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Management implications of the relationships between water chemistry and fishes within channelized headwater streams in the midwestern United States†

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ABSTRACT

Many headwater streams in the midwestern United States were channelized for agricultural drainage. Conservation practices are implemented to reduce nutrient, pesticide, and sediment loadings within these altered streams. The impact of these practices is not well understood because their ecological impacts have not been evaluated and the relationships between water chemistry and fishes are not well understood. We evaluated relationships between water chemistry and fish communities within channelized headwater streams of Cedar Creek, Indiana, and Upper Big Walnut Creek, Ohio. Measurements of water chemistry, hydrology, and fishes have been collected from 20 sites beginning in 2005. Multiple regression analyses indicated that the relationships between water chemistry and fish communities were weak, but significant ($P < 0{\cdot}05$). Fish communities exhibited negative relationships with ammonium and nitrate plus nitrite and positive relationships with dissolved oxygen, pH, and metolachlor. The strongest observed relationships occurred within those regression models that included a combination of nutrients, herbicides, and physicochemical variables. Multiple regression analyses also indicated that five water chemistry variables exhibited significant relationships ($P < 0{\cdot}05$) with hydrology. Our results suggest that if water chemistry is the focus of a conservation plan, then the most effective conservation practices may be those that have a combined influence on nutrients, herbicides, and physicochemical variables. Additionally, the use of a combination of conservation practices to address physical habitat and water chemistry degradation is most likely to provide the greatest benefits for fish communities within channelized headwater streams. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS fish communities; water chemistry; hydrology; headwater streams; conservation practices; Ohio; Indiana

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INTRODUCTION

Headwater streams are the smallest streams within a watershed and often comprise >70% of stream channel length of a watershed (Leopold *et al.*, 1964). The small size and large number of headwater streams makes them easily susceptible to and have a high probability of experiencing anthropogenic modifications (Smiley *et al.*, 2005). Many headwater streams within the midwestern United States have been channelized for draining excess water from agricultural fields (Mattingly *et al.*, 1993; Sanders, 2001). Channelization for agricultural drainage in the midwestern United States involves either the construction of streams or the deepening, widening, and straightening of existing streams. Channelized headwater streams experience physical and chemical habitat modifications resulting from channel and watershed management for agriculture. Management of these streams focuses on maintaining hydraulic capacity without regard to the impacts of hydrological, geomorphological, and riparian habitat alterations on fishes and other aquatic animals (Stammler *et al.*, 2008). The dominance of agricultural landuse within the watershed of channelized headwater streams results in increased sediment, nutrient, and pesticide loadings within these streams (Freeman *et al.*, 2007).

Toxicology experiments have documented increased fish mortality with increasing levels of sediment, nutrients, and pesticides (U.S. EPA, 1986; Waters, 1995). Additionally, laboratory-reared fathead minnows (*Pimephales promelas*) exhibited mortality and sublethal responses when exposed to water collected from channelized headwater streams in Indiana (Harkenrider, 2005), Arkansas, and Mississippi (Stephens *et al.*, 2008). Thus, laboratory results lead to the expectation that fish communities within agricultural streams should benefit from the reductions of sediment, nutrient, and pesticide loadings that should occur following implementation of conservation practices such as herbaceous riparian buffers, pesticide management, and nutrient management. However, impacts of conservation practices designed to reduce sediment, nutrient, and pesticide loadings on fish communities have not been evaluated despite their regular

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implementation adjacent to agricultural streams for the past 30 years (Bernhardt *et al*., 2005; Alexander and Allan, 2006).

