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ABSTRACT

Algal community structure on natural substrates of thermally altered artificial streams was studied for one year. These streams are fed by a natural stream near Aiken, South Carolina. Temperature-related shifts in the abundance of major species were demonstrated. Red algae were absent from a stream heated 12.5°C above ambient, but remained abundant in streams heated 7.5°C or less. Water temperatures above 30°C produced blue-green algal dominance and apparently eliminated several indigenous species. Substrate specificity was exhibited by all major taxa. Several taxa were abundant only on the bottom sediments and some showed a distinct affinity for either of the principal bottom types, sand or silt.

Key index words:

algae
artificial streams
natural substrates
thermal effluents

INTRODUCTION

The effects of power plant thermal effluents on algae have been extensively studied (4, 9, 10, 12, 13, 25, 28, 29), but few research programs have simultaneously focused on the structural characteristics of algal communities inhabiting a variety of natural substrates. Previous studies of periphytic algal community structure using artificial substrates (17, 18, 25) have provided valuable information on relationships between algae and temperature; however, potential disparities in algal abundance and species composition between artificial and natural substrates have been suggested by several authors (3, 8, 21, 24).

The principal objectives of this study were to describe differences in algal communities developed and maintained under different temperature regimes and to characterize the substrate affinities and associations of abundant taxa in a blackwater stream system.

DESCRIPTION OF STUDY AREA

Operational and design features of the Flowing Streams Laboratory (FSL) where this study was conducted have been described in detail by Harvey (11) and will be only briefly mentioned here.

The facility consists of six artificial streams housed in a greenhouse on the banks of Upper Three Runs Creek near Aiken, South Carolina. The U-shaped streams are primarily constructed of PVC and each contains an inlet and an outlet channel connected by a pool area. Stream beds were prepared from natural substrate materials, mainly sand, rocks, and sticks, to simulate conditions in Upper Three Runs.

Organisms were seeded naturally on substrates of the streams by the once-through flow of water continuously pumped from Upper Three Runs. Some of the influent water to four of the streams was heated in a head tank to a temperature 25°C above ambient. The heated water was mixed with unheated creek water in such a way that the streams received temperature regimes of 2.5, 5.0, 7.5, and 12.5°C above ambient. The other two streams served as controls and received only ambient temperature water.

Upper Three Runs Creek, the parent stream, is an unpolluted black water stream with over half of its drainage area within the boundaries of the Savannah River Plant. Water quality of Upper Three Runs is presented in Table 1.

MATERIALS AND METHODS

Preliminary studies indicated that all attached algae in the artificial streams could be subdivided into the following five distinguishable assemblages:

Rocky rapids algae. Taxa growing on rocks were influent water flows over a spillway and enters the inlet channels of the streams.

Scum algae. Taxa forming a surface mat attached to the sides of the stream channels.

TABLE 1. Chemical Characteristics of Upper Three Runs Creek, January to December 1977

Parameter	*No. Sampling Dates*	*Mean*	*Range*
pH	217	6.0	4.9 - 6.7
SO_4 (mg/1)	42	1.94	0.83 - 4.00
Alkalinity (mg/1-$CaCo_3$)	35	2.0	0.2 - 3.5
Conductivity (μmhos/cm)	32	23.5	20 - 28
Ca(mg/1)	32	1.37	1.17 - 1.80
NO_3 (mg/1-N)	21	0.279	<0.001 - 0.957
Ortho PO_4 (mg/1)	21	0.012	<0.001 - 0.034
Si(mg/1)	9	3.08	2.15 - 3.81
C1(mg/1)	9	2.38	2.03 - 2.62
Mg(mg/1)	9	0.332	0.287 - 0.370
Mn(mg/1)	5	<0.02	<0.019 - <0.02
Na(mg/1)	4	2.29	1.81 - 2.63

Sandy sediment algae. Taxa associated with the sand portions of the stream bottoms.

Silty sediment algae. Taxa associated with the silty portions of the stream bottoms.

