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IMPROVING NITROGEN USE EFFICIENCY IN CROP AND LIVESTOCK PRODUCTION SYSTEMS

Navigating the Socio-Bio-Geo-Chemistry and Engineering of Nitrogen Management in Two Illinois Tile-Drained Watersheds

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Abstract

Reducing nitrate loads from corn and soybean, tile-drained, agricultural production systems in the Upper Mississippi River basin is a major challenge that has not been met. We evaluated a range of possible management practices from biophysical and social science perspectives that could reduce nitrate losses from tile-drained fields in the Upper Salt Fork and Embarras River watersheds of east-central Illinois. Long-term water quality monitoring on these watersheds showed that nitrate losses averaged 30.6 and 23.0 kg nitrate N ha^{-1} yr^{-1} (Embarras and Upper Salt Fork watersheds, respectively), with maximum nitrate concentrations between 14 and 18 mg N L^{-1}. With a series of on-farm studies, we conducted tile monitoring to evaluate several possible nitrate reduction conservation practices. Fertilizer timing and cover crops reduced nitrate losses (30% reduction in a year with large nitrate losses), whereas drainage water management on one tile system demonstrated the problems with possible retrofit designs (water flowed laterally from the drainage water management tile to the free drainage system nearby). Tile woodchip bioreactors had good nitrate removal in 2012 (80% nitrate reduction), and wetlands had previously been shown to remove nitrate (45% reductions) in the Embarras watershed. Interviews and surveys indicated strong environmental concern and stewardship ethics among landowners and farmers, but the many financial and operational constraints that they operate under limited their willingness to adopt conservation practices that targeted nitrate reduction. Under the policy and production systems currently in place, large-scale reductions in nitrate losses from watersheds such as these in east-central Illinois will be difficult.

Managing agricultural nutrients in the interest of water quality is a critical global concern and is recognized as one of the grand challenges for engineering in the 21st Century (Schipper et al., 2010). The environmental impacts of hypoxia in the Gulf of Mexico have raised alarms about nutrients flowing through the Mississippi River Basin (Rabalais et al., 2002). Extensive hydrologic modifications, including channelization and subsurface tile drainage, are common in watersheds dominated by intensive corn–soybean production in the midwestern United States (Baker et al., 2008). This is a "leaky" system, particularly for nitrate N, and large nutrient loads are carried downstream even when farmers follow best management practice recommendations (Royer et al., 2006; Baker et al., 2008; Hatfield et al., 2009; David et al., 2010). Policies and plans to address the loss of nutrients from agricultural watersheds have been relatively ineffective. A 2008 plan (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008) called for 45% reductions in total N and total P loads in the Mississippi River, beyond the 30% reduction in total N called for in 2001, yet there is no evidence of any decrease in nutrient loading to date (Sprague et al., 2011; David et al., 2013).

Many approaches to addressing the agricultural nutrient loading problem have been proposed, including riparian buffers, cover crops, altering timing and mode of fertilization, water table management, and off-field practices to increase denitrification (USEPA, 2007; Schipper et al., 2010; Skaggs et al., 2012). Previous research has found riparian buffers to be ineffective in locations where agricultural fields are drained via tiles directly into streams and ditches (Kovacic et al., 2000; Lemke et al., 2012). Thus, additional engineered solutions at the end of tiles are recommended, such as constructed wetlands and bioreactors (Kovacic et al., 2000; Woli et al., 2010; Christianson et al., 2012). Seasonality of fertilizer applications and runoff

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Abbreviations: CCSWCD, Champaign County Soil and Water Conservation District; C–C, corn–corn rotation; C–S, corn–soybean rotation; DWM, drainage water management; FD, free drainage; NT, North Tile; ST, South Tile.

rarely correlate with the timing of poor water quality, creating a complex management situation (Royer et al., 2006). Despite their effectiveness, biogeochemists and engineers acknowledge that incentives may not be high enough to install engineered systems or to alter crop diversity (David et al., 2013).

In a 2011 memo (USEPA, 2011), the USEPA highlighted the importance of collaborative actions to reduce nutrient loading and develop watershed-scale plans and stewardship incentives to accelerate implementation of effective agricultural practices. Bridging from biophysical science and engineering to decision-making regarding water quality requires understanding what farmers are able and willing to adopt. Not all conservation practices are appropriate in every situation, and, even if adopted, they may not necessarily correlate with conservation intentions or other conservation behaviors (Nowak and Korsching, 1998). Whereas scientists and engineers may consider nutrient management a set of known truths regarding risks to water quality and ecosystems, farmers may have different experiences, knowledge, and perspectives influencing their willingness and ability to alter their practices (Raedeke and Rikoon, 1997).

Literature reviews have documented factors influencing farmers' adoption of water quality conservation practices (Christensen and Norris, 1983; Prokopy et al., 2008). Farm size and income, ownership versus renting, social networks, and various environmental or risk-related attitudes are among the few factors found to be influential, although often in different directions across studies. The lack of consistent findings across projects, time, or geographic study areas indicates that context likely matters when trying to understand farmers' motivations. Additionally, recent literature on agricultural conservation has focused largely on participation in conservation programs and combines inquiry on soil erosion with nutrient runoff and water quality (Arbuckle, 2013; Reimer and Prokopy, 2013), making it difficult to parse perspectives on water quality and nutrients from other more traditional farm conservation issues. Rural Iowa farmers and residents saw the benefits of conservation for water quality but rarely prioritized them or saw them as compatible with farming objectives or constraints (Atwell et al., 2009a, 2009b). Studies consistently highlight factors beyond finances as influencing farm practices, including family and social issues, skill and knowledge, attitudinal intensions, and interconnections and complexity in the farm context to design appropriate policies (Battershill and Gilg, 1997; Maloney and Paolisso, 2006). Scaling up or connecting local issues with meso- and macro-level factors and change drivers is advocated to situate individual farm producers in broader economic and political contexts for more effective policies and vulnerability mitigation than offered by individual producer-oriented programs and regulations (Stuart and Gillon, 2013). Our work builds on these ideas by assessing the empirical conditions related to individual farmers, farms, and small watersheds and connecting these findings to the broader context of policy and strategy at larger scales.

Building interdisciplinary research teams to combine sciences and methods generates the new knowledge needed to address complex issues (Kotchen and Young, 2007; Hufnagl-Eichiner et al., 2011; Jahn et al., 2012; Repko, 2012). Our team assessed social, biophysical, and engineering dimensions of nutrient management in two Illinois watersheds. Our overall objective was to investigate an array of practices and technological advancements through in-field installation and experimentation, including impacts on nutrient loading and farmer perspectives on nitrate losses and conservation practices. The guiding research questions for this work included: (i) What are the water quality conditions in intensive agricultural and headwater watersheds of east-central Illinois? (ii) What are the water quality perspectives of farmers, and how do they compare with field measurements? (iii) How do various in-field and end-of-tile water quality conservation techniques affect nitrate losses? (iv) Are farmers familiar with these nitrate conservation techniques, and are they willing to adopt them? What factors influence willingness to adopt new water management practices? and (v) What are the broader factors affecting farm and conservation decision-making and managing nutrients in the agricultural water system?

Materials and Methods

Study Area

The study involved two watersheds in east-central Illinois as designated by river monitoring stations managed by the USGS. The Embarras River watershed at the USGS site no. 03343400 is 481 km^2, and the Salt Fork of the Vermillion River watershed at USGS site no. 03336900 is 347 km^2. We have sampled these locations since January 1993 (Embarras) and April 2008 (Upper Salt Fork), and there are previously published studies on aspects of the Embarras River Watershed (e.g., David et al., 1997; Royer et al., 2006; Gentry et al., 2007). These watersheds consist of relatively flat landscapes (<2% slopes) with soils that are poorly or very poorly drained Mollisols, with Drummer being the dominant soil series (fine-silty, mixed, superactive, Mesic Endoaquolls). The dominant topographic features in this area of Illinois are glacial moraines, which often create watershed boundaries and provide recharge to streams. Before agricultural conversion, this area was a wet tall grass prairie. In the late 1800s, drainage districts were established, headwater streams were dredged and channelized, and tile drainage was extensively installed (David et al., 2001). These modifications greatly altered the hydrologic cycle by draining wetlands and creating fertile, arable soils. Enhanced drainage increased crop production, and today artificial drainage is often installed in grid patterns where entire fields are now drained. Land use in these watersheds is dominantly row crop agriculture (>80%) under a corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation. For more information see David et al. (1997).