Understanding fish–habitat relationships will provide predictions on which practices should have the greatest influence on fish communities and will assist with developing conservation plans for agricultural watersheds. Assessments of fish habitat use within channelized headwater streams in the midwestern United States have typically involved comparisons between unchannelized and channelized streams (Trautman and Gartman, 1974; Scarnecchia, 1988; Meneks *et al*., 2003; Rhoads *et al*., 2003; Lau *et al*., 2006). Our understanding of how fish communities within channelized headwater streams respond to habitat gradients or specific habitat factors is limited. Previous research has confirmed the importance of instream habitat or channel morphology on fish communities within channelized headwater streams (Gorman and Karr, 1978; Lau *et al*., 2006; Rhoads *et al*., 2003; Smiley *et al*., 2008). However, relationships between water chemistry and fish community structure in channelized headwater streams are not well understood. Limited information on the relationships between water chemistry and fish communities within headwater streams in the midwestern United States is available, but these studies sampled channelized and unchannelized headwater streams (Miltner and Rankin, 1998; Fitzpatrick *et al*., 2001; D'Ambrosio *et al*., 2009).

We sampled water chemistry, hydrology, and fish communities within channelized headwater streams in Indiana and Ohio to address the following research question: What is the relationship between fish communities and water chemistry within channelized headwater streams in Indiana and Ohio?

METHODS

Study area

Cedar Creek (CC) is a tributary of the St. Joseph's River located in northeast Indiana (latitudes 41°53′78″–41°19′23″, longitudes 85°31′88″–84°91′50″). Dominant landuse in CC is cropland consisting of corn or soybean. The majority of streams within the CC watershed have been channelized for agricultural drainage. Additionally, increased loadings of nutrients and pesticides from agricultural fields and bacteria from failed septic tanks are nonpoint source pollutants of concern within this watershed (St. Joseph Watershed Initiative, 2005). Upper Big Walnut Creek (UBWC) is located in central Ohio (latitudes 40°06′00–40°32′30″, longitudes 82°56′00″–82°42′00″) and is part of the Scioto River watershed. Dominant landuse in the UBWC watershed is cropland consisting of corn, soybean, or wheat. The majority of headwater streams in the watershed are impaired by nutrient enrichment, pathogens, and habitat degradation stemming from current agricultural management practices (Ohio EPA, 2003, 2004). These watersheds are also 2 of 14 benchmark watersheds within the Agricultural Research Service's Conservation Effects Assessment Project Watershed Assessment Study (Mausbach and Dedrick, 2004).

We sampled water chemistry and fishes at seven sites in three channelized headwater streams within CC and fourteen sites in seven channelized headwater streams within the UBWC. Joint measurements of water chemistry and fish communities began in CC in 2006 and in UBWC in 2005 and continued in both watersheds through 2007. Specifically, five sites in UBWC were sampled in 2005 in the summer and fall. All sites in CC and UBWC were sampled in 2006 and 2007 in the spring, summer, and fall. The watershed size of channelized streams in CC ranged from 13 to 43 km^2 and watershed size of study streams in the UBWC ranged from 0·7 to 10 km^2. Each site was 125-m long and located near the locations of the automated water samplers or locations where weekly water samples were obtained. Sites within the same stream were separated by a mean distance of 3·3 km (range 0·2–10·6 km).

Water chemistry and hydrology

Automated water samplers were used to collect water samples on a daily interval from CC sites and on a 1-mm volumetric flow depth interval from UBWC sites. Weekly grab samples were also obtained from UBWC sites. Periodically, additional water samples are collected during storm events in both watersheds. Water samples for measurement of nutrients (nitrate plus nitrite, ammonium, dissolved reactive phosphorus, total phosphorus, dissolved organic carbon) and herbicides (alachlor, atrazine, metolachlor, simazine) were collected from March to December of each year.

