ASSESSING NUTRIENT TRANSPORT FOLLOWING DREDGING OF AGRICULTURAL DRAINAGE DITCHES

D. R. Smith, C. Huang

ABSTRACT. *Agricultural drainage ditches are vital for many agricultural landscapes in the U.S. Previous research has indicated that dredging agricultural drainage ditches may degrade water quality. In this study, we monitored nutrient transport in two drainage ditches for six years (2003-2008), during which two dredging activities occurred. Ditch reach nutrient loads were calculated on a monthly and annual basis for the two ditches, as hydrology and water chemistry were monitored daily during the growing season. When dredging activities occurred within the previous 12 months, reach loads were significantly reduced for all nutrients monitored, with net losses in the dredged reaches of NH_4-N (-94 kg), soluble P (SP; -6.6 kg), and total P (TP; -5.4 kg). When examining annual reach loads, the nutrient losses from recently dredged reaches were generally significantly lower than the other reaches during the same year. The apparent improvements in water chemistry seem to be contrary to earlier reports of potentially degraded water quality immediately after dredging. We attribute this to: (1) oxidation of reduced sediments, (2) deposition of "fresh" sediments, (3) recolonization by filamentous algae and higher plants, and (4) formation of biofilms on the exposed sediments. To avoid the detrimental impacts on water quality immediately after dredging, and to maximize the benefit of ditch recovery, we propose that ditch managers work with agricultural producers to delay nutrient applications to adjacent fields for at least one month after dredging activities. This should allow the ditches sufficient time to recover their ecological function following dredging.*

Keywords. *Conservation practices, Dredging, Nitrogen, Phosphorus, Water chemistry.*

Nutrient losses from agricultural runoff have been identified as a primary contributor to eutrophication in lakes, reservoirs, and estuaries (Carpenter et al., 1998). Recent work has demonstrated that nutrient losses from agriculture can contribute to degradation of terrestrial ecosystems (Johnson et al., 2007).

Agricultural drainage ditches are a common landscape feature throughout many humid agricultural regions of the U.S. (Needleman et al., 2007). Water and contaminants are transported to these ditches via shallow surface ditches or subsurface drainage tiles. Several areas in the U.S. that have a high density of agricultural drainage ditches, such as the Midwestern U.S. and the Delmarva Peninsula, have been identified as contributing to water quality problems downstream. Agricultural drainage ditches serve as the first- or second-order streams through which many of the contaminants that contribute to water quality problems in the Gulf of Mexico, the Great Lakes, or the Chesapeake Bay are initially transported (Sharpley et al., 2007; Strock et al., 2007). One of the important ecological functions of headwater streams is the uptake, removal, or transformation of nutrients (Haggard et al., 1999; Peterson et al., 2001; Bernot et al., 2006).

Landscape disturbance has been shown to alter the ecological function of lower-order streams (Hall, 2003). Disturbance in streams and the return of ecological function following disturbance has also been a topic of research (Resh et al., 1988). However, in most of these studies, the streams are fairly pristine, and the disturbance has generally been identified as a high-discharge event. Previous research has demonstrated that immediately after dredging, sediments and their associated biota are no longer able to buffer water column nutrient concentrations as effectively as they were prior to dredging (Smith et al., 2006b; Smith and Pappas, 2007). There could be several reasons for this, including altering the physiochemical properties of the sediments that are exposed to the water column, and removal of vegetation and other biota that may remove nutrients from the water column. Recent work has also demonstrated that dredging agricultural drainage ditches may be immediately detrimental to water quality as a result of elevated pesticide concentrations (Pappas and Smith, 2007).

The influence of dredging activities on ecological function has been identified in lakes, reservoirs, large rivers, and estuaries (Kleeberg and Kohl, 1999; Lohrer and Wetz, 2003; Machesky et al., 2005; Nayar et al., 2007), but fewer studies have analyzed the water chemistry effects of dredging agricultural drainage ditches (Smith et al., 2006b; Smith and Pappas, 2007; Shigaki et al., 2008). The objective of this study was to determine the impacts of dredging on N and P transport within agricultural drainage ditches.

Submitted for review in September 2009 as manuscript number SW 8221; approved for publication by the Soil & Water Division of ASABE in February 2010.

Mention of a trade name, proprietary product or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable.

The authors are **Douglas R. Smith,** Research Soil Scientist, and **Chi-hua Huang,** Research Soil Scientist, Research Leader, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. **Corresponding author:** Douglas R. Smith, USDA-ARS NSERL, 275 S. Russell St., West Lafayette, IN 47907; phone: 765-494-0330; fax: 765-494-5948; e-mail: Douglas.R.Smith@ars.usda.gov.