Typical agriculture in these watersheds includes conservation tillage, extensive fall application of N fertilizers, and cultivation of corn and soybeans on >90% of the land area. There is almost no animal agriculture. The Upper Salt Fork Watershed has an active watershed group that formed first as a steering committee in 1990 of the Champaign County Soil and Water Conservation District (CCSWCD) and later as a watershed group involving diverse stakeholders, including the agricultural industry, Champaign-Urbana Sanitary District, environmental groups, university scientists, and local governmental representatives. Efforts to improve water quality have occurred through this group and through programs of the American Farmland Trust, who led the selection of the Upper Salt Fork Watershed as one of the USDA Natural Resources Conservation Service Mississippi River Basin Initiative watersheds in Illinois. Farmer characteristics from the study area, including participants, counties, and the state of Illinois, are included in the results section below in comparison to our survey respondents.

Biogeochemical and Engineering Data Collection and Analysis

Our research group is involved in many on-farm research trials in these two watersheds to evaluate various nutrient remediation practices under real-world conditions and constraints. We are evaluating end-of-tile techniques and in-field solutions for reducing the flow of nutrients (especially nitrate) from agricultural fields to surface waters.

River Sampling

Water grab samples were typically collected weekly at the gaging stations in the Embarras and Upper Salt Fork watersheds; we also attempted to sample all high flow periods on a daily basis. River samples were filtered (0.45 μm pore size) and analyzed for nitrate by ion chromatography (Dionex). Linear interpolation was used to estimate a nitrate N concentration for every daily discharge value to determine daily and annual loads, and earlier studies have published some of these data for the Embarras River (David et al., 1997; Royer et al., 2004, 2006). Annual riverine data are expressed on a water-year basis (1 Oct. of the previous year through 30 Sept. of the named year). Trends in nitrate concentration in the Embarras River were assessed using the Seasonal Kendall test from the USGS that performs the Mann-Kendall trend test for individual seasons of the year, which we defined as four seasons (Helsel et al., 2006). Possible trends in nitrate yields from the Embarras River watershed were assessed using linear regression in SAS v. 9.3, with year and cm of runoff as independent variables.

Drainage Water Management

The drainage water management study was conducted on a 34-ha field located in the Spoon River subwatershed of the larger Upper Salt Fork watershed. A corn and soybean rotation has been cultivated under continuous no-till farming for the past 27 yr. During 2011 soybean was grown; corn was grown in 2012. A side-dress fertilizer solution had been applied in the form of urea-ammonium nitrate (28%) at a rate of 180 kg N ha^{-1} during the spring of 2012. The 34-ha field was divided into two independent subsurface tile drainage systems: South Tile (ST) and the North Tile (NT), with areas of 10.9 and 23.1 ha, respectively. The field has a parallel subsurface tile drainage design with lateral tiles 15.2 cm in diameter that were installed approximately at a 1-m depth and 15 m apart. Each of the lateral tiles was connected to a tile main 20.3 cm in diameter that drained to an Agri Drain structure that was used to monitor the outflow and water table level from each field. The adjustable flashboards were used to increase and decrease the outlet depth of the drainage systems. To estimate the flow discharge from each field, a 60° V-notch board was installed and used as a reference point to measure the water table level in both Agri Drain structures. Both structures were equipped with pressure transducers and data loggers to continuously record the water level behind the v-notch. Water samples were collected weekly to biweekly during base flow conditions. Samples were collected at least daily during high discharge periods after precipitation events; a few high flow events were sampled several times a day. All samples were analyzed for nitrate as described above.

A nearby tile system (tile A described below) draining a corn/soybean field was used to estimate the flow from ST and NT during the drainage water management (DWM) periods (including 1 wk after the outlet was opened). Daily flow from this 6.9-ha field was regressed against daily flow from NT and ST outside of the DWM period in 2012 and 2013. It had the best relationship of daily flow with NT and ST tiles of five additional tiles that were monitored in the Upper Salt Fork Watershed. Regression equations explained about 80% of the daily flow between tile A and NT and ST, with separate equations developed for each.

Constructed Wetlands and Woodchip Bioreactors

In 1994, three wetlands were constructed in the floodplain of the Embarras River at the end of tile systems draining corn and soybean fields. Wetland sizes were based on a 20:1 drainage area and ranged from 0.3 to 0.8 ha. Input/output balances for N were determined (Kovacic et al., 2000). Currently we are studying these same wetlands to reassess their effectiveness of removing nitrate from tile drainage water nearly 20 yr after creation and establishment. The results are not presented here, but it is important to note that the Embarras Watershed has these wetlands in the context of the surveys conducted.

On the same farm, a woodchip bioreactor was constructed in March of 2012 on a pattern-drained, 20-ha field in a corn and soybean rotation. Located at the end of the 30-cm main tile outlet, the bioreactor area was 6 by 15 m by 1.3 m deep. A four-chamber Agri Drain structure fitted with three flashboard risers and V-notch boards, four pressure transducers, and two dataloggers was used to divert tile water into the woodchips and to receive the return flow from the bioreactor. Based on design parameters, the bioreactor was sized to remove approximately 50% of the tile nitrate load because high flow events can produce substantial bypass flow (tile water that flows over the middle V-notch board and does not pass through the woodchips and does not get treated). Weekly grab samples were supplemented with ISCO automatic water samplers to determine nitrate concentrations in and out of the bioreactor. This study evaluated bioreactor performance by quantifying input/output balances.

Fertilizer Timing

On another farm in the Upper Salt Fork, tile drainage from two adjacent fields under two different cropping systems was monitored: (i) a split application of fall and spring fertilizer N in continuous corn (C–C) and (ii) a split application of spring and side-dress fertilizer N in a corn–soybean rotation (C–S) where corn was planted in 2010 and 2012. In C–C, fall fertilizer N was applied as anhydrous ammonia with a nitrification inhibitor in late November, whereas spring fertilizer N was a 28% solution with herbicide. In C–S, spring fertilizer N was applied as a 28% solution with herbicide and side-dress was also a 28% solution. In C–C, the total fertilizer N applied in 2011 was 224 kg ha^{-1} with 135 kg ha^{-1} in the fall, and the total fertilizer N applied in 2012 was 246 kg ha^{-1} with 179 kg ha^{-1} in the fall. In C–S, total fertilizer N applied was 213 kg ha^{-1}, with 179 kg ha^{-1} applied as a side-dress. The tile in C–C drained 20 ha and the tile in C–S drained 7 ha. At the end of each tile system an Agri Drain structure with a V-notch board, pressure transducer and datalogger was installed. Water samples were collected weekly and supplemented with ISCO automatic water samplers during high flow events. Nitrate was analyzed as previously reported.

Cover Crops

After the severe drought of 2012, a cover crop was planted on another tile-drained field adjacent to the C–S field mentioned above to act as a N "catch" crop to absorb unused fertilizer after a year of limited corn growth and N accumulation. The C–S field without the cover crop was Tile A (7 ha), and the adjacent tile within the same C–S production system that received the cover crop was Tile B (17 ha). Again, an Agri Drain structure with a V-notch board was installed at the end of each tile system, along with a pressure transducer and datalogger. Water samples were collected weekly and supplemented with ISCO automatic water samplers during high flow events. Nitrate was analyzed as previously reported. A mixture of annual ryegrass and tillage radish was aerially seeded into standing corn on 8 September. Using 0.25-m^2 quadrats, aboveground biomass of the cover crop was measured on 8 November. Before initiating the cover crop experiment, there were two previous years of data from these two tile systems. Although the tile nitrate yield of Tile A was somewhat greater than Tile B, we used the previous 2 yr of data to account for this inherent difference between the two tile systems.

Social Science Data Collection and Analysis

Several social science research methods were implemented to reach farmers in different ways, including presentations at various CCSWCD events and interviews in addition to surveys, given the typical reluctance of farmers to respond to traditional surveys (Pennings et al., 2002). The results below draw predominantly on survey data collected in the two watersheds. Interview data and associated q-sort ranking activity results form the basis for addressing the last research question about farming complexity.

