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Using diatom assemblages to assess urban stream conditions

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Abstract

We characterized changes in diatom assemblages along an urban-to-rural gradient to assess impacts of urbanization on stream conditions. Diatoms, water chemistry, and physical variables of riffles at 19 urban and 28 rural stream sites were sampled and assessed during the summer base flow period. Near stream land use was characterized using GIS. In addition, one urban and one rural site were sampled monthly throughout a year to assess temporal variation of diatom assemblages between the urban and rural stream sites. Canonical correspondence analysis (CCA) showed that the 1st ordination axis distinctly separated rural and urban sites. This axis was correlated with conductivity ($r = 0.75$) and % near-stream commercial/industrial land use ($r = 0.55$). TWINSPAN classified all sites into four groups based on diatom assemblages. These diatom-based site groups were significantly different in water chemistry (e.g., conductivity, dissolved nutrients), physical habitat (e.g., % stream substrate as fines), and near-stream land use. CCA on the temporal diatom data set showed that diatom assemblages had high seasonal variation along the 2nd axis in both urban and rural sites, however, rural and urban sites were well separated along the 1st ordination axis. Our results suggest that changes in diatom assemblages respond to urban impacts on stream conditions.

Introduction

Urban ecosystem dynamics are driven by natural ecological processes, human activities, and their interactions (Grimm et al., 2000). Examining changes in ecosystem function and structure along an urban-to-rural gradient may identify predictable responses to different intensities of urbanization and generate hypotheses for these changes (McDonnell & Pickett, 1990). Urbanization in watersheds alters stream flow, riparian structure, and physical habitats (Leopold, 1968; Booth & Jackson, 1997; Finkenbine et al., 2000; Bledsoe & Watson, 2001). Cumulative impacts of urbanization on stream ecosystems may be best reflected by resident biota. Benthic biota such as macroinvertebrates and periphyton can integrate effects of multiple environmental stressors over time (Karr & Chu, 1999; Stevenson & Pan, 1999). Sonneman et al. (2001) examined changes in diatom community composition related to urban intensity and found that they related better to water quality, while macroinvertebrates were better indicators of catchment disturbance. Using diatoms as bioindicators has a long history (see review by Stevenson & Pan, 1999), but the potential for using diatoms as a bioassessment tool has not been fully realized. A recent survey showed that even though many US state agencies are interested, benthic diatoms have not been widely used by state water quality programs (Kroeger et al., 1999).

The metropolitan area of Portland, Oregon is an ideal place to study urban ecosystems. Unlike many metropolitan cities that have developed uncontrollably, growth in the Portland area has been managed in a way to prevent urban sprawl. An Urban Growth Boundary (UGB) around the metropolitan area was enacted in 1972 to constrain urban development within the boundary (Metro, 1997). This boundary allows the comparison of highly urbanized watersheds to rural watersheds with similar characteristics immediately outside the boundary. This study was designed to examine whether diatoms could be used to assess urban stream conditions. The first objective of this study was to examine changes in benthic diatom assemblages along an urban-to-rural gradient and relate those changes to environmental factors. Second, we wanted to assess temporal variability of diatom assemblages between an urban and a rural stream site.

Materials and methods

Study area

Sites were sampled from Clear Creek, Deep Creek, and Johnson Creek, located in the plains and foothills of the Willamette Valley Ecoregion (Clarke et al., 1991; Fig. 1). The plain, approximately 170 km long and 70 km wide, is a trough with modest relief between the Coastal Range in the west and the Cascades in the east (Uhrich & Wentz, 1999). Land use and cover in the ecoregion are predominately agriculture with some forest and urban area (Clarke et al., 1991). The proximity of the Willamette Valley to the Pacific Ocean and the prevailing weather patterns produce a temperature regime characterized by cool wet winters and warm dry summers. Annual precipitation ranged from 102 to 127 cm from 1961 to 1990 (Uhrich & Wentz, 1999). Most of the precipitation (≅75%) occurs from October through March with <5% occurring during July and August (Uhrich & Wentz, 1999).

