Public health perspectives of channelized and unchannelized headwater streams in central Ohio: a case study

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ABSTRACT

Headwater streams constitute the majority of watersheds in the United States and many in the midwest have been channelized for agricultural drainage. Public health implications of water chemistry and aquatic insects within channelized and unchannelized headwater streams have not been explored. We sampled water chemistry and aquatic insects in two channelized and two unchannelized headwater streams in central Ohio from December 2005 until November 2008. Maximum concentrations of ammonium, nitrate plus nitrite, and chlorothalonil were greater in channelized streams. Nitrate plus nitrite and atrazine also exceeded drinking water standards more often in channelized streams. Maximum concentrations of simazine and the percentage of times it exceeded the drinking water standards were greater in unchannelized streams. The predicted hazard potential of nutrient and pesticide mixtures was greater in channelized streams. Mosquito abundance did not differ between stream types. Chironomid abundance was greater in channelized streams. Biting dipterans did not exhibit consistent abundance trends and only differed between stream types in the summer and fall. Our results suggest that if whole stream uptake of nutrients and pesticides is minimal in channelized headwater streams then nutrient and pesticide inputs from these streams may impact downstream drinking water sources. Our results also suggest channelized and unchannelized headwater streams are not serving as a significant source of mosquitoes.

Key words | agriculture, aquatic insects, drinking water, headwater streams, herbicides, nutrients

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INTRODUCTION

Headwater streams are the smallest streams located within the upper reaches of a watershed. These first, second, and third order streams are the most abundant streams within a watershed in terms of numbers and percentage of total stream length (Leopold *et al.* 1964; Horton 1975; Nadeau & Rains 2007). Their small size and large numbers make them especially susceptible to anthropogenic modifications (Smiley *et al.* 2005), especially within agricultural watersheds. Channelized headwater streams or drainage ditches are common in agricultural watersheds around the world. These are constructed streams designed with straight trapezoidal channels or existing streams that have been deepened, widened, or straightened for draining excess water from adjacent fields (Smiley & Gillespie 2010). Available estimates of total length of channelized headwater streams range from 27,000 km in Minnesota (Minnesota Board of Water Resources 2006) to 56,000 km in Indiana (Needelman *et al.* 2007). Previous research has documented that habitat diversity and ecological health typically decrease following stream channelization (Smiley & Gillespie 2010). Public health issues related to channelized headwater streams and how they might influence the quality of downstream drinking water sources or serve as habitat for potential insect disease vectors and insect pests have not been explored.

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Streams, rivers, and reservoirs serve as surface drinking water sources for urban and rural communities in the midwestern United States. Agriculture constitutes a significant portion of land use in the midwestern United States and impaired water quality of surface drinking water sources as a result of agricultural nutrients and pesticides represents a potential human health risk (Pappas *et al.* 2008). Specific human health risks of agricultural contamination of surface drinking water sources include methomoglobinemia (blue baby syndrome), spontaneous abortions, and increased risks for certain cancers that results from high nitrate levels in drinking water (Squillace *et al.* 2002), cardiovascular, kidney, and endocrine problems linked with commonly used herbicides (Pappas & Huang 2008), and increased risks of birth defects associated with increases in nitrate and pesticides in surface water (Winchester *et al.* 2009). Additionally, the human health implications of previous assessments are most likely conservative risk assessments because the focus has been on the implications of single chemicals, not the nutrient and pesticide mixtures that frequently occur in agricultural watersheds (Kolpin *et al.* 2000; Squillace *et al.* 2002). Ninety-four watersheds in Ohio serve as surface drinking water sources and three central Ohio watersheds have been placed on Ohio EPA's watch list for nitrate and/or atrazine due to detections of elevated nitrate or atrazine concentrations (Ohio EPA 2008). Few, if any headwater streams serve as drinking water sources. However, excessive downstream transport of nutrients and pesticides from these small streams can degrade the water quality of downstream drinking water sources and result in increased treatment costs for community water suppliers. Thus, understanding the water quality trends within headwater streams is the first step towards evaluating their potential impact on the water quality of downstream drinking water sources.

Historically, stream channelization and other methods for draining wetlands were used for reducing mosquito abundance and control of malaria and other insect-vectored diseases in the United States (Willott 2004). Mosquito control continues to be important to public health agencies in the midwestern United States because of the ability of a small number of species (i.e. approximately 10% of all species) to serve as vectors for the West Nile virus, La Crosse encephalitis virus, and Eastern Equine encephalitis virus (Scheidler *et al.* 2006; Ohio Department of Health 2008). Mosquito control strategies used in channelized headwater streams in the region include larvicide application and channel modifications to ensure the maintenance of flowing water (Lyon & Steele 1998). Excessive nutrient inputs (Larimore 1974; Chaves *et al.* 2009), aquatic plants and herbaceous vegetation (Pierce & Pezeshki 2010), and standing water during periods of limited precipitation may promote mosquito colonization in agricultural headwater streams. Other dipteran pests found in streams include black flies (Family Simuliidae), biting midges (Family Ceratopogonidae), deer flies (Family Tabanidae), nonbiting midges (Family Chironomidae). Biting dipterans (i.e., black flies, biting midges, deer flies) can create severe nuisance problems because they bite humans and animals (Thorp & Covich 2001). Deer flies are documented vectors of tularemia (deer fly fever) in the western United States, but not the eastern United States (Farlow *et al.* 2005). Large swarms of nonbiting midges are also a nuisance and if inhaled may cause allergic reactions (Thorp & Covich 2001; Ballestros *et al.* 2006; Ferrington 2008). Understanding the ability of different types of midwestern headwater streams to serve as larval habitat for potential insect disease vectors and pests will assist in developing effective control and surveillance strategies (Joy & Clay 2002; Irwin *et al.* 2008).

We measured water chemistry and sampled aquatic insects in two channelized and two unchannelized headwater streams and then compared nutrients, pesticides, and larval abundances of potential insect disease vectors and pests between stream types to evaluate the public health hazards posed by channelized headwater streams. Specifically, we addressed the following questions: (1) Does the concentration of selected nutrients, herbicides, and fungicides exceed drinking water standards more often in channelized headwater streams than unchannelized headwater streams?; (2) Is the predicted hazard potential of nutrient and pesticide mixtures within channelized headwater streams greater than the hazard potential within unchannelized headwater streams?; and (3) Is the abundance of potential insect disease vectors (mosquitoes) and pests (biting dipterans and nonbiting midges) greater in channelized headwater streams than unchannelized headwater streams?

METHODS

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 (Figure 1). Cropland consisting of corn, soybean, or wheat is the dominant land use in the UBWC watershed. 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). Two channelized (A, B) and two unchannelized (C, D) headwater streams were selected and instrumented for this study (Figure 1). The dominant land use in the watershed of all study streams was row-crop agriculture. Watersheds of channelized streams consisted of large, systematic tile drained fields and watersheds of the unchannelized streams were characterized by smaller, more sloping fields. Channelized streams contained narrow riparian zones consisting mostly of herbaceous riparian vegetation. Channelized streams also exhibited the straightened, over-enlarged, trapezoidal channel shape typical of agricultural drainage ditches (Table 1). Unchannelized streams possessed forested riparian zones, sinuous channels, and variable bank heights that would be expected within unmodified headwater streams (Table 1). Hydrology differs between stream types and the frequency of zero discharge in the summer and out-of-bank discharge in the winter is greater in the unchannelized streams than the channelized streams (King *et al.* 2009).

