheds (Vanni et al., 2001). During the 1994 through 2006 study period, land use remained essentially constant with no significant change in the amount of land in row crops, but substantial changes in agricultural management occurred. These changes are typical of those occurring throughout the Corn Belt. Our monitoring system provides a high-resolution record, allowing statistical control for the effects of discharge and season to detect water quality trends. We focus on concentrations of ammonium, nitrate, soluble reactive phosphorus (SRP), and suspended sediment (SS) over that time period. Although the scale of this study of does not permit quantitative assignment of water quality trends to specific management practices, it provides evidence of the cumulative effects of changing agricultural management on water quality at the landscape scale.

Materials and Methods

Study Area

The Upper Four Mile Creek (UFMC) watershed in southwestern Ohio and southeastern Indiana is comprised mostly of agricultural land (Fig. 1). Soils are of high-lime glacial till capped with highly productive silt loess (USDA-Soil Conservation Service, 1992). Soils tend to be moderately poorly drained, and tile drains are common in the area. The watershed drains into Acton Lake, a eutrophic reservoir that typically exhibits poor water quality, including high nutrient concentrations, inorganic turbidity, and phytoplankton biomass (Vanni et al., 2005). Nutrient loads for the period 1994 through 2001 were 1530 to 3130 kg NO₃ (as N) km⁻² and 19 to 40 kg SRP km⁻², with significant impacts on the ecosystem of Acton Lake (Vanni et al., 2001, 2006). The lake has been categorized as affected by organic enrichment, ammonia, and total suspended solids, with agriculture a principal cause of impairment (USDA-Soil Conservation Service, 1992).

In the 1990s, the watershed was the focus of a watershed restoration project (USDA-Soil Conservation Service, 1992). This project included funding to convert about 3250 ha (about 16% of the watershed area) to conservation tillage and to install 30 ha of grassed waterways, 21 grade stabilization structures, and 17 sediment basins. Although the efforts to promote conservation tillage were highly successful, as of 2007 only four sediment basins had been completed, capturing runoff from about 3% of the watershed; the first of these went into operation in 1996 and the last in 2000.

The three sub-watersheds we studied vary in size by an order of magnitude and together comprise 86% of the UFMC Water-
Four Mile Creek (FM; 12,875 ha), Little Four Mile Creek (LF; 870 ha), and Marshall’s Branch (MB; 1206 ha) drain 50, 31, and 5% of the UFMC watershed, respectively. Although the UFMC watershed spans four counties in two states, 80% of the watershed lies in Preble County, Ohio, and the watershed comprises 18% of Preble County (Fig. 1). The portion of Preble County in which the watershed lies is somewhat more rural, lower relief, and more intensively agricultural than the county as a whole, but land use and land management data for the county are generally applicable to the watershed.

Data on tillage practices in Preble County have been collected by the Preble Soil & Water Conservation District for the years 1989 to 2002, 2004, and 2007. Comparable data were collected for the Four Mile Creek watershed for nine of these years beginning in 1994. The correlation between percent conservation tillage in Preble County and the same percent in the Four Mile Creek watershed is strong for soybeans ($R^2 = 0.92$) but weak for corn ($R^2 = 0.25$). We use Preble County rather than Four Mile Creek data because they include the early 1990s, a period in which conservation tillage was increasing rapidly. Anecdotal knowledge of the watershed suggests that practices in the Four Mile Creek watershed were not significantly different from those in the county as a whole.

### Water Quality Data Collection and Analysis

We installed monitoring stations on FM in 1992, on MB in 1993, and on LF in May 1994. To monitor discharge, pressure transducers were installed in stilling wells at each station, and a datalogger recorded stage at 10-min intervals. Water samples for nutrient analyses were collected using ISCO pumping samplers at 6- to 8-h intervals. All samples were processed for high-flow events; during low-flow periods, three or four samples per week were processed (Vanni et al., 2001). Thus, we have more frequent observations for high-flow periods than for baseflow. Samples were analyzed for ammonium N (NH$_4$), nitrate and nitrite-N (NO$_3$), SRP, and SS over all years of the study period on an average of >3100 samples per stream (9328 samples total; Table 2). From 1994 to 1998, we analyzed these nutrient fractions using manual methods and from 1999 onward with a Lachat auto-analyzer. Throughout the study, NH$_4$ was quantified with the phenol-hypochlorite method and SRP with the molybdenum blue method, and NO$_3$ was quantified with second-derivative spectroscopy from 1994 to 1998 and with the cadmium reduction method from 1999 onward. To standardize concentrations for methods changes (including the shift from manual methods to the auto-analyzer), we analyzed nu-