These three watersheds were selected across the UGB. Johnson Creek flows into a highly urbanized area within the UGB, both Clear Creek and Deep Creek are located immediately outside the UGB. The geologic characteristics in these three watersheds are similar. All watersheds have geology characterized by sandstone and alluvium derived from ancient volcanic activity and flood deposits (Swanson et al., 1993).

Johnson Creek has the common characteristics of many urban streams, severe alteration by channelization, storm water inputs, removal of riparian vegetation, increases in surrounding impervious surface area, and industrial discharges. As a result, it has poor water quality, habitat quality, and dwindling fish populations (Abrams & Prescott, 1999). It is a free-flowing stream beginning in rural areas outside the UGB and continues into the suburbs, and eventually flows into commercial and industrial areas. The Clear Creek watershed has mixed land use associated with forest, agriculture, and rural residential living. Land use within the Deep Creek watershed is similar to Clear Creek.

Field sampling

A total of 45 sites were sampled for physical, chemical, and biological variables during late August through early September of 1999. Of 45 sites, 25 were in Johnson Creek, 12 in Clear Creek, and 8 in Deep Creek. It was assumed that observations at these sites were spatially independent. Stevenson (1984) found that variability in species composition among adjacent sites was no different than among random sites. In addition, one downstream site in Johnson Creek located inside the UGB ('urban') and one in Clear Creek located outside the UGB ('rural') were selected for sampling throughout the year. These sites were sampled at least monthly for diatoms and water chemistry. Stream discharge was measured continuously in the lower urban Johnson Creek site by a United States Geological Survey (USGS) gaging station located just above the urban site.

Riffle habitats ranging from 5 to 20 m in length were defined as the sampling unit. Five cross-stream transects were set up in each riffle by dividing the riffle into four equal length intervals. Only three transects were used when the length of available riffle habitat was limited. Stream physical habitat was characterized by assessing channel morphology, substrate composition, riparian conditions, and discharge. Thalweg depth and channel width were measured at each transect. Channel gradient was measured for the entire sampling area using the Suunto PM-5/360 PC clinometer. Stream

Figure 1. Study area showing three watersheds (Johnson, Clear, and Deep Creek) and sampling sites. The downstream portion of the Johnson Creek Watershed is inside the UGB which is of the Portland Metropolitan Area located west of the boundary.

discharge was measured using a Swoffer flow meter. The percent of fine sediment (< 2 mm) at each site was assessed by randomly placing a grid on the streambed at 20 locations and counting intersections (Torquemada & Platts, 1989).

Two water samples were taken for nutrient analyses and stored on ice during sampling. One sample was unfiltered; and the other was filtered through 47 mm Millipore® type HA filters (0.45 μm pore size) using a Nalgene® hand pump filtration unit and frozen until analysis. Conductivity normalized for temperature at 25 °C, dissolved oxygen (DO), and stream temperature were measured using the YSI Model 85 meter. Turbidity was measured using the HACH Model 2100P Turbidimeter and pH was measured using the Orion Model 210A pH meter.

Diatoms were sampled by selecting two rocks, sizes ranging from coarse gravel to cobble, at random from each transect (a total of 10 rocks per site). Diatoms were then scraped from a known area of rock using a toothbrush and a rubber delimiter and combined into 1 composite sample per site.

Laboratory analysis

Diatom samples were digested with concentrated sulfuric acid and potassium dichromate, rinsed with deionized water repeatedly until pH was approximately neutral, then mounted on slides using Naphrax® high resolution mounting medium. Using a Nikon Eclipse E600 microscope at 1000× magnification, transects on slides were scanned until 500 diatom valves were enumerated and identified to the species level. Patrick & Reimer (1966, 1975) and Krammer & Lange-Bertalot (1986, 1988, 1991a, b) were used as primary references for diatom taxonomy.

Water samples were analyzed for nitrate and nitrite by ion chromatography and colorimetric methods (EPA methods 300.0, 1979, and 353.2, 1993). These two constituent's values were added together for this study (NO_3+NO_2). Soluble reactive phosphorus (SRP) concentrations were determined using colorimetric methods (EPA method 365.1, 1993). Total phosphorus (TP) concentrations were determined using persulfate digestion and colorimetric methods (EPA method 365.1, 1993).