Concentrations of nitrate plus nitrite, ammonium, and dissolved reactive phosphorus were determined colorimetrically. Ammonium and nitrate plus nitrite were determined by application of the copperized-cadmium or hydrazine sulfate reduction method and dissolved reactive phosphorus was determined by the ascorbic acid reduction method (Parsons *et al*., 1984). Total phosphorus analyses were performed on unfiltered samples following alkaline persulfate oxidation (Koroleff, 1983) with subsequent determination of nitrate plus nitrite and dissolved reactive phosphorus. Dissolved organic carbon was determined by heated-persulfate oxidation using a total organic carbon analyzer with in-line sample acidification and sparging (Menzel and Vaccaro, 1964). Herbicide concentrations of alachlor, atrazine, metolachlor, and simazine were determined using gas chromatography following standard protocols for pesticide analyses (U.S. EPA, 1995a). We measured these herbicides because they are more frequently detected and often occur in greater concentrations than insecticides within agricultural watersheds in the midwestern United States (Gilliom, 2007). Mean nutrient and herbicide concentrations used in our analyses were calculated from selected measurements obtained during a 3-week period that consisted of 1 week before, the week of, and 1 week after fish sampling. *In situ* measurements of dissolved oxygen, temperature, pH, and conductivity were obtained with a multiparameter meter from each site three times a year concurrently with fish sampling.

Measurements of water depth, water velocity, and wet width were obtained three times a year concurrently with fish sampling. One measurement of wet width and four measurements of water velocity and depth were obtained along six transects established at 25-m intervals throughout each site. Water velocity was measured with an electromagnetic velocity meter. Water depths were measured with a stadia rod or meter stick and wet widths were measured with a tape measure. Mean water depths, velocity, and wet width from each site during each sampling period were calculated.

Fish communities

Fish samples were collected three times a year in the spring (May–June), summer (July–August), and fall (September–November). Block nets were set at the upstream and downstream borders of the sites before sampling. Fishes were sampled with a backpack electrofisher (100–150 V, 60 Hz, DC current) and seine (2 m × 4 m, 0·32 cm mesh size). The use of two sampling techniques accounts for the sampling bias of individual techniques and ensures that we adequately characterized fish community structure in each site (Karr, 1999). Electrofishing began at the downstream border of a site and proceeded upstream. Care was taken to ensure that all habitat units within each site were sampled thoroughly during electrofishing. Five seine samples that were equally distributed throughout each site were also collected. Selected pools and slow flowing areas were sampled with a seine haul, and fast flowing riffle areas were sampled using the seine as a block net and kicking into the seine. Fishes that could be identified in the field were identified, enumerated, and released. Unidentifiable fishes were euthanized with tricaine methanesulfonate, fixed with a 10% formalin solution, and returned to the laboratory for subsequent identification.

We calculated 15 fish community response variables (i.e. species richness, abundance, evenness, headwater fish species richness, percent headwater fishes, percent creek chub, percent fathead minnow, trophic guild richness, percent omnivores, percent insectivores, reproductive guild richness, percent guarder-nest spawners, percent guarder-substrate choosers, percent Cyprinidae, percent Percidae) for each site during each sampling period using composited electrofishing and seining data. Species richness is the number of fish species captured and abundance is the number of fishes captured. Evenness is the reciprocal of the Simpson's index divided by species richness (Smith and Wilson, 1996). The richness and percent of headwater fishes, selected feeding guilds, reproductive guilds, and families are metrics of the diversity and abundance of fishes with similar habitat requirements, feeding strategies, or reproductive strategies. Fishes were assigned to habitat (i.e. headwater fish species), feeding, and reproductive guilds based on published literature sources (Pflieger, 1975; Becker, 1983; Robison and Buchanan, 1988; Etnier and Starnes, 1993; Ohio EPA, 2002; Ross, 2002; Smiley *et al.*, 2005). Headwater fish species are those fishes expected to found in first- to third-order streams in the midwestern United States, such as creek chub, white suckers, and orangethroat darters (Ohio EPA, 2002). Omnivores are fishes whose diet consists of plant and animal matter, and insectivores are fishes that primarily consume insects and other invertebrates. Guarder-nest spawners are fishes that construct a nest for their eggs and guard the nest and eggs, and guarder-substrate choosers are fishes that select substrate or cover types for egg deposition and then guard the deposited eggs.