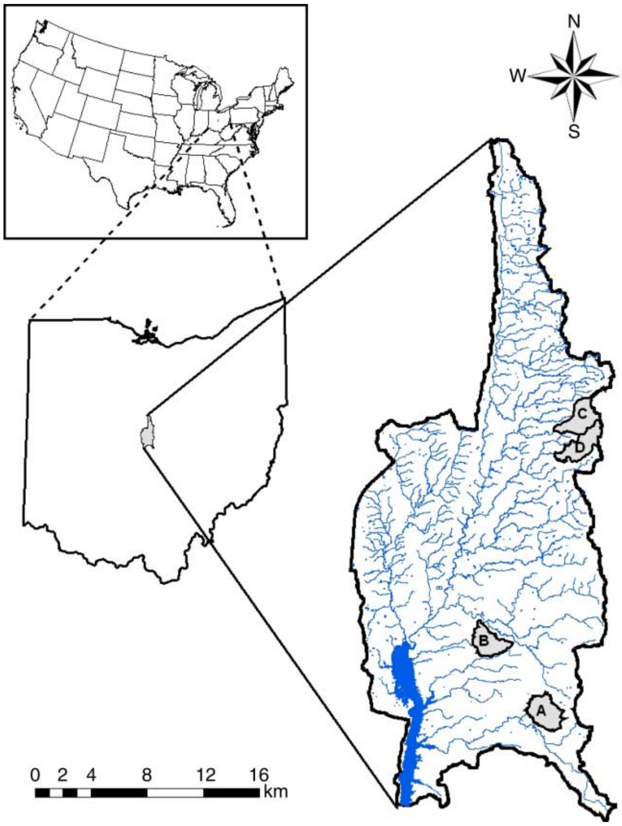

Figure 1 | Location of study streams within the Upper Big Walnut Creek watershed, Ohio, and the United States. Streams A and B are the channelized streams and streams C and D are the unchannelized streams.

Table 1 | Means (standard deviations) of selected watershed, riparian, and geomorphology variables in two channelized and two unchannelized headwater streams within the Upper Big Walnut Creek watershed, Ohio

	Channelized	**Unchannelized**
Watershed area (km^2)	4.2 (46.0)	4.3 (7.8)
Relief (m)	17.5 (2.4)	46.3 (5.9)
Channel length (m)	838.5 (228.4)	8,581.0 (2306.6)
Riparian width (m)	28.3 (6.9)	76.3 (29.3)
Percentage canopy cover (%)	10.2 (10.8)	74.0 (16.2)
Woody vegetation density (#/m^2)	0.09 (0.08)	0.84 (0.16)
Cross section area (m^2)	7.9 (2.0)	2.4 (0.6)
Top bank width (m)	8.3 (0.7)	4.5 (0.5)
Thalweg depth (m)	1.8 (0.2)	0.8 (0.1)

Watershed characteristics were measured using ArcGIS as described by King *et al.* (2008). In 2005 and 2006 riparian characteristics were measured with vegetation surveys and geomorphology characteristics were measured with surveying methods as described by Smiley *et al.* (2009*b*).

Water samples were collected at the downstream outlet of the watershed of each stream with automated water samplers programmed to collect water samples on a 1-mm volumetric flow depth interval and by weekly grab samples. Periodically, additional water samples were collected during storm events. Water samples for measurement of nutrients (ammonium, nitrate plus nitrite), herbicides (alachlor, atrazine, metolachlor, simazine), and one fungicide (chlorothalonil) were collected from December 2005 to November 2008. Concentrations of ammonium and nitrate plus nitrite were determined colorimetrically by flow injection analysis using an automated ion analyzer and the copperized-cadmium reduction method (Parsons *et al.* 1984). Pesticide concentrations of alachlor, atrazine, chlorothalonil, metolachlor, and simazine were determined using gas chromatography following standard protocols for pesticide analyses (U.S. EPA 1995). We collected and analyzed 920 water samples in a three-year period. The number of samples differed slightly among streams, seasons, and years as a result of precipitation, hydrology, and climate. We collected an average of 16 water samples (range–2 to 62) from each unchannelized stream each season and an average of 21 water samples (range–5 to 62) from each channelized stream each season.

We determined the maximum observed concentrations and calculated the percentage of water samples exceeding the maximum contaminant levels (MCL) or human health advisory levels for all measured nutrients and pesticides (U.S. EPA 2006, Table 2) during each season (winter–December to February; spring–March to May; summer–June to August; fall–September to November) from each stream. We also calculated the predicted hazard potential of each sample using an index derived through the concentration addition model (Verro *et al.* 2009) and the U.S. EPA drinking water standards for nutrients and pesticides (U.S. EPA 2006). Predicted hazard potential is calculated by the drinking water standards index (DWSI):

$$\mathrm{DWSI} = \sum C_i/\mathrm{DWS}_i$$

where C_i is the concentration of contaminant i in the water sample and DWS_i is the 2006 drinking water standard for contaminant i. This general equation is typically used to predict the toxicity of mixtures for aquatic animals knowing the concentration of the contaminant and the LC50 of the contaminant for the animal. We feel this modified index is a useful screening tool because it enables us to go beyond a single contaminant evaluation and to evaluate water quality relative to established drinking water standards. The index also has the advantage in that the scores can be interpreted in light of number of contaminants exceeding MCL or human health advisory levels. A DWSI score of 1 can occur if one contaminant in the sample occurs at the MCL concentration and all others contaminants are absent. Similarly, the DWSI score will be 6 if six contaminants occur in a mixture at their MCL concentrations. We calculated the mean DWSI and determined the maximum observed DWSI during each season from each stream.

Table 2 | Maximum contaminant levels (MCL) or human health advisory levels (HHL) for drinking water established by the U.S. EPA (2006) for measured nutrients and pesticides

	MCL	HHL
Ammonium (mg/L)	–	30
Nitrate plus nitrite (mg/L)	10	–
Alachlor (μg/L)	2	–
Atrazine (μg/L)	3	–
Chlorothalonil (μg/L)	–	200
Metolachlor (μg/L)	–	700
Simazine (μg/L)	4	–

Larval insects were collected from two channelized and two unchannelized streams (Figure 1) during spring (May), summer (July to August), and fall (September to November) of 2006, 2007, and 2008. Specifically, in each stream we sampled two 125 m long sites. One site was located at the downstream of the watershed outlet and the other site was located upstream as close to the headwaters as possible. Sites within a stream were separated by a mean distance of 1,128 m (range 175 to 3,000 m). We collected insects with three 1 m long dipnet sweeps from deeper slow flowing areas (i.e. pools and runs) in each site. We also used the surber sampler and obtained three insect collections from shallow and swift flowing areas (i.e. riffles) in each site. Individual collections were distributed throughout the site to ensure our sampling was distributed along the entire 125 m site. The combined use of the dipnet and surber sampler enabled us to effectively sample different habitat types in each site to ensure the capture of insects with different habitat preferences. The three collections from each sampling method were combined into one sample in the field and preserved with 70% ethanol. Our field processing methods resulted in one dipnet and one surber sample from each site during each season, four samples from each stream during each season, and the collection of 144 samples in a three-year period.