Near-stream land use characterization

Land use for each site was characterized by using a geographic information system (GIS). The program ArcView® (ESRI, 1997) was used for displaying and analyzing spatial coverage of maps and their corresponding databases created by Metro (1999). Sonoda et al. (2001) used GIS analyses to characterize near-stream land use and the relationship with water chemistry in Johnson Creek. They found that nutrients correlated well with near-stream land use characterized within a 30, 91, and 152 m radius around each site. A similar approach was taken but only a 91 m radius was used for this analysis. We realize that stream ecosystems are continuous and that conditions at a particular site on a stream reflect the cumulative inputs upstream in the watershed, however studies have also shown that local environmental conditions have a strong influence on biological assemblages (Carter et al., 1996; Pan et al., 1996; Richards et al., 1997).

Data analysis

Diatom assemblages and their relation to environmental variables were examined using canonical correspondence analysis (CCA). A separate CCA was performed on temporal and spatial data. All environmental variables, except land use percentage data and pH, were $\log_{10}$ transformed to 'normalize' their distribution prior to the analysis. Species proportions of assemblages were transformed by first taking the square root then their arc sine (thus arc-sine square root transformed). Monte Carlo permutation tests were used to select a set of environmental variables that relate best with species assemblages (ter Braak & Smilauer, 1998). A few variables that were not selected by this procedure, but were important to this study such as urban land use, were also included in the final analysis. Unrestricted global Monte Carlo permutation tests were used to test the significance of the first two CCA axes (999 permutations). Species with relative abundance <1% were excluded in the analysis. CCA was performed using the computer software CANOCO for windows (v. 4) (ter Braak & Smilauer, 1998).

Sites were classified into site groups based on diatom assemblages using TWINSPAN (two-way indicator species analysis) (Hill et al., 1975). Univariate analyses (ANOVA, or Kruskal-Wallis, and multiple comparison Student–Newman–Keuls (SNK) test) were used to test differences among classification site groups for environmental variables and land use (Zar, 1999). A paired *t*-test was used to test differences between the urban and rural sites throughout the year.

Results

Spatial patterns of diatom assemblages and relations to environmental variables

A wide range of physical, chemical, and biological variables were observed. Average stream widths ranged from 1.3 to 17.7 m and mean thalweg depths ranged from 0.1 to 0.47 m. Conductivity varied from 56 to 231 μS cm^{-1}. Nutrient concentrations such as SRP and $NO_3 + NO_2$ ranged from 0.02 to 0.37 and 0.12 to 5.68 mg l^{-1} respectively. Urban near-stream land use ranged from 0 to 100%.

A total of 84 diatom species and varieties were identified. Diatom assemblages were dominated by *Achnanthes pyrenaicum* Hustedt (26%), *Cocconeis placentula* Ehrenburg (14%), and *Rhoicosphenia abbreviate* Agardh (11%). CCA showed that the 1st two ordination axes accounted for 15.1% of variation in diatom species composition among sites (Fig. 2). Collectively, eight selected environmental variables explained 49.2% of the variation in diatom species distributions captured by the 1st two axes. The species-environmental correlations for the 1st two axes were high ($r = 0.81$ for axis I and II). Monte Carlo permutation tests showed that both axes were statistically significant ($p < 0.01$).

The 1st CCA axis may represent an urban-to-rural land-use gradient. Most of the rural sites were ordinated on the left side of the 1st axis based on species composition and their relation to measured environmental variables while urban sites were on the right side of the axis (Fig. 2). Several sites from Johnson Creek also ordinated on the left with other rural sites, but nearly all these Johnson Creek sites were headwater sites located outside the UGB. This axis was positively correlated with conductivity ($r = 0.75$) and % near-stream commercial/industrial land use ($r = 0.55$) (Table 1). Conductivity was highly correlated with % imperviousness of 'catchment area upstream of each site' ($r = 0.84$), however GIS data for this variable was only available in the Johnson Creek