Statistical analyses

We first conducted backward stepwise regression to identify the water chemistry variables that influenced fish community response variables. We then conducted multiple linear regression with regression models identified by backward stepwise regression to determine the explanatory power of the regression models, the statistical significance, the standardized coefficients, and the types of relationships that occurred between water chemistry and fish communities. Mean nutrient concentrations, mean herbicide concentrations, and values of physicochemical variables were used as independent variables and fish community response variables were used as the dependent variables in the regression analyses. Our data analysis approach represents the best choice for evaluating these previously unexamined relationships, despite the potential for nonlinear relationships. The combined use of backward stepwise regression and multiple linear regression provides an objective way to evaluate the relationships between fish communities and water chemistry and enabled comparisons among our 15 fish community response variables. Additionally, we examined the relationships between water chemistry and selected hydrology variables (i.e. water depth, velocity, wet width) because our previous assessment (Smiley *et al.*, 2008) of fish–habitat relationships from these sites indicated fish communities were more strongly influenced by instream habitat than riparian habitat or water chemistry. Knowing which water chemistry variables are correlated with hydrology will be indicative of the water chemistry and fish relationships that are potentially influenced by hydrology. We conducted multiple linear regression with hydrology variables as the independent variables and water chemistry variables as the dependent variables to determine the relationships between water chemistry and hydrology. Dependent variables that did not meet the assumptions of normality and equal variance were either log $(x + 1)$ transformed or arcsine transformed (Zar, 1984). All analyses were conducted with SigmaStat for Windows (Systat Software, 2004) and a significance level of $P < 0.05$.

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Table I. Relative abundance and number of captures of fishes within channelized headwater streams in Cedar Creek watershed, Indiana and the Upper Big Walnut Creek watershed, Ohio (2005–2007).

Common name (scientific name)	%	# Captures
Creek chub (*Semotilus atromaculatus*)	26·92	6591
Fathead minnow (*Pimephales promelas*)	17·65	4321
Bluntnose minnow (*Pimephales notatus*)	17·24	4221
Johnny darter (*Etheostoma nigrum*)	10·48	2565
Central stoneroller (*Campostoma anomalum*)	7·26	1777
Blacknose dace (*Rhinichthys atratulus*)	5·41	1325
Green sunfish (*Lepomis cyanellus*)	4·89	1197
Orangethroat darter (*Etheostoma spectabile*)	2·34	574
Common shiner (*Luxilus cornutus*)	1·78	436
Bluegill (*Lepomis macrochirus*)	1·68	412
White sucker (*Catostomus commersoni*)	1·52	372
Mottled sculpin (*Cottus bairdi*)	0·67	164
Largemouth bass (*Micropterus salmoides*)	0·49	120
Central mudminnow (*Umbra limi*)	0·46	113
Grass pickerel (*Esox americanus*)	0·38	94
Silverjaw minnow (*Ericymba buccata*)	0·18	43
Striped shiner (*Luxilus chrysocephalus*)	0·13	32
Yellow bullhead (*Ameiurus natalis*)	0·13	32
Black bullhead (*Ameiurus melas*)	0·08	20
Common carp (*Cyprinus carpio*)	0·06	15
Rainbow darter (*Etheostoma caeruleum*)	0·06	14
Hornyhead chub (*Nocomis biguttatus*)	0·04	11
Golden shiner (*Notemigonus crysoleucas*)	0·04	10
Northern hogsucker (*Hypentelium nigricans*)	0·04	10
Blackside darter (*Percina maculata*)	0·01	3
Greenside darter (*Etheostoma blennioides*)	0·01	2
Longear sunfish (*Lepomis megalotis*)	0·01	2
Brook stickleback (*Culaea inconstans*)	<0·01	1
Channel catfish (*Ictalurus punctatus*)	<0·01	1
Western mosquitofish (*Gambusia affinis*)	<0·01	1
Pumpkinseed (*Lepomis gibbosus*)	<0·01	1
Quillback (*Carpiodes cyprinus*)	<0·01	1
Redear sunfish (*Lepomis microlophus*)	<0·01	1
Steelcolor shiner (*Cyprinella whipplei*)	<0·01	1

Table II. Mean, coefficient of variation (CV), minimum and maximum values of nutrients, herbicides, and physicochemical water chemistry parameters measured in channelized headwater streams in Cedar Creek and Upper Big Walnut Creek watersheds (2005–2007).