Our field processing methods resulted in large volume samples containing sediment and detritus that required use of elutriation and subsampling. Our laboratory protocols follow that of Payne & Miller (1991). Macroinvertebrates were removed from sediments and detritus by elutriation.

Each sample was swirled in a 4-L bucket and suspended materials and macroinvertebrates were poured out of the bucket through a 250-micron mesh sieve. Each sample was elutriated seven times and then stained with a mixture of rose bengal and 70% ethanol. This elutriation process has been documented to retrieve 90 to 100% of all macroinvertebrates (Payne & Miller 1991). Organisms were then picked from subsamples of the elutriated samples with the aid of a dissecting scope and sorted to major groups. Subsampling methods are commonly used in macroinvertebrate stream studies in the United States (Vinson & Hawkins 1996; U.S. EPA 2002). We subsampled based on the fraction of the sample to avoid problems associated with the fixed count subsampling protocols and to obtain the standardization needed to ensure valid comparisons between stream types (Courtemanch 1996). Elutriated samples were mixed, placed into one or more petri dishes, and divided into equal subsamples within a dish(es). A series of randomly selected subsamples was taken until at least 100 animals had been removed or for a minimum processing time of four hours. However, the number of animals and processing time were only guidelines to identify the final subsample as all animals must be removed before the final subsample is considered complete. We then counted and identified all sorted organisms to Family level with standard taxonomic keys (Merritt & Cummins 1996; McCafferty 1998; Thorp & Covich 2001).

The abundance (number of captures) of selected insect Families (mosquitoes, chironomids (Family Chironomidae), biting midges, black flies, and deer flies) from each stream during each season were calculated using the abundance per sample and per site. First, we calculated the abundance of each Family per sample by dividing the number of each Family counted in each sample by the amount of sample examined. This first calculation standardizes the abundances to one sample. Secondly, we calculated the abundance of each Family from each site during each season by summing the abundances of each sample (i.e. one dipnet and one surber sample) collected in each site. The abundance of each Family from each stream in each season was then calculated by summing the abundance data of both sites in each stream. The abundance of biting dipterans (i.e. biting midges, mosquitoes, black flies, deer flies) from each stream during each season was then calculated as the sum of the abundances of these four Families in each stream during each season.

We used a three factor analyses of variance (ANOVA) coupled with the Student–Neuman–Keuls test to detect if differences in water chemistry and aquatic insect variables occurred between channelized and unchannelized headwater streams and if the effect of stream type was influenced by sampling season, year, or the interaction of both. We only report results on the effects of stream type and the interaction of stream type with season and/or year. We recognize that seasonal and annual effects are important. However, selective reporting of our results allows us to focus on the most important results for addressing our research questions and still enables us to account for the potential influence of season and year on the effect of stream type. The assumptions of normality and equal variance were not met for any response variable despite $\log x + 1$ transformation or arcsine square root transformation. Therefore, the three factor ANOVA was conducted with rank transformed values because a nonparametric analogue to the three factor ANOVA was not available. Rank transformation is commonly recommended in these situations and its use with a parametric test is the equivalent of a nonparametric three factor ANOVA (Conover 1999). All statistical tests were conducted with Sigma Stat 3.1 (Systat Software 2004) and a significance level of $P < 0.05$ was used.

RESULTS

Nutrients and pesticides

Maximum seasonal concentrations of ammonium and nitrate plus nitrite were greater in channelized than unchannelized streams (Table 3, Figure 2). No differences in maximum seasonal concentrations of atrazine and metolachlor occurred between stream types (Table 3, Figure 2). Maximum seasonal concentrations of chlorothalonil and simazine exhibited a significant interaction effect of stream type × season × year (Table 3). Maximum seasonal concentrations of chlorothalonil did not differ between stream types in 2006 and 2007, but greater maximum seasonal concentrations occurred in channelized streams than unchannelized streams in 2008 (Figure 3).

Table 3 | *P* values from three-factor ANOVA conducted to determine the effect of stream type (ST), stream type × season (ST × SE), stream type × year (ST × YR) and stream type × season × year (ST × SE × YR) on water chemistry and aquatic insects in two channelized and two unchannelized headwater streams in the Upper Big Walnut Creek watershed, Ohio, 2006–2008. Bolded *p* values are those <0.05

Response variable	ST	ST × SE	ST × YR	ST × SE × YR
Maximum values				
Ammonium	**< 0.001**	0.261	0.374	0.190
Nitrate plus nitrite	**< 0.001**	0.812	0.605	0.190
Atrazine	0.056	0.440	0.119	0.939
Chlorothalonil	0.066	0.507	**0.006**	**0.046**
Metolachlor	0.305	0.763	0.972	0.864
Simazine	0.820	0.305	**0.017**	**0.030**
Percentage times exceed MCL				
Ammonium	–	–	–	–
Nitrate plus nitrite	**< 0.001**	**< 0.001**	**0.047**	**< 0.001**
Atrazine	**0.013**	**0.044**	0.115	0.462
Chlorothalonil	–	–	–	–
Metolachlor	–	–	–	–
Simazine	0.087	0.137	**0.018**	0.190
Drinking water standards index index				
Mean	**< 0.001**	0.301	0.533	0.565
Maximum	**< 0.001**	0.215	0.982	0.552
Aquatic insects				
Mosquito abundance	0.507	0.846	0.892	0.397
Chironomid abundance	**0.014**	0.341	0.593	0.068
Biting dipteran abundance	0.410	**0.016**	0.146	0.559

Maximum seasonal concentrations of simazine did not differ between stream type in any season in 2006 and 2007, but in 2008 maximum seasonal concentrations of simazine were greater in unchannelized streams than channelized streams in the spring, but not the winter, summer, or fall (Figure 4). Alachlor was not detected in any of our water samples.

Ammonium, chlorothalonil, and metolachlor concentrations did not exceed drinking water standards during our study. The percentage of times nitrate plus nitrite exceeded the MCL exhibited a significant three-factor interaction effect of stream type × season × year (Table 3). In 2006 and 2008, nitrate plus nitrite exceeded the MCL more often in channelized streams than unchannelized streams during the spring and summer, but did not differ among stream types in the winter and fall (Figure 5). In 2007, nitrate plus nitrite exceeded the MCL more often in channelized streams than unchannelized streams only in the fall (Figure 5). The percentage of times atrazine exceeded the MCL exhibited a significant interaction effect of stream type and season (Table 3). Atrazine exceeded the MCL more frequently in channelized streams than unchannelized streams in the spring, but not the winter, summer, or fall (Figure 6). The percentage of times simazine exceeded the MCL exhibited a significant interaction effect of stream type and year (Table 3). Simazine exceeded the MCL more often in unchannelized streams than channelized streams in 2008, but not 2006 or 2007 (Figure 6). Mean and maximum values of DWSI differed between stream types and were greater in channelized streams than unchannelized streams (Table 3, Figure 7).