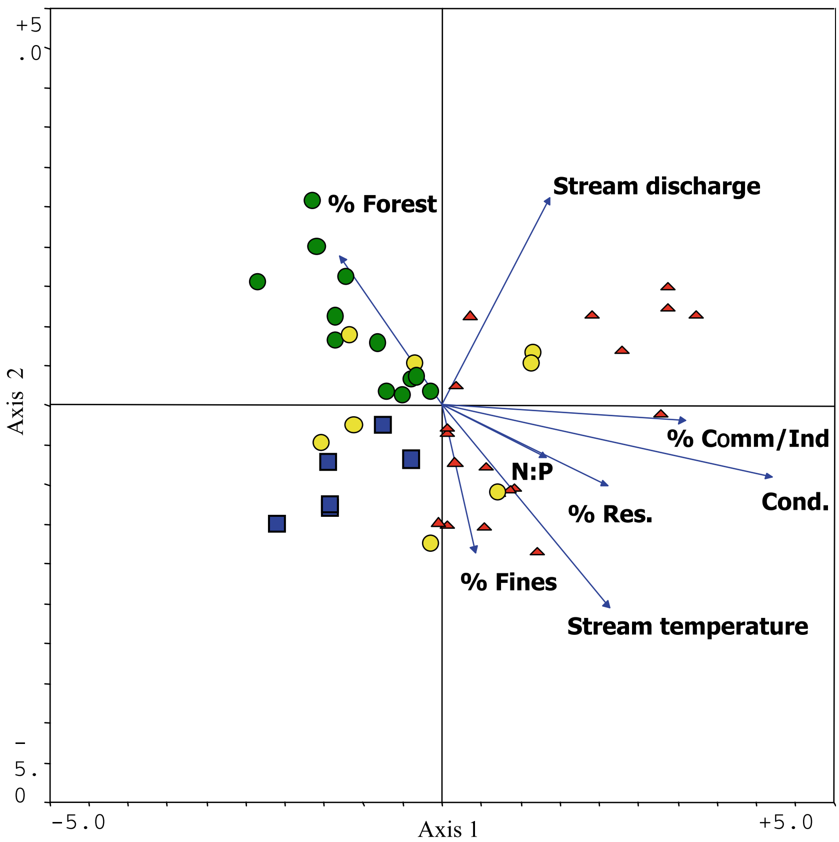

Figure 2. CCA ordination diagram showing the relation between diatom assemblages at each site and selected environmental variables (Clear Creek: dark circles, Deep Creek: light circles, squares = rural sites in Johnson Creek outside UGB, triangles = urban sites in Johnson Creek within UGB, N:P = dissolved inorganic nitrogen:dissolved inorganic phosphorus, Comm/Ind = commercial and industrial land use, Res. = residential land use, Cond. = conductivity).

Table 1. Correlation coefficients between selected environmental variables and the first two CCA axes

CCA axes		
Variables	1	2
N:P*	0.37	−0.22
% Fines	0.08	−0.41
Conductivity*	0.75	−0.20
Stream temperature*	0.38	−0.56
Stream Discharge*	0.24	0.58
% Residential	0.24	−0.15
% Commercial/industrial*	0.55	−0.04
% Forest	−0.23	0.41

(* = Significant correlation $p < 0.05$).

watershed, and therefore, was not used in this CCA. The 2nd axis may represent a stream longitudinal gradient. This axis correlated negatively with water temperature ($r = -0.56$) and positively with stream discharge ($r = 0.58$).

TWINSPAN classified all sites into four site groups based on diatom species composition (Fig. 3). Multiple comparison tests showed that relative abundance of *A. pyrenaicum* and *F. pinnata* Ehrenburg in sites of Group D were significantly different from sites in Groups A, B, and C (SNK, $p < 0.01$). Relative abundance of *C. placentula* in Group A was significantly different from Groups B, C, and D (SNK, $p < 0.01$). Relative abundance of *R. abbreviate* was significantly different between Groups A and D (SNK, $p < 0.05$). For this species, Group B was also significantly different than Group D, as well as Group A being different than C (SNK, $p < 0.025$). The species *Nitzschia inconspicua* Grunow, *Achnanthidium minutissimum* (Kütz.) Czarnecki, *N. fonticola* Grunow, and *Gomphonema parvulum* Kützing were also compared among groups but were not significantly different. Group A comprised mostly rural sites. In contrast, sites in Groups C and D were mostly urban sites. Group B contained a mix of sites from all three watersheds.

