Assessing the Effects of Nutrients on Agricultural Streams: The Importance of Assessing Both Biological Response and Nutrient Processes

Jeffrey W. Frey, U.S. Geological Survey, Indianapolis, IN; Mark D. Munn, U.S. Geological Survey, Tacoma, WA; John H. Duff, U.S. Geological Survey, Menlo Park, CA; Jill D. Frankforter, U.S. Geological Survey, Lincoln, NE; Anthony J. Tesoriero, U.S. Geological Survey, Portland, OR; Terry R. Maret, U.S. Geological Survey, Boise, ID; and Billy G. Justus, U.S. Geological Survey, Little Rock, AR

Background

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to develop long-term consistent and comparable information on streams, rivers, and groundwater in support of national, regional, state, and local information needs and decisions related to water-quality management and policy. Since 2003, NAWQA has studied nutrient-biota interactions in eight agricultural areas across the United States, four of which are located within the Mississippi River Basin (fig. 1). Within each study unit, 30 wadeable stream sites were selected to capture the broadest possible nutrient gradient in a single ecoregion. Data on nitrogen and phosphorus, algal and invertebrate communities, benthic and sestonic algal chlorophyll *a*, and habitat conditions were collected at each site during the growing season. Stream metabolism and nitrogen processing were assessed at a subset of sites. The study units were selected to represent different agricultural settings and practices across the nation.

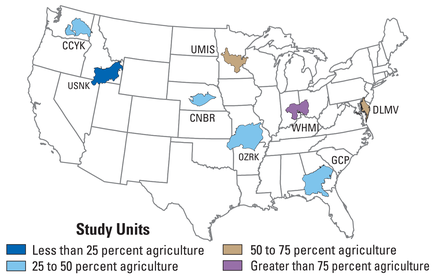


Figure 1. Location of the eight agricultural study areas, which included two Western Montane study units (Columbia Plateau – CCYK and Upper Snake – USNK), four Midwestern study units all of which drain into the Mississippi River Basin (Central Nebraska – CNBR, Ozark – OZRK, Upper Mississippi – UMIS, and White Miami – WHMI), and two Coastal Plain study units (Georgia Coastal Plain – GCP and Delmarva Peninsula – DLMV).

Many Agricultural Streams Have Nutrient Concentrations That Exceed Levels of Concern

The study units captured a wide range in both total nitrogen (TN) and phosphorous (TP) concentrations with lowest median TN and TP concentrations reported in the OZRK and highest median TN and TP measured in the WHMI and CNBR, respectively (fig. 2). In general, the concentrations of TN and TP increased as the percent agriculture increased. In the four areas with the most agricultural lands, the median TN and TP in-stream concentrations were greater than or near concentrations that could indicate eutrophic conditions.

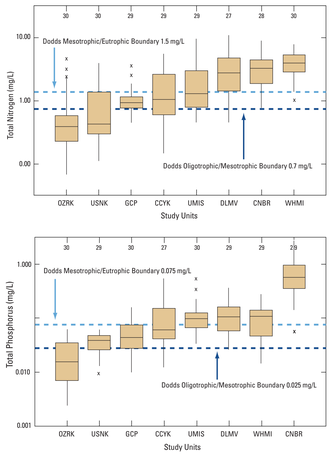


Figure 2. Box plots showing concentrations of total nitrogen (TN) and total phosphorus (TP) by study unit. The dashed lines refer to the concentrations that may indicate shifts in trophic conditions (Dodds and others, 1998); these trophic categories were based on a large national data set and used the lower and upper third distributions of the data to determine the oligotrophic and eutrophic boundaries. Valves above boxes are number of observations.

Relationships Between Benthic Algal Biomass and Nutrients Vary Regionally Due to Physical and Biological Interactions

Benthic algal biomass, expressed as chlorophyll *a* (mg/m^2), is a commonly used biological indicator for assessing nutrient conditions. In general, positive correlations between nutrients and algal biomass tend to occur when there is a wide range in nutrient concentrations including some low concentrations sites. When comparing the four Mississippi River Basin study units for TP, the OZRK and UMIS had slightly positive correlations between TP and algal biomass; however, the WHMI and CNBR had negative correlations (fig. 3). Figure 4 shows a conceptual model for explaining why sites deviate from predicted norms. The solid line represents a linear response of algal biomass as a function of increasing nutrient concentration. The development of nutrient criteria partially depends on models that can accurately predict some biological response (for example biomass) as a function of nutrient concentrations; however, various processes can greatly influence this relationship. For example, the upper left quadrant of figure 4 reflect those sites where algal biomass is sufficiently elevated to reduce nutrient concentrations due to algal uptake, whereas the lower right quadrant reflect sites where habitat limits primary production (lack of light penetration) or biological (grazing) and/or physical processes (scouring by streamflow) suppresses algal growth.

