The effects of dissolved heavy metals on attached diatoms in the Uintah Basin of Utah, U.S.A.

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Abstract

The relationships of diatom species to dissolved heavy metals in the streams of the Uintah Basin of Utah were studied through four seasons of 1977–1978. Niche center gradient analysis, cluster analysis and correlation analysis were performed. *Achnanthes minutissima, Cyclotella meneghiniana, Cymbella minuta, Gomphonema parvulum, Navicula secreta* var. *apiculata, Nitzschia frustulum, Nitzschia frustulum* var. *perminuta, Nitzschia frustulum* var. *perpusilla, Nitzschia palea,* and *Synedra ulna* appear to be indicator species of high or low heavy metal concentrations. Several other species also showed meaningful relationships to high or low heavy metal concentrations.

Introduction

The response of algal species and populations to various physical and chemical parameters has been studied for more than one hundred years by a large number of researchers. The effects of light, temperature, current velocity, dissolved chemicals, substrate type, input of organic and inorganic substances have been investigated, among others. The literature is voluminous. The approach we use here is new since we have developed niche metric methods to position diatom species along selected gradients of physical and chemical parameters (Evenson *et al.*, in preparation). Furthermore, we have determined the relative niche breadths of selected diatom species and clustered these species according to niche overlap. These analyses allowed us to determine diatom taxa which showed strong tendencies toward high or low ends of our gradients. As a final test, we correlated diatom populations with concentrations of our physical and chemical parameters to corroborate the results indicated by the above methods.

The Uintah Basin is a large, natural depression lying in northeastern Utah and northwestern Colorado (Fig. 1). The basin is limited in the north by the Uinta Mountain Range. The western end of the basin is at the headwaters of the Duchesne River, and in the extreme west the basin includes the area drained by the Strawberry River. The southern boundary of the basin is defined by the edge of the Tavaputs Plateau, which breaks off into the Brown cliffs (Graham 1973) both west and east of the Green River and includes the sources of all streams flowing northward into the Strawberry, Duchesne, and White Rivers. The eastern end of the basin is not strictly defined. It lies roughly along the ridge west of Government, Sheep, and Strawberry Creeks, Colorado.

The Uintah Basin is both a structural and a topographic basin. The area is approximately 31 000 km^2 extending in an east-west direction. The basin is encompassed within the latitudes of 39° and 41° N and the meridians of 108° and 111° 30′ W. The basin floor slopes gently southward with the average elevation ranging between 1500 and

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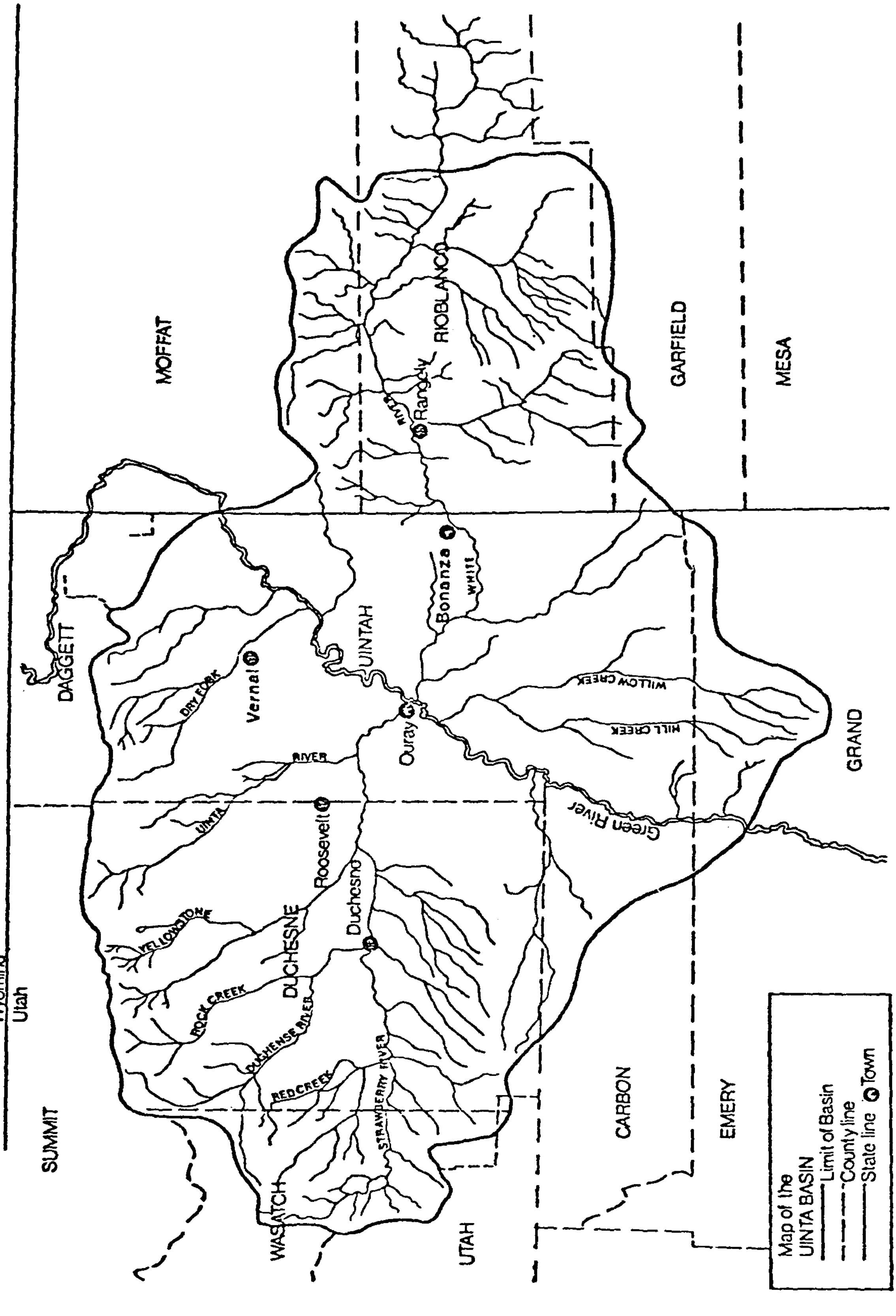