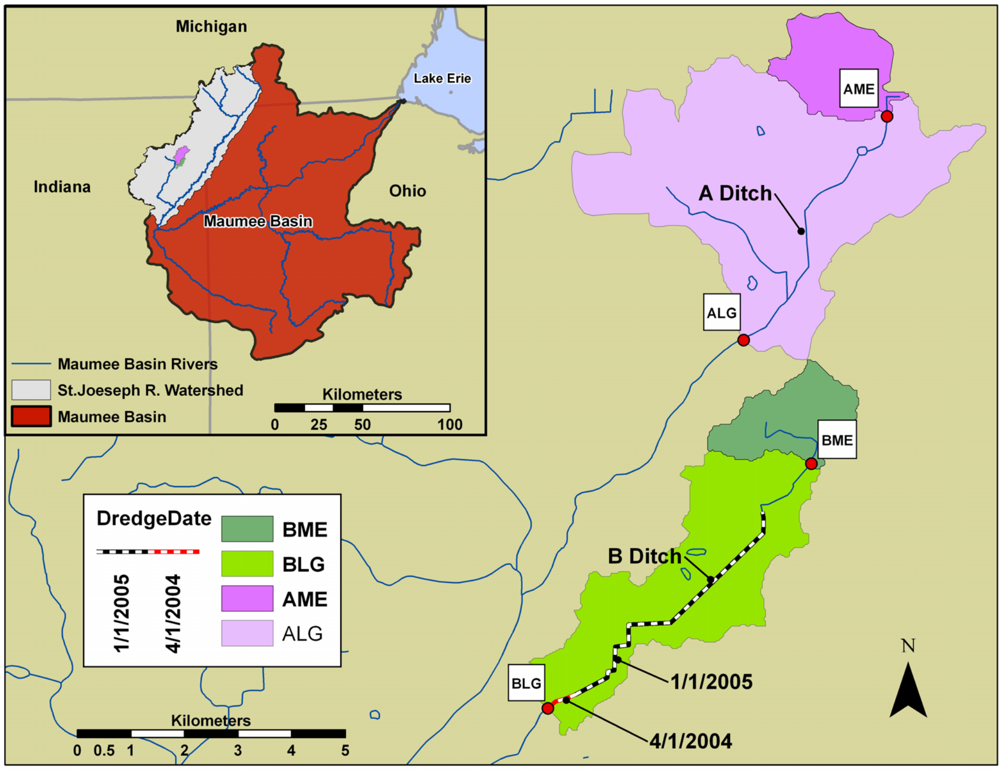

Figure 1. Map showing the study reaches on the A and B ditches in the St. Joseph River watershed in northeast Indiana. The extent and timing of dredging activities in the B ditch are indicated.

Table 1. Description of monitored watersheds used in this study.

Site	Size (ha)	Land-use
AME	299	79% agriculture, 15% grass/pasture, 4% forest
ALG	1,934	77% agriculture, 16% grass/pasture, 6% forest
BME	311	85% agriculture, 8% grass/pasture, 6% forest
BLG	1,417	83% agriculture, 12% grass/pasture, 3% forest

Materials and Methods

Study Area

Water quantity and quality monitoring of two drainage ditches in the Cedar Creek subwatershed of the St. Joseph River watershed near Waterloo, Indiana, has occurred since 2003 (fig. 1). On each of these ditches, at least two sites were monitored from approximately April 1 to November 15 of each year (table 1). On each ditch there was one monitored site that drained roughly 300 ha and another site that drained approximately 1,500 ha. These watersheds are predominately agricultural, with more than 77% of the land-use in row crop agriculture and an additional 8% to 16% grass or pasture land, with the remaining percentages in forest or residential land uses. Subsurface drainage tiles have been installed in the area for more than 150 years, so exact information is difficult to determine, but it has been estimated that more than 80% of the arable land in this region has had subsurface tile installed to enhance drainage (Smith and Pappas, 2007; Smith et al., 2008). A high-resolution color infrared (CIR) digital orthophotograph for the year 2005 with a resolution of

Table 2. Amount of crops in each watershed area expressed as a percentage of the total area.[a]

Year	Watershed	Corn (%)	Soybean (%)	Wheat (%)	Other (%)
2003	AME	18.3	34.6	9.9	4.9
	ALG	22.2	34.8	2.9	2.2
	BME	1.2	14.5	3.4	0.8
	BLG	6.2	12.0	1.6	0.5
2004	AME	21.4	44.8	5.8	6.2
	ALG	29.5	42.7	6.6	6.7
	BME	51.0	7.3	5.8	5.9
	BLG	33.6	23.3	4.7	7.4
2006	AME	0.0	0.3	1.2	0.0
	ALG	15.7	10.2	2.5	0.2
	BME	0.0	1.4	1.9	0.2
	BLG	0.1	0.6	1.0	0.1
2007	AME	29.8	36.8	11.4	0.0
	ALG	37.6	40.2	11.3	0.0
	BME	51.8	25.0	0.8	1.3
	BLG	33.2	38.6	2.2	0.3
2008	AME	13.4	41.8	3.9	0.0
	ALG	28.5	35.3	4.6	0.3
	BME	24.0	16.6	21.6	0.3
	BLG	22.1	26.6	9.5	0.1

[a] Cloud cover from satellite imagery available from the NASS source, only the available data are presented. In 2005, cloud cover represented a significant portion of the watersheds (>80%), so data cannot be estimated.

Figure 2. Photographs of B ditch near the BLG sampling site taken (top) after dredging in April 2004 and (bottom) in June 2005 before and after dredging. Upper photograph shows that the dredging activity is considered "dipping" because disturbance occurred only in the very bottom of the drainage ditch. Lower photograph shows the extent to which grass had returned to the disturbed ditch bank and bed after dredging occurred.

45 cm (18 in.) was obtained from the Indiana Geographic Information Council (IGIC, 2009) to estimate the area of specific crops in each watershed (table 2). More detailed information about the watersheds, agricultural drainage ditches, land use, soils, and cropping systems or conservation practices can be found in Heathman et al. (2008), Pappas et al. (2008), and Smith et al. (2008).

