

# Temporal trends in algae, benthic invertebrate, and fish assemblages in streams and rivers draining basins of varying land use in the south-central United States, 1993–2007

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**Abstract** Site-specific temporal trends in algae, benthic invertebrate, and fish assemblages were investigated in 15 streams and rivers draining basins of varying land use in the south-central United States from 1993–2007. A multivariate approach was used to identify sites with statistically significant trends in aquatic assemblages which were then tested for correlations with assemblage metrics and abiotic environmental variables (climate, water quality, streamflow, and physical habitat). Significant temporal trends in one or more of the aquatic assemblages were identified at more than half (eight of 15) of the streams in the study. Assemblage metrics and abiotic environmental variables found to be significantly correlated with aquatic assemblages differed between land use categories. For example, algal assemblages at undeveloped sites were associated with physical habitat, while algal assemblages at more anthropogenically

altered sites (agricultural and urban) were associated with nutrient and streamflow metrics. In urban stream sites results indicate that streamflow metrics may act as important controls on water quality conditions, as represented by aquatic assemblage metrics. The site-specific identification of biotic trends and abiotic–biotic relations presented here will provide valuable information that can inform interpretation of continued monitoring data and the design of future studies. In addition, the subsets of abiotic variables identified as potentially important drivers of change in aquatic assemblages provide policy makers and resource managers with information that will assist in the design and implementation of monitoring programs aimed at the protection of aquatic resources.

**Keywords** Trends · Multivariate · Land use · Algae · Benthic invertebrates · Fish

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## Introduction

Interpretation of trends in biotic assemblages in aquatic ecosystems (hereafter, aquatic assemblages) requires an understanding of how the structure and function of aquatic assemblages are influenced by abiotic conditions, such as physical habitat, water quality, land use, and climate. Quantification of aquatic assemblages and abiotic environmental conditions can provide insights into which abiotic environmental variables influence aquatic assemblages at a given site. The relations

between abiotic conditions and aquatic assemblages in aquatic ecosystems have been the subject of a number of investigations. For example, diatom assemblages were shown to be correlated with conductivity and major ion concentrations in streams across the United States (Potapova & Charles, 2003). Hydrologic characteristics have been shown to influence periphyton biomass and diversity in New Zealand streams (Clausen & Biggs, 1997), invertebrate assemblages in streams of the western U.S. (Konrad et al., 2008) and north-eastern U.S. (Kennen et al., 2010), and fish assemblages in the mid-western U.S. (Poff & Alan, 1995). In a study of invertebrate assemblages along gradients of urban land use intensity, changes in land use at the basin-scale were highly correlated with the response of specific invertebrate metrics (Cuffney et al., 2005). Roy et al. (2003) showed that, as urbanization increased in a watershed in the south-eastern U.S., and physical habitat and water quality conditions changed, there was a corresponding decrease in the diversity of aquatic invertebrates and an increase in the abundance of tolerant taxa.

Numerous studies have investigated the importance of the spatial scale at which abiotic environmental conditions are measured with respect to their influence on aquatic assemblages. For example, it has been demonstrated that stream biotic integrity, as measured by fish assemblages, habitat quality, and land use, was more strongly influenced by land use at the landscape scale as opposed to the local scale in a watershed in the mid-western U.S. (Roth et al., 1996). In a study of streams in northeastern Australia, regional or watershed-scale variables were important in determining which fish species were present at a given site, and the abundance of individual species was largely driven by local-scale factors (Pusey et al., 2000). A recent study of correlations between aquatic assemblages and environmental characteristics, measured at three spatial scales in agricultural streams, indicates that algal and invertebrate assemblages were highly correlated with reach- and segment-scale environmental characteristics, whereas fish assemblages were highly correlated with watershed-scale characteristics (Hambrook-Berkman et al., 2010).

In addition to quantification of the status of abiotic–biotic relations, many studies have investigated temporal trends in abiotic–biotic associations. For example, it has been demonstrated that relatively short-term hydrologic events, such as floods or droughts, have the

potential to alter aquatic assemblages in the near-term (Power & Stewart, 1987; Scarsbrook & Townsend, 1993; Biggs, 1995; Boulton, 2003; Collier & Quinn, 2003). At a longer temporal scale, annual fluctuations in streamflow have been shown to alter assemblage patterns in algae (Peterson, 1996), benthic invertebrates (Ward & Stanford, 1983; McElravy et al., 1989; Scarsbrook, 2002; Dewson et al., 2007), and fish (Ross & Baker, 1983; Grossman et al., 1998). The results of these studies highlight the importance of long-term monitoring in order to acquire sufficient data to characterize trends in aquatic assemblages and their correlations with abiotic environmental variables at multiple spatial scales. Indeed, in a review of long-term studies of aquatic invertebrates, Jackson & Füreder (2006) concluded that long-term monitoring is required to accurately document these often gradual changes in aquatic assemblages and habitat/environmental conditions over time.

We present and analyze data collected from selected streams in the south-central United States as part of the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) Program to identify (1) temporal trends in algae, benthic invertebrate, and fish assemblages, (2) assemblage metrics that represent the overall changes in aquatic assemblages, (3) abiotic environmental variables, including climate metrics, water quality metrics, streamflow metrics, and physical habitat variables, that are significantly correlated with aquatic assemblages, and (4) differences in abiotic–biotic correlations as a function of land use. It is important to note that identification of correlations between aquatic assemblages and assemblage metrics or abiotic environmental variables does not necessarily indicate cause-effect associations between abiotic and biotic conditions. However, this information is critical for identifying environmental stressors associated with ecological change, and will provide information required to design and implement management strategies aimed at protecting water resources.

## Materials and methods

### Site description

The 15 stream sites sampled during 1993–2007 are located in the south-central U.S. (Table 1; Fig. 1). The BoguePhalia, Buffalo River, North Sylamore Creek,