Fig. 1. Index map of the Uintah Basin of Utah showing the major drainage systems.

1800 meters. It reaches a maximum elevation of 2150 meters at the edge of the Uinta Mountains which reach up to about 4000 meters high. Annual precipitation in the basin is less than 26 centimeters.

The basin is drained in a somewhat centripetal pattern by three major streams and their tributaries. These are the Duchesne River flowing southwest, the White River flowing westward, and the Green River flowing southwest (Dastrup 1963; Marsell 1964).

Several important studies on the aquatic systems in the Uintah Basin of Utah have been performed. Baumann & Wingett (1975) studied the water quality and fauna of the White River, Uintah County, Utah. Merritt *et al.* (1977a, 1977b) studied physical, chemical and biological water quality of several major lakes and reservoirs as well as streams in the Uintah Basin. Algal studies have been performed by Johansen (1974), Johansen & Rushforth (in press), and Evenson *et al.* (1981).

The algal flora of the Intermountain West of North America has become better known in the past few years. Taxonomic studies (Anderson & Rushforth 1977; Benson & Rushforth 1975; St. Clair & Rushforth 1976, 1977, 1978) and ecological studies (Grimes *et al.*, in review; Squires *et al.* 1973, 1978; Whiting *et al.* 1978) have been performed. Such studies form the baseline for future work in western North America and, in particular, the Uintah Basin.

The response of algal species and populations to heavy metal concentrations has been studied by Berland *et al.* (1977); Elder (1974); Fogg & Rumer (1962); Foster (1976); Ibragim & Patin (1973); Keeney *et al.* (1976); Overnell (1976); Sartory & Lloyd (1976); Schelske *et al.* (1972); Shobe (1977); Stokes *et al.* (1973); Trallope & Evan (1976), among others.

The present study was performed to examine how diatoms differ in their response to heavy metal concentrations in natural systems. Furthermore, we have collected initial data on the response to heavy metals of important diatom species in order to point the way for future autecological studies.

Materials and methods

Field and laboratory

The present work was carried out through four seasons of 1977–1978. Samples of diatom populations were collected from 22 sites along selected streams in the Uintah Basin of Utah. Water samples were also collected for chemical analyses which were performed in the Brigham Young University Environmental Analysis Laboratory, using standard methods (A.P.H.A. 1971). We chose 14 heavy metals for gradient analyses (Table 1). Attached algae were sampled by scraping substrate materials, including immersed sticks, stones, etc., and placing the composite sample in a small vial which was iced and returned to the laboratory.