Water quality variables were significantly different among the site groups. Conductivity was significantly lower in Groups A and B than in Groups C and D (SNK, $p < 0.05$) (Table 2). $NO_3 + NO_2$ concentrations showed a similar pattern (SNK, $p < 0.05$) (Table 2). Percent of substrate as fine sediment was lowest in Group A. The amount of fine sediment for Group A was statistically different from Groups B and C (SNK, $p < 0.05$). Group A had significantly more urban residential land use (ANOVA, $p < 0.05$, $p = 0.001$) than all other groups (SNK, $p < 0.05$). Land use for agriculture, commercial/industrial, parks/open spaces, rural residential, and forest was not significantly different among groups. Stream discharge, pH, total phosphorus, and SRP did not differ among groups.

Temporal patterns of diatom assemblages and relations to environmental variables

Physical and chemical variables showed high seasonal variability at both urban and rural sites. Mean monthly discharge for Johnson Creek averaged 1.81 $m^3 s^{-1}$ and varied from 0.51 to 4.79 $m^3 s^{-1}$. Conductivity ranged from 121.5 to 216.0 $\mu S\ cm^{-1}$ averaging 166.4 $\mu S\ cm^{-1}$ in the wet season (Oct.–Apr.) and 196.8 $\mu S\ cm^{-1}$ during the dry season (May–Sept.). Nutrient concentrations such as SRP and $NO_3 + NO_2$ varied from 0.01 to 1.03 mg l^{-1} and 1.41 to 5.28 mg l^{-1}, respectively. For Clear Creek, conductivity varied from 38.2 to 71.5 $\mu S\ cm^{-1}$. Average conductivity was 51.9 $\mu S\ cm^{-1}$ during the wet season and 63.3 $\mu S\ cm^{-1}$ during the dry season. Concentrations of SRP ranged from 0.01 to 0.02 mg l^{-1} and $NO_3 + NO_2$ varied between 0.10 to 1.11 mg l^{-1}. Conductivity correlated well with nutrient measures such as N:P ratios ($r = 0.59$).

Physical, chemical, and biological variables were different between the urban and rural sites. Conductivity, SRP, and $NO_3 + NO_2$ were greater at the urban site than the rural site throughout the year (Paired *t*-test, $p < 0.001$) (Fig. 4). The species *Planothidium lanceolatum* Brébisson ex Kützing and *C. placentula* were common at both the urban and rural site. However, the diatom assemblages in each site were dominated by different species on average during the year. The urban site was uniquely comprised of *Fragilaria pinnata* Ehrenberg (20%) and the rural site was uniquely comprised of *A. pyrenaicum* (30%).

The 1st two CCA axes explained about 28% of the variation for diatom assemblages at the urban and rural site throughout the year and showed distinguishable spatial and temporal differences. The species-environmental correlations for CCA