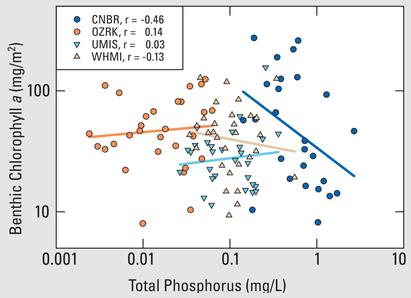


Figure 3. Relationship between benthic algal biomass (chlorophyll *a* mg/m^2) and TP in four Mississippi River Basin study units (*r* = Spearman correlation coefficients).

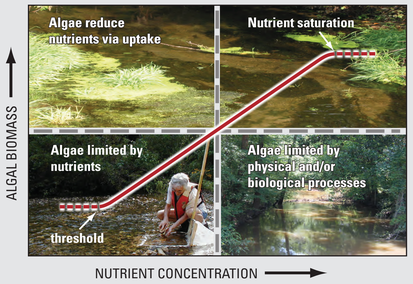


Figure 4. Nutrient-Algal Biomass Conceptual Model illustrating the interaction of nutrients and algal biomass. The solid line represents a linear response of algal biomass as a function of increasing nutrient concentration. Individual sites fall into one of the four quadrants depending on nutrient-biomass-habitat interactions.

Assessing Aquatic Communities Is Critical for Understanding Nutrient Conditions of Streams

It is well documented that algal, invertebrate, and fish communities provide important information on stream health. Whereas all three groups are known to respond to elevated concentrations of nutrients, there is less known about how the three groups compare during initial increases of nutrients in agricultural streams. The OZRK study unit provided a unique opportunity to assess and compare the responses of algae, invertebrate, and fish communities due to the study unit having moderate levels of agriculture, low to moderate nutrient concentrations, and high quality stream habitat. Results indicated that although all three groups did respond to increasing nutrient concentrations, the algal index had the strongest response (fig. 5). This indicates that benthic algae may be a useful indicator of biological changes due to low level increases of either nitrogen or phosphorus (Justus and others, 2009).

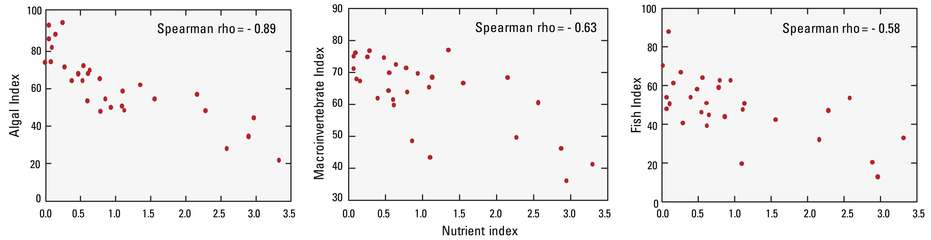
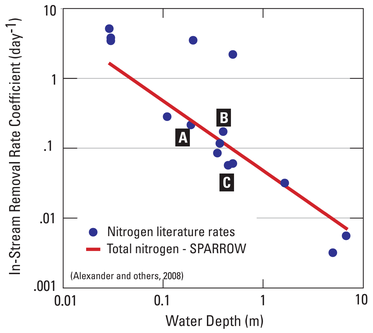


Figure 5. Relations between a nutrient index (that combines TN and TP concentrations) and algal, invertebrate, and fish indices (Justus and others, 2009).

Headwater Streams as Nutrient Filtering Systems

Headwater streams play a critical role in reducing nutrients due to biological uptake and transformations, whereas larger rivers tend to transport nutrients to downstream receiving waters. Nitrogen removal from a stream is often expressed as an in-stream removal rate coefficient, which generally describes the fraction of the nitrogen concentration or load that is removed per day of water travel time in a stream. This rate coefficient is theoretically expected to decline with increases in water depth or stream size, a relation that has been observed in field- and model-based studies of denitrification and long-term storage processes in streams (fig. 6). Recent studies by Duff and others (2008) of nitrogen removal rates in three agricultural streams found general agreement with the available literature for removal rates for nitrogen (fig. 6). However, the agricultural stream in Washington (fig. 6*C*) had a lower nitrogen removal rate largely due to irrigation practices, which reduces retention time.