Permanent diatom slides were prepared by using nitric acid oxidation techniques (Rushforth *et al.* 1976). Samples were mounted in Naphrax mountant and examined using a Zeiss RA microscope with Nomarski interference phase-contrast accessories. Following identification of diatom species, relative densities were calculated by counting 200–400 frustules in each sample. The twenty-six species with highest average relative density were selected for further analyses.

Data analyses

Reliable insight into relationships between species distributions and important abiotic factors often can be obtained only by looking at the data from several different points of view. In the present work, the results of three types of analyses were integrated to suggest indicator species for various aspects of water quality. Conclusions were based only on agreement between niche center gradient analysis, clustering on niche overlaps, and correlation analysis.

Niche center gradient analysis

We have developed standardized procedures during the past year to allow comparisons along and between environmental gradients (Evenson *et al.*, in preparation). Colwell & Futuyma (1971) have applied information theory to weight each resource state by its degree of distinctiveness, or its importance to the biota. In this study, resource states correspond to positions or classes on environmental gradients. Such classes were assigned according to natural breaks in the diatom distributions along the gradients. Then 'absolute' weight factors, as described by Colwell & Futuyma (1971) were calculated for these classes on an IBM 7030 computer.

A niche center index was calculated to indicate the relationship of a diatom species to an environmental gradient. The niche center index locates the effective mean position of the population distribution of a single taxon along the weighted environmental gradient. The calculation was done by summing diatom populations in each class on the environmental gradients, multiplying by the weight factor for that class and by a number representing the position of the class on the gradient. This product was then summed over classes and divided by the number of classes to give the average position of the species on the gradient.

The niche center was calculated according to the formula:

$$NC_{ik} = \sum_{j} \frac{N_{ijk} M_{jk}(X)\, D_{jk}}{J_k},$$

where NC_{ik} = niche center index of species 'i' for environmental gradient 'k'

N_{ijk} = relative density of diatom species 'i' within class 'j' on gradient 'k'

$M_{jk}(X)$ = weight factor for class 'j' on gradient 'k'

J_K = number of classes on gradient 'k'

D_{jk} = mean position of class 'j' on gradient 'k'

$$D_{jk} = \sum_{i} M_{ik}(X) - 1/2\, M_{jk}(X).$$

Using the calculated niche center indices, species were selected according to their occurrence at the high or low ends of the environmental gradients. Those species whose niche centers occurred in the upper or lower 25% of the observed range of niche centers for each gradient were selected as high or low for each season.

Cluster analysis

We have used niche overlap as a measure of association for twenty-six diatom species along the implicit environmental gradient defined by our entire set of sample sites for all four seasons. Species were clustered according to their degree of niche overlap with other species or species groups (Sneath & Sokal 1973). Niche breadth is a measure of the extent of the distribution of a species across the average environmental and seasonal gradient. Niche overlap measures the mutual distribution across the gradient by two species. That is, it indicates how much two diatom species have in common in their utilization of the total available resources under various environmental conditions. We calculated niche overlap according to Colwell & Futuyma (1971) using the complement of weighted 'mutual information' in two species distributions, with 'absolute' weight factors.

Correlation analysis

Pearson correlation coefficients were calculated on an IBM 360 computer (Nie *et al.* 1975) to measure the degree of association between environmental gradients and diatom species in selected streams of the Uintah Basin. Concentrations of 14 heavy metals (in mg/l) and relative densities of 26 diatom species were correlated for each season.

Results and discussion

Heavy metals gradients

Seasonal changes in the concentrations of heavy metals, together with their ranges for each season, are given in Table 1. The lowest concentrations occurred in the fall and winter seasons. During these seasons, the concentrations of some elements were constant for all sites: Ni and Zn in the fall, and Cr and Hg in the winter. Conversely, the ranges of heavy metal concentrations were widest in the spring and summer. Those elements whose highest concentrations and widest ranges occurred in the spring season were Ag, As, Cd, Cu, Pb, Ni, and Se. Those highest and widest in the summer season were: Al, Cr, Fe, Hg, Mn, and Zn.

These trends are largely due to runoff patterns and characteristics of the river drainage basins. Those elements most abundant in surface sediments commonly enter the aquatic system under periods of highest runoff. Conversely, those ele-

Table 1. Range of concentration of heavy metals in the waters of the Uintah Basin of Utah examined throughout four seasons. Heavy metal concentrations are recorded in milligrams per liter.