Non-benthic attached algae. Taxa growing epiphytically on macrophytes or attached to submerged objects such as rocks (epilithon) or sticks (epidendron).

During 1977, monthly samples were taken from each of the five substrate types (when present) in each of the six artificial streams. Although three or more collections were usually made from each assemblage on each occasion, collections were combined to provide 360 data sets (12 months x 6 streams x 5 assemblages).

Collection techniques varied with the substrate. Sandy and silty sediment samples were mainly collected with a large-orificed pipette. Patches of visible algae, including small portions of the surface mat, were collected using forceps. Algae attached to rocks and other submerged objects were collected with a knife. Small portions of macrophytes were cut with a knife for examination of epiphytes.

Sample collections and analyses were generally conducted during three consecutive days of each month with approximately four hours devoted to each stream. Collections were placed in 35-ml vials and a few milliliters of creek water were added to keep the algae submerged prior to and during microscopic examinations which were always begun within 30 minutes of collection.

A Wild dissecting microscope with magnifications of 6X, 12X, 25X,and 50X was used for the initial examination of each sample. About 2 ml of the sample was then placed in a counting chamber and examined at 300X, 750X, and 1180X using a *Zeiss* Invertoscope equipped with fluorescence microscopical capabilities. Taxonomic advantages of using fluorescence illumination in combination with a conventional light source have been discussed by Wilde and Fliermans (30). The principal disadvantage of this microscopical technique was that several diatoms could not be positively identified to species and had to be grouped at the genus level. Acid-cleaned *Hyrax* preparations of algal material from each of the five assemblages were examined prior to the initiation of the study and at least once during each season of the study. This made it possible to consistently identify some of the more distinctively shaped diatoms to species in the unpreserved samples.

Initial attempts to quantitatively characterize algal community structure on the various substrates revealed numerous problems which included enormous differences in mean cell size of the more frequently observed species, and the presence of taxa which could not be differentiated into cells (e.g., *Vaucheria*). Furthermore, a suitable technique by which representative samples could be collected from unbiased, exact areas of all substrate types was not found. To circumvent some of these problems, a procedure was developed in which qualitative samples were examined at a variety of magnifications and all living algae were categorized as abundant, or less than abundant. This technique was similar to one used by McIntire (14) to assess algal community structure in another artificial stream system, however, his method involved examination of all algae at 500X and utilized presence or absence data to assess relative abundance. The categorization procedure used in this study provided a way of comparing algal abundance between streams and over time rather than just a comparison of relative abundance for the taxa within a specific sample.

Criteria used to rank taxonomically-separable algae as abundant were as follows:

1. Readily visible to the naked eye (macroscopic taxa and mat-forming filamentous algae), or
2. Observed in more than 90% of the appropriate-sized microscopic fields examined (smaller algae). An appropriate-sized field was one large enough to enclose several cells, colonies, or filaments of the taxon in question at a magnification suitable for identification.

Water temperature measurements were made with a mercury thermometer and recorded approximately five times a week for the duration of the study.

Chi-square tests and Spearman's rank correlations were used for statistical comparisons of results. Determinations regarding requirements for the tests were based on Snedecor and Cochran(22).

RESULTS

Dominant Taxa Observed. Thirty-two taxa were ranked as abundant in at least one sample during the study (Table 2). All abundant occurrences by taxa in the 360 samples were considered ordinal measurements and examined for potential trends linking major algae with actual water temperature, ΔT, season, and substrate type. Due to the limitations of the categorization procedure, it was not possible to quantitatively compare abundant taxa to one another in terms of population size or biomass. However, one aspect of community structure that was obvious to the unaided eye was that *Vaucheria* and *Schizothrix* were the most abundant taxa observed during the study in terms of biomass or biovolume. Substantial mats (encompassing several sq. cm.) of one (rarely both) of these algae were clearly visible to the naked eye in all streams on all sampling dates.