B: Delaware–Stream is deep, turbid, high organic matter, and low primary production. In-stream nitrogen removal at expected rates.

A: Nebraska–Stream is shallow with low turbidty, low organic matter, and moderate primary production. In-stream nitrogen removal at expected rates.

C: Washington–Stream is deep, moderately turbid, high organic matter, and low primary production. In-stream nitrogen removal rates low due to lack of sufficient retention time resulting from irrigation practices.

Figure 6. Comparison of in-stream removal rates nitrogen in three agricultural streams.

Nutrient Pathways Important to Management Practice

Understanding nutrient pathways to streams will improve nutrient management strategies and estimates of the time lag between when changes in land use practices occur and the resulting changes in water quality are observed. The utility a of base flow index (BFI), the ratio of base flow to total flow volume for a given time period, as an indicator of the relative importance of runoff versus base flow in nitrate and orthophosphorus (OP) input was examined. Estimates of the proportion of stream nitrate derived from groundwater increased as BFI increased, while for OP it did not (fig. 7). In three of the watersheds, most of the nitrate load was derived from groundwater. Although groundwater was not typically the dominant source of the OP in these streams, groundwater discharge was an important pathway of OP when BFI values were very high and during base-flow conditions in watersheds where geochemical conditions favored OP mobility in groundwater. A groundwater source of nitrate and in some cases OP has important implications for nutrient management strategies. Groundwater derived nitrate and OP in these agricultural watersheds can result in increased time lags between when changes in land use practices occur and the resulting changes in stream water quality are observed (Tesoriero and others, 2009).

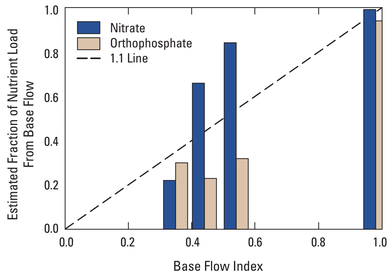


Figure 7. Estimated fraction of stream nitrate and orthophosphate load that is derived from base flow versus the base flow index of the stream (based on data from October 2002 to September 2004). Dashed line shows 1:1 relation between BFI and the fraction of total load derived from base flow.

Conclusions

Regardless of what strategy is adopted for managing nutrients in agricultural streams, it is important to understand a system sufficiently in order to set realistic expectations as to the degree and timing of changes in the biological condition from nutrient reduction. This is particularly true in agricultural systems where high loading combined with reduced retention times can result in a low percentage of nutrient removal, and the potential legacy effects from groundwater sources of nitrate or OP because of long lag times between nutrient applications to the land surface and discharge to streams. Incorporating biological community assessments will assist in tracking stream health changes due to nutrient reductions. Last, although the reduction of nutrient loads may have variable results in local streams, the benefits to downstream rivers, reservoirs, and coastal waters may prove to be critical due to the large number of small streams influencing the larger systems.

References Cited:

Alexander, R.B., Smith, R.A., Schwarz, G.S., Boyer, E.W., Nolan, J.V., and Brakebill, J.W., 2008, Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin: Environmental Science and Technology, v. 42, no. 3, p. 822-830, doi: 10.1021/es0716103.

Dodds, W.K., Jones, J.R., and Welch, E.B., 1998, Suggested classification of stream trophic state: Distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus: Water Research, v. 32, p. 1455-1462.

Duff, J.H., Tesoriero, A.J., Richardson, W.B., Strauss, E.A., and Munn, M.D., 2008, Whole-stream response to nitrate loading in three streams draining agricultural landscapes: Journal of Environmental Quality, v. 37, p. 1133–1144.

Justus, B.G., Petersen, J.C., Femmer, S.R., Davis, J.V., and Wallace, J.E., 2009, A comparison of algal, macroinvertebrate, and fish assemblage indices for assessing low-level nutrient enrichment in wadeable Ozark streams: Ecological Indicators, doi:10.1016/j.ecolind.2009.10.007.

Tesoriero, A.J., Duff, J.H., Wolock, D.M., Spahr, N.E., and Almendinger, J.E., 2009, Identifying pathways and processes affecting nitrate and orthophosphate inputs to streams in agricultural watersheds: Journal of Environmental Quality, v. 38, p. 1892–1900.

For more Information contact:

Mark D. Munn
U.S. Geological Survey
Washington Water Science Center

mdmunn@usgs.gov / (253) 552-1686
http://wa.water.usgs.gov/neet/