**Table 1** General site characteristics for the 15 sample sites

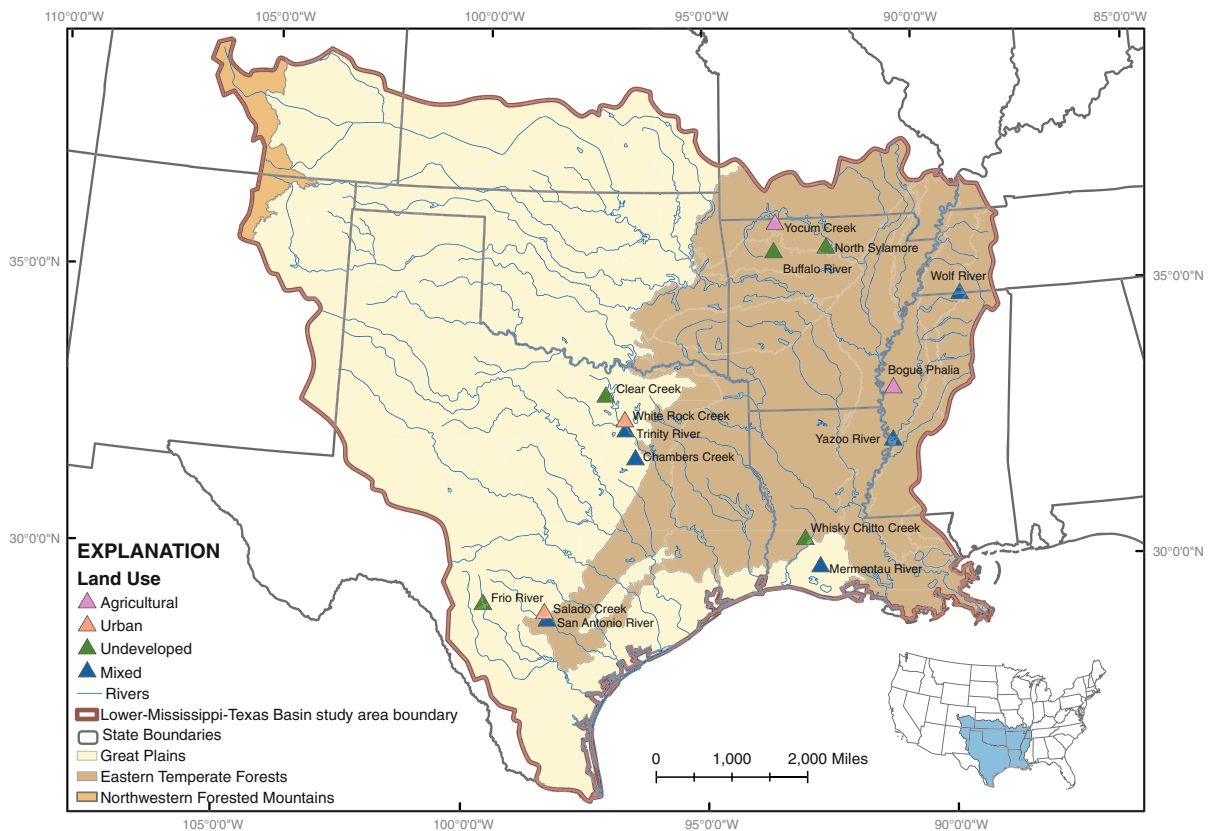
Site Name	Drainage area (km <sup>2</sup> )	Mean Elevation (m)	Population density (people/km <sup>2</sup> )		Land cover (%)		
			1990	2000	Forest	Agriculture	Urban
Agricultural sites							
Bogue Phalia	1,301	40	13	14	0.06	87.15	4.25
Yocum Creek	134	298	16	20	23.76	70.2	5.32
Urban sites							
Salado Creek	506	167	511	624	29.34	0.15	53.47
White Rock Creek	173	148	988	1,510	1.53	3.26	91.04
Undeveloped sites							
Buffalo River	153	344	2	1	93.01	3.99	2.18
Clear Creek	763	183	6	8	13.23	17.04	4.66
Frio River	1,028	372	1	1	47.45	0.1	0.19
North Sylamore	150	169	2	2	94.92	1.49	2.78
Whisky Chitto Creek	1,305	15	17	4	49.63	2.81	5.4
Mixed sites							
Chambers Creek	2,136	109	28	37	12.4	36.31	7.42
Mermentau River	3,576	1	33	35	7.32	57.38	7.34
San Antonio River	4,528	121	247	289	34.36	8.35	21.42
Trinity River	16,227	119	176	227	12.79	14.62	20.95
Wolf River	543	162	8	7	42.8	28.52	3.57
Yazoo River	34,850	72	16	17	22.36	50.04	5.52

Whisky Chitto Creek, Wolf River, Yazoo River, and Yocum Creek are located in the Eastern Temperate Forests Level I ecoregion; whereas Chambers Creek, Clear Creek, Frio River, Mermentau River, Salado Creek, San Antonio River, Trinity River, and White Rock Creek are located in the Great Plains Level I ecoregion (Commission for Environmental Cooperation, 1997). Average annual precipitation and temperature from 1990–2007 at the sites located in the Eastern Temperate Forests Level I ecoregion was 134.5 cm and 16.7°C, respectively (<http://www.prism.oregonstate.edu>, accessed April 2008). The sites in the Great Plains Level I ecoregion were generally drier and warmer than those in the Eastern Temperate Forests Level I ecoregion, with an average annual precipitation and temperature of 90.4 cm and 19.4°C, respectively. Each site was classified based on dominant land use in the watershed (Gilliom et al., 2006; <http://landcover.usgs.gov/uslandcover.php>, Table 1). Specifically, sites were classified as agricultural (>50% agricultural land and ≤5% urban land), urban (>25% urban land and ≤25% agricultural land), undeveloped (≤5% urban land and ≤25% agricultural land), or mixed (all

other combinations of agricultural, urban, and undeveloped land). All sites are low elevation (1–372 m above sea level) with drainage areas ranging from 134 to 34,850 km<sup>2</sup> (Table 1). Population density data are available for 1990 and 2000 and there was not a consistent change in density among the 15 sites. In 2000, population density was lowest at the undeveloped sites (1–8 people/km<sup>2</sup>), followed by agricultural sites (14–20 people/km<sup>2</sup>), mixed sites (7–289 people/km<sup>2</sup>), and urban sites (624–1,510 people/km<sup>2</sup>) (U.S. Census Bureau, 1991, 2000).

#### Data collection

All data, with the exception of climate data (temperature and precipitation), were collected between 1993 and 2007 with a consistent study design and uniform methods of data collection as part of the USGS NAWQA Program (Cuffney et al., 1993; Meador et al., 1993a; Porter et al., 1993; Fitzpatrick et al., 1998; Moulton et al., 2002). Each of the 15 study sites had a minimum time series of 5 years of biologic data (algae, invertebrates, and fish; Table 2). It has been



**Fig. 1** Map showing the locations of the 15 sample sites in the south-central U.S. Dominant land use in the basin at each site is indicated by the color of the symbol. Also shown are the Level 1 ecoregions in the study area

suggested that 5 years is the minimum amount of data required to detect temporal trends in ecological data (Jackson & Füreder, 2006).

#### *Aquatic biota sampling*

Algae samples were collected from either cobbles or snags depending on the availability of coarse bed material. Cobbles or snags were collected from five locations within the study reach, scraped with a brush to remove algal cells, and measured to calculate the area sampled. Samples from the five locations were composited to form a single sample. Algae were identified to the lowest practical taxonomic level and enumerated by the Phycology Section of the Academy of Natural Sciences in Philadelphia, Pennsylvania (Charles et al., 2002).

Benthic invertebrate samples were collected from either riffles or snags. At sites containing riffles, five samples were collected, each from an area of 0.25 m<sup>2</sup> using a Slack sampler (500 μm mesh). The five

subsamples were combined to form a single composite sample (total area sampled = 1.25 m<sup>2</sup>). At sites that lacked riffle habitat, well-conditioned woody debris (snag samples) were sampled. Snag samples were collected by removing a section of snag with lopping shears or a saw while holding the slack sampler under the snag to collect any dislodged invertebrates. Benthic invertebrates were removed by gently brushing and rinsing the snag into the slack sampler and complemented with visual inspection. Five snag samples were collected at each site and all benthic invertebrates collected were combined to form a single composite sample. Snags were measured to calculate the area sampled. Benthic invertebrate samples were sent to the USGS National Water Quality Laboratory in Denver, Colorado where they were identified to the lowest practical taxonomic level and enumerated (Moulton et al., 2000).