In the B ditch, approximately 3 km were dredged in April 2004, and approximately 5.9 km were dredged in January 2005 (fig. 1). The April 2004 dredging extended approximately 300 m upstream from the BLG sampler, which accounted for approximately 3.5% of the length of this ditch upstream from the BLG sampling site (fig. 1). The January 2005 dredging was initiated where the previous year's dredging ceased and continued upstream, accounting for approximately 67% of the 8.78 km total upstream length from the BLG monitoring site.

All dredging activities removed approximately 30 cm of ditch sediments. Both dredging operations on the B ditch would be considered "dipping" operations, in which only the sediments and vegetation at the very bottom of the drainage ditch were disturbed (fig. 2). The exposed sediments were generally the glacial till layer, which had a dense, massive structure, and was for the most part the depth of the ditch bed when originally constructed. The trapezoidal shape of these ditches was maintained during the dredging process. Vegetation along the sides of the ditches was composed of various grass species, with no woody vegetation along any of the dredged ditch reaches.

Sampling and Analysis

Water chemistry samples from the four monitored sites were collected daily between April 1 and November 15 each year with autosamplers (ISCO 6712, Teledyne ISCO, Inc., Lincoln, Neb.). A 50 mL sample was drawn every 4 h, with six draws composited into one 300 mL glass bottle. In 2003 and 2004, ice was placed in the ISCO samplers every day to cool samples. In 2005, the samplers were equipped with refrigeration units to maintain 4°C in the chamber holding the glass sample bottles. From 2003 to 2005, ditch discharge was measured at each site using pressure transducers (ISCO 720). In 2006, area velocity sensors (ISCO 2150) replaced the pressure transducers at all sites. During the monitoring period, discharge was recorded every 10 min. Precipitation was monitored at the AME and BLG sites from 2004 through 2007 using standard rain gauges. Tipping-bucket rain gauges were added to the instrumentation at the ALG and BME sites in 2007.

Samples were removed from the ISCO samplers every two to four days. A 60 mL aliquot was taken for subsequent digestion and analysis of total Kjeldahl N (TKN) and total Kjeldahl P (TP). A 20 mL aliquot was filtered (0.45 μm) and acidified to pH < 2 with H_2SO_4 for later analysis of soluble nutrients. After initial processing and transport to the laboratory, samples were frozen (−4°C) until analysis was performed. All nutrient analyses were conducted colorimetrically with a Konelab Aqua 20 (EST Analytical, Medina, Ohio). Soluble nutrients (NO_3-N, NH_4-N and SP) were analyzed on the filtered acidified samples. Nitrate-N was analyzed using EPA method 353.1 (U.S. EPA, 1983), ammonium-N was analyzed using EPA method 350.1 (U.S. EPA, 1983), soluble P (SP) was analyzed using EPA method 365.2 (U.S. EPA, 1983), and total Kjeldahl N and TP were analyzed using EPA method 351.2 for TKN and EPA method 365.4 for TP (U.S. EPA, 1983) after mercuric sulfate digestion of the unfiltered samples.

Data Analysis

Nutrient loads (NL) from each site were calculated as:

$$NL_z = Q_{ts} \times C_{zts} \qquad (1)$$

where z represents the nutrient of interest, Q is the discharge, t represents the time, s is the site, and C is the concentration. Monthly nutrient loads were calculated from each site during the 2003 to 2008 study period by summing the NL_z from each day for each month of the study period. Study reach nutrient loads (RNL_{zr}) were calculated on a monthly time step as:

$$RNL_{zr} = NL_{zl} - NL_{zm} \qquad (2)$$

where NL_{zl} is the nutrient load for nutrient z from the large (~1,500 ha) site, and NL_{zm} is the nutrient load for nutrient z from the medium (~300 ha) site.

We used the unreplicated before-after/control-impact (BACI) experimental design to evaluate treatment effects of dredging (Clausen and Spooner, 1993; Downes et al., 2002). The effect of dredging was determined by comparing dredged and untreated treatments, as defined by whether or not dredging had occurred in the last 12 months. Treatment main effects of dredging were conducted using analysis of covariance (ANCOVA) (Clausen and Spooner, 1993; Steel et al., 1997) in JMP (ver. 6.0, SAS Institute, Inc., Cary, N.C.) with monthly precipitation as the covariate. Mean separation was performed using the Tukey-Kramer test. In this analysis of treatment main effects, the reach nutrient load data from the B ditch in 2004 and 2005 were identified as dredged (i.e., treatment), and all other data were identified as undredged (i.e., control). In the second statistical analysis, nutrient load data from one reach were compared against the other ditch reach during each year. ANCOVA was used for this statistical analysis instead of ANOVA or t-tests because of the unreplicated design, to account for differences in precipitation across the watersheds.

Results and Discussion

Overall Effects of Dredging on Monthly Nutrient Loads

The treatment main effects from analysis of covariance, with precipitation as the covariate, for dredging were significant for NH_4-N, NO_3-N, TKN, SP, and TP loads (table 3). For each of the comparisons, RNL was reduced when dredging had occurred within the last 12 months. Dredging reduced RNL_{NH4N} from 67 kg to a net removal of NH_4-N within the reach (−94 kg), and RNL_{NO3N} decreased from 860 kg to approximately −335 kg. As with NH_4-N, there were mean monthly net removals of TKN (−36 kg), SP (−7 kg), and TP (−5 kg) in the study reaches following dredging.