Actual Temperature Effects. The mean water temperature for the 30 days prior to sampling was computed for each stream (Table 3). These temperatures ranged from 5.8°C in one of the control streams in February, to 34.7°C in the +12.5°C stream in July. Mean monthly temperatures in each stream ranged approximately 16.5°C during the annual cycle.

TABLE 2. *Major algal taxa and conditions of greatest abundance, Flowing Streams Laboratory, Aiken, SC*

Taxa	Abundant Occurrences	Growing Temperature (°C) Relations	Temperature Elevation Relations	Seasonal Relations	Substrate Relations
Chrysophyta (yellow-green algae)					
Vaucheria geminata (Vauch.) De Cond.	139	15-20 optimum absent >25°C	Reduced at ΔT 5°C and above	NS[a]	56% benthic 18%surface scum
Bacillariophyta (Diatoms)					
Navicula spp.	101	10-15 optimum absent >30°C	Reduced at ΔT 5°C and above	NS	80% benthic
Eunotia pectinalis (Kutz.) Rabh.	82	NS	No obvious pattern	NS	43% NBA[b]
Pinnularia mesolepta Ehr. W. Smith	78	NS	NS	NS	100% benthic (64% sand)
Surirella spp.	41	20-25 optimum absent >30°C	Absent from ΔT 12.5°C	39% Summer 34% Spring	100% benthic
Nitzschia spp.	38	5-10 optimum absent >30°C	NS	63% Winter	100% benthic (63% sand)
Navicula capitata Ehr.	33	20-25 optimum absent <10&>30	NS	39% Fall	100% sandy benthos
Achnanthes spp.	26	5-10 optimum absent >25	NS	NS	81% sandy benthos
Frustulia rhomboides Ehr. De T.	24	NS	62% in ΔT's 7.5°C & 12.5°C	46% Winter	NS
Cymbella cuspidata Kutz	19	NS	NS	NS	100% benthic (95% sand)
Gomphonema parvulum Kutz	15	ID[c]	NS	NS	80% Rocky Rapids
Pinnularia biceps f. *petersenii* Ross	4	ID	ID	NS	ID
Cymbella minuta Hilse *ex* Rabh.	2	ID	ID	ID	ID
Fragilaria vaucheriae (Jutz) Peters	1	ID	ID	ID	ID
Chlorophyta (Green algae)					
Spirogyra sp.	57	15-20 optimum absent >30	No obvious pattern	46% Fall	49% NBA
Nitella sp.	33	NS	Absent ΔT 0°C[d]; 2.5°C	NS	100% benthic (73% silt)
Mougeotia sp.	33	NS	Absent ΔT 0°C (Both)	48% Winter	48% NBA 45% surface scum
Closterium acerosum (Schrank) Ehr.	30	NS	NS	43% Spring	100% benthic
Closterium navicula (Breb.) Lutkem	27	NS	NS	56% Fall	100% benthic (85% sand)
Undetermined coccoid green sp.	12	ID	NS	NS	NS
Ulothrix sp.	9	ID	NS	100% Winter	56% surface scum 44% NBA
Closterium moniliferum Breb.	6	ID	100% in ΔT 5°C and above	NS	100% benthic (67% silt)
Netrium digatus (Ehr.) Itz. and Rothe	5	ID	ID	NS	100% benthic (80% silt)
Stigeoclonium sp.	4	ID	ID	NS	ID (all rocky rapids)
Cyanophyta (Blue-green algae)					
Schizothrix sp.	92	>30 optimum absent <10°C	Positively correlated ΔT 0°C-12.5°C	NS	54% benthic 30% surface scum
Oscillatoria princeps Vauch.	45	NS	NS	NS	91% silty benthos
Undetermined coccoid blue-green sp.	10	ID	NS	NS	NS
Anabaena sp.	5	ID	ID	NS	NS
Merismopedia glauca (Ehr.) Naeg.	2	ID	ID	ID	ID
Cylindrospermum trichotospermum Fremy	2	ID	ID	ID	ID
Rhodophyta (Red algae)					
Audouinella violacea (Kutz.) Hamel	53	NS	Absent ΔT 12.5°C	NS	98% Rocky Rapids
Tuomeya fluviatilis Harvey	40	NS	Absent ΔT 12.5°C	NS	100% Rocky Rapids

a. NS = No significant difference determined
b. NBA = Non-benthic attached algae
c. ID = Insufficient data for statistical analysis
d. Absent in one of the two ambient temperature streams