Farm Operator Survey Methods

Embarras farm operators were surveyed in summer 2012, and those from the Upper Salt Fork watershed were surveyed in spring 2013. All farm operators in each watershed (EMB 336, USF 284) were eligible for participation and were identified by combining CCSWCD geo-referenced farm data with Farm Service Agency contact information for farmers. Surveys were administered using the Modified Tailored Design Method (Dillman et al., 2009), including an initial mailing of survey and cover letter, a reminder/thank you postcard 2 weeks later, and a second survey wave shortly thereafter. A $2 bill incentive was included in the Embarras survey, and a $5 gift card to a local farm supply store was included as an incentive in the Upper Salt Fork survey (for consistency with a previous survey).

Survey questions focused on current farm characteristics and practices, perceptions of water quality, factors influencing water quality management decisions, willingness to adopt specific practices, and personal characteristics. A number of questions were taken or modified from the Social Indicators for Planning and Evaluation System program (Genskow and Prokopy, 2011), and others came from interviews and project leader experience. Questions regarding factors influencing water quality management decisions included the level of interest in new agricultural practices related to production and conservation as well as three batteries of questions, including (i) importance of issues when making water quality management decisions on farm, (ii) how much issues limit one's ability to implement water quality conservation practices on farm, (iii) willingness to modify farm operation to improve water quality under various circumstances, and (iv) personal characteristics, including age (year born), gender, level of education, and gross farm income.

Survey data from the two watersheds were aggregated and statistically analyzed using SPSS, Version 21. Our quantitative analysis focused on descriptive statistics for key variables and on various appropriate bivariate analyses (independent t test or chi-square, depending on the nature of the variables) to assess differences across watersheds and the influence of farm size and ownership characteristics.

Farm Operator and Landowner Interview Methods

Postcards were used in both watersheds to encourage participation in interviews regarding farming and water quality. In the Embarras watershed, 47 postcards were returned out of 650 sent to all agricultural landowners (identified by merging publically accessible parcel ownership data with watershed boundary file). In the Upper Salt Fork watershed, 17 of 270 postcards sent with the mail survey packet were returned by those willing to be interviewed. Additional participants were identified using snowball sampling, whereby participants were asked to identify additional people to interview. Some of the postcard respondents were not available. A total of 39 interviews were completed with Embarras farm operators and landowners in the spring 2012, and 14 interviews were conducted in the Upper Salt Fork watershed in spring 2013. Interviewees represented a diverse set of farm operators and landowners from different sized farms and ownership characteristics. Interviews were conducted until a saturation point was achieved in which few new insights were found.

Interview questions focused on farming experiences and practices and perspectives on water quality. Interviews were analyzed thematically across the various research questions and read by three researchers to assure reliability in conclusions drawn. An additional Q-sort activity was conducted with the Upper Salt Fork interview participants to gather information on factors influencing farm decision-making. Q-methodology allows for a form of factor analysis based on participants' subjective ranking of statements. In this study, participants sorted 23 cards stating possible farm decision factors (see Supplemental Information for list of statements used in the Q-sort). After initially sorting factors into high-, medium-, or low-influence categories, the cards were sorted again from least to most influential (with corresponding values from −3 to +3). A picture recorded each template of sorted cards. Data were entered and analyzed using PQ Method Software for descriptive statistics and factor analysis (Watts and Stenner, 2012).

We were more successful than most similar efforts in reaching farm operators using survey research methods (Pennings et al., 2002). For the Embarras, 116 surveys were returned out of 336 sent, minus 30 deemed ineligible due to watershed boundary error and 8 undeliverable addresses, yielding a 38.9% response rate. For the Upper Salt Fork, 90 completed surveys were returned out of 284 surveys sent, minus 13 returned for ineligibility and 1 undeliverable address, yielding a 33.3% response rate. Although limiting in terms of representation, these rates are higher than similar recent studies (e.g., 21.9%, as reported by Reimer and Prokopy [2013]). Comparisons were made with agricultural census statistics for the two counties and the state of Illinois (Table 1). Survey respondents were broadly representative in terms of gender, age (though slightly older), and average farm acreage. Smaller farms (1–99 acres) were underrepresented, as were farms income less than $49,999. Larger farms yielding greater income were overrepresented, and survey respondents were more highly educated than state agriculture statistics indicate. In the findings presented below, we explore differences between the two watersheds: (i) those with majority of acres owned versus rented and (ii) those farming large (>500 acres) versus small (≤499 acres) farms.

Results and Discussion

Assessments of Water Quality

The Embarras and Upper Salt Fork rivers have typical nitrate concentration patterns of flashy, tile drained, headwater watersheds in the upper Midwest, with high concentrations during winter and spring and low concentrations (approaching 0 mg N L^{-1}) during the low-flow periods of summer and fall (Fig. 1). Nitrate concentrations typically reach about 14 mg N L^{-1} each year in the Embarras River, whereas the Upper Salt Fork typically has peak concentrations of approximately 12 mg N L^{-1}. Both watersheds had near record-high flows on 18 Apr. 2013 and had the greatest nitrate concentrations in our period of record for each watershed in early June 2013 (17.9 and 14.3 mg N L^{-1} for the Embarras and Upper Salt Fork Rivers, respectively). These record nitrate concentrations followed the drought year of 2012, when Champaign County had average corn yields of only 5.9 Mg ha^{-1}, compared with an average of 9.3 Mg ha^{-1} for 2002 to 2011 (USDA-NASS, 2014). The flow-weighted mean concentration of nitrate in the Embarras River for 2013 was 11.7 mg N L^{-1}, which was the largest value in our period of record. These rivers often have nitrate concentrations greater than the USEPA drinking water standard of 10 mg N L^{-1}. No trend in nitrate concentrations ($p = 0.53$) was found for the 22 yr record of the Embarras River using the seasonal Kendall test for trend.

The long-term average water yield for the Embarras River watershed during 1993 to 2013 water years was 35.3 cm of flow, leading to the export of 30.6 kg N ha^{-1} yr^{-1} (Fig. 2). During the past 5 water years, the Embarras River had an average of 36.3 cm of flow with a nitrate yield of 29.8 kg N ha^{-1} yr^{-1}. The Upper Salt Fork River had corresponding values for the past 5 yr of 35.6 cm of flow and 23.0 kg N ha^{-1} yr^{-1}. Although the watersheds have similar runoff, the Embarras River has greater nitrate yields. However, the pattern of nitrate loss was nearly identical; when cumulative daily nitrate load of the Embarras River was regressed against cumulative daily load of the Upper Salt Fork (15 Apr. 2008 through 30 Sept. 2013), the linear regression equation

Table 1. Survey respondent comparisons for the Embarras River and Upper Salt Fork Watershed with county and statewide agricultural census statistics.†

	Survey respondents‡		Ag census county statistics		
	EMB watershed	USF watershed	Douglas County	Champaign County	Illinois
Gender					
Male	95.5%	97.6%	94.7%	90.7%	90%
Female	4.5%	2.4%	5.3%	9.3%	10%
Average age, yr	60.1	59.7	54.7	57.6	56
Farm size, acres					
1–99	15.5%	10.3%	56.0%	42.6%	50.7%
100–499	32.7%	46.0%	21.8%	30.1%	28.3%
500–999	24.5%	23.0%	8.8%	14.9%	10.8%
1000–1999	19.1%	18.4%	8.7%	9.3%	7.2%
≥2000	8.2%	2.3%	4.7%	3.1%	3.0%
Average acreage	374	340	398	396	348
Farm income					
<$10,000	4.2%	0%	40.6%	27.2%	46.9%
$10,000–49,999	9.5%	6.7%	16.3%	17.9%	14.7%
$50,000–99,999	11.6%	18.7%	9.0%	11.5%	8.1%
$100,000–499,000	47.4%	49.3%	21.4%	30.7%	21.0%
≥$500,000	27.4%	25.3%	12.6%	12.7%	9.3%
Education					
Some high school	0.9%	2.3%	NA§	NA	13.5%
High school graduate	24.3%	30.2%	NA	NA	37.3%
Some college	38.7%	46.5%	NA	NA	32.3%
College degree	28.8%	19.8%	NA	NA	17%
Postgraduate college	7.2%	1.2%	NA	NA	NA

† Sources: USDA ERS 2007 county and statewide data; education level for Illinois from USDA ERA (Illinois Fact sheet 2007–2011 rural data).