Aquatic insects

Chironomids were the most abundant dipteran taxa captured and constituted 85% of all dipteran captures.

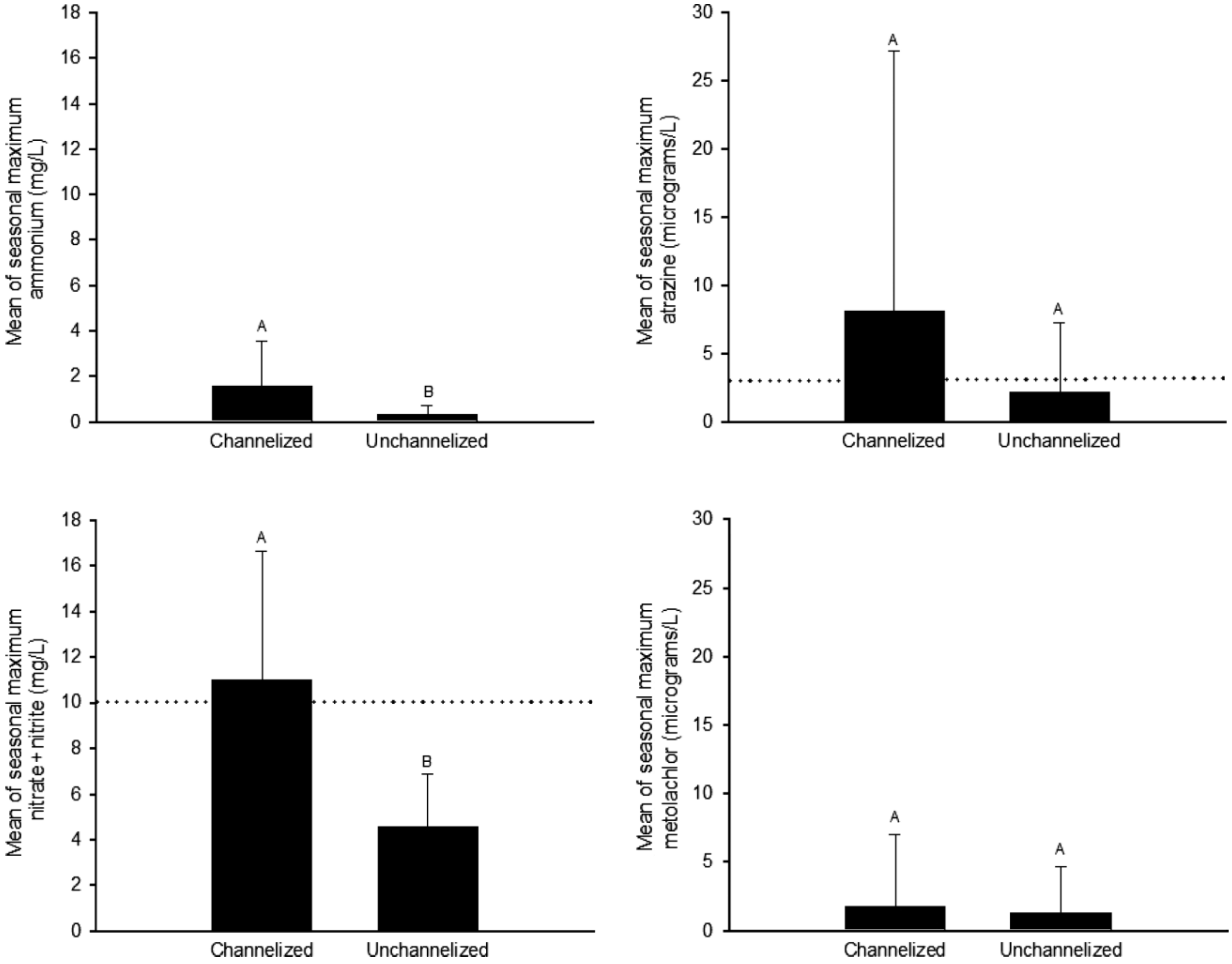

Figure 2 | Means and standard deviation of the seasonal maximum concentrations of ammonium, nitrate plus nitrite, atrazine, and metolachlor in two channelized and two unchannelized headwater streams within the Upper Big Walnut Creek watershed, Ohio, 2006 to 2008. The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means. The dotted lines within nitrate plus nitrite and atrazine figures depict the drinking water standards for these contaminants.

Mosquitoes constituted less than 1% of all dipteran captures and the abundance of biting dipterans represented 11% of all dipteran captures. Mosquito abundance did not differ between stream types (Table 3, Figure 8). Chironomid abundance differed between stream types and was greater in channelized streams than unchannelized streams (Table 3, Figure 8). The abundance of biting dipterans exhibited a significant interaction effect of stream type and season (Table 3). No differences in biting dipterans occurred in the spring (Figure 8). The abundance of biting dipterans was greater in channelized than unchannelized streams in the summer and the opposite trend occurred in the fall (Figure 8).

DISCUSSION

Nutrients and pesticides

Information on nutrient and pesticide comparisons between channelized and unchannelized streams is lacking because previous assessments of channelization have focused on the physical impacts. The occurrence of nitrate concentrations above the drinking water standards in agricultural headwater streams in the midwestern United States is not uncommon. Smiley *et al.* (2009*a*) previously reported a maximum nitrate plus nitrite concentration of 21 mg/L for seven channelized headwater streams in central Ohio (UBWC) and three in northeastern Indiana from summer

2005 to fall 2007. Additionally, maximum reported nitrate concentrations range from 15 to 26 mg/L for two channelized headwater streams in Indiana (Smiley & Gillespie 2010). Median concentrations of nitrate in three channelized headwater streams in northeastern Ohio ranged from 5.2 to 17.4 mg/L (Herrman *et al.* 2008). Maximum nitrate values >17 mg/L in channelized headwater streams in east-central Illinois are considered typical (Schaller *et al.* 2004). Maximum concentrations of nitrate in eight channelized and unchannelized headwater streams in Minnesota ranged from 7 to 37 mg/L (Magner *et al.* 2004). Our results are consistent with these results as mean of the seasonal maximum concentrations observed over a three-year period in channelized headwater streams were greater than the drinking water standards.

Nitrate concentrations exceeded drinking water standards 30 to 50% of the time within east-central Illinois channelized headwater streams (Royer *et al.* 2004; Schaller *et al.* 2004). In the spring 2006 and 2008, summer 2006 and 2008, and fall 2007 we observed that nitrate plus nitrite exceeded drinking water standard between 12 to 29% of the time in channelized headwater streams. Our findings suggest that channelized headwater streams in the Upper Big Walnut Creek watershed may exceed nitrate drinking water concentrations less often than channelized headwater streams in east-central Illinois. Less information is readily available for ammonia, but our means of the seasonal maximum ammonium concentrations were comparable to maximum concentrations ranging from 2 to 6.7 mg/L reported from channelized headwater streams in Ohio, Indiana, and Illinois (Larimore 1974; Smiley *et al.* 2009*a*; Smiley & Gillespie 2010).