TABLE 3. *Mean Water Temperature (°C) for 30-Day Periods Prior to Collection of Samples in the FSL Streams*

Collection Date (1977)	Stream ΔT					
	0°C (Cont #1)	0°C (Cont #2)	+2.5°C	+5°C	+7.5°C	+12.5°C
January	9.4±0.5	9.3±0.5	11.9±0.5	14.0±0.5	17.0±0.5	21.7±0.5
February	5.8±0.2	6.2±0.4	8.2±0.2	10.8±0.2	13.1±0.2	18.5±0.4
March	11.7±0.6	12.6±0.6	14.4±0.6	16.7±0.6	19.1±0.5	25.0±0.6
April	16.3±0.5	16.4±0.5	18.8±0.5	21.3±0.5	23.8±0.5	28.8±0.5
May	17.3±0.4	17.5±0.4	19.9±0.4	22.4±0.4	24.9±0.4	29.9±0.3
June	20.7±0.3	20.8±0.3	23.2±0.3	25.7±0.3	28.0±0.3	33.3±0.3
July	22.2±0.1	22.3±0.1	24.7±0.1	27.2±0.1	29.7±0.1	34.7±0.1
August	22.0±0.2	22.0±0.1	24.4±0.1	27.0±0.2	29.5±0.1	34.5±0.5
September	21.2±0.2	21.2±0.2	23.7±0.2	26.3±0.2	28.7±0.3	33.7±0.2
October	16.2±0.6	15.4±0.4	18.7±0.6	21.2±0.6	23.9±0.6	27.9±0.4
November	15.6±1.0	15.5±0.9	18.2±1.0	20.6±1.0	23.1±1.0	28.1±0.9
December	12.0±0.9	12.0±0.8	14.5±0.9	17.1±0.9	19.6±1.0	24.6±0.8

The distributions of frequencies of abundant occurrences for the different taxa among temperatures spanning 5°C increments were compared with chance (Table 2); significant (P = <0.05) departures from expected patterns were detected for *Vaucheria geminata*, *Navicula* spp., *Schizothrix* spp., *Spirogyra* sp., *Surirella* spp., *Nitzschia* spp., *Navicula capitata*, and *Achnanthes* spp. The number of abundant occurrences of *Vaucheria geminata* was highest between 15 and 20°C and the taxon was never abundant in samples over 25°C. *Navicula* spp. were most abundant between 10 and 15°C. Abundant occurrences of *Navicula* were not recorded at temperatures above 30°C. *Schizothrix* was abundant in 60% of the samples above 30°C and never abundant in samples below 10°C. *Spirogyra* was most frequently abundant in the 15-20° samples and was never abundant in samples above 30°C or below 10°C. *Spirogyra* was most frequently abundant in the 15-20°C samples and was never abundant in samples above 30°C or below 10°C. Abundant occurrences of *Surirella* spp. were relatively most frequent in samples exposed to a 20-25°C growing temperature and never observed in +30°C samples. Abundance frequencies of *Nitzschia* and *Achnanthes* were negatively correlated with temperature and neither taxon was ever abundant above 30°C. *Navicula capitata* had an apparent maximum percent abundance in the 20-25°C range with no abundant occurrences above 30°C or below 10°C.

Eunotia pectinalis, Pinnularia mesolepta, and *Oscillatoria princeps* displayed fairly consistent frequencies of abundant occurrence across temperatures from 5 through 30°C, but the number of abundant occurrences was reduced above 30°C. Overall, the numbers of taxa scored as abundant remained similar for the 5°C intervals from 5 to 30°C, but dropped drastically above 30°C.