Metal	Winter			Spring			Summer			Fall		
	High	Low	Range	High	Low	Range	High	Low	Range	High	Low	Range
Ag	3.1	2.0	1.1	14.7	2.0	12.7	13.0	1.0	12.0	11.1	1.0	10.0
Al	810.0	100.0	710.0	1200.0	200.0	1000.0	14 000.0	10.0	13 990.0	670.0	100.0	570.0
As	18.0	6.4	11.6	27.0	3.0	24.0	24.0	.4	23.6	5.8	.7	5.1
Ba	600.0	10.0	590.0	–	–	–	480.0	25.0	445.0	1000.0	30.0	970.0
Cd	1.0	.3	.7	5.7	.5	5.2	1.5	. .1	1.4	1.8	.3	1.5
Cr	5.0	5.0	–	12.0	3.0	9.0	28.0	10.0	18.0	13.0	5.0	8.0
Cu	14.0	5.0	9.0	40.0	10.0	30.0	25.0	5.0	20.0	10.0	5.0	5.0
Fe	982.0	18.0	964.0	1202.0	88.0	1114.0	8300.0	61.0	8239.0	677.0	20.0	657.0
Hg	.003	.003	–	.27	.04	.23	72.0	.03	71.97	3.6	.05	3.55
Pb	9.0	2.0	7.0	68.0	2.0	66.0	41.0	1.0	40.0	34.0	2.0	32.0
Mn	229.0	10.0	219.0	433.0	10.0	423.0	1400.0	10.0	1390.0	191.0	7.0	184.0
Ni	11.0	5.0	6.0	201.0	3.0	198.0	30.0	5.0	25.0	20.0	20.0	–
Se	11.0	.5	10.5	41.0	3.0	38.0	8.3	.3	8.0	3.5	.5	3.0
Zn	31.0	5.0	26.0	22.0	5.0	17.0	70.0	5.0	65.0	5.0	5.0	–

Table 2. List of species that occurred only at the high or low end of the heavy metal gradients. Only those species are listed which showed high or low distribution for a minimum of three seasons. The elements toward which the species responded are listed at the right of the table.

Species	Species responses showing the number of seasons of high or low concentration of heavy metals	Elements
Achnanthes deflexa	3, low	Ag, Al, Cd, Mn
Achnanthes minutissima	3, low	Ag, Cd, Mn
Amphora perpusilla	4, high	Fe
Cocconeis placentula	3, high	Ag, As, Pb
	3, low	Zn
Cyclotella meneghiniana	3, high	Mn, Se
Cymbella affinis	3, low	Ag, Ni
Cymbella microcephala	3, low	Ag, Cd, Cu, Mn
Cymbella minuta	4, low	Ag, Mn
	3, low	Al, Ba, Cd, Ni, Se
Cymbella minuta var. *latens*	3, low	Ag, Al, Cd, Cu, Fe, Mn
Diatoma vulgare	4, low	Ag, Cd, Mn
	3, low	Se
Fragilaria vaucheriae	3, low	Ag
Gomphonema parvulum	3, high	Al, Cd
Navicula secreta var. *apiculata*	4, high	Ag
	3, high	Al, Cu, Fe, Mn
Navicula tripunctata	4, high	Fe
	3, high	As
Nitzschia dissipata	3, high	Ba
Nitzschia frustulum	3, high	Pb
Nitszchia frustulum var. *perminuta*	3, high	Al
Nitzschia frustulum var. *perpusilla*	3, high	Pb
Nitzschia palea	3, high	Cr
Synedra ulna	3, low	Ag, Pb, Ni, Se

Table 3. Summary of the responses of diatom species to heavy metals. The number of heavy metals to which a taxon responded at the high or low end of the gradient is recorded according to species. Wi represents the winter season; Sp represents the spring season; Su represents the summer season; Fa represents the fall season.