Historical and recent surveys from a wide range of stream sizes indicate that pesticides are common in streams within the midwestern United States (Thurman *et al.* 1991; Gilliom 2007), but information on concentrations of pesticides within agricultural headwater streams is not widely available. Smiley *et al.* (2009*a*) and Smiley & Gillespie (2010) reported maximum concentrations of atrazine ranging from 15 to 1,444 μg/L, maximum concentrations of metolachlor from 0.3 to 52 μg/L, maximum concentrations of simazine from 6 to 30 μg/L from channelized headwater streams in central Ohio and northeastern Indiana. Maximum atrazine concentrations

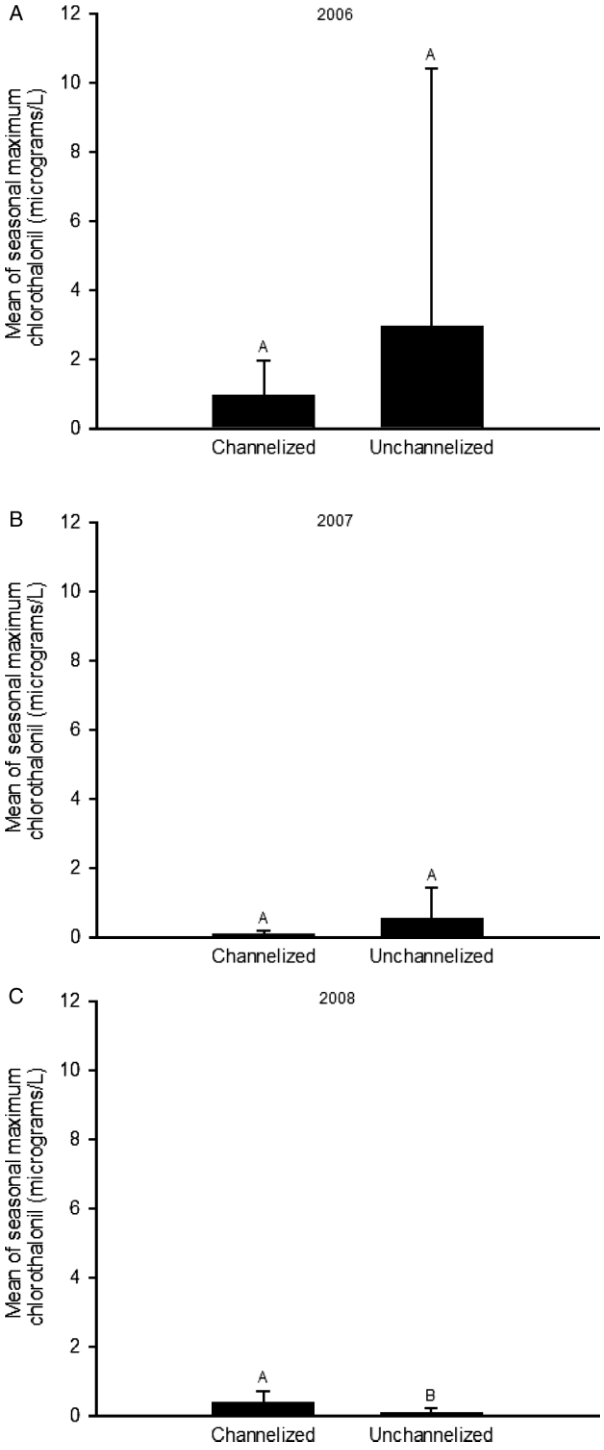

Figure 3 | Means and standard deviation of the seasonal maximum concentrations of chlorothalonil in two channelized and two unchannelized headwater streams within the Upper Big Walnut Creek watershed, Ohio, 2006 to 2008 (A to C). The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means.

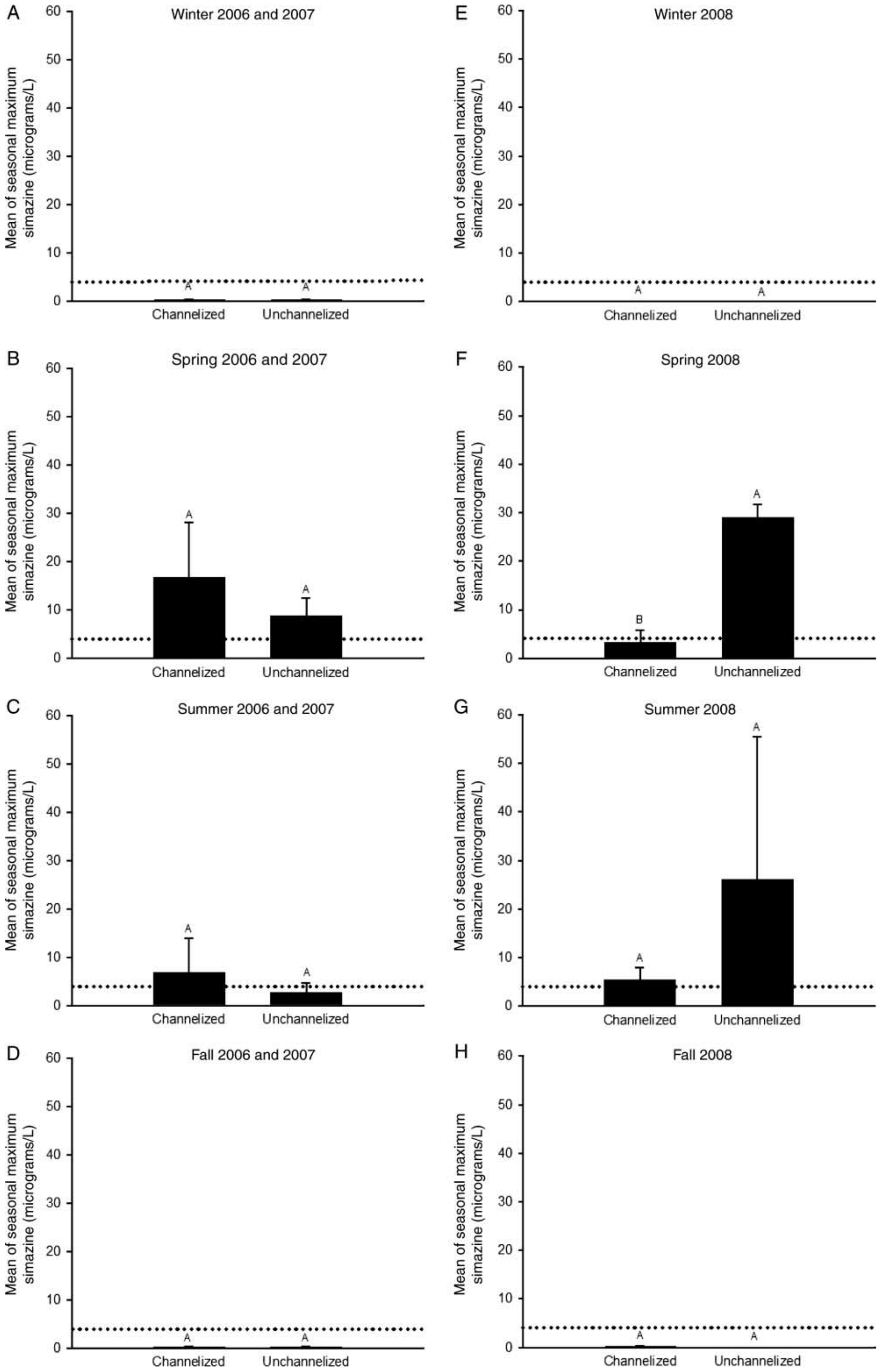

Figure 4 | Means and standard deviation of the seasonal maximum concentrations of simazine in two channelized and two unchannelized headwater streams among seasons in 2006 and 2007 (A to D) and among seasons in 2008 (E to H) within the Upper Big Walnut Creek watershed, Ohio. The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means. The dotted lines within figures indicate the drinking water standard for simazine.