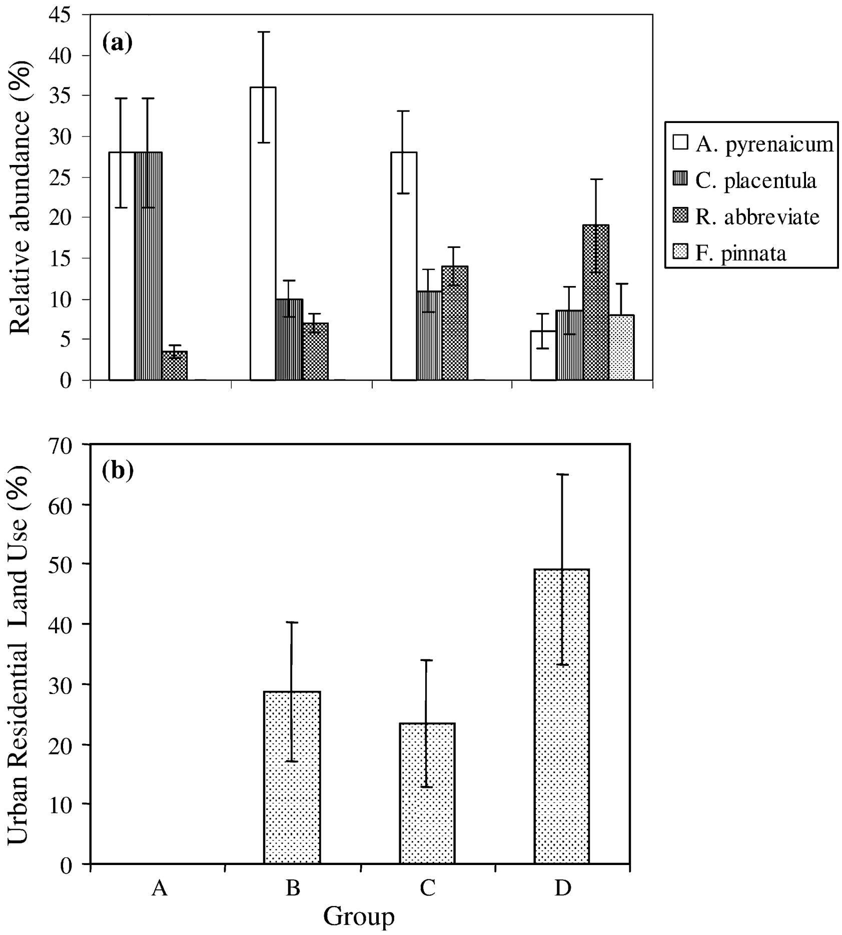

Figure 3. Common species, (a), and near-stream land use (b) that were significantly different ($p < 0.05$) for groups classified based on diatom assemblages using TWINSPAN.

axes I and II were high ($r = 0.91$ and 0.80, respectively). Collectively, the selected environmental variables explained 55.1% of the variation of diatom species composition captured by the 1st two axes. Monte Carlo permutation tests showed that both axes were statistically significant ($p < 0.01$).

The 1st axis may represent an urban-to-rural land use gradient. The rural sites with different sampling dates were ordinated on the left side of the 1st axis, while the urban sites were on the right side of the axis. This axis was correlated with conductivity ($r = 0.89$), SRP ($r = 0.79$), and $NO_3 + NO_2$ ($r = 0.81$). The 2nd axis was weakly correlated with stream temperature ($r = 0.39$) and turbidity ($r = -0.37$). This axis may represent seasonal changes in stream conditions. Samples from both urban and rural sites varied along the 2nd axis.

Discussion

Spatial patterns of diatom assemblages along the urban-to-rural gradient

Changes in diatom species distributions correlated well with the urban-to-rural gradient. Ordination analysis showed that diatom assemblages changed along the 1st CCA axis, which correlated most strongly with conductivity and % near-stream commercial/industrial land use. Our results are consistent with a previous study in the region (Carpenter & Waite, 2000) where conductivity

Table 2. Comparison of environmental variables ($n = 45$) for TWINSPAN groups (mean and SD)

Stream groups				
Variables	A	B	C	D
$NO_3 + NO_2$* (mg l^{-1})	0.78 (1.13)	0.58 (0.49)	2.23 (1.81)	2.23 (2.20)
SRP (mg l^{-1})	0.06 (0.11)	0.03 (0.04)	0.05 (0.04)	0.05 (0.03)
Total P (mg l^{-1})	0.08 (0.12)	0.07 (0.04)	0.22 (0.46)	0.09 (0.02)
Conductivity* (mS cm^{-1})	78.0 (30.5)	102.9 (36.5)	136.1 (52.1)	152.8 (52.1)
Temperature* (°C)	13.3 (2.0)	15.1 (2.2)	15.4 (1.7)	15.2 (1.6)
pH	7.37 (0.35)	7.35 (0.29)	7.32 (0.44)	7.44 (0.33)
Discharge	0.36 (0.23)	0.41 (0.45)	0.09 (0.10)	0.45 (0.40)
% Fines*	7 (7)	24 (22)	24 (17)	19 (16)

(* = Significant difference, $p < 0.05$, ANOVA).

distinguished urban and agricultural streams from forested sites in a study examining 25 streams in Oregon's Willamette Valley.