The fish assemblage at each site was sampled with a combination of electrofishing and seining. Electro-fishing techniques varied between sites and included

**Table 2** Flow record and years of biological sampling for the 15 sample sites

Site name	Flow record	Years of biological community sampling														
		1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
<b>Agricultural sites</b>																
Bogue Phalia	1996–2007				C	C	C	C						A	A, F	
Yocum Creek	1994–2007	C	C	C		C	C					C	C	A, I	C	A, I
<b>Urban sites</b>																
Salado Creek	1988–2007				C	C	C							A, I	C	
White Rock Creek	1995–2007				C	C	I, F							A, I	C	I, F
<b>Undeveloped sites</b>																
Buffalo River	1993–2007	C	C	C												
Clear Creek	1988–2007		C	C		C								A, I		I, F
Frio River	1988–2007				C	C	C								C	
North Synamore	1992–2007	C	C	C		C	C							A, I	C	A, I
Whisky Chitto Creek	1997–2007							C	A, I					I	C	I
<b>Mixed sites</b>																
Chambers Creek	1988–2007	C	C	C										A, I		
Mermentau River	1990–2007							C	A, I					I	C	
San Antonio River	1988–2007				C	A, I	C									
Trinity River <sup>a</sup>	1988–2007	C	C	A, I		C	I, F							A, I	C	
Wolf River	1996–2007				C	C	C								C	
Yazoo River	1996–2007				C	C	C	I, F						A	A, F	

C complete sample (algae, invertebrates, and fish), A algae, I invertebrates, F fish

<sup>a</sup> The primary sampling reach on the Trinity River was moved after 1998 due to bridge construction and the analysis used only samples from after 1998

backpack, towed barge, or boat mounted electrofishing units, depending on water depth and conductivity. All electrofishing sampling efforts utilized pulsed-direct current with power output adjusted for water conductivity. Fish were collected from all habitat types within the study reach utilizing a two pass method. Supplemental seining was done with either a flat or bag seine with a 6.4-mm mesh to capture species that evaded electrofishing. Fish were identified, enumerated, weighed, and measured on site before being released unharmed back into the stream.

#### *Climate, water quality, streamflow, and physical habitat variable sampling*

Daily air temperature data were obtained for each site from the nearest National Oceanic and Atmospheric Administration weather observation station (<http://www.ncdc.noaa.gov/oa/climate/research.html>, accessed March 2008). Monthly precipitation estimates were derived from data developed by Oregon State University's Parameter-elevation Regressions on Independent Slopes Model (PRISM) of the conterminous United States (<http://www.prism.oregonstate.edu>, accessed April 2008). Nitrite + nitrate ( $\text{NO}_2 + \text{NO}_3$ ) and phosphorus concentration data were obtained from the USGS National Water Information System (NWIS) database (<http://waterdata.usgs.gov/nwis>, accessed April 2008). Daily stream discharge data were also acquired from NWIS (<http://waterdata.usgs.gov/nwis>, accessed April 2008), and periods of record available for analysis ranged from 12 to 20 years (Table 2). At each site physical habitat data, including geomorphic channel units (pools, riffles, runs), wetted channel width and depth, bankfull width and depth, substrate, embeddedness, riparian canopy closure, and hydraulic radius were measured at six equally spaced transects in each reach prior to 1998 (Meador et al., 1993b) and eleven equally spaced transects in each reach from 1998–2007 (Fitzpatrick et al., 1998).

#### Data processing

##### *Aquatic biota data processing*

Algal abundance data were converted to densities (cells/ $\text{cm}^2$ ) and a broad set of metrics were calculated using the

USGS Algal Data Analysis System software (ADAS; Cuffney&Brightbill, written communication). Algal assemblage samples often contained numerous taxa that comprised only a small fraction of the total community at a site which may confound trend analyses. Therefore, algal trend analyses at each site utilized only taxa that comprised at least two percent of the algal assemblage at that site. Algal assemblage metrics calculated were those identified by Porter et al. (2008) and included metrics based on richness, saprobity, organic nitrogen tolerance, ability to fix atmospheric nitrogen, trophic preference, pollution tolerance, salinity tolerance, pH tolerance, benthic/sestonic, motility, and oxygen tolerance. Redundant assemblage metrics (Spearman's rank correlation coefficient ( $\rho$ ) > 0.70) were eliminated prior to statistical analyses.

Invertebrate assemblage data were aggregated to the taxonomic level of genus to reduce disparities in taxonomic resolution between samples, and abundance data were converted to densities (individuals/ $\text{m}^2$ ). A broad set of assemblage metrics, including those based on community composition, life history, mobility, morphology, and ecology, were calculated using the USGS Invertebrate Data Analysis System software (IDAS; Cuffney, 2003). Ambiguities were resolved by keeping samples separate and distributing parents among children, which represents a compromise between removing redundant taxonomic information and conserving quantitative information on taxa richness and abundance (Cuffney et al., 2007). A further set of assemblage metrics describing functional traits associated with benthic invertebrate life history, mobility, morphology, and ecology (Poff et al., 2006) were also calculated for each sample. Redundant assemblage metrics ( $\rho$  > 0.70) were eliminated prior to statistical analyses.

Fish metrics were derived from fish abundance data, and fish taxa were combined into predominant groups for analysis of community composition. Fish status (native, endemic, or introduced) was determined based on freshwater fish information from Froese & Pauly (2009). Fish tolerance designations were compiled using the U.S. Environmental Protection Agency (EPA) Rapid Bioassessment Protocols (Barbour et al., 1999), which include a descriptive tolerance (intolerant, intermediate or moderate, and tolerant) classification for individual fish species relevant to non-specific stressors. Six fish species traits described by Goldstein & Meador (2004) were

used to describe fish assemblages. Some of the trophic ecology, substrate and geomorphic preference, and reproductive strategy metrics were combined to reduce the overall number of metrics. Redundant assemblage metrics ( $\rho > 0.70$ ) were eliminated prior to statistical analyses.

#### *Climate, water quality, streamflow, and physical habitat variable data processing*

Air temperature and precipitation data were used to calculate climate metrics. Specifically, values for average air temperature were calculated for 30 and 90 days prior to biological sampling to evaluate the effects of recent temperature conditions on biological assemblages (Table 3). Precipitation values were calculated for the entire water year and for the 3 months (April, May, and June) preceding the start of the sampling season (spring). The time frames used to generate climate, water quality, and streamflow metrics were chosen to represent what are expected to be biologically relevant time frames.

Nitrate concentration data were modeled to generate water quality metrics. Average  $\text{NO}_2 + \text{NO}_3$  concentrations 30 and 90 days prior to biological sampling were estimated using the USGS Load Estimator (LOADEST) software (Runkel et al., 2004). Phosphorus, which is frequently a limiting nutrient in aquatic ecosystems, was not modeled due to a high number of censored data points (concentrations less than the instrument detection limit). LOADEST regression models, using streamflow and time as independent variables, were developed for each site to estimate daily loads in  $\text{NO}_2 + \text{NO}_3$  concentrations. Regression models were then used in conjunction with flow records to estimate daily  $\text{NO}_2 + \text{NO}_3$  concentrations over the assessment period for each site, and to calculate the average estimated concentrations for 30 and 90 days prior to biotic sampling (Table 3).

Stream discharge data were processed with the Indicators of Hydrologic Alteration (IHA) software to calculate streamflow metrics (Richter et al., 1996) and to characterize streamflow in terms of magnitude, frequency, duration, timing, and rate of change. A set of streamflow metrics, chosen based on prior experience and best professional judgment, were calculated for 30 and 90 days prior to each biological sampling event. Spearman rank correlation was used to identify highly correlated metrics ( $\rho > 0.7$ ) and reduce the

overall number of streamflow metrics used in the analysis to eight relatively non-redundant metrics (Table 3).