	Mean	CV (%)	Minimum	Maximum
Nutrients				
Ammonium (mg/l)	0·25	172	0·001	3·04
Nitrate plus nitrite (mg/l)	4·04	106	0·013	20·92
Soluble reactive phosphorus (mg/l)	0·10	131	0·000	0·97
Total phosphorus (mg/l)	0·35	205	0·016	5·44
Dissolved organic carbon (mg/l)	9·35	41	2·775	22·57
Herbicides				
Alachlor (mg/l)	0·0000	—[a]	0·000	0·0001
Atrazine (mg/l)	0·0017	457	0·000	0·09
Metolachlor (mg/l)	0·0006	255	0·000	0·02
Simazine (mg/l)	0·0007	402	0·000	0·03
Physicochemical				
Water temperature (°C)	18·79	35	5·80	36·21
D.O. (mg/l)	8·13	51	0·33	26·33
Conductivity (microsiemens/cm)	714·28	48	235·00	2309·00
pH	7·71	15	3·34	10·50

[a] We were not able to calculate the coefficient of variation because the mean was equal to 0.

RESULTS

We documented 34 fish species from 24 483 captures. The five most abundant fish species captured constituted 79% of all captures and were creek chub (*Semotilus atromaculatus*), fathead minnow (*Pimephales promelas*), bluntnose minnow (*Pimephales notatus*), Johnny darter (*Etheostoma nigrum*), and central stoneroller (*Campostoma anomalum*) (Table I). Nutrient concentrations were greater than herbicide concentrations and physicochemical variables exhibited the least variability in these channelized streams (Table II).

Backward stepwise regression identified 15 different models describing relationships between water chemistry and fish communities (Table III). Regression models that contained nutrient, herbicide, and physicochemical variables occurred most often (Table III). Additionally, ammonium, nitrate plus nitrite, metolachlor, pH, and dissolved oxygen were the water chemistry variables retained by the backward stepwise regression model most often (Table III).

Multiple linear regression indicated that relationships between fish communities and water chemistry were weak as the greatest observed R^2 value was $<0{\cdot}3$ (Table III). All regression models but one were statistically significant (Table III). Regression models with the greatest R^2 values were those models that contained a combination of nutrient, herbicide, and physicochemical variables (Table III). Examination of the standardized coefficients indicated ammonium had the greatest effect on fish communities most frequently (four of 15 times) (Table IV). However, physicochemical variables as a group had the greatest standardized coefficients most frequently (8 of 15 times) (Table IV). Additionally, the standardized coefficients indicated ammonium and nitrate plus nitrite had a negative relationship with fish communities and metolachlor, pH, and dissolved oxygen had positive relationships (Table IV).

Five of thirteen water chemistry variables exhibited significant relationships hydrology (Table V). Specifically, ammonium, dissolved organic carbon, dissolved oxygen, conductivity, and pH exhibited significant relationships with water depth, water velocity, and/or wet width (Table V).

DISCUSSION

We found that fish communities exhibited weak ($R^2 < 0{\cdot}3$) and statistically significant relationships ($P < 0{\cdot}05$) with water chemistry variables in channelized headwater streams in Indiana and Ohio. Our results are consistent with others who have observed statistically significant

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Table III. Multiple regression models, R^2 values, and P values indicating the relationships between water chemistry and fish communities from channelized headwater streams in Cedar Creek and Upper Big Walnut Creek watersheds (2005–2007).

