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Primary Research Paper

The role of substrate type on benthic diatom assemblages in the Daly and Roper Rivers of the Australian wet/dry tropics

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Abstract

The selection of one or more river substrata for the collection of benthic diatoms is fundamental to any monitoring or research programme because it can potentially bias the diatom data set. In the wet/dry tropics of Australia, where the use of benthic diatoms for river health assessment is in its infancy, the comparability of diatom assemblages on river substrata has been assessed. Benthic diatoms were sampled from seven river sites, with a range of ionic chemistries (conductivities 27–6500 μS cm^{-1}) but low nutrient concentrations. At each site, triplicate samples were collected from 3 to 6 substrata. The diatom assemblages sampled were: epilithon (assemblages on rock), epiphytes on macroalgae and macrophytes, epidendron (assemblages on wood), epipsammon (assemblages on sand), epipelon (assemblages on mud) and bacterial slime. The variability between substrate assemblages, at each site, were assessed according to the following: (1) a multivariate analysis of diatom assemblages, (2) ANOVA tests of species richness, (3) ANOVA tests of the relative abundance of common species (defined by an abundance of at least 10% in any one sample), and (4) a comparison of the number of species unique to a substrate. A total of 198 taxa were identified, with some taxa common to temperate Australia. Common species were found on all substrata, with sometimes statistically significantly different relative abundances. Taxa unique to a substrate had low relative abundances (0.1–2%), were most often found on only one replicate, and are unlikely to be substrate specific because many are known to occur on other substrata. The assemblages on hard substrata, epilithon and epidendron, were found to be most similar. Diatom assemblages on macroalgal and macrophyte substrata, compared to other substrata, were highly variable. This is attributed to the loss of diatoms from grazing and sloughing, followed by recolonisation of newly exposed substrate. Other assemblages, notably epipsammon, were similar to epilithon and epidendron but sometimes differed in their relative abundance of common species. The principal finding of the study was the similarity of the epilithon and epidendron, which are considered to be indistinguishable. Rock and wood hard substrata can be substituted for one another during field surveys, thereby increasing the number of potential sample sites available for monitoring activities that standardise to a hard substrate.

Introduction

The spatial distribution of benthic algae, including diatoms, is determined by a hierarchy of factors (Biggs, 1996; Stevenson, 1997), from climate, geology and land-use at the catchment scale, to the availability of light and nutrients at the substrate scale. At the spatial scale of the sample site, substrate is another potential source of diatom assemblage heterogeneity. Benthic diatoms are present on almost all stable substrata (Lowe & Laliberte, 1996); for example, rocks (epilithon), sand

(epipsammon), woody debris (epidendron), sediment (epipelon), aquatic vegetation (epiphyton) and dead leaves. The micro-topography of sand has been shown to influence diatom assemblages (Krecji & Lowe, 1986), whilst other substrate influences include the release of chemicals by plants that inhibit the growth of epiphytic diatoms, and supply of nutrients, especially from sediment (Burkholder, 1996). Studies into the effect of substrate on diatom assemblage have, however, reached varying conclusions (see reviews by Stevenson & Hashim, 1989; Jüttner et al., 1996). Their collective interpretation is confounded by the different methods and analytical rigour, as well as criteria for assessment.

Monitoring programmes that provide information about river health often standardise benthic diatom collection to one substrate, usually from a single habitat (e.g. pool or riffle), to minimise substrate influence on diatom heterogeneity. The most common benthic assemblage sampled is epilithon, typically from a riffle (Round, 1991; Chételat et al., 1999; Gell et al., 1999; Wunsam et al., 2002). Such an approach, however, constrains sample collection to the distribution of the selected substrate, which may in turn limit the efficacy of the monitoring programme. When the objective is to assess species richness, samples are often collected from multiple substrata (Jüttner et al., 1996; Moulton et al., 2002).