Conductivity, a measure of total dissolved ions in water, is largely a function of basin biogeochemistry and land use. Distinguishing effects of natural and anthropogenic sources of variability in stream conductivity is important for determining effects of the urban-to-rural gradient on diatom species composition. Increases in conductivity may be accompanied by elevated dissolved nutrients in streams. In this study, conductivity and nutrient measures correlated well. Leland (1995) also found that conductivity and nutrients correlated well with algal species distributions ($r = -0.78$) in Columbia Plateau streams of the Yakima Basin.

Welch et al. (1998) suggested that conductivity might be a surrogate of urban development in the Pacific Northwest. Bryant (1995) found that base flow conductivity related well to impervious surface area in Puget Sound lowland streams, Washington ($r^2 = 0.83$). Our data showed that conductivity correlated well with near-stream urban land use.

Classification analysis was consistent with CCA in reflecting urban and rural conditions. For example, Group D included sites characterized by the highest average conductivity and urban land use and the diatom assemblage was dominated by *R. abbreviate*, a species classified as halophilous taxon (Lowe, 1974). Leland (1995) reported that this species was associated with waters of relatively higher ionic strength and occurred at levels of higher conductivity in Yakima Basin streams ($\cong$391 μS cm^{-1} at 25 °C). This species is also known to prefer stable habitats with high nutrient supply (Biggs et al., 1998). Biggs (1995) observed this species at sites in nutrient-rich watersheds during base flow conditions. Stream sites in Group D were characterized by the highest average conductivity and urban land use. In comparison, sites in Group A had the lowest conductivity and had more land cover as forest. The diatom assemblages in Group A sites were co-dominated by *A. pyrenaicum* and *C. placentula*, two species that both prefer waters of lower ionic strength (Lowe, 1974). *A. pyrenaicum* is thought to prefer low-nutrient conditions and was shown to decrease in abundance at stream sites highly polluted by effluent input from a sewage treatment plant (Klotz et al., 1976).

Temporal patterns of diatom assemblages between the urban and rural sites

Changes in diatom assemblages may result from both natural and anthropogenic factors (Pan et al., 1996). Diatom assemblages can change spatially and temporally. In this study, the 2nd CCA axis correlated well with discharge and temperature indicating longitudinal changes of diatom species. Species change may be related to stream size or other factors that change longitudinally from headwaters to mouth. Molloy (1992) found differences in algal biomass accumulation rates and benthic algal species assemblages longitudinally in