Effects of Heating. Thirteen (65%) of the 20 major taxa were recorded as abundant in all six streams during the study. Twelve (60%) of these 20 taxa exhibited significant departures from chance in the pattern of distribution of abundant occurrences among the six streams (Table 2). The frequency of occurrence of *Vaucheria* as an abundant taxon diminished strikingly at ΔT's of 5°C or more. Three taxa, (*Schizothrix* spp., *Frustulia rhomboides* and *Closterium monilifenum*) were significantly increased at ΔT's of 7.5 or above. *Schizothrix* spp. frequencies were positively correlated with ΔT's from 0 through 12.5°C.

Red algae, *Audouinella violacea* and *Tuomeya fluviatilis*, were never observed (not even as "less than abundant" taxa) in the +12.5°C stream although they were usually abundant in one habitat (rocky rapids) of the other five streams throughout the year.

There was evidence of an effect of heating independent of actual temperature for the four most abundant taxa. *Vaucheria geminata, Navicula* spp., and *Eunotia pectinalis* were logged as abundant in the heated streams with a frequency significantly lower than predicted by their occurrence at the same temperatures in ambient streams. *Schizothrix* spp., in contrast, was recorded significantly more frequently in the heated streams.

Increases in ΔT resulted in a very conspicuous shift from *Vaucheria* dominance to dominance by *Schizothrix*. Visual differences between streams were most pronounced during summer when *Vaucheria* mats were at their maxima in the control streams and blue-green mats were maximal in the artifically heated streams. Abundant quantities of *Schizothrix* were observed in the +12.5°C stream on all sampling dates.

Seasonal Effects. Nine taxa had seasonal distributions of abundant occurrence deviating significantly from change expectations. *Ulothrix* sp. was only abundant in the winter. *Closterium navicula* and *Spirogyra* sp. were most frequently abundant in the fall. *Navicula capitata* was also most abundant in the fall, but in addition exhibited a significantly lower winter frequency than chance predicted, occurring abundantly only twice during that season. *Mougeotia* sp., *Nitzschia* spp. and *Frustulia rhomboides* exhibited winter peaks in frequencies which were significantly greater than chance predicted. *Closterium acerosum* had a significant spring peak, as did *Surirella* sp. which was the only taxon clearly showing a significantly higher frequency in summer as well.

Substrate Affinities and Associations. All major taxa displayed some degree of substrate specificity. Highly significant differences in the number of abundant occurrences among the five microhabitat types were observed for all taxa with 25 or more abundant occurrences showing with >99.5% confidence that observed differences in abundance frequency between substrates were greater than expected by chance alone.

Taxa which appeared to grow almost exclusively in the rocky rapids areas of the streams included the red algae *Audouinella violacea* and *Tuomeya fluviatilis*, and the green alga *Stigeoclonium* sp. Surface scum, usually present, was primarily comprised of taxa which were also abundant on other substrates. *Vaucheria* formed the basic matrix of the surface mat in the control streams and *Schizothrix* formed initial portions of the mat in the heated streams. Once filamentous mats became established, their net-like structures provided substrates suitable for the growth of *Spirogyra, Eunotia, and Mougeotia* — taxa often dominant in older portions of the surface scum.

Some of the algal taxa that were often abundant on the stream bottoms were never observed in substantial quantities on any of the other substrates and are thus considered true benthic forms. Most notable of these were *Pinnularia mesolepta, Surirella* spp., *Nitzschia* spp., *Navicula capitata, Nitella* sp., *Closterium acerosum, C. navicula,* and *Cymbella cuspidata.* These taxa were abundant in 78, 41, 38, 33, 33, 30, 27, and 19 sediment samples, respectively, and none was ever ranked as abundant on any of the other substrates. Most of the major benthic taxa displayed an affinity for either sandy or silty sediments. Taxa most frequently abundant on sandy sediments included: *Pinnularia Mesolepta*, *Nitzschia* spp., and *Cymbella cuspidata*. *Navicula capitata* cells were almost always attached to sand grains. This species and a few undetermined *Achmanthes* species comprised the major portion of the epipsammic (20) community. Taxa most frequently abundant on silty sediments included *Closterium acerosum*, *Oscillatoria princeps*, and *Nitella* sp.