The number of physical habitat variables retained for use in statistical analyses was reduced by starting with the subset listed in Kennen et al. (in review). Of these variables, only those for which data were available at all sites were retained. It was often the case that habitat data were not collected on the same date as the biotic samples. Therefore, habitat data collected during the same year as the biotic samples (generally within 1–2 weeks) were used. At some sites, habitat data were not collected in all years that biotic samples were collected.

#### Statistical analyses

##### *Temporal trends in aquatic assemblages*

Temporal trends in aquatic assemblages (algae, invertebrates, and fish) were investigated at each of the 15 sites using a multivariate statistical approach. Algae density, invertebrate density, and fish abundance data were imported into the statistical software package Plymouth Routines In Multivariate Ecological Research (PRIMER v6; Clarke & Gorley, 2006). Density (algae and invertebrates) and abundance (fish) data were standardized by total density or abundance, respectively, and square root transformed prior to generation of Bray-Curtis similarity resemblance matrices. The aquatic assemblage resemblance matrices were then represented as non-metric multidimensional (NMDS) ordination plots. In NMDS plots, sites that plot closer together to one another have more similar aquatic assemblages. The effectiveness of the NMDS plots in representing the temporal relation at a given site was assessed through calculation of a two-dimensional stress value. Clarke & Warwick (2001) suggest that stress values less than 0.05 indicate an excellent representation of the temporal relations, values between 0.05 and 0.1 indicate a good representation, and values greater than 0.3 indicate that the points in the ordination could occur randomly. The statistical significance of temporal changes in aquatic assemblages at each site was tested using PRIMER's non-parametric seriation procedure known as "relate" (Clarke & Gorley, 2006; Clarke et al., 2006).

**Table 3** Environmental (climate, water quality, and streamflow) metrics and physical habitat variables used to investigate potential temporal relations with aquatic assemblages

Variable (units)	Variable abbreviation
Climate metrics	
Average air temperature for 30 days prior to sampling (°F)	Temp30a
Average air temperature for 90 days prior to sampling (°F)	Temp90a
Total estimated precipitation for water year (Oct 1–Sept 30) (mm)	PY
Total estimated precipitation for spring season (April 1–June 30) (mm)	PS
Water quality metrics	
Average estimated NO <sub>2</sub> + NO <sub>3</sub> concentration – 30 days prior to sampling (mgN/l)	N30a
Average estimated NO <sub>2</sub> + NO <sub>3</sub> concentration – 90 days prior to sampling (mgN/l)	N90a
Streamflow metrics	
Average discharge for 30 days prior to sampling (cfs)	F30a
Median discharge for 30 days prior to sampling (cfs)	F30m
Coefficient of variation for average discharge for 30 days prior to sampling	F30cv
Average discharge for 90 days prior to sampling (cfs)	F90a
Median discharge for 90 days prior to sampling (cfs)	F90 m
Coefficient of variation for average discharge for 90 days prior to sampling	F90cv
Number of days since discharge $\geq 2 \times$ median flow (days)	2mQ
Number of days since discharge $\geq 3 \times$ median flow (days)	3mQ
Physical habitat variables	
Mean wetted channel width (m)	Wwidth
Coefficient of variation of wetted channel width	WidthCV
Mean wetted channel depth (cm)	Depth
Coefficient of variation of wetted channel depth	DepthCV
Mean wetted channel width-depth ratio of reach	Width/Depth
Relative proportion where the dominant substrate is boulder (%)	Bould
Relative proportion where the dominant substrate is sand (%)	Sand
Relative proportion where the dominant substrate is silt or clay (%)	Silt
Relative proportion where the dominant substrate is cobble (%)	Cob
Percent occurrence of bank erosion (%)	BankEros
Mean open canopy angle (°)	OpenCan
Coefficient of variation of open canopy angle	OpenCanCV
Mean perimeter of wetted channel (m)	WetPer
Mean wetted channel shape	WetArea
Mean wetted channel hydraulic radius	HydRad

*Associations among aquatic assemblage and assemblage metrics, environmental metrics, and physical habitat variables*

At sites where there was a statistically significant temporal trend in the aquatic assemblage of a biotic group ( $P < 0.05$ ), the subset of assemblage metrics (Table 4), environmental metrics (climate, water

quality, and streamflow metrics), and physical habitat variables that best explain the variation in the aquatic assemblages were identified. Assemblage metrics identified in this way provide insight into which components of the aquatic assemblages are related to the overall temporal change in the aquatic assemblages. Similarly, environmental metrics and physical habitat variables identified as explaining the variation



**Table 4** Algae, invertebrate, and fish assemblage metrics derived for the 15 sample sites

Metric	Abbreviation
Algae metrics	
Green Algae (Chlorophytes)	GREEN
Polysaprobous diatoms (O <sub>2</sub> saturation: <10%)	LowOx
Autotrophic diatoms intolerant of organically bound nitrogen	IntolON
Taxa capable of fixing atmospheric nitrogen	NitFix
Oligotrophic diatoms	Olig
Diatoms very tolerant to nutrient/organic enrichment	MorTol
Diatoms less tolerant to nutrient/organic enrichment	LessTol
Fresh-brackish water diatoms (<0.9 ppt salinity)	FreshBrack
Sestonic algae	Sest
Non-motile algae	NonMot
Invertebrate metrics	
EPT taxa	EPT
Coleoptera taxa	COLEOP
Diptera taxa	DIP
Non-insect taxa	NONINS
Adult life span <1 month	Life
Rare in drift	RareDrift
Abundant in drift	AbunDrift
Respire with Gills	RespGill
Burrowers	Burrow
Skaters	Skate
Fish metrics	
Herbivores	Herb
Carnivores	Carn
Prefer rocky substrates	Rock
Prefer vegetation	Veg
Prefer pools and backwaters	PoBa
Tolerant to pollution	Tol
Introduced species	Intro

Only those assemblage metrics identified by BVSTEP as explaining a significant amount of temporal variation in the aquatic assemblage time series are listed. All metrics are in units of percent of total density (algae and invertebrates) or abundance (fish)

in aquatic assemblages represent likely abiotic drivers of change in the aquatic assemblages. Assemblage metrics data were square root transformed, while

environmental metrics and physical habitat variables were fourth root transformed. Following transformation, assemblage metrics, environmental metrics, and physical habitat variables were standardized to a mean of zero and standard deviation of one prior to generation of resemblance matrices based on Euclidian distance. The subset of assemblage metrics, environmental metrics, and physical habitat variables that were most strongly correlated with the underlying aquatic assemblage resemblance matrices were identified using the PRIMER routines known as BVSTEP (assemblage metrics; Clarke & Warwick, 1998) and BIOENV (environmental metrics and physical habitat variables; Clarke & Ainsworth, 1993). BVSTEP and BIOENV compare the aquatic assemblage matrix with the assemblage metrics or environmental metrics and physical habitat similarity matrices, respectively, using Spearman rank correlations. BVSTEP uses a stepwise approach, whereas BIOENV compares the aquatic assemblage matrix with environmental and physical habitat matrices constructed with all possible subsets of environmental metrics or physical habitat variables. The subset of assemblage metrics, environmental metrics, and physical habitat variables that produce the highest  $\rho$  values are then identified. The subsets of physical habitat variables that best explain the temporal variation in the aquatic assemblages were identified separately from the subsets of environmental metrics that best explain the temporal variation in the aquatic assemblages because the physical habitat data were not collected on all dates for which biotic samples and the environmental metrics were collected.