Species	High				Low				Total		(High − Low)/(High + Low)
	Wi	Sp	Su	Fa	Wi	Sp	Su	Fa	High	Low	
Achnanthes deflexa	2	–	–	1	9	–	10	8	3	27	-.80
Achnanthes minutissima	1	–	2	1	6	11	2	6	5	25	-.67
Amphora perpusilla	8	5	3	5	–	1	–	–	21	1	.80
Cocconeis pediculus	–	2	1	1	6	1	–	2	4	9	-.38
Cocconeis placentula	–	7	7	8	6	2	1	–	22	9	.42
Cocconeis placentula var. *lineata*	1	–	4	7	3	6	–	3	12	12	0.00
Cyclotella meneghiniana	3	6	6	6	–	3	1	–	21	4	.68
Cymbella affinis	–	1	–	1	3	8	3	4	2	18	-.68
Cymbella microcephala	–	–	2	2	8	10	1	6	4	25	-.80
Cymbella minuta	–	1	–	1	7	11	11	4	2	33	-.88
Cymbella minuta var. *latens*	–	–	–	–	9	–	13	10	0	32	-1.00
Diatoma vulgare	1	–	–	2	5	7	10	5	3	27	-.80
Fragilaria capucina	–	–	–	–	–	–	13	9	0	22	-1.00
Fragilaria construens var. *venter*	2	1	2	–	6	2	3	–	5	11	-.38
Fragilaria vaucheriae	1	2	–	–	4	2	10	6	3	22	-.76
Gomphonema olivaceum	2	–	1	4	–	–	2	–	7	2	.38
Gomphonema parvulum	8	5	8	9	–	2	–	–	30	2	.76
Navicula cryptocephala var. *veneta*	4	1	2	4	–	1	3	–	11	4	.47
Navicula secreta var. *apiculata*	8	7	10	6	–	1	–	–	31	1	.94
Navicula tripunctata	3	3	9	3	1	4	–	3	18	8	.38
Nitzschia dissipata	2	1	6	1	2	2	2	–	10	6	.25
Nitzschia frustulum	5	6	6	5	1	–	–	–	22	1	.91
Nitzschia frustulum var. *perminuta*	9	2	9	–	1	–	–	5	20	6	.54
Nitzschia frustulum var. *perpusilla*	–	5	5	7	–	2	1	1	17	4	.62
Nitzschia palea	4	4	6	1	2	–	–	–	15	2	.72
Synedra ulna	–	1	–	3	6	8	9	–	4	23	-.70

ments more abundant in deeper sediments, or perhaps common in feeder springs, reach higher concentrations under lower runoff conditions (Merritt, personal communication). Likewise, the increasing concentration of hydroxyl and carbonate ions as the season progresses, renders some heavy elements less soluble, but has little effect upon others. In addition, precipitation patterns and geochemistry of the drainage basin are important. It is beyond the scope of this paper to discuss the reasons for seasonality of heavy metal concentrations further except to point out that a good deal more research in this area is warranted.

Niche center gradient analysis

Those species whose niche center index as discussed above fell in the upper or lower 25% of the observed range of niche center indices were selected for each season.

Twenty species occurred at the high or low end of certain heavy metal gradients for three seasons or four seasons (Table 2). Only five species, *Amphora perpusilla, Cymbella minuta, Diatoma vulgare, Navicula secreta* var. *apiculata,* and *Navicula tripunctata* demonstrated high or low distribution through all four seasons. However, *Achnanthes deflexa,* and *Cymbella minuta* var. *latens* were absent from the spring samples but occurred at the low end of several heavy metal gradients for the other three seasons. *Nitzschia frustulum* var. *perpusilla* was absent from the winter sample, but occurred at the high end of the Pb gradient in the other three seasons. *Fragilaria capucina* was absent from both winter and spring samples but occurred at the low end of several gradients in both summer and fall. In addition, Ba, Cr, Hg, Ni, and Zn occurred across a measurable concentration gradient in only three seasons (since in certain seasons all sites showed essentially the same concentration of the element). Thus, species could only occur at the high or low ends of these gradients for three seasons.

Species distributions along heavy metal gradients for each season were summarized by adding the number of times a species occurred at the low or high end of gradients for each of the four seasons (Table 3). *Amphora perpusilla, Cocconeis placentula, Cyclotella meneghiniana, Gomphonema olivaceum, Gomphonema parvulum, Navicula cryptocephala* var. *veneta, Navicula secreta* var. *apiculata, Navicula tripunctata, Nitzschia frustulum, Nitzschia frustulum* var. *perminuta, Nitzschia frustulum* var. *perpusilla,* and *Nitzschia palea* all tended to occur at the high ends of our heavy metal gradients. On the other hand, *Achnanthes deflexa, Achnanthes minutissima, Cocconeis pediculus, Cymbella affinis, Cymbella microcephala, Cymbella minuta, Cymbella minuta* var. *latens, Diatoma vulgare, Fragilaria capucina, Fragilaria construens* var. *venter, Fragilaria vaucheriae,* and *Synedra ulna* tended to occur at the low ends of the gradients.