Fish response variable	Nutrient	Herbicide	Physicochemical	R^2	P value
Percent insectivores	NH_4 NO_3	Metolachlor Simazine	Temp. D.O. pH	0·294	<0·001
Percent headwater fishes	NH_4 NO_3 DOC	Metolachlor	D.O. Cond. pH	0·291	<0·001
Percent creek chub	NH_4 PO_4 DOC	Metolachlor	Temp. Cond. pH	0·283	<0·001
Percent Percidae	NH_4 NO_3 TP		D.O. Cond.	0·279	<0·001
Reproductive guild richness	NH_4 NO_3	Metolachlor	D.O. pH	0·242	<0·001
Species richness	NH_4	Alachlor	pH	0·179	<0·001
Percent Cyprinidae	NH_4	Metolachlor	pH	0·176	<0·001
Percent guarder-nest spawner	TP DOC	Metolachlor	Temp.	0·166	<0·001
Abundance	NH_4 NO_3	Metolachlor	D.O. pH	0·220	<0·001
Headwater fish species richness	NH_4 NO_3	Metolachlor	D.O.	0·192	<0·001
Trophic guild richness	NH_4		pH	0·158	<0·001
Percent fathead minnow	NO_3		Temp. Cond.	0·151	<0·001
Percent guarder-substrate chooser	TP DOC		D.O.	0·116	0·002
Evenness		Atrazine Metolachlor		0·043	0·073
Percent omnivore			Cond.	0·037	0·032

NH_4, ammonium; NO_3, nitrate plus nitrite; DOC, dissolved organic carbon; PO_4, soluble reactive phosphorus; TP, total phosphorus; Temp., water temperature; D.O., dissolved oxygen; Cond., conductivity.

($P < 0.05$) relationships of headwater stream fish communities with water chemistry variables (Miltner and Rankin, 1998; Fitzpatrick *et al.*, 2001). However, we observed instream habitat had a greater influence on fish community structure than riparian habitat or agricultural chemicals (i.e. nutrients and herbicides) in our previous assessment of fish–habitat relationships in these small streams in Indiana and Ohio (Smiley *et al.*, 2008). Additionally, fish communities in headwater streams of eastern Wisconsin were more strongly correlated with landuse or instream habitat than conductivity, nitrogen, or phosphorus (Fitzpatrick *et al.*, 2001). Riparian, geomorphology, instream habitat, or watershed size variables were more important than water chemistry in influencing fish communities in headwater streams in central Ohio (D'Ambrosio *et al.*, 2009) and statewide in Ohio (Miltner and Rankin, 1998). These results suggest that water chemistry influences fish community structure in agricultural headwater streams, but has less influence than other types of habitat factors.

We identified relationships between fish communities with selected water chemistry variables. Specifically, fish communities exhibited negative relationships with ammonium and nitrate plus nitrite and positive relationships with metolachlor, pH, and dissolved oxygen. Our results are consistent with those of Miltner and Rankin (1998) who observed that headwater stream sites in Ohio with ammonia concentrations >1 mg/l had decreased index of biotic integrity (IBI) scores compared to sites with ammonia concentrations <1 mg/l. Conversely, significant correlations of fish communities with ammonium and nitrate plus nitrite did not occur in headwater streams in eastern Wisconsin (Fitzpatrick *et al.*, 2001) or with nitrate plus nitrite in central Ohio (D'Ambrosio *et al.*, 2009). The lack of a relationship between nitrogen compounds and fish communities in eastern Wisconsin (Fitzpatrick *et al.*, 2001) and IBI scores in central Ohio (D'Ambrosio *et al.*, 2009) may be a result of the low maximum ammonium values (0·38 mg/l), low maximum ammonia values (0·27 mg/l), low maximum nitrate plus nitrite (6·15 mg/l), low maximum nitrate (6·70 mg/l), and low maximum nitrite (0·33 mg/l) observed during these studies. Conversely, maximum observed ammonium concentration from our sites was 3·05 mg/l and 16% of all values in Miltner and Rankin (1998) study sites exceeded ammonia concentrations of 1 mg/l. Additionally, the

Table IV. Standardized coefficients from multiple regression between water chemistry and fish communities in Cedar Creek and Upper Big Walnut Creek watersheds (2005–2007). Standardized coefficients are only reported for those water chemistry variables included in the final regression models identified by backward stepwise regression analyses. Bolded and underlined standardized coefficients identify the water chemistry parameter that had the most influence on each community response variable.