Monotonic (generally increasing or decreasing with time) or non-monotonic (not consistently increasing or decreasing with time) temporal trends in the assemblage metrics, environmental metrics, and physical habitat variables identified using BVSTEP and BIOENV were determined by investigating the time series plots of each metric/variable. At sites where a monotonic relation was present, the direction and magnitude of temporal change in the aforementioned metrics/variables were investigated through calculation of Kendall's tau correlation coefficients (Helsel & Hirsch, 1992). It should be noted that this approach simply tests the null hypothesis that there is not a monotonic change in a given metric/variable over time, but does not provide an estimate of the rate of change (i.e., a slope).

## Results

Statistically significant temporal trends in aquatic assemblages were identified at eight of the 15 sites (Table 5), including significant trends in algal assemblages at four sites, invertebrate assemblages at four sites, and fish assemblage at one site. The two-dimensional stress values were less than 0.1 at 7 of 8 sites with statistically significant temporal trends in aquatic assemblages (Table 5); indicating that the NDMS plots provide good representations of the temporal relations in aquatic assemblages. The only site with statistically significant temporal trends in more than one biotic group (algae and invertebrates) was North Sylamore Creek. The results presented below summarize the statistically significant temporal trends in aquatic assemblages in each land use category. In addition, assemblage metrics, environmental metrics, and physical habitat variables that were most strongly correlated with the aquatic

assemblages at the eight sites with statistically significant temporal trends in aquatic assemblages are identified.

### Agricultural sites

Of the two agricultural sites, the only site with a significant temporal trend in aquatic assemblage was the algal assemblage at Yocum Creek (Table 5). No significant trends in the invertebrate or fish assemblages were found at any of the agricultural sites. Statistically significant relations were not found between any subset of algal assemblage metrics and the algal assemblage resemblance matrix at Yocum Creek (Table 6).

The subset of environmental metrics that most strongly correlated with the underlying algal assemblage resemblance matrix at Yocum Creek include the average  $\text{NO}_2 + \text{NO}_3$  concentration and the median discharge 30 days prior to sampling (N30a and F30m,

**Table 5** Results of the PRIMER seriation trend analysis of aquatic assemblage data for algae, benthic invertebrates, and fish from 15 sample sites

Site name	Benthic algae			Benthic invertebrates			Fish		
	$\rho$	$P$	2D stress value	$\rho$	$P$	2D stress value	$\rho$	$P$	2D stress value
Agricultural sites									
Bogue Phalia	0.20	0.154	–	0.23	0.158	–	0.30	0.064	–
Yocum Creek	<b>0.74</b>	<b>&lt;0.001</b>	0.05	0.25	0.063	–	0.22	0.120	–
Urban sites									
Salado Creek	<b>0.40</b>	<b>0.041</b>	0.06	0.23	0.123	–	0.09	0.375	–
White Rock Creek	0.26	0.172	–	<b>0.39</b>	<b>0.034</b>	0.07	0.35	0.062	–
Undeveloped sites									
Buffalo River	0.50	0.052	–	<b>0.68</b>	<b>0.005</b>	0.00	0.12	0.338	–
Clear Creek	0.33	0.141	–	<b>0.40</b>	<b>0.040</b>	0.02	0.18	0.786	–
Frio River	<b>0.49</b>	<b>0.042</b>	0.07	0.02	0.429	–	0.01	0.503	–
North Sylamore	<b>0.56</b>	<b>0.002</b>	0.07	<b>0.38</b>	<b>0.004</b>	0.16	0.27	0.088	–
Whisky Chitto	0.34	0.125	–	0.19	0.768	–	0.22	0.246	–
Mixed sites									
Chambers Creek	0.08	0.384	–	0.09	0.375	–	NA	NA	–
Mermentau River	0.37	0.100	–	0.50	0.051	–	0.33	0.180	–
San Antonio River	0.31	0.203	–	0.09	0.367	–	NA	NA	–
Trinity River	0.20	0.312	–	0.03	0.546	–	NA	NA	–
Wolf River	0.21	0.226	–	0.20	0.766	–	0.01	0.514	–
Yazoo River	0.17	0.191	–	0.18	0.774	–	<b>0.34</b>	<b>0.043</b>	0.03

Spearman's rank correlation coefficient ( $\rho$ ),  $P$  values, and two-dimensional stress values associated with the NMDS plots are shown. Statistically significant trends ( $P < 0.05$ ) are presented in bold. NA indicates that there are insufficient data for analysis

**Table 6** Ecological response modeling results (PRIMER BVSTEP) correlating assemblage metrics to the underlying aquatic assemblage resemblance matrix for algae, invertebrates, and fish

Site name	Metrics			$\rho$	$P$
	Increasing trend	Non-monotonic	Decreasing trend		
<i>Algae</i>					
Agricultural sites					
Yocum Creek	NS			–	–
Urban sites					
Salado Creek	GREEN, LowOx, MorTol, Sest**	LessTol, NonMot	IntolON	0.94	0.001
Undeveloped sites					
Frio River	Sest, NonMot	–	MorTol, FreshBrack	0.85	0.037
North Sylamore	–	–	NitFix**	0.65	0.011
<i>Invertebrates</i>					
Urban sites					
White Rock Creek	EPT, RespGill*	DIP, NONINS	COLEOP*	0.86	0.002
Undeveloped sites					
Buffalo River	NS			–	–
Clear Creek	–	Life, RareDrift	–	0.89	0.008
North Sylamore	COLEOP*, AbunDrift, RespGill, Burrow, Skate	NONINS	–	0.74	0.004
<i>Fish</i>					
Mixed sites					
Yazoo River	–	Herb, Intro	Rock, Carn*, Veg*, PoBa, Tol	0.94	0.001

Spearman's rank correlation coefficient ( $\rho$ ) and  $P$  values are shown. Only those sites where there was a statistically significant temporal trend in the aquatic assemblage are shown. Assemblage metrics listed in the table are the subset of metrics that were most strongly correlated with the underlying aquatic assemblage resemblance matrix. NS indicates that there was not a statistically significant correlation between any subset of the assemblage metrics and the aquatic assemblage resemblance matrix ( $P < 0.05$ ). The direction of the temporal trend (increasing, non-monotonic, or decreasing) and statistical significance of the temporal trend ( $*P < 0.05$ ;  $**P < 0.01$ ), as measured by Kendall's tau, of each metric are also indicated

respectively; Table 7). N30a had a non-monotonic temporal trend, whereas F30m decreased significantly over time. There was not a statistically significant relation between any subset of the physical habitat variables and the algal assemblage at Yocum Creek (Table 8).

#### Urban sites

Both of the urban sites had statistically significant temporal changes in aquatic assemblages (Table 5). There was a statistically significant temporal change in algal assemblage at Salado Creek, where seven algal assemblage metrics, including the percent of green algae (GREEN), the percent of polysaprobous diatoms that tolerate  $O_2$  saturation  $<10\%$  (LowOx), the percent of diatoms intolerant of organically bound nitrogen (IntolON), the percent of diatoms very tolerant to

nutrient/organic enrichment (MorTol), the percent of diatoms not tolerant of nutrient/organic enrichment (LessTol), the percent of algae that are sestonic (Sest), and the percent of algae that are non-motile (NonMot), were identified as the subset of assemblage metrics that most strongly correlated with the algal assemblage (Table 6). GREEN, LowOx, MorTol, and Sest increased with time. Of these four metrics, the only statistically significant ( $P < 0.01$ ) increase with time was for Sest. LessTol and NonMot had non-monotonic temporal trends at Salado Creek, and IntolON decreased with time.