The principal algae collected from macrophytes and other submerged objects were *Eunotia pectinalis*, *Spirogyra* sp., and *Mougeotia* sp. These taxa were found growing epiphytically on *Nitella*, dead *Vaucheria*, and the vascular plant, *Bacopa*, but were also observed in long filaments draped around submerged objects of all kinds.

DISCUSSION

The algae classified as abundant in the FSL streams consisted primarily of relatively common taxa which are typically found in, but not restricted to, blackwater streams of the Southeastern United States (6, 15, 26, 27).

Optimal temperature ranges indicated by major taxa were similar to those suggested by earlier studies (16, 26). Some diatoms grew best at the lowest temperatures found in the streams (5-10°C), whereas most blue-green algae grew best at the highest temperatures observed (30-35°C). Yellow-green algae, red algae, and most green algae grew best at intermediate temperatures (15-25°C) but decreased markedly at either end of the temperature spectrum. Few literature comparisons of the temperature ranges for specific taxa could be made because of the absence of positive species identifications for some genera and because few temperature related studies of the algal flora in the Southeast have been published. However, Whitford and Schumacher (26) also found 15-20°C to be the best growing temperature for *Vaucheria* in North Carolina streams, and the genus *Schizothrix* [based on the classification of Drouet (7)] contains numerous forms which have been reported from thermal habitats such as hot springs (23).

Potential long-term effects from the occasional exceeding of a critical temperature were indicated by the year-long absence of red algae in the +12.5°C stream while these algae were abundant in streams heated 7.5°C or less throughout most of the year. This exclusion of red algae may be due to the importance of environmental conditions in the life cycle of these algae. Studies have shown that certain stages in the life history of red algae (i.e., tetrasporangia formation) are tightly regulated by light and temperature (5).

Structural differences between streams were most pronounced during summer, when temperatures above 30°C in the stream heated 12.5°C above ambient appeared to result in elimination of most taxa abundant in the other streams. The persistence of substantial mats of blue-green algae in the +12.5°C stream during winter despite water temperatures well below those generally associated with excessive blue-green quantities was unexpected and merits additional study. Investigations by Patrick, et al. (17) have indicated that blue-green algae become dominant in some systems at temperatures above 35°C. Brock (2) suggested that 40°C was the critical temperature for blue-green algal dominance. A water temperature above 30°C appeared to result in blue-green algal dominance in the FSL streams, but blue-greens were often abundant along with several nonblue-green algal species at temperatures well below 30°C.

The distinctive influence of substrate on species composition at all temperatures provides evidence that characterization of algal community structure in lotic systems requires sampling from a wide variety of microhabitats. Many of the relationships between substrate and taxa demonstrated in this study have been previously reported. For example, the association of *Audouinella violacea*, *Tuomeya fluviatilis*, and *Stigeoclonium* with rapid flowing water has often been described (1, 19, 26), and the affinity of *Closterium acerosum* for silty sediments was previously noted by Blum (1).

The most obvious effect of chronic temperature elevations observed in these streams was the replacement of *Vaucheria* by *Schizothrix*. It is uncertain what functional correlates this structural alteration may involve. The two taxa are similar in several important ways. They are both mat-formers and provide the dominant matrix for much of the system. Neither seem to be grazed upon very much by the fauna present. Both tend to persist and provide system structure including attachment for other organisms even when conditions are beyond their favorable range for normal maintenance and growth. Blue-green algae are considered to be a poor food source (16), but in this instance the yellow-green alga replaced may not be any better, and, hence, the substitution may not be trophically significant.

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