‡ EMB, Embarras River; USF, Upper Salt Fork Watershed.

§ Not applicable.

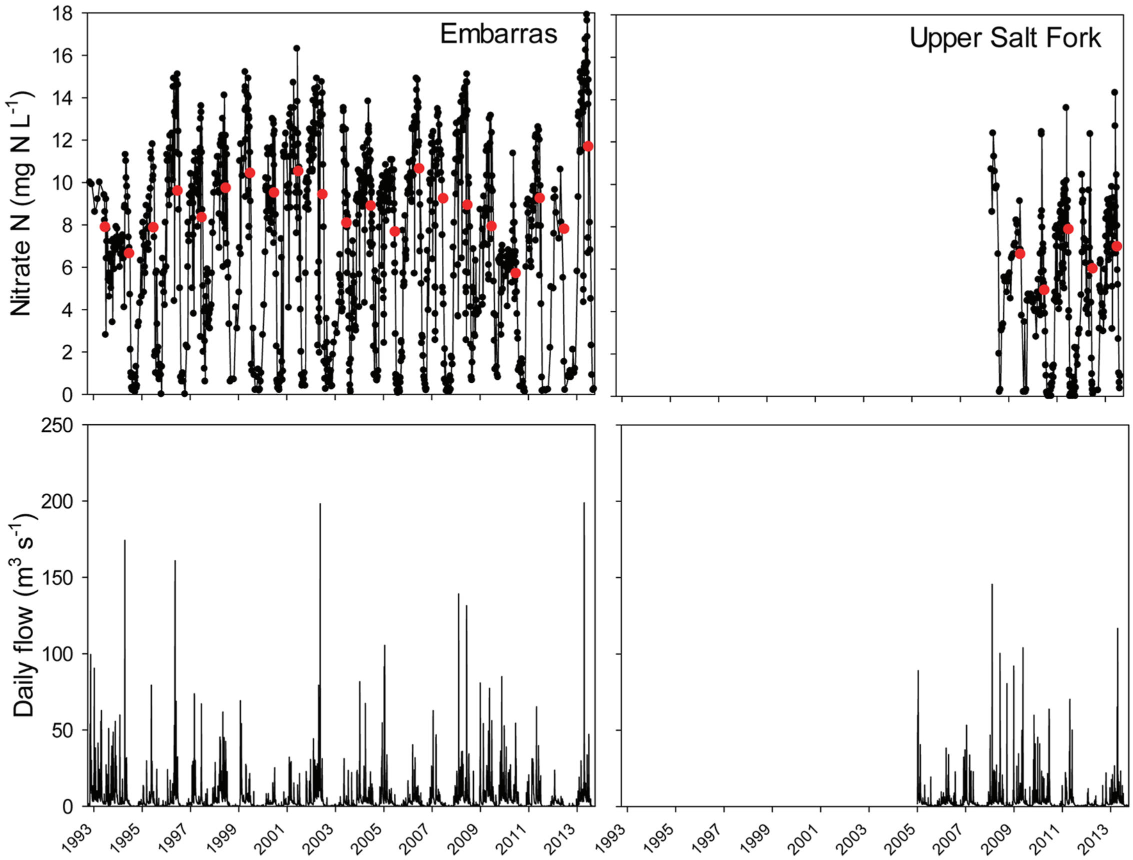

Fig. 1. Daily stream flow and nitrate concentrations in the Embarras River at Camargo, IL, and the Upper Salt Fork River at St. Joseph, IL. Flow-weighted annual nitrate concentrations are indicated with red dots.

explained 99.7% of the variation ($p < 0.0001$). Royer et al. (2006) also noted that watersheds in east-central Illinois have similar patterns of loss and discussed the importance of high flow periods and limited in-stream removal of nitrate. The difference in watershed yields of nitrate in the Embarras and Upper Salt Fork may be due to the density of tile drainage, subsurface flow paths, amount of fall fertilizer N application, fertilization rates, or other unknown differences between the two watersheds. However, both watersheds have large nitrate losses when viewed across the Mississippi River basin, and these loads are consistent with those estimated by David et al. (2010), where the tile-drained Corn Belt has the greatest nitrate losses in the Mississippi River basin. Watersheds such as the Embarras and Upper Salt Fork would be targeted for 45% reductions in nitrate loads as described in the federal action plan for reducing hypoxia in the Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). Similar to nitrate concentrations in the Embarras River, no trend was found in nitrate yield through time in the Upper Salt Fork using linear regression ($p = 0.76$).

Farm operators generally rated water quality conditions as neither "very poor" nor "excellent" (Table 2). The average water quality rating for ditches and streams in the watershed was 3.32 on a scale from 1 (very poor) to 5 (excellent); Upper Salt Fork respondents were significantly more likely to rate their water quality higher than Embarras respondents. Regarding potential sources of water quality problems, only a small proportion of respondents (18.4%) rated nitrogen a problem (4 or 5 on a scale of 1 to 5). Only two potential sources of problems, sediments (23.4%) and municipal discharge (22.4%), were rated higher than nitrogen as a problem, and phosphorus was indicated as a problem by 15.6%. Approximately 16 to 20% of respondents indicated they did not know if the above sources were a problem for water quality.

Levels of concern about water quality in watershed ditches and streams were moderate, with an average score of 3.30 on a scale from 1 to 5 (not at all concerned to very concerned), although owners were found to be more concerned than renters (Table 2). Comparing concern at various geographic scales, there was little variation from home to the Gulf of Mexico, although the drainage district and watershed were the focus of greater concern than other scales. Farmers rated the Gulf of Mexico no less or more important than water quality concern for their own farm. There were no differences by watershed, farm size, or ownership for geographic scales of water quality concern. These findings address the second research questions and indicate that, although nitrate levels measured in the study watersheds exceeded common standards, fewer than 20% of farmers in the study perceived nitrates to be problematic for water quality.

Assessments of Nitrogen Management Conservation Practices and Adoption Factors

Drainage Water Management

In 2012, DWM was applied for 70 d on NT, and ST was managed as free drainage (FD). The outlets levels were set at 40 and 120 cm from the soil surface for the DWM and FD fields, respectively. The water level in the DWM tile was an

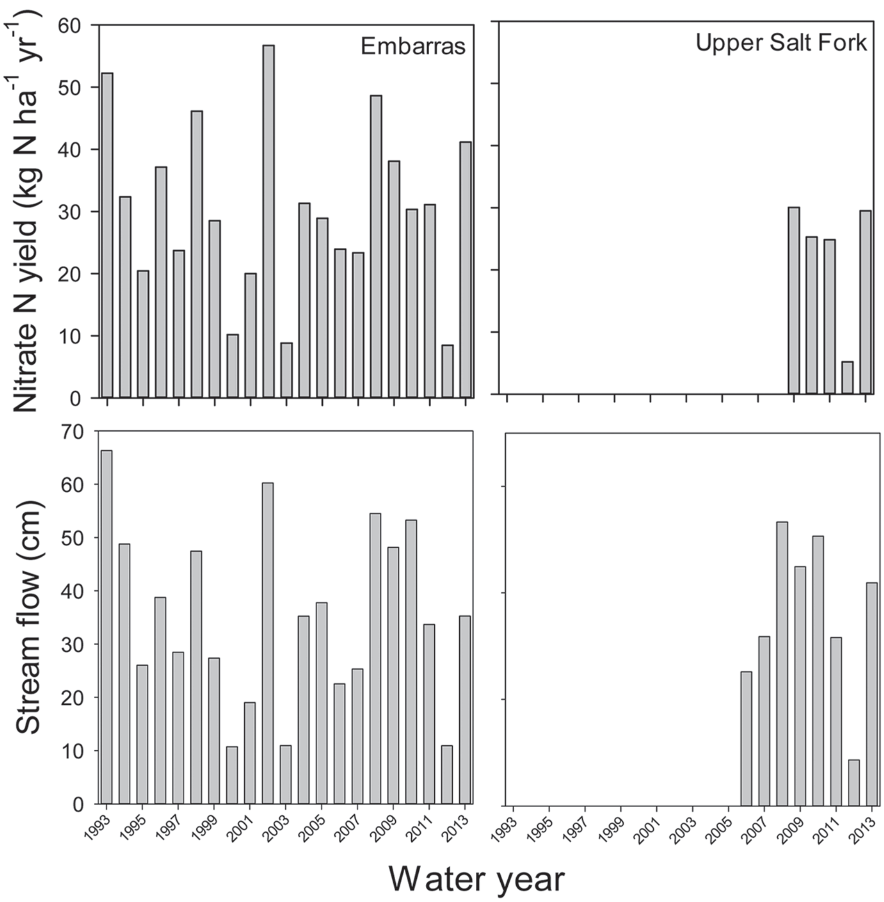

Fig. 2. Annual nitrate N yields and stream flow in the Embarras River at Camargo, IL, and the Upper Salt Fork River at St. Joseph, IL.