Three environmental metrics, including the average  $NO_2 + NO_3$  concentration for the 90 days prior to sampling (N90a), the average discharge for the 90 days prior to sampling (F90a), and the coefficient of variation for average discharge for the 30 days prior to sampling (F30cv), were identified as the subset of

**Table 7** Ecological response modeling results (PRIMER BIOENV) correlating environmental variables (climate, water quality, and streamflow) to the underlying aquatic assemblage resemblance matrix for algae, invertebrates, and fish

Site name	Variables			$\rho$	<i>P</i>
	Increasing trend	Non-monotonic	Decreasing trend		
<i>Algae</i>					
Agricultural sites					
Yocum Creek	–	N30a	F30m*	0.69	0.002
Urban sites					
Salado Creek	N90a	–	F90a, F30cv	0.70	0.042
Undeveloped sites					
Frio River	NS			–	–
North Sylamore	NS			–	–
<i>Invertebrates</i>					
Urban sites					
White Rock Creek	F90a, F30cv*	–	–	0.66	0.033
Undeveloped sites					
Buffalo River	NS			–	–
Clear Creek	Temp90a	N90a, F90a	–	0.82	0.007
North Sylamore	NS			–	–
<i>Fish</i>					
Mixed sites					
Yazoo River	NS			–	–

Spearman's rank correlation coefficient ( $\rho$ ) and *P* values are shown. Only those sites where there was a statistically significant temporal trend in the aquatic assemblage are shown. Variables listed in the table are the subset of environmental variables that were most strongly correlated with the underlying aquatic assemblage resemblance matrix. NS indicates that there was not a statistically significant correlation between any subset of the environmental variables and the aquatic assemblage resemblance matrix ( $P < 0.05$ ). The direction of the temporal trend (increasing, non-monotonic, or decreasing) and statistical significance of the temporal trend ( $*P < 0.05$ ), as measured by Kendall's tau, of each variable are also indicated

environmental metrics most strongly correlated with the algal assemblage at Salado Creek (Table 7). N90a increased with time, whereas F90a and F30cv decreased with time. Statistically significant relations were not found between any subset of physical habitat variables and the algal assemblage at Salado Creek (Table 8).

Invertebrate assemblages showed a statistically significant temporal trend at White Rock Creek (Table 5). At this site, the percent of taxa classified as Ephemeroptera, Plecoptera, or Trichoptera (EPT), the percent of taxa classified as Coleoptera (COLEOP), the percent of taxa classified as Diptera (DIP), the percent of taxa classified as non-insects (NONINS), and the percent of taxa that respire with gills (RespGill), were identified as the subset of invertebrate assemblage metrics most strongly correlated with the invertebrate assemblage (Table 6). EPT and

RespGill increased with time, DIP and NONINS had non-monotonic temporal trends, and COLEOP decreased with time. Of these assemblage metrics, there was a statistically significant ( $P < 0.05$ ) temporal increase in RespGill and a statistically significant ( $P < 0.05$ ) temporal decrease in COLEOP.

At White Rock Creek that average discharge for the 90 days prior to sampling (F90a) and the coefficient of variation for average discharge for the 30 days prior to sampling (F30cv) were the subset of environmental metrics that were most strongly correlated with the invertebrate assemblage (Table 7). Both F90a and F30cv increased with time, and the temporal change in F30cv was statistically significant ( $P < 0.05$ ). Statistically significant relations were not found between any subset of physical habitat variables and the invertebrate assemblage at White Rock Creek.

**Table 8** Ecological response modeling results (PRIMER BIOENV) correlating physical habitat variables to the underlying aquatic assemblage resemblance matrix for algae, invertebrates, and fish

Site name	Variables			$\rho$	$P$	Years analyzed
	Increasing trend	Non-monotonic	Decreasing trend			
<i>Algae</i>						
Agricultural sites						
Yocum Creek	NS			–	–	93, 97, 98, 02-07
Urban sites						
Salado Creek	NS			–	–	96, 98, 02-06
Undeveloped sites						
Frio River	DepthCV*, Bould, WetPer	–	–	0.86	0.043	96, 98, 02-04, 06
North Sylamore	–	–	Cob	0.67	0.016	93, 97, 98, 02-07
<i>Invertebrates</i>						
Urban sites						
White Rock Creek	NS	–	–			97, 98, 02-07
Undeveloped sites						
Buffalo River	Not analyzed; < 5 years of habitat data					
Clear Creek	NS			–	–	97, 02-05, 07
North Sylamore	NS			–	–	93, 97, 98, 02-07
<i>Fish</i>						
Mixed sites						
Yazoo River	NS			–	–	97, 99, 02-04, 06

Analyses were conducted at sites with a minimum of 5 years of habitat data collected during the same year as the biotic data. Spearman's rank correlation coefficient ( $\rho$ ) and  $P$  values are shown. Variables listed in the table are the subset of physical habitat variables that were most strongly correlated with the underlying aquatic assemblage resemblance matrix. NS indicates that there was not a statistically significant correlation between any subset of physical habitat variables and the corresponding aquatic assemblage resemblance matrix ( $P < 0.05$ ). The direction of the temporal trend (increasing, non-monotonic, or decreasing) and statistical significance of the temporal trend ( $*P < 0.05$ ), as measured by Kendall's tau, of each variable are also indicated

#### Undeveloped sites

Four of the five undeveloped sites showed statistically significant temporal changes in aquatic assemblages (Table 5). Algal assemblages showed a statistically significant temporal trend at the Frio River and North Sylamore Creek. Four algal assemblage metrics, including the percent of algae that are sestonic (Sest), the percent of algae that are non-motile (NonMot), the percent of diatoms that are tolerant to nutrient/organic enrichment (MorTol), and the percent of diatoms that prefer fresh-brackish water habitats (FreshBrack), were identified as the subset of algal assemblage metrics that were most strongly correlated with the algal assemblage at the Frio River (Table 6). Sest and NonMot increased with time, while MorTol and FreshBrack decreased with time. At North Sylamore Creek, the percent of algal taxa capable of fixing

atmospheric nitrogen (NitFix) was identified as the assemblage metric most strongly correlated with the algal assemblage, and showed a statistically significant ( $P < 0.01$ ) decrease with time.

Statistically significant relations were not found between any subset of environmental metrics and the algal assemblage at the Frio River or North Sylamore Creek (Table 7). However, three physical habitat variables, including the coefficient of variation of wetted channel depth (DepthCV), the percent of substrate dominated by boulders (Bould), and the mean wetted channel perimeter (WetPer), were identified as the subset of physical habitat variables most strongly correlated with the algal assemblage the Frio River (Table 8). There was a monotonic increase in the values of all three physical habitat variables, and there was a statistically significant temporal increase in DepthCV. At North Sylamore Creek only the

percent of substrate dominated by cobbles (Cob) was found to be strongly correlated with the algal assemblage, and decreased with time.