### Table 1. Watershed area and land use. Data derived from Ohio Department of Natural Resources (1997).

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Watershed area</th>
<th>Agriculture</th>
<th>Forest</th>
<th>Urban</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four Mile Creek</td>
<td>12,875</td>
<td>91.2</td>
<td>8.0</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Little Four Mile Creek</td>
<td>7968</td>
<td>94.1</td>
<td>4.9</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Marshall’s Branch</td>
<td>1206</td>
<td>91.7</td>
<td>7.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Fig. 1. Map of study area. Land use data from USGS National Land Cover Dataset (U.S. Geological Survey, 2007).
Two factors combine to make statistical analyses of water quality trends difficult: (i) inherent variability and (ii) multiple independent variables influencing water quality. Discharge is often the most important among the independent variables, and trends in discharge can easily overwhelm the effects of factors such as land use and land management. Our approach to this problem is twofold: (i) a very high resolution sampling program that includes the full range of discharge and seasonal conditions and (ii) several statistical methods that account for the effects of variations in runoff.

An event-based sampling strategy such as ours, with a greater number of samples at high discharge than at low discharge, raises the possibility that analyses of trends over time may be biased toward conditions in high discharge. In one sense, this is appropriate because that is when most of the water is flowing. On the other hand, it may be suggested that a time-based sampling program would show different results. To investigate this problem, we calculated monthly mean concentrations by two methods: (i) simple monthly geometric mean concentrations and (ii) time-weighted geometric mean concentrations. For time-weighting, we assumed that the concentration was representative of the entire duration until the next sample up to a maximum of 3 days and weighted each concentration by that duration in our calculation of monthly geometric means. We then regressed the monthly means calculated by this time-weighting method against the simple geometric means. The $r^2$ values from these regressions averaged 0.993 and ranged from 0.863 to 0.996, depending on stream and constituent. Based on this analysis, we concluded that, in our dataset, the timing of samples does not significantly affect our results.

Stream discharge is correlated with the concentrations of nutrients and sediments at different time scales: the individual storm event and the season (for examples of how streamflow and concentrations are related in these streams, see Vanni et al. (2001)). Effects observed at the storm event scale are associated with the proportion of runoff that is derived from overland flow as opposed to subsurface paths. Typically, if a greater proportion of runoff is derived from overland flow, then concentrations of sediment and associated substances are elevated by soil surface and headwater stream erosion. This leads to a positive relation between discharge and concentration, usually with variation occurring in relatively short time scales. In our streams, we observe such positive correlations for $\text{NH}_4$, SRP, and SS (Vanni et al., 2001). For some constituents, especially those dominated by ground water sources, high discharge may have a dilution effect in which concentration is higher at low discharges and lower at high discharges. In our streams, we often see such an effect on $\text{NO}_3$, but during some periods (probably soon after fields are fertilized), we observe a positive correlation between discharge and nitrate (Vanni et al., 2001). Seasonal effects on concentration include those associated with varying runoff volumes and those caused by land-management effects, such as crop fertilization. Lack of vegetation in winter, especially on fields that are plowed in the fall, can cause high concentrations of SS and associated nutrients. These factors may simultaneously affect nutrient or sediment concentrations in opposing directions. This is particularly true for $\text{NO}_3$ at the event scale, increased discharge may cause dilution and reduced concentrations, but at the seasonal scale, discharge is positively correlated with concentration. Because seasonal runoff volumes and to some extent event runoff volumes are correlated with annual total runoff, we observed relations among discharge and concentration at the annual scale. We hypothesized that stream discharge and time each have a strong influence on sediment and nutrient concentrations. Specifically, we hypothesized that concentrations—corrected for discharge—decline over time because of the changes in agricultural practices described previously.

### Statistical Methods

Because discharge and concentration data exhibit strong autocorrelation and significant seasonal effects, we used an autoregressive moving average (ARIMA) model to analyze trends over time in a way that can distinguish trends caused by changing discharge patterns from those independent of flow. This approach was applied to each of the 12 data series (4 water quality variables $\times$ 3 streams). Seasonal effects were modeled using Fourier analysis, and discharge was used as a covariate. Except for the inclusion of discharge as a covariate (which was necessary due to the strong correlations between discharge and concentrations), our ARIMA approach is nearly identical to that used by Burkholder et al. (2006) to analyze long-term trends in nutrient concentrations in the Neuse River. All ARIMA analyses were conducted using PROC ARIMA in SAS version 9.1.3.