The removal of nutrients from the water column by sediment and biota are in part related to the long-term or chronic exposure to nutrient concentrations (Earl et al., 2006). Our results suggest that there was a decrease in nutrient mass transported in the ditch reaches in the months following dredging (table 3). We propose that the sediments present prior to dredging had been chronically exposed to the high nutrient levels in these ditches, and thus the relative ability of the sediments and biota to remove nutrients from the water column is limited because of nutrient saturation. Sediments collected immediately prior to dredging contained 163 mg P kg^{-1}, whereas sediments collected immediately after dredging contained 92 mg P kg^{-1} (Smith et al., 2006b). Immediately after dredging, the newly exposed sediments would tend to not be able to buffer elevated in-stream nutrient concentrations as well as the sediments that were present prior to dredging due to their physiochemical characteristics (Smith et al., 2006b; Smith and Pappas, 2007; Shigaki et al., 2008). Another change that decreases the nutrient removal efficiency from sediments following dredging is the removal of the vital biotic component of the sediments (Woodruff et al., 1999; Schaller et al., 2004).

Table 3. Monthly mean reach nutrient loads (RNL) for NH_4-N, NO_3-N, TKN, soluble P, and total P in undredged and dredged reaches of agricultural drainage ditches.[a]

Variable	Dredged[b]	Undredged[c]	p-Value
NH_4-N	-94.0 b	67.1 a	<0.01
NO_3-N	-335 b	856 a	<0.001
TKN	-35.9 b	367 a	<0.001
Soluble P	-6.6 b	10.9 a	<0.05
Total P	-5.4 b	63.9 a	<0.001

[a] Values within a row followed by different letters are significantly different at $p < 0.05$.
[b] Dredged refers to RNL from a reach that had been dredged within the previous 12 months, specifically the B ditch during the 2004 and 2005 monitoring period.
[c] Undredged refers to RNL from any reach of the two drainage ditches where there was no dredging during the previous 12 months.

The results of this study suggest that in the few months up to a year following dredging, several changes occurred that allowed sediment and associated biota to be stronger sinks for water column nutrients than they were before dredging. The first change is a physiochemical shift in sediment. Immediately after dredging, the sediments tended to be highly reduced (Smith et al., 2006b). Upon exposure, the reduced conditions at the surface of the exposed sediment layer would likely become oxidized within days to weeks. The second change is the deposition of fresh sediments during storm events or via mass wasting from within the dredged area. These processes may also produce surficial ditch sediments with a greater affinity for removal of nutrients from the water column (Smith et al., 2006a). The third change is the revegetation of the ditch bed by filamentous algae and higher plants, which would temporarily increase nutrient removal. The fourth is the formation of biofilms on the sediment particles (Tolhurst et al., 2008), which would also increase nutrient uptake. Within several months up to a year after the dredging, these dynamic changes would prevent the system from returning to steady-state conditions. While the nutrient concentrations in the water might well be chronically high, the sediment and associated biota would be in a state of flux. We propose that the non-steady-state conditions of the sediment and vegetation biogeochemistry during this period reduces the mass of nutrients transported following dredging.

Inter-Annual Effects of Dredging on Monthly Nutrient Loads

In years where no dredging had occurred in the previous 12 months, RNL_{NH4N} from the B ditch was not significantly different from that of the A ditch, but this changed with dredging. In 2004 and 2005 following dredging, NH_4-N loads were significantly less (fig. 3). During these two years, mean monthly removals of 87 and 0.1 kg of NH_4-N for 2004 and 2005, respectively, occurred in the dredged reach.

Nitrification has been reported to be an important component of NH_4-N loss in streams (Merseburger et al., 2005). Previous work in these ditches has shown that nitrification is inhibited immediately after dredging (Smith and Pappas, 2007). Based on results of the current study, this does not appear to be a long-lasting effect of dredging. The greater change in RNL_{NH4N} for the B ditch in 2004 relative to 2005 may indicate that this is a localized effect. In 2004, approximately 300 m of the B ditch was dredged immediately upstream of the BLG sampler, and several km of the B ditch were dredged in 2005. In April and May 2004, the NL_{NH4N} from BME was 340 kg. By the time that water reached the BLG site, 35% of the NH_4-N mass had been removed from the ditch water.

Mean RNL_{NO3N} for each year and ditch ranged from −320 to 3,500 kg (fig. 4). When comparing the two monitored ditch reaches for each year, the only significant differences in RNL_{NO3N} values occurred in the dredged years (fig. 4). In

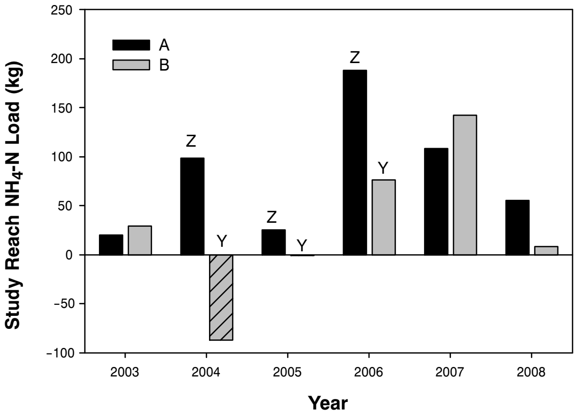

Figure 3. Study reach nutrient loads (RNL) of NH_4-N for each study reach during the monitored years (2003-2008). Bars with different letters are significantly different when comparing RNL for the specified year. There are no significant differences for RNL when there are no letters above the bars. Diagonal lines within a bar indicate when the study reach for the B ditch had been dredged within the previous 12 months.