Cluster analysis

We determined niche overlap for our twenty-six diatom species along the implicit environmental gradient defined by our entire set of sample sites for all four seasons. The association patterns showed two major groups (Fig. 2). The first group consisted of *Amphora perpusilla, Cocconeis pediculus, Cocconeis placentula, Cocconeis placentula* var. *lineata, Cyclotella meneghiniana, Fragilaria construens* var. *venter, Gomphonema olivaceum, Gomphonema parvulum, Navicula cryptocephala* var. *veneta, Navicula secreta* var. *apiculata, Navicula tripunctata, Nitzschia dissipata, Nitzschia frustulum, Nitzschia frustulum* var. *perminuta, Nitzschia frustulum* var. *perpusilla and Nitzschia palea.* The second group consisted of *Achnanthes deflexa, Achnanthes minutissima, Cymbella affinis, Cymbella microcephala, Cymbella minuta, Cymbella minuta* var. *latens, Diatoma vulgare, Fragilaria capucina, Fragilaria vaucheriae,* and *Synedra ulna.*

The first group is composed of species with high niche center indices, except for *Cocconeis pediculus, Cocconeis placentula* var. *lineata,* and *Fragilaria construens* var. *venter* which showed mixed responses to the gradients (Tables 2 and 3). Conversely, the second cluster group is formed of species which occurred at the low ends of the gradients.

Correlation analysis

We considered correlations of species relative densities with heavy metals concentrations. Since the twenty-six species and fourteen heavy metals

Table 4. Results of correlation analysis between diatom population densities and heavy metal concentrations for each season. Fa represents the fall season; Wi represents the winter season; Sp represents the spring season; and Su represents the summer season. All entries are significant at $p < 0.001$. Negative correlations are indicated by minus sugns.

Species	Heavy metals													
	Ag	Al	As	Ba	Cd	Cr	Cu	Fe	Hg	Pb	Mn	Ni	Se	Zn
Achnanthes minutissima				–Fa							–Wi			
Cocconeis pediculus			Fa					Sp						
Cocconeis placentula			Sp			Sp				Sp	Sp, Fa		Sp	
Cyclotella meneghiniana						Sp					Fa		Wi	
Cymbella minuta				–Fa										
Gomphonema olivaceum							Wi						Wi	
Gomphonema parvulum				Su	Su						Su, Fa			
Navicula secreta var. *apiculata*						Sp				Su	Fa, Wi		Wi, Sp	
Nitzschia dissipata				Su	Su			Wi			Su			
Nitzschia frustulum	Su	Fa					Su			Su	Fa			Sp
Nitzschia frustulum var. *perminuta*	Wi	Wi									Wi	Wi		
Nitzschia frustulum var. *perpusilla*	Su									Su				
Nitzschia palea		Su						Su			Su			Sp
Synedra ulna										–Su				