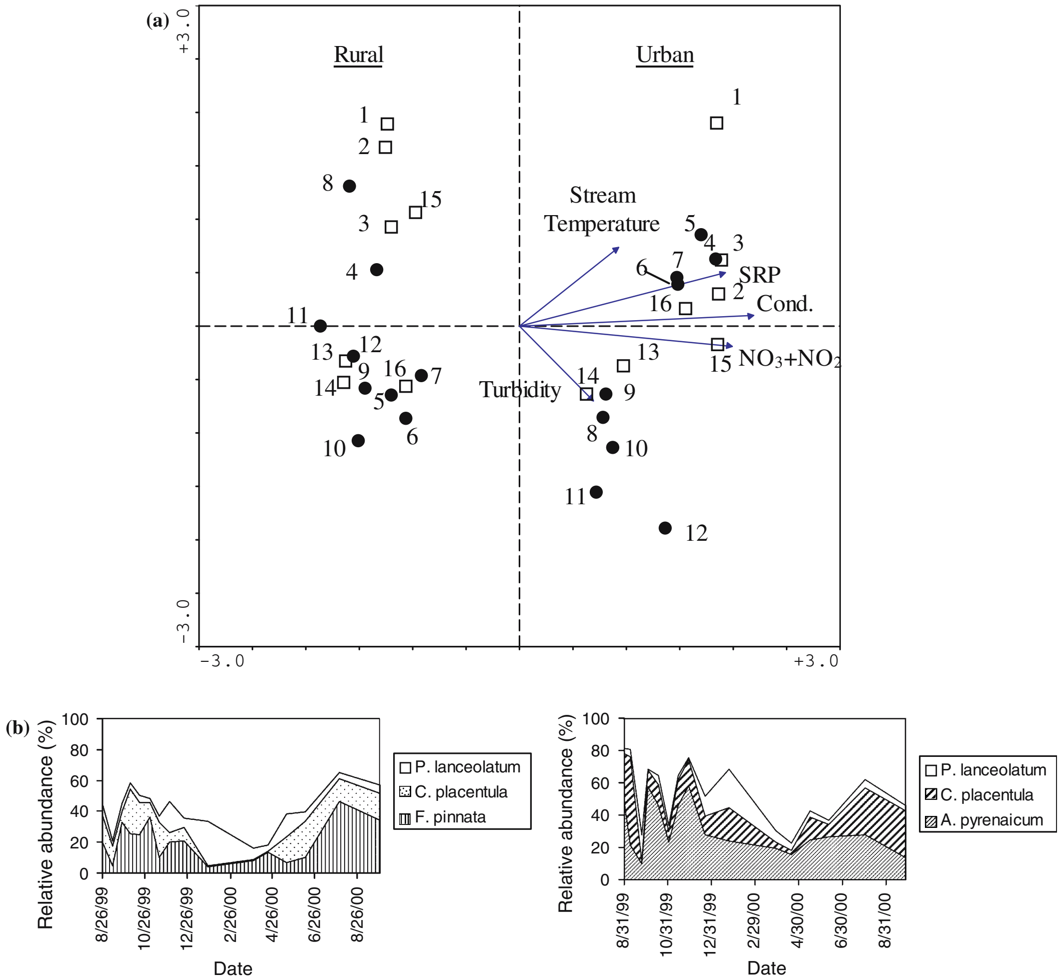

Figure 4. CCA ordination diagram (a) showing the relation between diatom assemblages in Johnson and Clear Creek and selected environmental variables. The numbers correspond to sampling date and sequence (Urban: right, Rural: left, closed circles = wet season, open squares = dry season). Seasonal variation (b) of relative abundance (%) for dominant diatom species in Johnson and Clear Creek (Johnson Creek:right, Clear Creek:left).

streams. Seasonal variation of diatoms or recovery of diatom assemblages after flood disturbance has been well documented (Biggs, 1996).

In bioassessment, it is crucial to distinguish the variability in biota due to anthropogenic factors (signal) and the variability due to natural variation (noise). A high signal-to-noise ratio is often considered as one of the most important criteria for selecting bioindicators. In this study, diatom species and environmental variables varied seasonally in both urban and rural streams. We expected seasonal patterns in diatom assemblages to be similar between the two sites due to their proximity. Our data showed that changes in diatom species composition had similar patterns in both urban and rural sites throughout the year. Despite the high seasonal variation, differences in overall diatom assemblages between the urban site and rural site remained distinct. CCA showed that the urban site and rural site were separated along the 1st axis regardless of sampling dates. This axis was highly correlated with conductivity and dissolved nutrients, two environmental variables which co-varied with diatom assemblages along the urban-to-rural gradient during the summer base flow period.

It is tempting to attribute differences among diatom assemblages to watershed land use alone. However, stream sites may have different characteristics such as geology, channel geomorphology, and riparian conditions. In this study, these watersheds were chosen specifically to alleviate confounding factors by selecting watersheds with similar characteristics, including geology, gradient, and climate. Also, due to the proximity of all watersheds to each other and the dispersal ability of diatoms, it is likely they share a similar species pool.

In summary, changes in diatom assemblages correlated well with conductivity along the urban-to-rural gradient. Also, despite the high seasonal variation, diatom assemblages were consistently different between the urban and rural sites, even though the urban and rural watersheds exhibited many similar characteristics. This study provides evidence that diatom assemblages can be used as a biotic indicator of urban stream conditions.

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