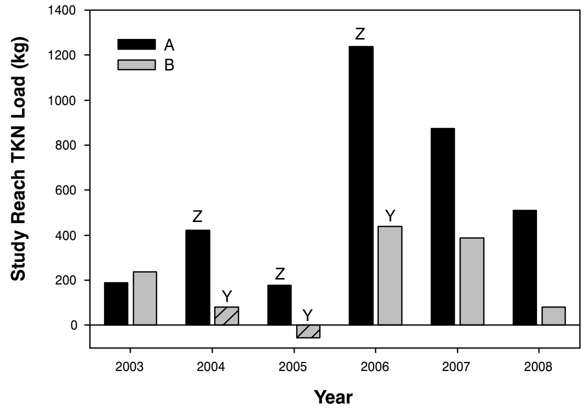

Figure 5. Study reach nutrient loads (RNL) of TKN for each study reach during the monitored years (2003-2008). Bars with different letters are significantly different when comparing RNL for the specified year. There are no significant differences for RNL when there are no letters above the bars. Diagonal lines within a bar indicate when the study reach for the B ditch had been dredged within the previous 12 months.

2004, there was an average loss of 320 kg NO_3-N per month from the B ditch study reach, compared to a gain of 1,200 kg for the A ditch. In 2005, the mean RNL_{NO3N} for the B ditch (14 kg) was more than an order of magnitude lower than that observed in the A ditch (352 kg).

Sediments in agricultural ditches have been found to be important sites for denitrification (Schaller et al., 2004). In Illinois streams, denitrification rates as high as 360 mg N m^{-2} d^{-1} have been observed; however, these rates were not sufficient to significantly decrease stream NO_3-N concentrations that were typically greater than >8 mg NO_3-N L^{-1} (Royer et al., 2004). Opdyke et al. (2006) reported that denitrification rates were directly related to sediment organic matter content and silt plus clay size fractions. Previous experiments in this watershed demonstrated that denitrification was also lower immediately following dredging (Smith and Pappas, 2007), due in part to the removal of organic matter and silt plus clay size fractions. Another potential reason for the observed decrease in denitrification immediately after dredging was reported to be due to the removal of the sediment-associated biota responsible for denitrification (Smith and Pappas, 2007). However, it is possible that denitrification may have been enhanced in the months after dredging, since there was significantly less RNL_{NO3N} from the B ditch study reach relative to the A ditch study reach in both 2004 and 2005 (fig. 4). Increased denitrification rates in the months after dredging are possible because storm flows deposited fresh sediments, including silt and clay size particles, during this period (Smith et al., 2006a). Furthermore, revegetation and recolonization by the sediment-associated biota would increase the amount of organic matter and biological activity that contribute to denitrification.

As with RNL_{NO3N}, RNL_{TKN} was significantly less for the B ditch study reach than for the A ditch study reach in both 2004 and 2005 (fig. 5). The only negative RNL_{TKN} value was for the B ditch study reach during 2005 (–56 kg), which was significantly less than the RNL_{TKN} values observed from the A ditch. When comparing RNL_{TKN} from the B ditch among years, the value from 2005 was significantly less than the RNL_{TKN} in 2006 or 2007.

Noticeable changes in mass transport of SP and TP also occurred in the B ditch following dredging. In 2005, the mean

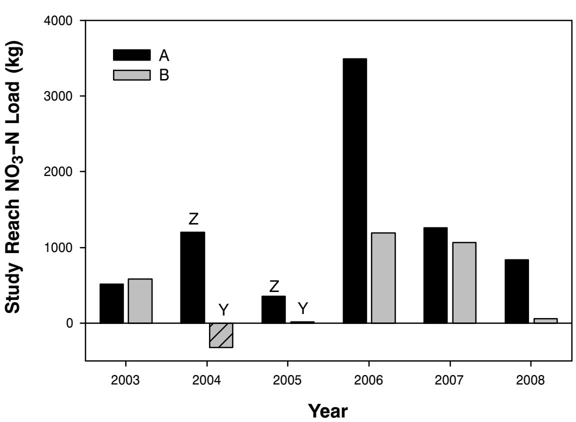

Figure 4. Study reach nutrient loads (RNL) of NO_3-N for each study reach during the monitored years (2003-2008). Bars with different letters are significantly different when comparing RNL for the specified year. There are no significant differences for RNL when there are no letters above the bars. Diagonal lines within a bar indicate when the study reach for the B ditch had been dredged within the previous 12 months.

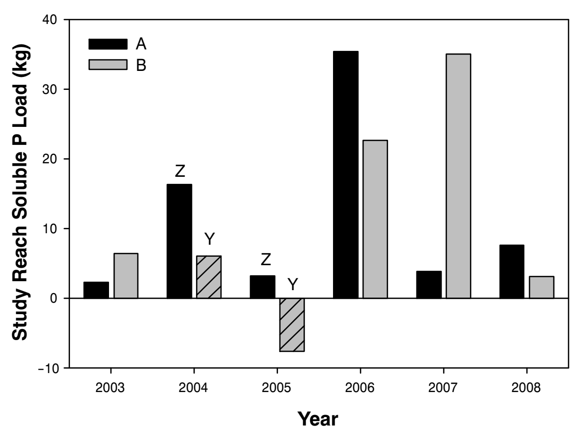

Figure 6. Study reach nutrient loads (RNL) of SP for each study reach during the monitored years (2003-2008). Bars with different letters are significantly different when comparing RNL for the specified year. There are no significant differences for RNL when there are no letters above the bars. Diagonal lines within a bar indicate when the study reach for the B ditch had been dredged within the previous 12 months.