Invertebrate assemblages showed statistically significant temporal trends at three of the five undeveloped sites, including the Buffalo River, Clear Creek, and North Sylamore Creek (Table 5). There was not a statistically significant relation between any subset of invertebrate assemblage metrics and the invertebrate assemblage at the Buffalo River (Table 6). At Clear Creek, the percent of invertebrate taxa that have an adult life span less than 1 month (Life) and the percent of invertebrate taxa that are rare in drift (RareDrift) were identified as the subset of invertebrate assemblage metrics most strongly correlated with the invertebrate assemblage. Both Life and RareDrift had non-monotonic temporal trends. Six invertebrate assemblage metrics, including percent coleopterans (COLEOP), percent of taxa abundant in drift (AbunDrift), percent of taxa that respire with gills (RespGill), percent of taxa that are burrowers (Burrow), percent of taxa that are skaters (Skate), and percent of non-insect taxa (NONINS), were identified as the subset of assemblage metrics that most strongly correlated with the invertebrate assemblage at North Sylamore Creek. NONINS had a non-monotonic trend, whereas the other five metrics increased with time. Of the five invertebrate assemblage metrics that increased with time at North Sylamore Creek, COLEOP was the only metric with a statistically significant ( $P < 0.05$ ) increase.

Statistically significant relations were not found between any subset of environmental metrics and the invertebrate assemblage at the Buffalo River or North Sylamore Creek (Table 7). Three environmental metrics, including the average air temperature for 90 days prior to sampling (Temp90a), the average  $\text{NO}_2 + \text{NO}_3$  concentration 90 days prior to sampling (N90a), and the average discharge 90 days prior to sampling (F90a), were identified as the subset of environmental metrics that most strongly correlated with the invertebrate assemblage at Clear Creek. Temp90a increased with time, whereas N90a and F90a had a non-monotonic temporal trend. The relation between physical habitat variables and the underlying invertebrate assemblage resemblance matrix was not investigated at the Buffalo River due to data limitations (Table 8). Statistically significant relations were not found between any subset of physical habitat

variables and the invertebrate assemblages at Clear Creek or North Sylamore Creek.

### Mixed sites

Of the six mixed land use sites, only the Yazoo River site showed a trend, with the fish assemblage appearing to have changed significantly with time (Table 5). The Yazoo River is also the only site of all 15 included in this study where a statistically significant temporal change in the fish assemblage was found. The subset of fish assemblage metrics that were most strongly correlated with the fish assemblage at the Yazoo River includes seven metrics (Table 6). Of these seven assemblage metrics, the percent of herbivorous fish (Herb) and introduced fish (Intro) had a non-monotonic temporal trend. The percent of fish that prefer rocky substrates (Rock), are carnivorous (Carn), prefer vegetation (Veg), prefer pools and backwaters (PoBa), and are tolerant to pollution (Tol) all decreased with time in the Yazoo River. Of these five assemblage metrics, Carn and Veg showed statistically significant ( $P < 0.05$ ) decreases over time. Statistically significant relations were not found between any subset of environmental metrics or physical habitat variables and the fish assemblage at the Yazoo River (Tables 7, 8).

## Discussion

A systematic multivariate approach to the analysis of biotic and abiotic data has proven to be an effective method for identifying site-specific temporal trends in aquatic assemblages. This approach was also able to identify subsets of assemblage metrics that represent the overall change in the aquatic assemblages, as well as environmental metrics and physical habitat variables that are correlated with the aquatic assemblages in streams and rivers in the south-central U.S. Moreover, this approach has provided insights into differences in abiotic–biotic correlations as a function of land use.

Investigation of algal assemblages and their correlations with algal assemblage metrics, environmental metrics, and physical habitat variables in three different land use settings highlights the importance of land use in determining the nature of the association between algal assemblages and abiotic environmental

conditions. The statistically significant correlations between algal assemblages and decreasing median discharge, average discharge, and flow variability at Yocum Creek (agricultural site) and Salado Creek (urban site), and increasing average nitrogen concentrations at Salado Creek (Table 7) indicate that changes in these streamflow and nutrient metrics may be important drivers of temporal change in algal assemblages at these sites. While no subset of algal assemblage metrics was identified as being significantly correlated with the algal assemblage at Yocum Creek, the temporal change in the algal assemblage at Salado Creek was represented by temporal changes in algal assemblage metrics that indicate potential eutrophication (Table 6; increases in the percent of green algae, diatoms tolerant of low oxygen and nutrient/organic enrichment, and sestonic algae, and a decrease in the percent of diatoms intolerant of organically bound nitrogen). The observed correlation between increasing nitrogen concentrations and the algal assemblage, represented by the aforementioned algal metrics, is consistent with the findings of other studies that increasing nutrient concentrations have the potential to result in eutrophic conditions that favor algal taxa tolerant of such conditions (McCormick et al., 1996; Köhler & Hoeg, 2000; Porter et al., 2008; Black et al., 2010). Moreover, it is possible that the increasing nitrogen concentrations at Salado Creek were caused, in part, by concentration effects due to decreasing discharge.

In contrast to the streamflow metrics and nutrient concentrations that are correlated with algal assemblages at agricultural and urban sites, physical habitat variables were shown to be the only abiotic variables correlated with algal assemblages at undeveloped sites. At the Frio River, increases in channel dimensions (depth variability and wetted perimeter) and the percent of substrate composed of large substrate favored non-motile and sestonic algae. At North Sylamore Creek, decreases in the percent of substrate composed of cobbles was significantly correlated with the algal assemblage, as was the percent of algal taxa capable of fixing atmospheric nitrogen. The statistically significant decrease in the percent of taxa capable of fixing atmospheric nitrogen could be an indication that the concentrations of dissolved biologically available nitrogen are increasing at North Sylamore Creek. Peterson & Grimm (1992) reported that environments enriched with nitrate favored

non nitrogen-fixing diatoms, whereas unenriched environments favored diatoms capable of nitrogen fixation. Alternatively, it is possible that the decrease in nitrogen-fixing taxa could be attributed to a temporal change from nitrogen limitation, which would favor nitrogen-fixing algae, to phosphorus limitation. Either of these scenarios could be driven, in part, by atmospheric deposition of nitrogen, which has been shown to alter nutrient conditions (Williams et al., 1996; Sickman et al., 2002) and algal nutrient limitation in other undeveloped sites (e.g. Elser et al., 2009a, b). The finding that algal assemblages at undeveloped sites were correlated with physical habitat variables, while algal assemblages at more anthropogenically altered (agricultural and urban) sites were correlated with nutrient and streamflow metrics, provides direct support for the idea that differences in abiotic–biotic correlations between sites are due, in part, to land use in the watersheds.

In light of the aforementioned role of land use as having an important influence on abiotic–biotic correlations, the temporal changes in aquatic assemblages at undeveloped sites sampled in this study may help guide interpretation of data collected from streams draining different land uses. Undeveloped sites are often selected to represent “reference” conditions as the least impacted sites in an area. In comparison with sites that have high human impacts (urban and agricultural sites), these sites are presumed to have relatively pristine conditions with corresponding aquatic assemblages. National monitoring and assessment programs use these sites as a reference against which to compare sites that are impacted by human activities. Interestingly, albeit a relatively small sample size, there was a statistically significant temporal change in aquatic assemblages at 80% of the undeveloped sites sampled in this study; suggesting that the use of undeveloped or “reference” sites as ecological endpoints requires careful consideration. A similar observation was made for streams and rivers in the north-eastern United States where there was a statistically significant temporal trend in aquatic assemblages at four of six reference sites (Kennen et al., in review). The lack of direct human impacts at undeveloped sites suggests that larger scale climate drivers, such as atmospheric nitrogen deposition for example, may be driving the trends in aquatic assemblages at these sites.