average of 70 cm from the soil surface, and water was held back in the field during the entire study period, with the exception of a rain event that occurred on 2 March, which was the only flow event observed during DWM (Fig. 3). In the FD field, there was continuous tile outflow. There was 20,428 m^3 of flow from ST (18.7 cm) and 17,472 m^3 from NT (7.6 cm) in the DWM tile. Although water was held back in NT, flow was increased in ST. Predicted flow (from nearby tile A) from both tile systems was 10.0 cm of runoff for the water year, clearly showing that water moved from NT to ST. A closer look at the instantaneous tile flow data revealed that the flow in ST increased shortly after initiating DWM on NT, suggesting that tile water was moving laterally from one tile system to the other. The base flow was elevated in the FD tile during the entire period of DWM.

Tile nitrate concentrations varied little between the two tile systems, with concentrations near 10 mg N L^{-1} for the entire winter and spring (Fig. 3). Additionally, tile nitrate concentrations remained relatively constant before and after the period of DWM, suggesting that field denitrification was not an important N sink.

Overall, we found no reduction in tile nitrate load using DWM due to lateral seepage of water to the adjacent system. This brings up new questions about how this technique could improve water quality using some existing tile drainage systems. However, the affected area on the NT was only about 2 ha, well below the recommended affected area size of 8 ha. Most studies to date on DWM have been on small (<5 ha) experimental fields (Skaggs et al., 2012), with the exception of Cooke and Verma (2012). Cooke and Verma (2012) used larger fields but did not determine the flow path of the held back water. There has been no study to date (other than modeling) that has documented the fate of the held-back water and nitrate in DWM systems, and this remains a major limitation to our understanding of this management tool.

Table 2. Embarras River and Upper Salt Fork Watershed water quality perception perspectives.

	$\bar{x}$	SD	Watershed comparison	Influence by size or ownership
Rating of water quality in ditches and streams in watershed (1 = very poor; 5 = excellent)	3.32	0.85	t = 6.31†***	NS
Level of concern about water quality in ditches and streams in watershed (1 = not at all concerned; 5 = very concerned)	3.30	1.19	NS	t = 2.63‡**
Geographic scales of concern (1 = not at all concerned; 5 = very concerned)				
Home	3.10	1.50	NS	NS
Farm	3.09	1.41	NS	NS
Drainage district	3.20	1.30	NS	NS
Watershed	3.20	1.20	NS	NS
Wabash River	3.04	1.17	NS	NS
Mississippi River	3.11	1.20	NS	NS
Gulf of Mexico	3.09	1.23	NS	NS

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Upper Salt Fork Watershed farm operators more likely to rate water quality condition higher than the EMB farm operators.

‡ Owner operators were more likely to indicate higher level of concern of water quality issues than renters.

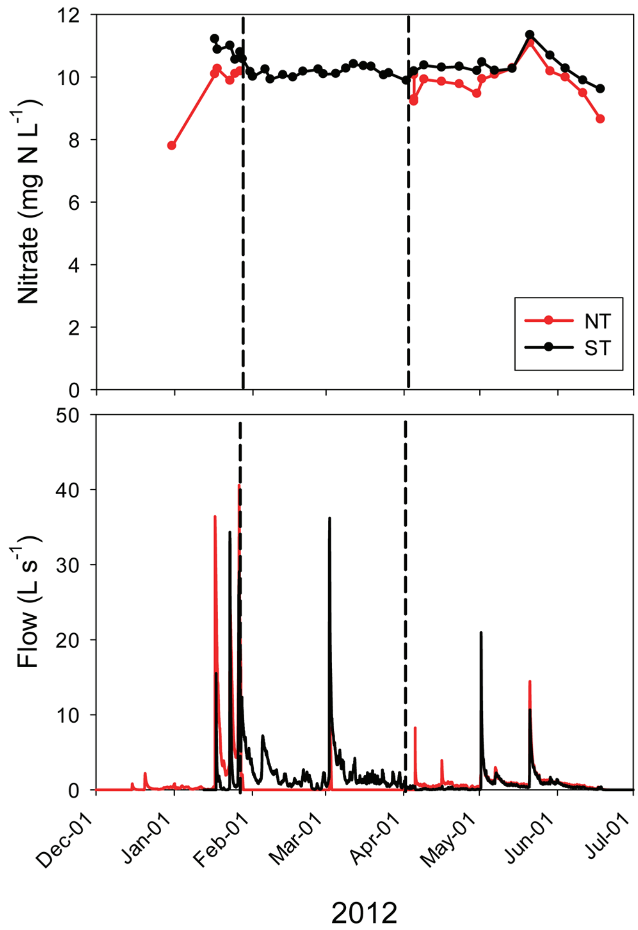

Fig. 3. South tile (ST) and North tile (NT) nitrate concentrations and tile flow during 2012. Vertical dashed lines show period of drainage water management on NT.

Wetlands and Bioreactors

End-of-tile and edge-of-field remediation techniques, such as constructed wetlands and woodchip bioreactors, use the microbial process of denitrification to remove nitrate from tile drainage water. Kovacic et al. (2000) found that constructed wetlands designed to intercept tile drainage water removed 45% of the tile nitrate (n = 9 wetland water years). Although these initial results were promising, there have been no new wetlands constructed in these watersheds since this study was published. Compared with wetlands, woodchip bioreactors are less expensive to install, have a much smaller footprint, and can fit into grassed riparian buffers without taking land out of row crop production.

In 2012, the newly constructed bioreactor performed well with an 80% nitrate removal rate (257 kg N in, 51 kg N out with 38 kg of this N as by-pass flow); however, the spring was unseasonably warm with little precipitation. Lack of rainfall limited tile flow and ultimately produced a severe drought in this region of the state. During this dry year, only 14% of the total tile flow bypassed the woodchips, which occurred during the week after high flow on 1 May (Fig. 4). Based on a volume of 117 m^3, the nitrate removal rate was 21 g m^{-3} d^{-1}, which is one of the highest removal rates reported for woodchip denitrification sinks (Schipper et al., 2010). Overall, bioreactor performance depends on the balance between residence time

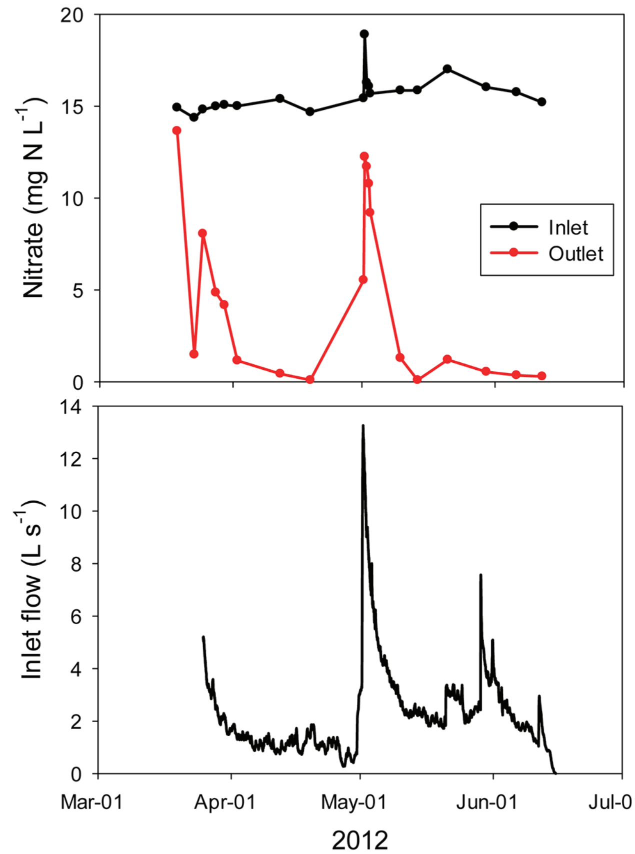

Fig. 4. Tile nitrate concentrations and flow of the inlet to the bioreactor, along with outlet concentrations during 2012.

and the amount of bypass flow; the lack of rainfall and tile flow during the spring of 2012 created favorable conditions for nitrate removal.