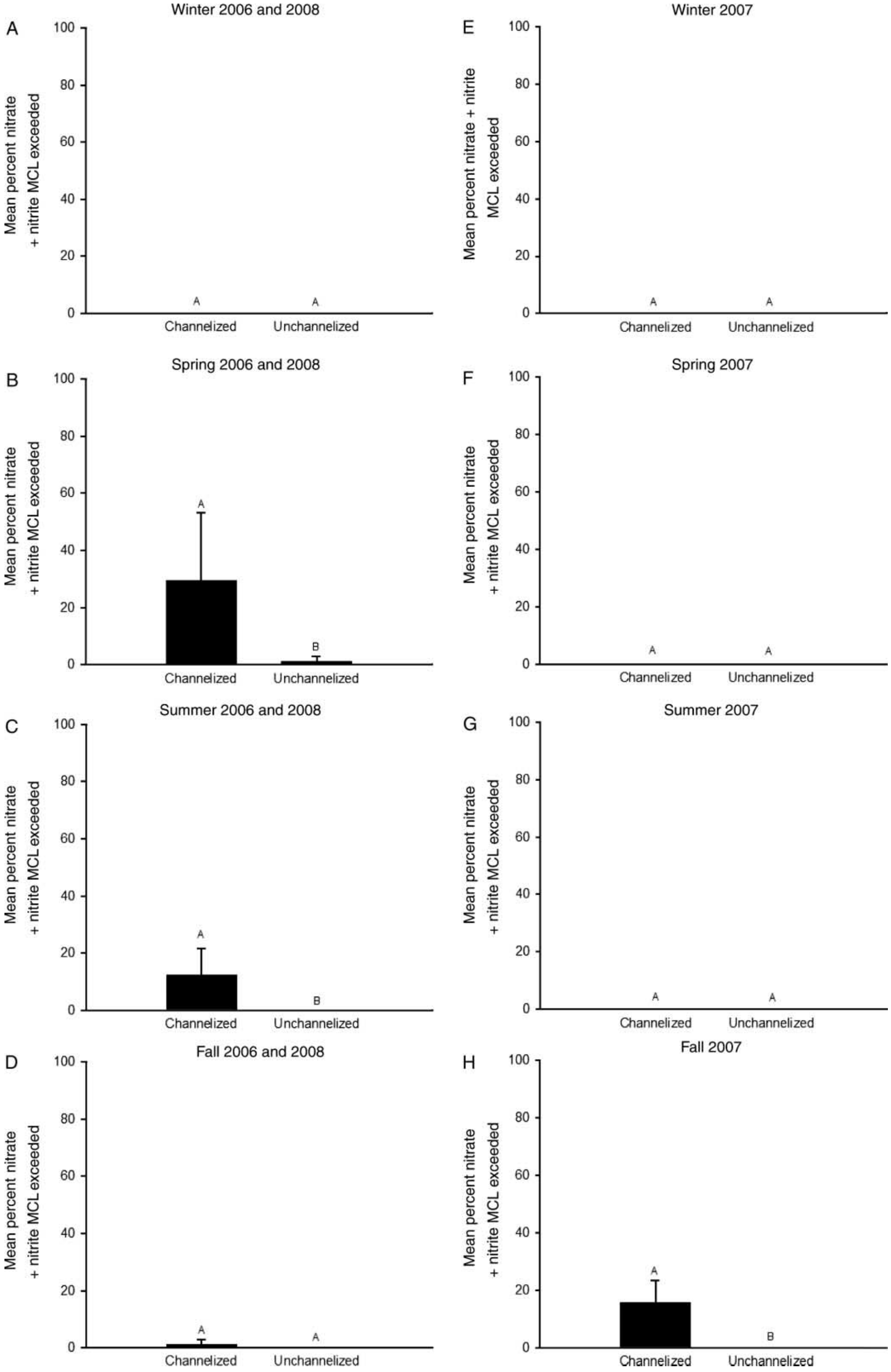

Figure 5 | Mean and standard deviation of the percentage of times nitrate plus nitrite exceeded the drinking water standards in two channelized and two unchannelized headwater streams among seasons in 2006 and 2008 (A to D) and among seasons in 2007 (E to H) within the Upper Big Walnut Creek watershed, Ohio. The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means.