For an ARIMA $(p,q)_{(1,1)}$ model, we can determine the autoregressive order $p$, the moving average order $q$, and the degree of differencing $d$ (done initially to make the series stationary) by

### Table 2. Summary of water quality data for Four Mile Creek (FM), Little Four Mile Creek (LF), and Marshalls Branch (MB), 1994–2006 inclusive.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NH$_4$–N</th>
<th>NO$_3$–N</th>
<th>SRP</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μg L$^{-1}$</td>
<td>mg L$^{-1}$</td>
<td>μg L$^{-1}$</td>
<td>mg L$^{-1}$</td>
</tr>
<tr>
<td>Number of samples</td>
<td>2927</td>
<td>2749</td>
<td>3233</td>
<td>3070</td>
</tr>
<tr>
<td>Months with at least one sample</td>
<td>134</td>
<td>117</td>
<td>156</td>
<td>135</td>
</tr>
<tr>
<td>Maximum concentration</td>
<td>2368</td>
<td>1391</td>
<td>17,948</td>
<td>18,082</td>
</tr>
<tr>
<td>75th percentile concentration</td>
<td>18,082</td>
<td>1391</td>
<td>17,340</td>
<td>18,082</td>
</tr>
<tr>
<td>Median concentration</td>
<td>55.4</td>
<td>63.7</td>
<td>79.8</td>
<td>6553.7</td>
</tr>
<tr>
<td>50th percentile concentration</td>
<td>32.0</td>
<td>34.4</td>
<td>44.0</td>
<td>4277.4</td>
</tr>
</tbody>
</table>

studying the autocorrelation, partial autocorrelation, and inverse autocorrelation plots of the residuals to identify a potential model. The ARIMA method requires regularly spaced observations, and our samples were collected at irregular intervals. We therefore calculated monthly means of log-transformed (base 10) concentrations. Because not all months have samples, the dataset contains gaps. The resulting data series averaged 138 (89%) of the possible 156 mo, depending on stream and water quality element. Missing values were estimated in SAS by the Expectation Maximization algorithm, which uses the maximum likelihood method on the incomplete data and then “predicts” the missing values.

Including all independent variables, our full model is:

\[ Y_t = \mu + \alpha t + \beta X_t + C_1 c_1 + S_1 s_1 + C_2 c_2 + S_2 s_2 + C_3 c_3 + S_3 s_3 + C_4 c_4 + S_4 s_4 + C_5 c_5 + S_5 s_5 + C_6 c_6 + V_t \]

where \( Y_t \) is the dependent variable (the monthly geometric mean of the concentration in log scale at time \( t \)), \( \mu \) is the long-term mean for the series of \( Y_t \), \( \alpha \) is the trend coefficient, \( t \) is the time trend variable (1 is for Jan. 1994; 2 is for Feb. 1994, etc.), \( X_t \) is the discharge variable (the monthly geometric mean of discharge in log scale at time \( t \)), \( C_i \) is a variable for Fourier approximation (\( C_i = \cos[2\pi i f t] \) and \( S_i = \sin[2\pi i f t] \), where \( f \) (frequency) = 1/12 and \( i = 1, 2, \ldots, 6 \); \( C_i \) and \( S_i \) are called \( k \)th harmonic terms and should be considered together, and \( V_t \) is the ARIMA\( (p,i,q) \) process, which is defined as:

\[ (1 - \xi_B)(1 - \xi_i B)(1 - \xi_c B)(1 - B)V_t = (1 - \phi_B)(1 - \phi_i B)(1 - \phi_c B)e_t \]

where \( B \) is a lagged operation such that \( BV_{t-1} = V_t \), and \( e_t \) is white noise (a series of independent identical distribution with mean zero), \( \sum \xi_i < 1 \) for \( i = 1, 2, \ldots, p \), and \( \sum \phi_j < 1 \) for \( j = 1, 2, \ldots, q \).

Through an iterative process, a model is developed so that the error terms from that model show little or no autocorrelation. The Ljung-Box statistic can be used to determine whether the first several autocorrelations are sufficiently small. If that is the case, the model is considered adequate. If that is not the case, the different autocorrelation plots of the residuals from the current model are examined to identify an improved model. This is repeated until an adequate model is obtained. If more than one model is deemed adequate, the model having the lowest Akaike Information Criterion is considered the best.