Fertilizer Timing

Tile nitrate concentrations from two production systems (C–C with split application of fall and spring N vs. C–S with split application of spring and side-dress N) were compared, which are both widely used in our two study watersheds (Fig. 5). During the first 2 yr of this investigation, there were

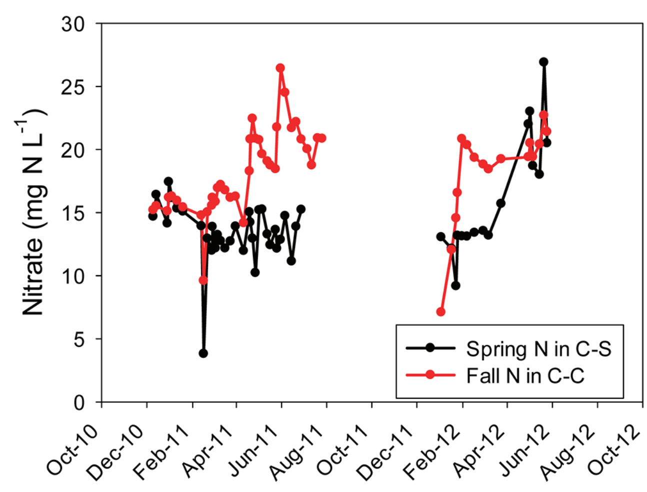

Fig. 5. Continuous corn (C–C) and corn–soybean (C–S) tile nitrate concentrations during 2011 through 2012. For the C–S, corn was grown in 2010 and 2012, and soybean was grown in 2011.

greater tile nitrate yields in the C–C system compared with the C–S system (54 vs. 38 kg N ha^{-1} in 2011 and 15 vs. 11 kg N ha^{-1} in 2012). It is not surprising that tile nitrate yields were greater from the C–C system than the C–S system because no fertilizer was applied during the soybean year in C–S in 2011. However, numerous studies have shown that fall and winter applications of fertilizer N can lead to increased tile nitrate losses compared with spring applications (Welch et al., 1971; Frye, 1977; Gentry et al., 1998; Randall et al., 2003; Clover, 2005). After corn in 2010, nitrate concentration in both tiles tracked one another until a large precipitation and tile flow event on 16 Feb. 2011. From that point onward until tile flow ceased in July, tile nitrate concentrations from the field that received fall N application were greater than the field and tile system that remained unfertilized in 2011. The field that received fall N fertilizer had tile nitrate concentrations that reached 20 mg N L^{-1} 2 mo earlier than the year before (February 2012 vs. April 2011). This is likely due to the effect of unseasonably warm winter temperatures on the effectiveness of the nitrification inhibitor. During flow events after spring fertilization in C–S in 2012, however, both tiles had about the same nitrate concentrations, demonstrating how quickly tile nitrate can respond to fertilizer application.

Cover Crop

Dry conditions during the growing season of 2012 limited corn yield and N uptake, leaving large soil nitrate pools after crop harvest. Rainfall before aerially seeding the cover crop in September allowed for immediate germination and 100% ground cover. Cover crop aboveground biomass and N accumulation were 2 Mg ha^{-1} and 65 kg N ha^{-1}, respectively. The cover crop appeared to have the greatest effect on tile nitrate during high flow events in the winter and spring, suggesting that cover crop N accumulation in the fall reduced the amount of soil nitrate available for leaching. Based on the difference in annual nitrate yields from the paired fields in 2012, we estimated that the cover crop reduced the tile nitrate yield by 34% (Fig. 6). Cover crops have long been used to protect the soil from erosion; however, few studies have investigated the impact of cover crops on tile nitrate losses. Although Qi et al. (2011) did not detect a reduction in tile nitrate yield with a rye cover crop, Strock et al. (2004) found a modest reduction in tile nitrate yield of 13%, whereas Kaspar et al. (2007) found large tile nitrate reductions (59%) using rye as a winter cover crop. Cover crops may be the only practice that can reduce both erosion and tile nitrate yields.

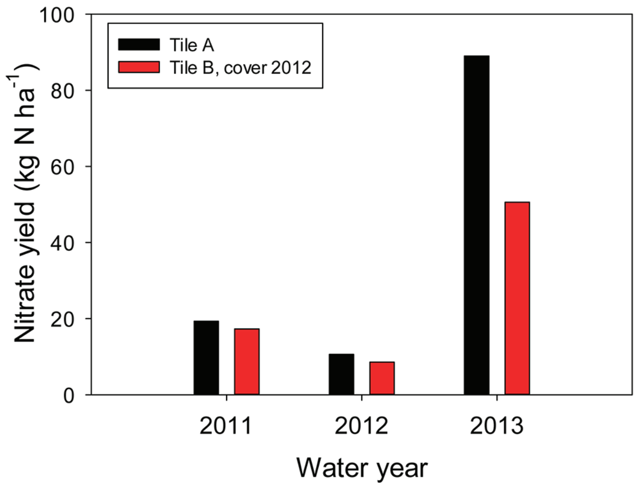

Fig. 6. Nitrate yields from tile drains in two fields during 2011 through 2013. Tile B had a cover crop planted in the fall of 2012. The 2011 water year was a partial year, with data from 1 April through 30 Sept. 2011.

Survey Results

Survey findings about the current use of various water quality–related practices are shown in Table 3. The majority of surveyed farmers indicated they conducted regular soil tests, followed a nutrient management plan, followed university-recommended fertilization rates, and used variable-rate application technology. Farmers of larger farms and renters were more likely to use these practices than those farming smaller farms or owning the majority of their farm acreage. In contrast, hardly any respondents indicated using practices specific to managing nutrients, such as cover crops, wetlands, controlled drainage, or bioreactors.

For farmers who did not indicate current use of the practices discussed above, a majority were familiar with the commonly used practices but less familiar with cover crops, wetlands, controlled drainage, and bioreactors, with about half of the respondents indicating they had never heard of bioreactors (Table 4). Watershed differences for controlled drainage and bioreactors

Table 3. Embarras River and Upper Salt Fork Watershed survey responses about currently used conservation practices.

	Currently use it	Watershed	Influence by size or ownership
	%		
Conduct regular soil test	84.9	NS†	$\chi 2 = 15.31$‡***; $\chi 2 = 9.39$§**
Follow a nutrient management plan	61.0	NS	$\chi 2 = 5.11$§*
Follow university fertilization rates	54.6	NS	$\chi 2 = 19.12$‡***; $\chi 2 = 4.82$§*
Use variable-rate application technology	54.6	NS	$\chi 2 = 20.38$***; $\chi 2 = 6.43$§*
Cover crops	9.4	NS	NS
Wetlands	5.9	NS	NS
Controlled drainage	5.6	NS	$\chi 2 = 5.13$‡*
Bioreactors	0.5	NS	NS

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Not significant.

‡ Farmers of larger farms more likely to use practice than farmers of smaller farms.

§ Renters more likely to use practice than owner operators.

Table 4. Embarras River and Upper Salt Fork Watershed level of familiarity with conservation practices that respondents were not currently using.