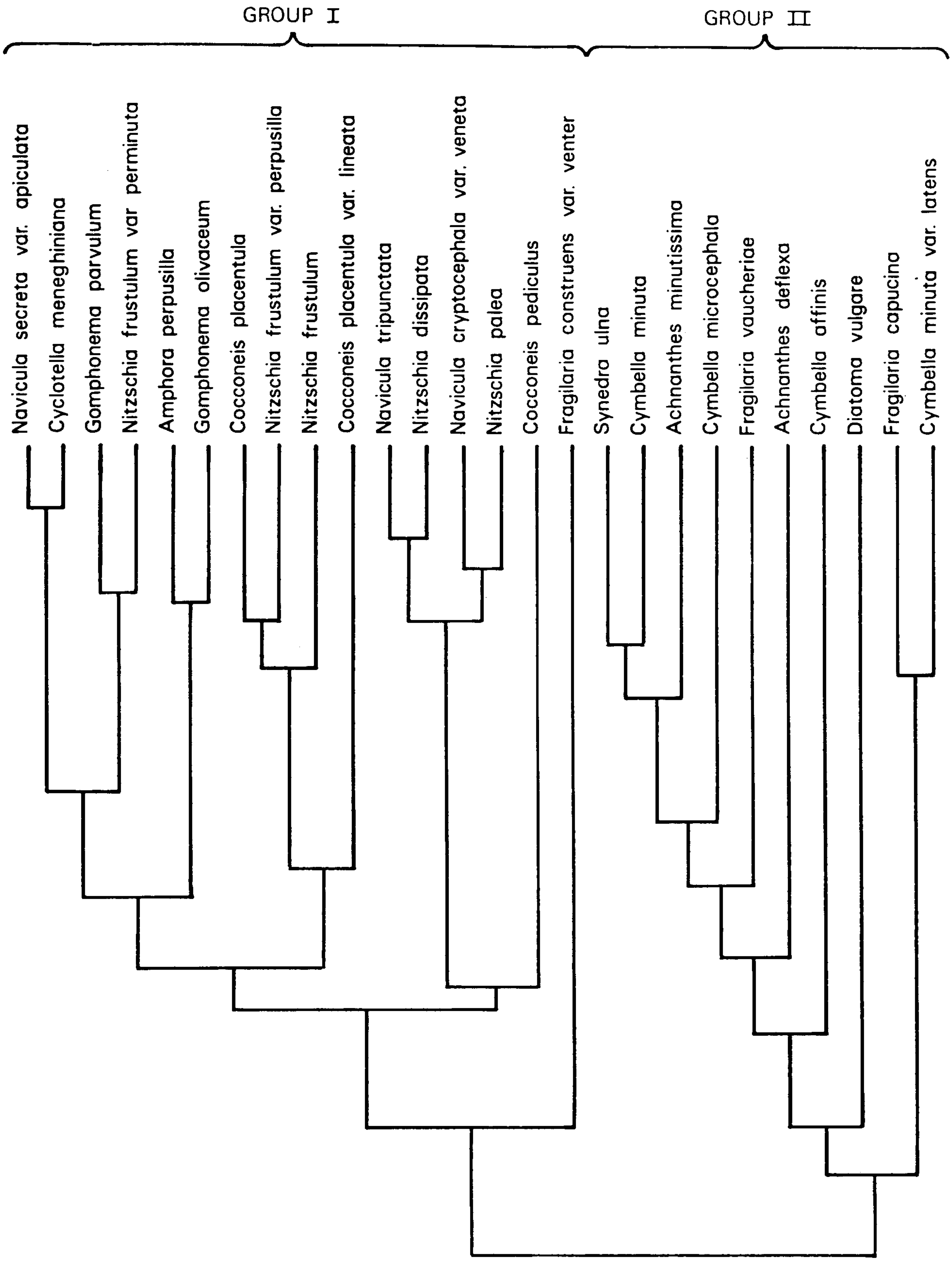

Fig. 2. Cluster dendrogram based upon degree of niche overlap of diatom species along average heavy metal gradient for all four seasons.

were considered for four seasons, there are 1456 correlation coefficients (actually 1251 because of missing data). With so many coefficients, we have only kept correlations significant at $p < 0.001$, since even at this level, we expect about one of our large set of correlation to appear significant purely by chance. With this criterion, fourteen species showed significant correlations with heavy metal concentrations (Table 4). *Achnanthes minutissima, Cymbella minuta* and *Synedra ulna* showed negative correlations with heavy metals. These three species are included within the cluster of low niche center indices as shown in the cluster dendrogram (Fig. 2, Group II; also Table 3). Since these threee species occurred consistently under low heavy metal concentrations, we conclude that they are indicator taxa.

Eleven diatom species showed positive correlations with heavy metals. All of these species are included within the cluster of high niche center indices, as shown in the cluster dendrogram (Fig. 2, Group I; also Table 3). Nine of these eleven species, *Cocconeis placentula, Cyclotella meneghiniana, Gomphonema parvulum, Navicula secreta* var. *apiculata, Nitzschia dissipata, Nitschia frustulum, Nitzshia frustulum var. perminuta, Nitzschia frustulum* var. *perpusilla,* and *Nitzschia palea,* also occurred in the high niche center index group (Table 2). Again, these taxa seem to be valid indicators of high levels of heavy metals (although *Cocconeis placentula* also occurs with a low niche center index for Zn in three seasons).

Indicator species

The three types of analysis discussed above suggest that some diatom species may be indicators of high or low heavy metal concentrations in aquatic systems. Detailed relationships of the diatom species to the heavy metal gradients are shown in Tables 2–4.