The use of diatoms for river health monitoring in the wet/dry tropics of northern Australia is in its infancy. The region is sparsely populated, with the primary land-use being low intensity grazing of savanna woodlands. The establishment of a monitoring programme for river health in the Australian wet/dry tropics, that includes benthic diatoms, provides a unique opportunity to collect baseline data before significant development and its potential impact on river water quality. As a precursor to more extensive studies, and to guide the choice of substrate for monitoring benthic diatoms, the influence of substrate on diatom assemblages has been examined.

Methods

Sample sites

Seven sites were selected in the Daly and Roper River catchments of the 'Top End' of the Northern Territory in the Australian wet/dry tropics (Table 1). The sites were chosen according to the following criteria: (1) ease of vehicle access, (2) a reach undisturbed by anthropogenic activity, (3) the presence of riffle or river run habitat, (4) the presence of at least three substrata, and (5) a benthic sample depth of no more than 50 cm. The seven sites were also selected to cover a wide range of water qualities.

Benthic diatom and water sample collection

Benthic diatoms were collected during the dry season of 2000, in July and August, and more than 8 weeks after the last storm runoff event of the preceding wet season (December–April) that may have disturbed the assemblages. This period of undisturbed flow exceeds the 3 week delay before sample collection, recommended by Stevenson & Bahls (1999), for colonisation and succession to a mature periphyton assemblage.

At each site, triplicate samples were collected from each substrate. Epilithic, epidendric and consolidated epipelic samples were first shaken under the water, to remove any diatoms growing amongst silt covering these hard surfaces. The diatom flora were then sampled by scraping the surface with a clean wooden spatula.

Epipsammic samples were collected from areas of low flow by moving the sample container along the sand bed to collect the surface material. Leaves of the macrophytes *Vallisneria* and *Juncus* were scaped with a blade, whilst macroalgal and bacterial slime samples were placed directly in a container. Macroalgae were growing attached to rocks and tree roots protruding into the stream, whereas the bacterial slime was attached to rock. The slime was similar in morphology to a 5 cm long tuff of macroalgae, being a discrete mass of living and organic material. It was white in colour, felt smooth and under the microscopic examination could be seen to be a mat of bacterial cells amongst mucilage. Macroalgal strands were also squeezed by hand, when there was sufficient quantity, and the water and other material collected. This method of sample collection has been suggested by Porter et al. (1993). All samples were preserved with Lugol's iodine.

In the laboratory, samples were treated with dilute HCl and H_2O_2 following the methods of Battarbee (1986) and Gell et al. (1999).

Table 1. Sample sites, substrata and substrate species richness. (Footnotes provide information about macrophyte species sampled)

	Location	Number of substrata	Epilithon	Epidendron	Epipsammon	Algae	Squeezed algae	Other macrophytes	Other substrata	Species richness (all substrata)
Flora River, Kathleen Falls (Daly River tributary)	14°45′ S 131 36′ E	3	40			23 (1)			29 (2)	57
Salt Ck (Roper River tributary)	15°1′ S 133°14′ E	4	26	24				31 (3) 22 (4)		41
Roper River (Moroak Station)	14°50′ S 133°39′ E	4	55	68		31 (5)	50 (5)			87
Katherine River (Daly River tributary)	14°22′ S 132°22′ E	3	37		51	52 (6)				69
Douglas River (Hot Springs Reserve, Daly River tributary)	13°46′ S 131°27′E	5	49	37	49	32 (7), 60 (8)			46 (9)	84
Douglas River, Crystal Falls (Daly River tributary)	13°51′ S 131°9′E	5	30	37	48	53 (10)	39 (10)			77
Daly River, Beeboom Crossing	13°52′ S 131°5′ E	6	38	33	44	52 (10)	30 (10)	14 (11)		74

(1) *Batrachospermum australicum*; (2) bacterial slime; (3) *Chara*; (4) *Juncus*; (5) *Spirogyra*, *Oedogonium*, *Vaucheria* and *Cladophora* complex; (6) Zygnematales; (7) cyanobacterium; (8) chlorophyte; (9) epipelon; (10) *Spirogyra*; (11) *Vallisneria nana* leaves.