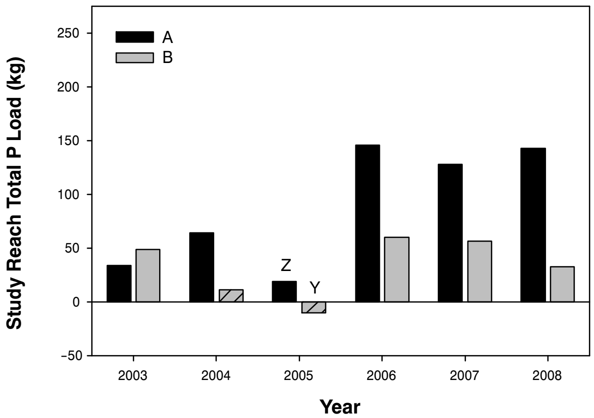

Figure 7. Study reach nutrient loads (RNL) of TP for each study reach during the monitored years (2003-2008). Bars with different letters are significantly different when comparing RNL for the specified year. There are no significant differences for RNL when there are no letters above the bars. Diagonal lines within a bar indicate when the study reach for the B ditch had been dredged within the previous 12 months.

reduction in SP of 8 kg per month was significantly lower than the RNL_{SP} for the A ditch (3.2 kg; fig. 6). As with TKN and SP, a negative RNL_{TP} value was observed for the B ditch study reach during 2005 (−10.4 kg; fig. 7). The RNL_{TP} values from the B ditch study reach were also less in 2005 than in 2006 or 2007, as was the case with TKN and SP.

Sediments of first-order agricultural streams in North Carolina were estimated to remove approximately 37% of the SP mass based on modeled and monitored data (Ensign et al., 2006). Agricultural stream SP loadings have been shown to be negatively correlated to P uptake by sediments (Bernot et al., 2006). McDowell and Sharpley (2003) indicated that biotic and abiotic factors were important contributors to SP removal from agricultural streams. Stream water temperature and velocity have been shown to be of greater importance for in-stream P retention than the amount or composition of detritus (D'Angelo et al., 1991). Similarly, the reduction in stream velocity by detritus and artificial baffles has been shown to increase in-stream P removal from the water column (Ensign and Doyle, 2005). When comparing P flux into sediments before and several months after dredging using short-term P additions, Macrae et al. (2003) observed increased removal of SP when calculated as monthly reach loads, from 2.1 kg SP removed for the reach prior to dredging to 3.7 kg SP removed for the reach following dredging. In the current work, we observed SP removal from the water column by as much as 11 kg in July 2005 and TP removal by as much as 54 kg in October 2007. These observations support the conclusions of Macrae et al (2003) that SP removal by sediment increased for several months after dredging.

Plant uptake is another potential pathway for increased nutrient removal from the B ditch following dredging. In New Zealand streams, loss of NO_3-N within a study reach could be accounted for by the aquatic plant species actively growing in the stream, with peak uptake rates as high as 1.14 g NO_3-N m^{-2} d^{-1} (Howard-Williams et al., 1982). While this does occur in the undredged reaches, the recolonization by the algae and higher plant species in the ditch bed after dredging may result in greater uptake rates due to an increasing biological demand.

The presence of macrophytes in New Zealand streams was shown to decrease the removal of NH_4-N, NO_3-N, and soluble P in streams, presumably due to an increase in water velocity that resulted from reduced stream cross-sectional areas (Wilcock et al., 2002). Likewise, NH_4-N and SP retention efficiency were reduced after logging a riparian forest near a Mediterranean stream (Butturini and Sabater, 1998). This increase in NH_4-N and SP retention efficiency was attributed to the reduction of detritus in the stream. These results would appear to be in contrast to our results, but following the removal of macrophyte communities and detritus immediately after dredging, these materials returned in the weeks and months after this large-scale disturbance. However, Marti et al. (1997) observed that macrophyte assemblages in streams were very important for in-stream NO_3-N processing. Similarly, removal of riparian cover due to logging resulted in increased NH_4-N and SP retention efficiency, most likely as a result of greater macrophyte assemblages in the logged stream reach (Sabater et al., 2000). Macrophyte assemblages as well as higher plants in this study returned to the dredged reaches in the months and years after dredging (fig. 2).

Summary and Conclusions

In this study of dredging activities within agricultural drainage ditch reaches in northeast Indiana, we observed a significant reduction in N and P transport during the 12-month period following dredging. During this period of "recovery," physiochemical and biological shifts occurred in the sediment and sediment-associated biological communities. We propose that until the sediment and sediment-associated biota returned to equilibrium, the ditch sediments played an important role in altering the ditch water chemistry by removing a greater amount of nutrients from the water column. Once the sediment system returned to equilibrium, it appeared that most of the nutrients in the highly enriched ditch water were transported downstream. In previous work, it was determined that nutrient applications to agricultural fields that drain into the ditches should not occur immediately before or immediately after dredging occurs (Smith and Pappas, 2007). From this research, it would appear that the greater than normal risk of nutrient transport that is associated with sediments freshly exposed by dredging is only temporary (i.e., less than one month). In fact, nutrients that enter the ditch in the months following dredging may actually have a greater opportunity to be transformed (i.e., nitrification/denitrification), adsorbed, or biologically removed from the water column than prior to dredging.