	Nutrients					Herbicides				Physicochemical			
	NH4	NO_3	PO_4	TP	DOC	Alachlor	Atrazine	Metolachlor	Simazine	Temp.	D.O.	Cond.	pH
Species Richness	−0·226					0·218							**0·246**
Abundance	**−0·273**	−0·189						0·239			0·240		0·189
Evenness							−0·488	**0·540**					
Headwater fish species richness	**−0·290**	−0·211						0·282			0·245		
Percent headwater fishes	−0·253	−0·196			−0·228			0·249			**0·301**	0·192	0·174
Percent creek chub	−0·223		0·179		−0·196			0·222		−0·249		0·294	**0·332**
Percent fathead minnow		0·254								**0·256**		−0·231	
Trophic guild richness	**−0·164**												0·052
Percent omnivores												**−0·193**	
Percent insectivores	−0·221	−0·249						0·202	0·209	−0·265	0·211	**0·363**	0·221
Reproductive guild rich.	**−0·303**	−0·180						0·205			0·250		0·211
Percent guarder-nest spawner				**0·279**	−0·251			0·173		−0·183			
Percent guarder-substrate chooser				−0·187	**0·250**						0·247		
Percent Cyprinidae	−0·220							0·214					**0·288**
Percent Percidae	−0·209	−0·245		−0·190							**0·385**	0·288	

NH_4, ammonium; NO_3, nitrate plus nitrite; PO_4, soluble reactive phosphorus; TP, total phosphorus; DOC, dissolved organic carbon; Temp., water temperature; D.O., dissolved oxygen; Cond., conductivity.

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Table V. Results and implications of multiple linear regression between water chemistry and hydrology within Cedar Creek and Upper Big Walnut Creek watersheds (2005–2007).

Water chemistry variable	*P* value	Potential for hydrology to influence observed water chemistry—fish relationships?
Ammonium	**0·033**	Yes
Nitrate plus nitrite	0·632	No
Soluble reactive phosphorus	0·077	No
Total phosphorus	0·326	No
Dissolved organic carbon	**0·016**	Yes
Alachlor	0·488	No
Atrazine	0·855	No
Metolachlor	0·343	No
Simazine	0·525	No
Water temperature	0·110	No
Dissolved oxygen	**<0·001**	Yes
Conductivity	**0·009**	Yes
pH	**0·008**	Yes

Bolded *P* values are <0·05.

maximum nitrate plus nitrite value observed from our sites was 20·92 mg/l.

IBI scores in headwater streams in eastern Wisconsin and Ohio were negatively correlated with total nitrogen and total phosphorus (Miltner and Rankin, 1998; Fitzpatrick *et al*., 2001). We were not able to evaluate the influence of total nitrogen as this data is not available from both study watersheds. Only three fish community response variables exhibited a relationship with total phosphorus and two response variables (i.e. percent guarder-substrate choosers and percent Percidae) exhibited negative relationships. Perhaps the limited response of fishes to total phosphorus in our study was because we sampled only within channelized headwater streams, while others (Miltner and Rankin, 1998; Fitzpatrick *et al*., 2001) examined these relationships within unchannelized and channelized headwater streams. Miltner and Rankin (1998) concluded that relationships of fish communities with total phosphorus in headwater streams of Ohio reflected a response to total phosphorus and physical habitat quality as the greatest total phosphorus concentrations occurred within the most degraded streams.