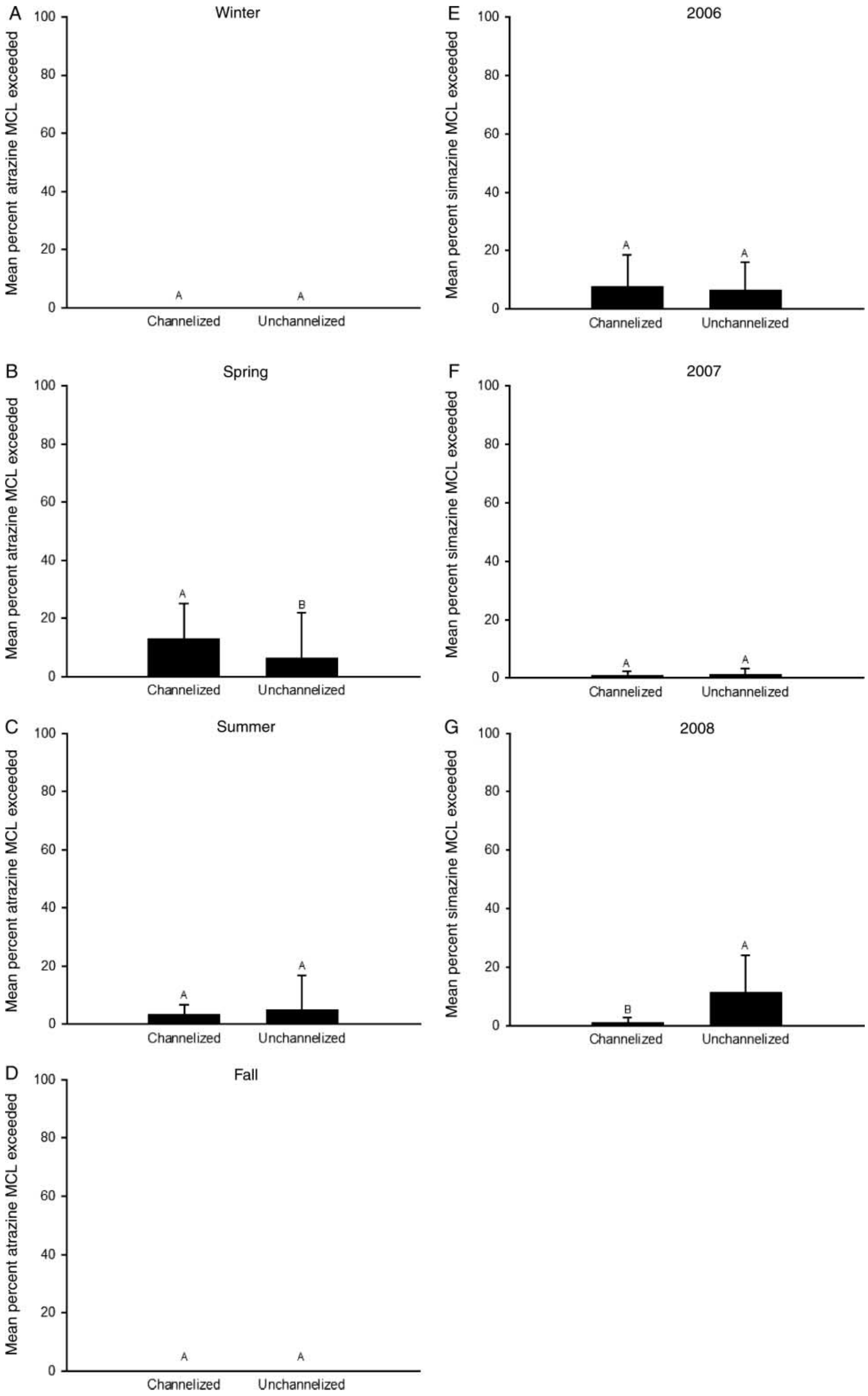

Figure 6 | Mean and standard deviation of the percentage of times atrazine exceeded the drinking water standards in two channelized and two unchannelized headwater streams among seasons (A to D) and mean percentage of times simazine exceeded the drinking water standards in channelized and unchannelized streams among years (E to G) within the Upper Big Walnut Creek watershed, Ohio, 2006 to 2008. The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means.

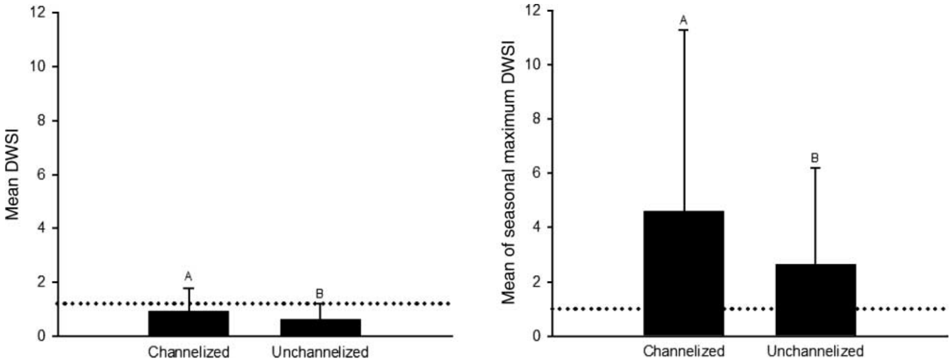

Figure 7 | Mean and standard deviation of the drinking water standards index (DWSI) and mean and standard deviation of the seasonal maximum DWSI values in two channelized and two unchannelized headwater streams within the Upper Big Walnut Creek watershed, Ohio, 2006 to 2008. The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means.

in channelized headwater streams in northeastern Indiana ranged from 27 to 86 μg/L and exceeded MCL between 5 and 19% of the time (Pappas & Huang 2008). Additionally, from 2004 to 2005 maximum concentrations of atrazine, simazine, alachlor, acetochlor, and metolachlor in a channelized headwater stream in northeastern Indiana were well above MCL (Rocha *et al.* 2008). However, in these streams atrazine only exceeded MCL 12% of time, simazine exceeded MCL 3% of the time, and alachlor exceeded MCL <1% of the time (Rocha *et al.* 2008). Our results in central Ohio are consistent with results from northeastern Indiana (Pappas & Huang 2008; Rocha *et al.* 2008). We observed annual means of the maximum seasonal concentrations of atrazine and seasonal means of the maximum seasonal concentrations of simazine were greater than the MCL. We also observed the mean percentage of times atrazine and simazine concentrations exceeded MCL was typically <16%. These results from channelized headwater streams in central Ohio and northeastern Indiana suggest concentrations of commonly occurring herbicides can reach rather large values, but that concentrations above the drinking water standards may occur only periodically.

A recent nationwide assessment of pesticides in surface waters found that annual means of pesticides concentrations exceeded drinking water standards more often in agricultural watersheds than urban or undeveloped streams (Gilliom 2007). The potential toxicity of pesticide mixtures in agricultural streams is greater than urban or undeveloped streams because pesticide mixtures in agricultural streams contained more contaminants (Gilliom 2007). Our results from DWSI are consistent with this finding as we found channelized headwater streams lacking forested riparian zones had greater DWSI scores than unchannelized headwater streams with remnant forested riparian zones.

If the trends we observed from our streams are representative of other streams in the Upper Big Walnut Creek watershed and if minimal whole stream uptake of nutrients and pesticides occurs within channelized headwater streams (Royer *et al.* 2004; Herrman *et al.* 2008) then nutrient and pesticide inputs from these streams may impact downstream surface water sources and represent a potential public health concern during spring and summer. Our results suggest that management needs to focus on channelized headwater streams and implementing agricultural conservation practices capable of reducing nutrient and pesticide inputs to protect downstream drinking water sources.

Aquatic insects

Chironomids are typically the most abundant dipteran taxa in agricultural headwater streams in the midwestern United States (Stone *et al.* 2005; Hutchens *et al.* 2009). Information on mosquito abundance and their frequency of occurrence within agricultural headwater streams in this region is limited. Others (Zimmer & Bachman 1978; Rife & Moody 2004; Stone *et al.* 2005; Ogren & King 2008; Hutchens *et al.* 2009) reporting on results of aquatic macroinvertebrate surveys in agricultural headwater streams did not document mosquitoes as one of the most abundant taxa captured. Larimore (1974) used drift nets to sample four channelized headwater streams in Illinois in March, May, July and