In presenting the results, we converted the trend parameter \( \alpha \) to percent per year using the formula \( Pct = 10(10^{\frac{\alpha}{120-1}} - 1) \times 100 \), where \( Pct \) is the change in concentration in percent per year.

The analysis of highly dynamic data, as stream sediment and nutrient concentrations, is somewhat problematic because the statistical significance of trends can be sensitive to the model used, and analysis of time trends can be sensitive to the temporal scale at which data are aggregated. Therefore, we used multiple methods to analyze time trends, using a variety of temporal scales and methods relevant to analysis at that scale. In addition to the ARIMA analyses (which examined trends at the monthly scale), we examined how the residuals of the log discharge vs. log concentration relation varied over time. First, we regressed the logarithms of nutrient and sediment concentrations on log of discharge using monthly data over the entire dataset and examined the changes in residuals over time. A decline in residuals over time indicates that concentrations, standardized for discharge, are decreasing. We also performed a locally weighted regression smoothing (LOWESS) of the data (Cleveland, 1979) to better portray nonlinearity in the trends. We used PROC LOWESS (SAS) to analyze individual concentrations using a smoothing parameter of 0.2. We also examined changes in the relations between concentration and discharge at the annual scale. First, we calculated regressions between log concentration and log discharge for each constituent for each calendar year, using all individual samples for that year. Then we examined trends over the 13 yr in the intercepts and slopes of these year-specific regressions. Therefore, we used a variety of analyses, including high-frequency temporal scale (LOWESS on individual concentrations, obtained with a variable sampling interval but often just a few hours), monthly scale (ARIMA and analysis of residuals), and annual scale (trends in annual regression parameters).

**Results**

**Changing Agricultural Practices**

All three of the key trends in agricultural management described previously (increased conservation tillage, more intensive nutrient management, and restructuring the meat production industry) have taken place in the UFMC watershed during the study period (Fig. 2–4). Total area of farmland in Preble County decreased (Fig. 2), although most of this decrease took place in parts of the county outside the UFMC watershed. Simultaneously, the total area planted in corn and soybeans increased from 35 to 40% to 40 to 50%. The average size of farms increased, which is important because it favors the adoption of new technologies, such as conservation tillage, that are only economical for large operations.

The use of conservation tillage methods grew rapidly during the 1990s (Fig. 3), from about 15% of the soybean crop in 1991
to >90% in 2001. During that period, the percent of corn planted using conservation tillage methods increased from about 20% to 30 to 60%. Land planted in soybeans as a percent of all cropland also increased significantly during the study period, from 30 to 35% in the early 1990s to about 50% by 2000. Because soybeans are more likely to be planted using no-till methods, this further increased the portion of the watershed in conservation tillage. These trends are slightly stronger than those occurring generally in the Corn Belt. For example, in the Midwest, in 1990 32% of corn and 32% of soybeans were in conservation tillage, and by 2004 the proportions had risen to 38 and 58%, respectively (Conservation Technology Information Center, 2007).

The second trend, more intensive nutrient management (Fig. 4), has been driven by several factors, including rising fertilizer costs and the development of new technologies for targeted and variable rate fertilizer application. Local scale variations in weather also influence fertilizer use. Declines in fertilizer P were more consistent than those for N, although for both nutrients, the decline in use was temporarily reversed in the late 1990s to the early 2000s.

The third important trend in agriculture affecting water quality is consolidation and automation in the meat production industry. Although in general large feeding operations have become more geographically concentrated, Preble County has not emerged as a locus of meat production. In Preble County in 1987, 255 farms had an average of 312 animals per farm; in 2002 the number of farms with hogs and pigs was down to 73, with an average of 498 animals per farm (USDA-National Agricultural Statistics Service, 2007). This should positively affect water quality by reducing the total amount of animal waste generated and by concentrating the waste at sites where it is actively managed rather than being left on the ground in a feedlot. It also reduces the need for commercial fertilizers and may contribute to the declining use of those fertilizers observed in Fig. 4. Some farms in the UFM Creek watershed have imported manure from animal feeding operations outside the watershed (D. Bunger, personal communication).