Achnanthes minutissima showed a preference for low concentrations of Ag, Cd, and Mn in three seasons. It was negatively correlated with Ba in the fall and Mn in the winter at the 0.001 level. It was also negatively correlated with all other metals except Hg at significance levels between 0.1 and 0.001. Correlation with As was positive in winter and negative in the other three seasons.

Cyclotella meneghiniana showed a preference for high concentrations of Mn and Se in three seasons. It was positively correlated with Cr in the spring, Mn in the fall and Se in the winter at the 0.001 level. It was also positively correlated with Al, Cu, Fe and Pb at a significance level between 0.01 and 0.001.

Cymbella minuta showed a preference for low concentrations through all four seasons for Ag and Mn and low concentration preferences through three seasons for Al, Ba, Cd, Ni and Se. In addition, this taxon showed significant negative correlation with Ba in the fall at the 0.001 level and negative correlations with all other metals except Cr and Hg at a significance level between 0.1 and 0.01.

Gomphonema parvulum showed preference for high concentrations of Al and Cd in three seasons. It was positively correlated with Ba, Cd and Mn in the summer and with Mn in the fall, all at the 0.001 level. It was also positively correlated with all other metals except Cr, Fe, and Hg at a level between 0.1 and 0.001.

Navicula secreta var. *apiculata* showed preference for high concentrations of Ag in all four seasons and for high concentrations of Al, Cu, Fe, and Mn in three seasons. There were significant positive correlations at the 0.001 level with Cr in spring, Pb in summer, Mn in fall and winter, and Se in winter and spring. It was also correlated positively with all other metals except Al, Hg, and Zn at a level between 0.1 and 0.001.

Nitzschia frustulum showed a preference for high concentrations of Pb in three seasons, and significant positive correlation with lead in summer at the 0.001 level. It was also significantly positively correlated with Ag and Cu in summer, Al and Mn in fall, and Zn in spring at the 0.001 level. It showed positive correlations with all metals in at least one season at a level between 0.1 and 0.001.

Nitzschia frustulum var. *perminuta* showed a preference for high concentrations of Al in three seasons and significant positive correlation with Al in winter at the 0.001 level. It was also positively correlated at the 0.001 level with Ag, Mn, and Ni in winter. It was positively correlated with all other metals except Cr, Cu, and Hg in at least one season at a level between 0.1 and 0.001. It was negatively correlated with As in winter at the 0.1 level, although positively correlated with As in summer at the 0.01 level.

Nitzschia frustulum var. *perpusilla* showed a preference for high concentrations of Pb in three seasons and significant positive correlation with Pb in summer at the 0.001 level. It was also positively correlated with Ag in summer at 0.001. It was positively correlated with all other metals except Cr, Fe, and Hg in at least one season at a level between 0.1 and 0.001.

Nitzschia palea showed a preference for high concentrations of Cu in three seasons and significant positive correlation with Cu in summer at the 0.001 level. It was also positively correlated at the 0.001 level with Ag and Pb in summer and Zn in spring. It was positively correlated with Al, As, Cr, Fe, Mn, and Se at a level between 0.1 and 0.001.

Synedra ulna showed a preference for low concentrations of Ag, Pb, Ni, and Se in three seasons. It was negatively correlated with Pb in summer at a significance level of 0.001. It was also negatively correlated with Ag, Al, As, Cu (winter), Fe, Mn, Ni, and Se at a significance level between 0.1 and 0.001. It was positively correlated with Ba, Cd, Cu (spring) and Hg at a level between 0.1 and 0.001.

Our study has demonstrated that under field conditions several different diatom species show different patterns of abundance with varying concentrations of heavy metals. We have additionally shown that such responses may relate to seasonal differences. This is due to the fact that environmental factors do not operate separately from one another, but rather in some sort of interaction, be it complementary or antagonistic. Thus, the effects of heavy metals on diatoms species would be expected to be mitigated by other environmental parameters, such as day-length, temperature, nutrients, water-hardness, etc. (Evenson *et al.*, 1981). We are currently performing experiments to measure the interactions of these and other parameters and to determine their relative importance in shaping diatom floras.

The information we have provided on heavy metal-diatom interactions is of value for several reasons. First, it provides specific information that will aid aquatic biologists is assessing biological water quality. Second, it demonstrates the use and value of niche center metric methods in determining biological association patterns. And third, it provides information on diatom species response patterns to heavy metals in natural systems which will be of use for future laboratory experiments on tolerance, growth rates, etc.

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