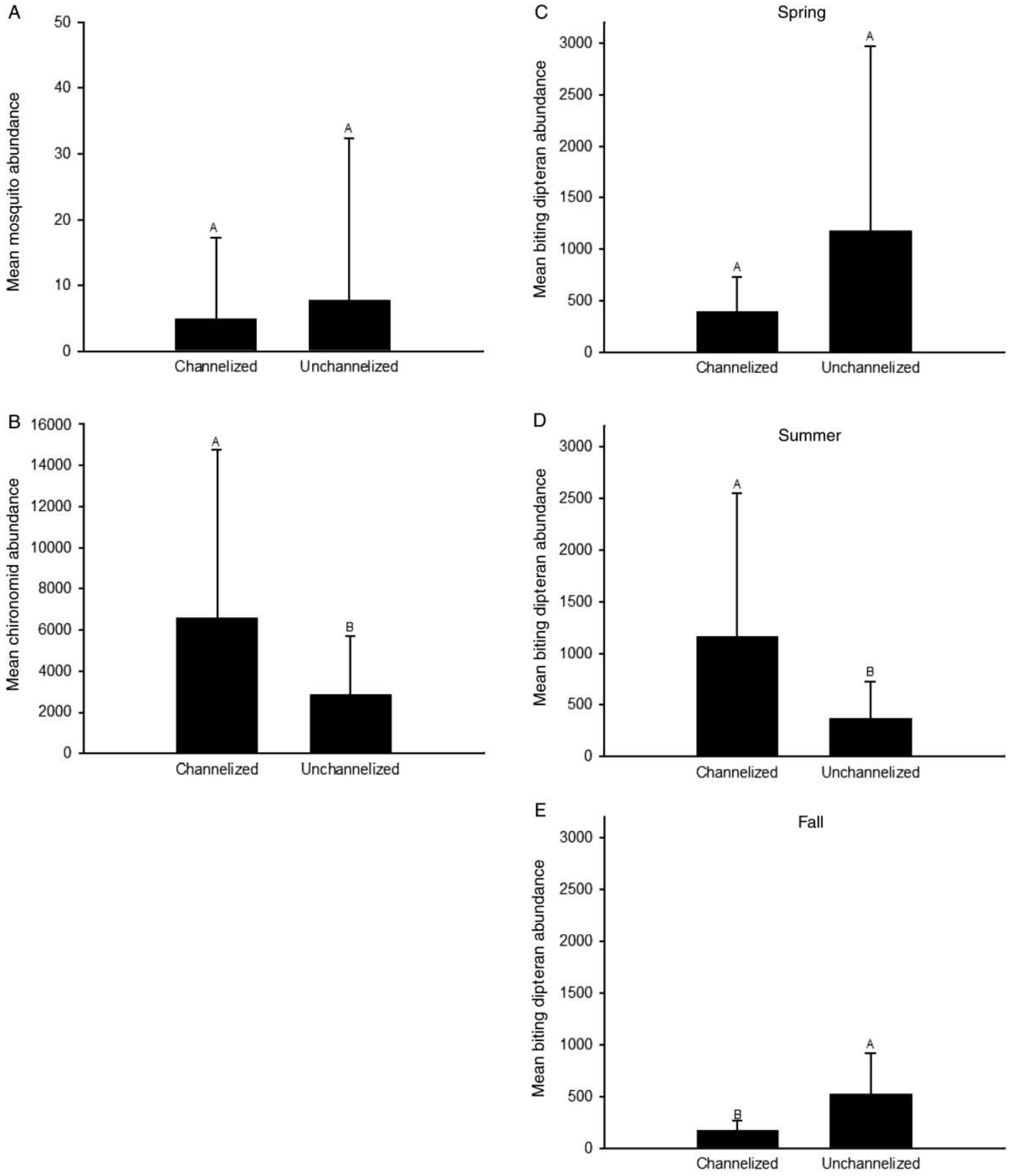

Figure 8 | Mean and standard deviation of abundance of mosquitoes (A) and chironomids (B) in two channelized and two unchannelized headwater streams and the abundance of biting dipterans (C–E) in channelized and unchannelized headwater streams among seasons in the Upper Big Walnut Creek watershed, Ohio, 2006 to 2008. The letters above the bars depict the SNK test results and different letters indicate significantly different ($P < 0.05$) means.

October of 1966. Mosquitoes were only captured from two of the most heavily polluted sites in October and the mean abundance for these four streams was 43 mosquitoes per 100 m^3 of water (Larimore 1974). Irwin *et al.* (2008) observed mosquitoes occurred more often in urban ditches than streams within Madison, Wisconsin. Our results and others from agricultural streams in this region suggest mosquitoes can colonize agricultural headwater streams, but their abundances will be less than other aquatic macroinvertebrate taxa.

Our aquatic insect results suggest that channelized headwater streams may not represent a greater public health concern relative to unchannelized headwater streams. The relative abundance (percentages captured) of mosquitoes and biting dipterans was low ($<11\%$) compared the relative abundance of other dipterans. Additionally, the minimal number of mosquitoes captured during this three-year study suggests headwater streams are not a significant source of this potential disease vector and pest. This result is not surprising as mosquitoes exhibit a preference for standing water habitat. In contrast, our study streams contain flowing water most of the year and exhibit the flashy hydrology typical of headwater streams (King *et al.* 2009). Additionally, insectivorous fishes are common throughout the watersheds of these streams (King *et al.* 2008) and may have assisted with limiting larval mosquito abundances during periods of no flow. However, we note that our conclusions are based on the relative hazards suggested by larval abundances of mosquitoes. Future studies examining abundance trends of mosquito species will be valuable for documenting if known disease vectors exhibit a preference for either channelized or unchannelized headwater streams. Additionally, future studies examining the abundance of adult mosquitoes, presence of potential disease pathogens within adult mosquitoes, and the degree of exposure experienced by farmers, rural families, and recreational users (i.e. hunters, fishers, bird watchers, etc.) are needed to more fully quantify the public health risks posed by mosquitoes within the riparian corridors of agricultural headwater streams.

The number of West Nile virus cases in Ohio have declined since 2002 (DeGroote *et al.* 2008), but mosquito control in central Ohio remains a public health concern because mosquitoes within counties encompassing Columbus and immediately north of it (Franklin, Delaware, and Licking counties) have tested positive for West Nile virus every year (Ohio Department of Health, unpublished data). Our initial results suggest that application of insecticides and channelizing headwater streams for larval mosquito control may not be warranted unless the presence of mosquito species that are known disease vectors has been documented. Avoiding unnecessary insecticide application within headwater streams has the added benefit of not introducing another contaminant to the existing nutrient-pesticide mixture that already occurs in these streams as a result of agricultural production. Instead, our results suggest that agricultural conservation practices that reduce nutrient loading and facilitate presence of fishes within these headwater streams may also assist with limiting mosquito populations and represent a more environmentally friendly mosquito control strategy. Our results also suggest that conservation practices that increase habitat quality within channelized headwater streams have the potential to decrease chironomid larval abundance (Hutchens *et al.* 2009).

CONCLUSIONS

Our case study of two channelized and two unchannelized headwater streams in a central Ohio watershed represents the first documented assessment of the public health aspects of agricultural headwater streams. Specifically, we observed: (1) maximum concentrations of ammonium, nitrate plus nitrite, and chlorothalonil were greater in channelized headwater streams; (2) nitrate plus nitrite and atrazine exceeded drinking water standards more often in channelized headwater streams; (3) maximum concentrations and the percentage of time simazine exceeded the drinking water standards were greater in unchannelized headwater streams; (4) predicted hazard potential of nutrient and pesticide mixtures was greater in channelized headwater streams; (5) mosquito abundance did not differ between stream types; and (6) chironomid abundance was greater in channelized headwater streams. Our water chemistry results suggest that nutrient and pesticide exports from channelized headwater streams represent a greater hazard to downstream sources of drinking water than unchannelized headwater streams. Our aquatic insect results suggest channelized headwater streams do not represent a greater public health hazard than unchannelized headwater streams. Future research needs to examine if our results are representative of the other headwater streams in the Upper Big Walnut Creek watershed and other agricultural watersheds in the midwestern United States.

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