**Stream Discharge**

Averaged over the study period, May had the highest mean runoff of 60 mm per month, and September had the lowest at 5 mm per month. Stream discharge during the 13-yr study period varied substantially. The first year of data (1994) was relatively dry. This was followed by four wetter years, from 1995 to 1998. Discharge was below average in 1999 through 2002, and the period 2003 through 2006 was similar to the wetter period of 1995 through 1998. Annual runoff was lowest in calendar year 1994 (168 mm) and highest in 1996 (763 mm). Over the 156 mo of this study, 11 mo at Four Mile and 12 mo at Little Four Mile and Marshall’s Branch had no discharge, whereas monthly runoff exceeded 180 mm twice (once in May 1996 and once in January 2005).

For each of the constituents (SS, SRP, NO₃, and NH₄), concentrations ranged through 3 to 4 orders of magnitude (Table 2). Water quality trends were strongly seasonal (Vanni et al., 2001), with NH₄, NO₃, SRP, and SS having peak concentrations in the high-discharge season (winter through early summer). Nitrate showed an especially strong seasonal signal, with late summer/early autumn minima 3+ orders of magnitude below the spring maximum. Graphical summaries of trends are presented in Fig. 5 through 8.

Mean monthly discharge positively affected mean monthly concentrations of SS in all three streams (Table 3). Discharge had a significant positive effect on SS at FM only and a positive effect on NH₄ at LF only and had a positive effect on mean monthly NO₃ concentrations at FM and LF. In all three streams, the effects of discharge were greater for SS than other constituents.
Fig. 5. Water quality trends in Four Mile Creek, Little Four Mile Creek, and Marshall’s Branch for NH₄. Top panel: Logarithms (base 10) of individual concentrations plotted with a LOESS smoothing function. Second panel: Mean monthly log concentrations. Third panel: Slopes of annual regressions of log concentration against log discharge. Fourth panel: Intercepts of annual regressions of log concentration against log discharge. Fifth panel: Mean monthly residuals of regressions of log concentration on log discharge. Bottom panel: Monthly stream discharge.
Fig. 6. Water quality trends in Four Mile Creek, Little Four Mile Creek, and Marshall's Branch for NO₃. Top panel: Logarithms (base 10) of individual concentrations plotted with a LOESS smoothing function. Second panel: Mean monthly log concentrations. Third panel: Slopes of annual regressions of log concentration against log discharge. Fourth panel: Intercepts of annual regressions of log concentration against log discharge. Fifth panel: Mean monthly residuals of regressions of log concentration on log discharge. Bottom panel: Monthly stream discharge.
Fig. 7. Water quality trends in Four Mile Creek, Little Four Mile Creek, and Marshall's Branch for soil reactive P (SRP). Top panel: Logarithms (base 10) of individual concentrations plotted with a LOESS smoothing function. Second panel: Mean monthly log concentrations. Third panel: Slopes of annual regressions of log concentration against log discharge. Fourth panel: Intercepts of annual regressions of log concentration against log discharge. Fifth panel: Mean monthly residuals of regressions of log concentration on log discharge. Bottom panel: Monthly stream discharge.
Fig. 8. Water quality trends in Four Mile Creek, Little Four Mile Creek, and Marshall’s Branch for suspended sediment (SS). Top panel: Logarithms (base 10) of individual concentrations plotted with a LOESS smoothing function. Second panel: Mean monthly log concentrations. Third panel: Slopes of annual regressions of log concentration against log discharge. Fourth panel: Intercepts of annual regressions of log concentration against log discharge. Fifth panel: Mean monthly residuals of regressions of log concentration on log discharge. Bottom panel: Monthly stream discharge.
Based on ARIMA results, significant declines in mean monthly concentrations (corrected for discharge effects) are indicated for NH₄ at all three streams over the 13-yr period. Significant declines in NO₃ occurred at MB, in SRP at FM and MB, and in SS at FM and LF. The coefficients for time are in units of discharge; time; q = 1; cos1t, sin1t***, cos2t*, sin2t*, cos3t, sin3t**.

The annual regressions of instantaneous log concentration on log discharge confirm the patterns observed in the ARIMA analyses. The intercepts of these regressions (the fourth row of panels in Fig. 5–8) show trends that generally parallel mean monthly concentrations. We regressed these intercepts on year (Table 4), and the slopes against year are positive in every case except NO₃ at FM and LF, although only significant for NH₄ at LF and NO₃ at MB. These regressions are subject to problems of serial correlation, but they are nonetheless useful. Specifically, the tendency for negative trends in intercepts combined with weak positive trends in slopes suggests that the declines in concentrations are mainly at medium and lower discharges, with high-discharge events maintaining or perhaps increasing their effects on concentrations.