Acknowledgements

The authors would like to express their gratitude to Stan Livingston, Ben Zuercher, Chris Smith, Sara Walling, Dennis Bucholtz, Rachel Bowman, Kevin Breit, and the numerous students who have helped in this project.

References

Bernot, M. J., J. L. Tank, T. V. Royer, and M. B. David. 2006. Nutrient uptake in streams draining agricultural catchments of the Midwestern United States. *Freshwater Biol.* 51(3): 499-509.

Butturini, A., and F. Sabater. 1998. Ammonium and phosphate retention in a Mediterranean stream: Hydrological versus temperature control. *Canadian J. Fish. Aqua. Sci.* 55(8): 1938-1945.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Applic.* 8(3): 559-568.

Clausen, J. C., and J. Spooner. 1993. Paired watershed study design. Report 841-F-93-009. Washington, D.C.: U.S. Environmental Protection Agency, Office of Water.

D'Angelo, D. J., J. R. Webster, and E. F. Benfield. 1991. Mechanisms of stream phosphorus retention: An experimental study. *J. N. American Benth. Soc.* 10(3): 225-237.

Downes, B. J., L. A. Barmuta, P. G. Fairweather, D. P. Faith, M. J. Keough, P. S. Lake, B. D. Mapstone, and G. P. Quinn, eds. 2002. *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters.* New York, N.Y.: Cambridge University Press.

Earl, S. R., H. M. Valett, and J. R. Webster. 2006. Nitrogen saturation in stream ecosystems. *Ecology* 87(12): 3140-3151.

Ensign, S. H., and M. W. Doyle. 2005. In-channel transient storage and associated nutrient retention: Evidence from experimental manipulations. *Limnol. Oceanogr.* 50(6): 1740-1751.

Ensign, S. H., S. K. McMillan, S. P. Thompson, and M. F. Piehler. 2006. Nitrogen and phosphorus attenuation within the stream network of a coastal, agricultural watershed. *J. Environ. Qual.* 35(4): 1237-1247.

Haggard, B. E., E. H. Stanley, and R. Hyler. 1999. Sediment-phosphorus relationships in three northcentral Oklahoma streams. *Trans. ASAE* 42(6): 1709-1714.

Hall, R. O., Jr. 2003. A stream's role in watershed nutrient export. *Proc. Natl. Acad. Sci.* 100(18): 10137-10138.

Heathman, G. C., D. C. Flanagan, M. Larose, and B. W. Zuercher. 2008. Application of SWAT and AnnAGNPS in the St. Joseph River watershed. *J. Soil Water Cons.* 63(6): 552-568.

Howard-Williams, C., J. Davies, and S. Pickmere. 1982. The dynamics of growth, the effects of changing area, and nitrate uptake by watercress *Nasturium officinale* R. Br. in a New Zealand stream. *J. Appl. Ecol.* 19(2): 589-601.

IGIC. 2009. Indiana State Digital Orthophotography Program. Indianapolis, Ind.: Indiana Geographic Information Council. Available at: www.in.gov/igic/. Accessed 10 December 2009.

Johnson, P. T. J., J. M. Chase, K. L. Dosch, R. B. Hartson, J. A. Gross, D. J. Larson, D. R. Sutherland, and S. R. Carpenter. 2007. Aquatic eutrophication promotes infection in amphibians. *Proc. Natl. Acad. Sci.* 104(40): 15781-15786.

Kleeberg, A., and J. G. Kohl. 1999. Assessment of the long-term effectiveness of sediment dredging to reduce benthic phosphorus release in shallow Lake Muggelsee (Germany). *Hydrobiologia* 394: 153-161.

Lohrer, A. M., and J. J. Wetz. 2003. Dredging-induced nutrient release from sediments to the water column in a southeastern saltmarsh tidal creek. *Marine Poll. Bull.* 46(9): 1156-1163.

Machesky, M. L., J. A. Slowikowski, R. A. Cahill, W. C. Bogner, J. C. Marlin, T. R. Holm, and R. G. Darmody. 2005. Sediment quality and quantity issues related to the restoration of backwater lakes along the Illinois River waterway. *Aquat. Ecosys. Health Mgmt.* 8(1): 33-40.

Macrae, M. L., M. C. English, S. L. Schiff, and M. A. Stone. 2003. Phosphate retention in an agricultural stream using experimental additions of phosphate. *Hydrol. Proc.* 17(18): 3649-3663.

Marti, E., N. B. Grimm, and S. G. Fisher. 1997. Pre- and post-flood retention efficiency of nitrogen in a Sonoran Desert stream. *J. N. American Benth. Soc.* 16(4): 805-819.

McDowell, R. W., and A. N. Sharpley. 2003. Uptake and release of phosphorus from overland flow in a stream environment. *J. Environ. Qual.* 32(3): 937-948.

Merseburger, G. C., E. Marti, and F. Sabater. 2005. Net changes in nutrient concentrations below a point-source input in two streams draining catchments with contrasting land uses. *Sci. Total Environ.* 347(1-3): 217-229.