	Currently not using and			Watershed	Influence by size or ownership
	Never heard of it	Somewhat familiar with it	Familiar with it		
	%				
Conduct regular soil test	3.3	30.0	66.7	–	–
Follow a nutrient mgmt. plan	5.3	53.9	40.8	–	–
Follow university fertilization rates	10.1	36.0	53.9	–	–
					NS (ownership)
Use variable-rate application technology	6.7	19.1	74.2	–	–
Cover crops	25.4	31.8	42.8	–	χ^2 = 11.25†** NS (ownership)
Wetlands	15.3	41.5	43.2	NS	NS
Controlled drainage	21.0	35.5	43.5	χ^2 = 34.69‡***	NS
Bioreactors	50.8	26.5	22.8	χ^2 = 13.72§**	χ^2 = 6.09¶* NS (ownership)

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Farmers of larger farms more likely to be familiar with cover crops than farmers from smaller farms.

‡ Embarras River farm operators more likely to be familiar with controlled drainage than Upper Salt Fork Watershed farm operators.

§ Embarras River farm operators more likely to never have heard of bioreactors than the Upper Salt Fork Watershed farm operators.

¶ Farmers of smaller farms more likely to have never heard of cover crops than farmers of larger farms.

are likely explained by varying degrees of local engagement by professionals regarding these practices. Farmers of larger farms were generally more familiar with cover crops and bioreactors than those of smaller farms. However, limitations in the size of the dataset warrant caution in interpretation of the data.

Respondents indicated a relatively high level of interest in new agricultural practices for production and conservation (Table 5). Renters showed more interest than owners in new practices for production, and farmers of larger farms had more interest in practices for production and conservation than those farming smaller farms. In addition to assessing current use, familiarity, and general interest regarding various practices, the survey assessed factors influencing or constraining adoption of new water quality management practices (Table 6). The first battery of questions asked about the importance of various issues when making water quality management decisions. All stated factors were rated above 4.00 on a scale of 1 to 5. The top factor with a mean of 4.40 was "improving or maintaining the condition of my farm for future generations of farmers." This was followed by "improving my farm production" and "improving my bottom line."

"Personal out-of-pocket expense" (mean of 3.49 on a scale of 1 to 5) was the highest rated factor seen to limit the ability to implement water quality management decisions. This was followed by "lack of government funds for cost share," "concerns about reduced yields," and "possible interference with my flexibility to change land use practices as conditions warrant." Embarras respondents were more likely to indicate the limitations of "lack of government funds for cost share" than Upper Salt Fork respondents. Farmers of smaller farms were more likely to indicate limitations related to "no one else I know is implementing the practice" and "approval of my neighbors," suggesting they are possibly more influenced by social dynamics than farmers of larger farms. As for what circumstances would influence willingness to modify farm operation to improve water quality, respondents rated "if you saw convincing evidence from local demonstration plots that modifications would increase nutrient loss" highest (mean of 3.68 on a scale of 1 to 5 on willingness). This was followed by "if financial incentives were provided to cooperating farmers" (mean, 3.57). The lowest-rated factor related to circumstances influencing willingness to modify farm operation to improve water quality was "if federal or state regulations were established governing water quality of agricultural runoff" (mean, 2.79).

Table 5. Embarras River and Upper Salt Fork Watershed survey responses regarding interest in new agricultural practices for their farm (1 = not interested; 5 = very interested).

	$\overline{x}$	SD	Watershed comparison	Influence by size or ownership
For production	4.11	0.99	NS	$t = -2.37$†*; $t = -3.21$‡**
For conservation	3.93	1.01	NS	$t = -2.71$‡**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Renters more interested in new practices for production than owner operators.

‡ Farmers of larger farms more interested in new practices for production and conservation than farmers of smaller farms.

Findings from surveys of farm operators shed light on the fourth research question about adoption of conservation practices, suggesting there are substantial barriers to adoption of specific water quality conservation practices that would help address nitrate problems in intensively farmed watersheds. These barriers include social and informational factors as well as oft-cited financial limitations. The data also show that just establishing policies to regulate water quality may not increase adoption of particular practices.

Assessments of Complexity Regarding Nutrient Management and Farm Decision-Making

Each of the in- and edge-of-field N management techniques we evaluated had biophysical and social constraints. David et al. (2013) briefly summarized some of these constraints, and this study has illustrated the constraints in some detail. Weather (frequency and intensity of precipitation and winter temperatures) is a major limitation for edge-of-field N management methods. There has been an increased frequency of intensive precipitation during the winter and spring in the upper Midwest (MRCC, 2013). The flow event on 19 Apr. 2013 (13 cm of precipitation during 15–18 Apr. 2013 [Fig. 1]) would overwhelm any wetland or bioreactor. Kovacic et al. (2000) indicated that large storm flows where the river inundates the wetland created periods of no nitrate removal. The April 2013 storm did inundate the wetlands and bioreactor such that they had no nitrate removal (data not shown). Given that most of the nitrate load is transported down river during these major storm events in the winter and spring (Royer et al., 2006), edge-of-field methods cannot be designed with a large enough capacity to reduce these loads. Increased winter temperatures (Villarini et al., 2013) lead to greater winter and early spring tile flow, where techniques such as wetlands and bioreactors that depend on microbial denitrification for nitrate reduction have slow rates of removal.

For the watersheds of east-central Illinois, there are many landscape-level limitations for placement of many nutrient reduction techniques. Woodchip bioreactors, for example, fit best into existing filter strips located along ditches and streams. However, at current commodity prices, many conservation areas (e.g., filter strips) are returning to row crop production on contract expiration, which will further constrain suitable sites for bioreactors. In general, by the time a tile line outlets into a ditch, it may have passed through multiple fields with multiple landowners and may have drained hundreds of hectares of land.

Table 6. Embarras River and Upper Salt Fork Watershed survey factors influencing water quality management decisions.†

	$\bar{x}$	SD	Watershed comparison	Influence by size/ ownership
Importance of issues when making water quality management decisions on farm (1 = not at all important; 5 = very important)				
Improving my farm production	4.25	0.91	NS	NS
Improving my bottom line	4.24	0.94	NS	NS
Improving the quality of water	4.14	0.90	NS	NS
Promoting conservation	4.14	0.79	NS	NS
Improving or maintaining relationships with neighboring farmers	4.10	0.93	NS	NS
Improving/maintaining appearance of my farm	4.08	0.98	NS	NS
Improving or maintaining the condition of my farm for future generations of farmers	4.40	0.84	NS	NS
How much issues limit ability to implement water quality management decisions on farm (1 = not at all; 5 = a great deal)				
Personal out-of-pocket expense	3.49	1.27	NS	NS
Lack of government funds for cost share	3.39	1.28	t = 2.73‡**	NS
Not having access to the equipment that I need	3.09	1.21	NS	NS
Lack of available information about a practice	2.96	1.18	NS	NS
No one else I know is implementing the practice	2.74	1.21	NS	t = 3.60§***
Concerns about reduced yields	3.38	1.35	NS	NS
Approval of my neighbors	2.52	1.32	NS	t = 2.40§*
Don't want to participate in gov. programs	2.51	1.26	NS	NS
Requirements or restrictions of gov. programs	3.31	1.29	NS	NS
Possible interference with my flexibility to change land use practices as conditions warrant	3.34	1.24	NS	NS
Environmental damage caused by the practice	3.08	1.24	NS	NS
I do not own the property	2.93	1.51	t = 2.88‡**	NS
Not being able to see a demonstration of the practice before I decide	3.03	1.23	NS	NS
Willingness to modify farm operation to improve water quality under the following circumstances (1 = not at all willing; 5 = very willing)				
If federal or state regulations were established governing water quality of agricultural runoff	2.79	1.15	NS	NS
If financial incentives were provided to cooperating farmers	3.57	0.97	NS	NS
If most neighboring or family farmers adopted water quality improvement management practices	3.29	0.97	NS	NS
If you saw convincing evidence from local demonstration plots that modifications would increase nutrient loss	3.68	0.92	NS	NS
If recommended by your county Farm Bureau	2.90	0.96	NS	NS
If recommended by your county Soil and Water Conservation District	3.24	0.92	NS	NS
If recommended by University of Illinois Extension	3.08	0.99	NS	NS

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Questions were adapted and modified from the Social Indicator Planning and Evaluation System (see Genskow and Prokopy [2011]).