**Discussion**

The diffuse nature of agricultural pollution and the tendency for nutrients to accumulate in soils and ground water suggest that downstream-water-quality responses to changing agricultural practices will be muted. For example, on a percent per year basis, the water quality trends observed by Richards and Baker (2002) are similar in direction but generally smaller than those in this study. In Latvia, Stalnacke et al. (2003) found strong downward trends in PO₄ but only weak downward trends in dissolved inorganic nitrogen (NO₃−N + NO₂−N + NH₄−N) after a 15-fold decrease in mineral fertilizer use and fourfold decrease in livestock populations between 1987 and 1996. In that context, the dramatic changes in water quality seen in our data are particularly striking.

Our study was not designed to evaluate specific causal links between land management changes and water quality responses; this is difficult to impossible at the scale of our watersheds. Each of the three watersheds contains many farms that differ in management practices within any given year and from one year to another. Nonetheless, we are confident that the trends we have observed are linked to one or more of the three dominant agricultural changes described previously: conservation tillage, nutrient management, and consolidation of meat production.

One strong indicator of these linkages is the dramatic reduction in sediment and phosphorus concentrations, a signature of the water quality trends that is strongly indicative of changes in conservation tillage (Cogo et al., 1984; Gaynor and Findlay, 1995). Although the decreases in P concentrations we report here are for the soluble fraction of this element, often the soluble and particulate fractions are closely associated, and P is exchanged between those other fractions.
fractions (Bowes et al., 2003; Schulz and Herzog, 2004). Our watersheds are overwhelmingly agricultural with no known point sources of P. Thus, we may expect decreases in particulate and dissolved P fractions in response to conservation tillage. In these streams, particulate P is highly correlated with SS ($r^2 = 0.67–0.84$ depending on stream; Vanni et al., 2001), and therefore particulate P concentrations also declined over the 13-yr period. In the UFMC watershed, approximately 53 to 66% of total P export is in particulate form based on data from 1994 through 1998 (Vanni et al., 2001). Thus, declines in total P concentrations are also occurring, resulting in decreased P loading to Acton Lake. Conservation tillage may also reduce the mineralization of organic phosphorus (Addiscott and Thomas, 2000; Al-Kaisi et al., 2005), which would reduce concentrations of SRP. In contrast, conservation tillage has relatively little effect on NO$_3$, because it travels in soluble form and is strongly associated with shallow subsurface flow, which is favored by the higher infiltration rates associated with conservation tillage (Spalding and Exner, 1993; Nolan and Stoner, 1995). The strong negative trend in NH$_4$ may be caused by improvements in manure handling, and perhaps increased nitrification of NH$_4$ in the soil due to improved aeration, which is a common effect of conservation tillage (Iragavarapu and Randall, 1995; Martens and Dick, 2003; Mumme et al., 1998). In addition, conservation tillage may reduce the mineralization of organic N and thus reduce production of NH$_4$ in the soil (Kristensen et al., 2003).

The decreasing late summer NO$_3$ minima, which are most pronounced in MB, are difficult to understand. The strong seasonal pattern in NO$_3$ concentrations is driven by two factors: (i) high spring runoff rates, primarily from shallow subsurface flow, at the same time of year that N fertilizers are being applied and (ii) uptake in stream and riparian ecosystems during summer. Plant uptake of NO$_3$ in the growing season may also reduce concentrations in shallow ground water. The strong time trend in NO$_3$ concentrations at MB may be driven primarily by these decreasing summer minima, although high-discharge concentrations have also decreased.

Our results have implications for the mitigation of eutrophication in lakes and reservoirs subject to nonpoint sources of nutrients. Reductions in nutrient supply usually result in improved water quality (decreased nutrient and phytoplankton concentrations) in lakes previously subject to eutrophication (Jeppesen et al., 2005, 2007). However, nearly all cases are those in which point sources have been reduced or eliminated. Much less is known about the impacts of reductions in nonpoint nutrient supply, but these impacts may be more gradual and variable, owing to the strong influence of weather variability on nutrient loading. Long-term, high-resolution sampling programs such as ours can play a key role in assessing the magnitude and timing of reductions in nonpoint nutrient supply to downstream lakes and the speed at which downstream ecosystems respond to these changes.

Conclusions

Although there is ample field-scale evidence of the impacts of specific land management techniques on water quality, relatively few watersheds have been described with high-resolution, long-term data that demonstrate the effects of changing land manage-