Nayar, S., D. J. Miller, A. Hunt, B. P. L. Goh, and L. M. Chou. 2007. Environmental effects of dredging on sediment nutrients, carbon, and granulometry in a tropical estuary. *Environ. Monit. Assess.* 127(1-3): 1-13.

Needleman, B. A., P. J. A. Kleinman, J. S. Strock, and A. L. Allen. 2007. Improved management of agricultural drainage ditches for water quality protection: An overview. *J. Soil Water Cons.* 62(4): 171-178.

Opdyke, M. R., M. B. David, and B. L. Rhoads. 2006. Influence of geomorphological variability in channel characteristics on sediment denitrification in agricultural streams. *J. Environ. Qual.* 35(6): 2103-2112.

Pappas, E. A., C. Huang, and D. Buchholz. 2008. Implications of sampling frequency to herbicide conservation effects assessment. *J. Soil Water Cons.* 63(6): 410-419.

Pappas, E. A., and D. R. Smith. 2007. Effects of dredging an agricultural drainage ditch on water column herbicide concentration, as predicted by fluvarium techniques. *J. Soil Water Cons.* 62(4): 262-268.

Peterson, B. J., W. M. Wollheim, P. J. Mulholland, J. R. Webster, J. L. Meyer, J. L. Tank, E. Marti, W. B. Bowden, H. M. Valett, A. E. Hershey, W. H. McDowell, W. K. Dodds, S. K. Hamilton, S. Gregory, and D. D. Morrall. 2001. Control of nitrogen export from watershed by headwater streams. *Science* 292(5514): 86-90.

Resh, V. H., A. V. Brown, A. P. Covish, M. E. Gurtz, H. W. Li, G. W. Minshall, S. R. Reice, A. L. Sheldon, J. B. Wallace, and R. C. Wissmar. 1988.The role of disturbance in stream ecology. *J. N. American Benth. Soc.* 7(4): 433-455.

Royer, T. V., J. L. Tank, and M. B. David. 2004. Transport and fate of nitrate in headwater agricultural streams in Illinois. *J. Environ. Qual.* 33(4): 1296-1304.

Sabater, F., A. Butturni, E. Marti, I. Munoz, A. Romani, J. Wray, and S. Sabater. 2000. Effects of riparian vegetation removal on nutrient retention in a Mediterranean stream. *J. N. American Benth. Soc.* 19(4): 609-620.

Schaller, J. L., T. V. Royer, M. B. David, and J. L. Tank. 2004. Denitrification associated with plants and sediments in an agricultural stream. *J. N. American Benth. Soc.* 23(4): 667-676.

Sharpley, A. N., T. Krogstad, P. J. A. Kleinman, B. Haggard, F. Shigaki, L. S. Saporito. 2007. Managing natural processes in drainage ditches for nonpoint-source phosphorus control. *J. Soil Water Cons.* 62(4): 197-206.

Shigaki, F., P. J. A. Kleinman, J. P. Schmidt, A. N. Sharpley, and A. L. Allen. 2008. Impact of dredging on phosphorus transport in agricultural drainage ditches of the Atlantic coastal plain. *J. American Water Resources Assoc.* 44(6): 1-12.

Smith, D. R., and E. A. Pappas. 2007. Effect of ditch dredging on the fate of nutrients in deep drainage ditches of the Midwestern United States. *J. Soil Water Cons.* 62(4):252-261.

Smith, D. R., E. A. Warnemuende, B. E. Haggard, and C. Huang. 2006a. Changes in sediment-water column phosphorus interactions following sediment disturbance. *Ecol. Eng.* 27(1): 71-78.

Smith, D. R., E. A. Warnemuende, B. E. Haggard, and C. Huang. 2006b. Dredging of drainage ditches increases short-term transport of soluble phosphorus. *J. Environ. Qual.* 35(2): 611-616.

Smith, D. R., S. J. Livingston, B. W. Zuercher, M. Larose, G. C. Heathman, and C. Huang. 2008. Nutrient losses from row crop agriculture in Indiana. *J. Soil Water Cons.* 63(6): 396-409.

Steel, R. G. D., J. H. Torrie, and D. A. Dickey. 1997. *Principles and Procedures of Statistics: A Biometrical Approach.* 3rd ed. Boston, Mass.: McGraw-Hill.

Strock, J. S., C. J. Dell, and J. P. Schmidt. 2007. Managing natural processes in drainage ditches for nonpoint-source nitrogen control. *J. Soil Water Cons.* 62(4): 188-196.

Tolhurst, T. J., M. Consalvey, and D. M. Paterson. 2008. Changes in cohesive sediment properties associated with the growth of a diatom biofilm. *Hydrobiologia* 596(1): 225-239.

U.S. EPA. 1983. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. Cincinnati, Ohio: U.S. Environmental Protection Agency.

Wilcock, R. J., M. R. Scarsbrook, K. J. Costley, and J. W. Nagels. 2002. Controlled release experiments to determine the effects of shade and plants on nutrient retention in a lowland stream. *Hydrobiologia* 485(1-3): 153-162.

Woodruff, S. L., W. A. House, M. E. Callow, and B. S. C. Leadbeater. 1999. The effects of biofilms on chemical processes in surficial sediments. *Freshwater Biol.* 41(1): 73-8.