Investigation of trends in invertebrate assemblages, correlations between invertebrate assemblages and

invertebrate assemblage metrics and abiotic environmental metrics identifies streamflow metrics as potentially important drivers of change in aquatic assemblages. Environmental metrics found to be significantly correlated with invertebrate assemblages were limited to increasing average air temperature and non-monotonic trends in water quality and streamflow metrics at Clear Creek, which is an undeveloped site; and increasing trends in average discharge and the coefficient of variation of average discharge at the urban site White Rock Creek. While no monotonic trends in the invertebrate assemblage metrics were identified at Clear Creek, the finding that the invertebrate assemblage was correlated with increases in the percent EPT taxa and taxa that respire with gills, and a decrease in the percent of Coleoptera taxa at White Rock Creek, indicates that abiotic conditions may have improved in such a way as to favor invertebrate taxa that are intolerant of degraded water quality conditions. EPT taxa are frequently considered to be indicators of good water quality (Lenat, 1983; Wallace et al., 1996; Barbour et al., 1999), and have low tolerance values as compared with Coleoptera (Lenat, 1993). Similarly, taxa that respire with gills are more commonly associated with oxygenated streams.

Interestingly, the streamflow metrics that were significantly correlated with the invertebrate assemblage at White Rock Creek (average discharge and coefficient of variation for average discharge) are the same metrics that were significantly correlated with the algal assemblage at Salado Creek, the other urban site included in the study. However, while these streamflow metrics decreased at Salado Creek and the algal metrics indicate potential eutrophication, the streamflow metrics increased at White Rock Creek and the invertebrate metrics indicate potential improvement in water quality conditions. These findings suggest that streamflow metrics may be important drivers of change in water quality conditions, as represented by aquatic assemblages, in urban streams in the south-central United States. Moreover, the seemingly opposite hydrologic and biologic responses of these two urban streams indicate that site-specific conditions have the potential to generate different biogeochemical responses in streams within the same land use category. If average discharge and variability in discharge are indeed important drivers of change in aquatic assemblages it is interesting to note that there was not a significant response of the algal assemblage at White Rock Creek or the invertebrate assemblage at Salado

Creek to temporal change in streamflow metrics. This highlights the complex biogeochemical interactions taking place in these systems that are likely to be driving changes in aquatic assemblages. Identification of the exact mechanisms responsible for driving the observed changes, or lack thereof, in aquatic assemblages in these streams is beyond the scope of this study. However, continued monitoring and/or future process-based studies may be able to elucidate the possible links between streamflow metrics and water quality conditions.

While there was a lack of correlation between environmental metrics or physical habitat variables and the fish assemblage at the Yazoo River, the only site for which there was a statistically significant temporal trend in fish assemblage (Table 5), a diverse set of fish assemblage metrics, including functional feeding groups, habitat preference, and pollution tolerance, were identified as being significantly correlated with the fish assemblage at this site (Table 6). This wide diversity in fish assemblage metrics that are significantly correlated with the fish assemblage, and lack of identifiable environmental metrics or physical habitat variables, may be a function of the fact that the Yazoo River is a mixed site draining a large basin that contains multiple land uses. Indeed, the Yazoo River site drains an area that is ~30 times larger than the area of the next largest site that was identified as having a significant temporal trend in aquatic assemblage (the Frio River; Table 1). It is likely that a large basin draining multiple land uses would result in heterogeneous abiotic habitat conditions, which in turn may dampen any temporal trend in environmental metrics or physical habitat variables. In addition, it is conceivable that heterogeneous environmental conditions could support a fish community that occupies a diversity of ecological niches. Through a set of laboratory experiments, Cardinale (2011) demonstrated that heterogeneous physical habitat conditions supported greater algal taxa richness than did homogeneous habitats, and that algal taxa took advantage of the increased niche opportunities provided by the heterogeneous abiotic conditions. The idea that large basins draining multiple land uses could support heterogeneous in-stream habitat conditions, and thereby support a fish community that occupies a diversity of ecological niches, could be verified through continued monitoring and implementation of process-based field- and lab-studies.



The temporal scale at which environmental conditions influence different aquatic assemblages is an important consideration when interpreting temporal trends in aquatic assemblages and the environmental metrics and physical habitat variables to which they are correlated. It is of note that at all of the sites where statistically significant temporal trends in algal assemblages were identified, at least one environmental metric or physical habitat variable was identified as being correlated with the algal assemblages. In contrast, environmental metrics were identified as being significantly correlated with the invertebrate assemblage at only half of the sites with statistically significant temporal trends in invertebrate assemblages, and no environmental metrics or physical habitat variables were found to be correlated with the fish assemblage at the Yazoo River. These observations raise the possibility that different aquatic assemblages respond to environmental change at different rates; with algal assemblages responding most rapidly, followed by invertebrate assemblages, and lastly fish assemblages. Other studies report that algae respond quickly to abiotic environmental conditions and are therefore effective indicators of short-term environmental change (e.g., McCormick & Carins, 1994; Barbour et al., 1999). Continued monitoring may result in identification of more correlations between invertebrate or fish assemblages and environmental metrics and physical habitat variables at the sites included in this study. Regardless, the hypothesis that different aquatic assemblages respond to environmental change at different rates warrants further investigation through continued monitoring and implementation of detailed studies designed to address the temporal response of aquatic assemblages to environmental change.

## Conclusion

The results presented here identify site-specific temporal trends in algae, benthic invertebrate, and fish assemblages in streams and rivers of the south-central U.S. Assemblage metrics that represent temporal change in the aquatic assemblages, and abiotic environmental variables found to be correlated with those aquatic assemblages, were identified, and differed between and within land use categories. For example, algal assemblages were correlated with physical habitat at undeveloped sites, whereas they were correlated with

nutrient and streamflow metrics at agricultural and urban sites. Within the two urban sites, aquatic assemblages and correlated assemblage metrics indicate that water quality conditions have degraded over time at one site and improved at the other. Interpretation of continued monitoring data and design of future process-based studies aimed at quantifying abiotic–biotic correlations can be informed by the results presented here. Specifically, future studies could build on our results suggesting possible links between streamflow metrics and invertebrate assemblages, and the potentially important role of watershed size and land use in driving abiotic habitat conditions, which in turn may control the diversity of ecological niches. The site-specific temporal trends in aquatic assemblages and correlated abiotic environmental conditions discussed here can assist policy makers and resource managers with the identification of environmental stressors associated with ecological change at these sites. In turn, this information can be used to design and implement programs for the protection of aquatic resources by, for example, identifying subsets of abiotic variables to monitor that are likely to be related to changing aquatic assemblages. The success of the methodological approach presented in this study is dependent upon the availability of long-term data that has been collected in a consistent manner over time; and thereby highlights the importance of continued long-term monitoring programs. While long-term data is defined as 5 years or longer in this study, the ability to identify temporal trends in aquatic assemblages and correlations between aquatic assemblages and abiotic variables would be greatly improved through the use of data sets that span a larger temporal range than what is presented here.

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