Field evaluations of the relationships between fish communities and herbicides within channelized headwater streams in the midwestern United States are lacking. Benchmark toxicity values that represent the most sensitive toxicity endpoint identified from laboratory experiments suggest fish experience acute toxicity to the herbicides we measured at concentrations ranging from 0·90 (alachlor) to 3·20 mg/l (simazine) and chronic toxicity at concentrations ranging from 0·06 (atrazine) to 0·96 mg/l (simazine) (U.S. EPA, 1995b, 1998, 2003, 2005a, b). None of the measured herbicides exceeded concentrations during this study that have been reported to cause acute toxicity in fish, and only the maximum observed values of atrazine (Table II) exceeded concentrations capable of causing chronic toxicity. We were surprised by the positive relationship of metolachlor with fish community structure in headwater streams. Concentrations of metolachlor, which will cause mortality in 50% of fishes in laboratory studies are species dependent and ranges from 2 to 15 mg/l (Wolf and Moore, 2002). The maximum metolachlor concentration observed in our study streams was 0·02 mg/l. Therefore, the absence of a negative relationship is reasonable because our results occurred over a range of values well below toxic levels. We examined correlations of metolachlor with the other measured water chemistry variables and no explanatory relationships were observed. Perhaps the positive relationship we observed results from metolachlor serving as a surrogate for an unmeasured physical or chemical parameter or from an indirect effect resulting from metolachlor's effect on lower trophic levels (algae, macroinvertebrates). More research is needed to determine the effect of low concentrations of metolachlor on fish communities in the field.

Our assessment of the relationships between water chemistry and hydrology suggested that hydrology may be an underlying factor in some of the observed relationships between water chemistry and fish communities. Specifically, these results suggest that the observed relationships of fish communities with ammonium, pH, and dissolved oxygen may also be a function of fish community responses to hydrology or the combined effect of hydrology and water chemistry. However, the relationships of fish communities with nitrate plus nitrite and metolachlor appear to be independent of hydrology.

The positive relationships we observed of fish communities with pH and dissolved oxygen are consistent with expectations based on fish biology and findings from headwater streams in Ohio (Miltner and Rankin, 1998). Fishes are capable of surviving at low dissolved oxygen levels (<5 mg/l) and low pH values (<6), but their growth and other life functions are impacted (Herlihy *et al*., 1993; Garvey *et al*., 2007). Additionally, positive correlations of fish communities with dissolved oxygen have been observed in headwater streams throughout Ohio (Miltner and Rankin, 1998).

The strongest relationships between water chemistry and fish communities occurred in those regression models that contained nutrient, herbicide, and physicochemical variables. We feel these results suggest that the most effective conservation practices may be those that have a combined influence on nutrients, herbicides, and physicochemical variables. We also feel a holistic approach is needed for designing conservation plans for channelized streams. The interrelationships among habitat factors and fish communities are highlighted in the observed hydrology–water chemistry relationships and the importance of physical habitat factors on fish community structure within these channelized headwater streams. Ecological evaluations conducted in larger wadable channelized streams in Mississippi suggest that the greatest benefits may be achieved with a combination of practices that alter water chemistry and physical habitat (Shields *et al*., 2007). We feel the use of a combination of conservation practices to address physical habitat and water chemistry degradation is most likely to provide the greatest benefits for fish communities in channelized headwater streams within the midwestern United States.

CONCLUSIONS

The observed relationship between nutrients, herbicides, and physicochemical variables with fish communities in channelized headwater streams in Indiana and Ohio is the first step toward quantifying the role of water chemistry in structuring fish communities. Additionally, fish communities were not influenced by one water chemistry variable, but a combination of water chemistry variables. Developing conservation plans that address both physical habitat and water chemistry degradation may provide the greatest ecological benefits for channelized headwater streams. The challenge for future research will be to determine which combinations of conservation practices will provide the greatest benefits.

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