‡ Embarras River farm operators rated greater limitation than Upper Salt Fork Watershed farm operators.

§ Farmers of smaller farms rated greater limitation than farmers of larger farms.

Based on the footprint-to-nitrate removal ratio, bioreactors cannot effectively treat large tile flow volumes from these extensive tile systems. On the other hand, constructed wetlands can be designed large enough to accommodate these extensive tile systems and to intercept overland runoff. However, constructed wetlands have a much greater footprint than do bioreactors and are best positioned below an adjacent field within a natural floodplain. In areas covered by the most recent glacial episode (the Wisconsinan glaciation), stream drainage networks are relatively immature and floodplains are not well developed, which greatly limits the potential for siting treatment wetlands on many tile systems. In fact, most drainage ditches did not exist before they were carved out of the flat landscapes by the steam shovel in the late 1800s, which created mounds of dredge spoil on both sides of the ditch. This situation makes siting a bioreactor a challenge due to the depth of the tile as it passes from field to ditch and renders siting a wetland impossible due to lack of slope in these areas.

Drainage water management works best when implemented on new tile systems designed for this capability (Ehmke, 2013). Our implementation on an existing tile system documented movement of the held-back water from the DWM system to the nearby free drainage system. Perhaps this was not a suitable field for retrofit of DWM, but we had few choices when looking for cooperators as few landowners wanted to be part of this study, even when there was no cost.

In-field techniques, such as fertilizer timing and cover crops, may have the best chance for broad implementation and may reduce nitrate losses before it reaches the tile line. Given the weather constraints discussed previously, this is a great advantage. Fertilizer timing has few costs but can increase risks for corn production. Cover crops add costs and management complexities. For the Upper Salt Fork Watershed, attempts have been made through NRCS and the American Farmland Trust, and more recently through the fertilizer industry, to greatly expand cover crop use (with full cost share). There have been few acres enrolled to date, likely because of the many economic and social constraints acting on farmers and landowners in this watershed. This watershed has excellent soils that produce high yields, and when combined with high grain prices this may limit interest in practices that might be viewed as having a potential negative effect on yields.

Interviews with farm operators and landowners highlighted the complex issues affecting farming. Participants described economic, environmental, and social factors influencing their ability or willingness to adopt new practices to improve water quality. Some respondents indicated "bottom line" and input costs as motivating factors:

> "Well, and most farmers, they're going to do what, you know, they want to make enough money to do it again next year. That's the first thing, and then, you know, if it's good for water quality so be it. But, you know, it usually boils down to money."

> "Well the cost of it and implementation would be a big factor for us. Everybody wants better water quality but you have to see the cost associated with those things that you would do. So the economical to me would be the primary concern I guess."

However, other farmers reflected that environmental considerations might outweigh the economic in some circumstances as indicated by these quotes:

> "If there was a practice that showed a great economic return, but yet resulted in, losing nitrogen, or losing nutrients or, you know, something that was really bad for water quality, I would think twice about it."

> "Well, conservation in the idea of saving the soil that we have, so that you don't get erosion, that part of it, yes. That would be my first concern."

Interviews also revealed strong social dimensions to decision-making in terms of future generations and the influence of observing the actions of others, as indicated by these quotes:

> "I've got sons and grandsons that I think will want to farm and what's it going to be like in 70 years if we don't start taking care of some of the issues now?"

> "I think most of the farmers are like sheep, one leads, the rest of them follow. My dad's 84 years old and I had a hard time convincing him to no-till corn, but after he saw it could be done and the results, boy now he wouldn't have it any other way."

The Q-sort activity shed additional light on the complexity of farming, revealing, at least preliminarily, that there is heterogeneity among farmers in terms of what influences overall farm decision-making. The factor analysis of 23 sorted farm decision-making factors revealed four factors with Eigenvalues over 1, explaining 54% of the total variance across participants. There were no key differences in farmer characteristics (farm size, ownership, age). The factor arrays of the statements sorted indicated how the farm decision factors clustered among the participants. Eleven of the 14 farmers fell into one of four thematic groups, identified based on factors with eigenvalues above or close to 1.0. Groups of farmers with similar sorting patterns were found to fall into the following categories of dominant decision-making influence: (i) Economics and Information, (ii) Family Oriented and Environmentally Conscious, (iii) Water Quality Concern, and (iv) Agricultural Focus.

The Economics and Information factor explained 22% of the total variance and influential statements for this group were bottom line, increased crop yield, access to information, and supportive evidence from science. The Family Oriented and Environmental Conscious factor explained 16% of the total variance, and influential statements were future generation farming, soil erosion, and family farming history. The Water Quality Concern factor explained 11% of the total study variance, and influential statements were water quality impacts from tile, water quality impacts from surface runoff, and promoting conservation. Finally, the Agricultural Focus factor explained 5% of the total variance in the study and included three highly rated statements about commodity market prices, land ownership, and availability of technology. The Q-methodology is helpful for disentangling the heterogeneity among farmers. However, although designed explicitly for small sample sizes, 40 to 60 is an oft-cited optimal range according to Watts and Stenner (2012), suggesting that caution may be warranted in interpreting findings based on 14 participants.

Biophysical and Social Science Results Inform Policy Decisions

Our biophysical and social studies of the Upper Salt Fork and Embarras River watersheds demonstrate a disconnect between field and stream measurements and water quality perspectives of farm operators as well as complexity of reducing nitrate concentrations and loads in the river systems. Various in-field and edge-of-field techniques can help to reduce nitrate loads but have limitations and little social acceptance under our current policy and management systems. In addition, large-scale (nearly every field) adoption would be needed for substantial reductions in nitrate yields to occur, as was documented recently in the Iowa nutrient assessment (Iowa Nutrient Reduction Strategy, 2013).

Based on our long-term data set for the Embarras River, we have not observed a significant trend in river nitrate yield during the past 21 yr. It is possible that competing factors are at work and have produced a virtual draw regarding improved water quality in the Embarras River watershed. For example, conservation benefits may be offset by increased tile drainage installations, and gains in N use efficiency may be offset by an increase in corn acreage. If USDA farm subsidy programs continue to reward only crop yield, then gains in N use efficiency will likely be nullified by increases in corn acreage and tile installations; improvements in surface water quality will go undetected in these watersheds.

The inconsistency of findings across studies of conservation adoption (Prokopy et al., 2008), the complexities affecting technical efficacy of new practices, and the combination of factors influencing decision-making found here and by others (Battershill and Gilg, 1997; Maloney and Paolisso, 2006) suggest there is not likely a simple policy or technical solution or policy that would readily solve the nutrient–water quality problem. Priorities are multiple and heterogeneous across the farming community (Atwell et al., 2009a, 2009b), and policies are needed that allow for flexibility under changing socio-economic and physical conditions. Programs that bring farmers together and generate a collective sense of what is needed for improving conservation may also be helpful (McGuire et al., 2013). Without creating new efficiency-based subsidy programs, we will need every farm and every farmer in Illinois actively implementing some form of end-of-pipe remediation practice to address this issue on such a scale. Incentivizing on-farm research and collaborative arrangements among farmers will be increasingly important. Our finding of higher levels of concern for water quality at drainage district and watershed scales suggests that scaling up, or connecting individual and local efforts to meso- or macro-scale policies, programs, and strategies as advocated by Stuart and Gillon (2013) to mitigate collective vulnerabilities and contextualize policies in terms of economic and political realities, is essential.

Conclusions

Two tile-drained watersheds in east-central Illinois had large losses of nitrate, with no trend through time observed in the 21-yr record of the Embarras River. We determined that that fertilizer timing, cover crops, wetlands, and tile bioreactors could reduce these nitrate losses but found problems with DWM that was retrofitted to existing tile systems. Surveys indicated that although landowners and farmers had strong stewardship ethics, financial and operational constraints limited their willingness to adopt conservation practices that specifically targeted nitrate reduction and did not increase yields. With the policy and production systems currently in place on these corn- and soybean-dominated watersheds, large-scale nitrate reductions that are called for in nutrient reduction strategies for the Mississippi River Basin will be difficult to meet.

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