Sub-samples of 400 μl were placed on each of two coverslips and allowed to dry. These were inverted on drops of warm Naphrax mountant on a microscope slide, gently pressed, and allowed to set. Diatoms were viewed under a Nikon Axiolab microscope with Differential Interference Contrast at 1500 × magnification using immersion oil. Species were identified using the standard taxonomic texts of Krammer & Lange-Bertalot (1986, 1988, 1991a, b) and regional floras such as John (1983). Images of most taxa were produced using a polaroid and Sony video camera and captured electronically using miraVideo to ensure taxonomic consistency amongst operators. The names used here have been updated following the review of Fourtanier & Kociolek (1999). Three hundred valves were counted along set vertical transects from two coverslips. Such a count will identify approximately 90% of all species, whilst at least 600 valves needed to be counted to identify nearly all species based on an examination of counting effort verses the number of species identified (Townsend et al. 2002).

Temperature, dissolved oxygen, pH and conductivity were measured with a multi-parameter instrument, and turbidity by a Hach 2100 nephelometer. Water samples were analysed by standard methods (APHA, 1998) for the following parameters: nutrients (nitrate, nitrite, total Kjeldahl nitrogen (TKN), total phosphorus (TP), filterable reactive phosphorus (FRP) and silicon), major cations and anions, and total alkalinity.

Data analyses

Two complementary analytical approaches were employed to examine the relationship between substrate and diatom assemblage at a site. Univariate analyses of variance (ANOVA tests), followed by Tukey pair-wise comparisons, tested hypotheses that the relative abundance of common taxa and species richness on substrata were equal. Common taxa were defined as any taxon with greater than 10% relative abundance in a single sample. Data were transformed to satisfy the assumptions of normality and equal variance. The statistical power of each test was determined, with a value >0.8 considered satisfactory.

To examine the relationship amongst diatom assemblages simultaneously, multi-variate ordination was applied. This approach is useful in identifying any patterns in the data at the assemblage level, and indirectly addresses other measures such as diversity and eveness. The analysis was performed using the PATN multi-variate software package (Belbin, 1993). A matrix of similarity amongst diatom relative abundances was constructed using the Bray Curtis measure, then ordinated by the semi-strong hybrid (SSH) method.

Results

Substrata

A total of nine substrata were sampled, with between 3 and 6 sampled at a single site (Table 1). Rock surfaces were the most common substrate, being present at each site. Other common substrata were macrophytes (6 sites), wood (5 sites) and sand (4 sites). Epiphytic assemblages were collected from several species of macroalgae and macrophytes, though typically only one macrophyte was present at a site. Epipelic and the bacterial slime samples were each collected from only one site, whilst soft sediment substrata were absent.

Water chemistry

The rivers were warm (20–27 °C), clear (turbidity 1.0–4.8 NTU) and well oxygenated ($>94\%$ saturation). Nutrient concentrations were indicative of low trophic conditions (FRP: 1–2 $\mu g\ l^{-1}$; TP: 3–7 $\mu g\ l^{-1}$; nitrite $<1\ \mu g\ l^{-1}$; TKN 50–160 $\mu g\ l^{-1}$; Si 6–12 $mg\ l^{-1}$), and typical of the region's river water chemistry. Nitrate concentrations were low (1–11 $\mu g\ l^{-1}$) at all sites, excluding Crystal Falls where the concentration was 91 $\mu g\ l^{-1}$.

Conductivity (27–6500 $\mu S\ cm^{-1}$) and ionic dominance, however, varied markedly between sites. Calcium and magnesium dominated the ionic composition of the Flora (776 $\mu S\ cm^{-1}$), Douglas (Reserve 43 $\mu S\ cm^{-1}$; Crystal Falls 481 $\mu S\ cm^{-1}$) and Daly (538 $\mu S\ cm^{-1}$) Rivers whilst sodium and magnesium were dominant in Salt Creek (6520 $\mu S\ cm^{-1}$) and the Katherine River (27 $\mu S\ cm^{-1}$). Sodium, calcium and magnesium were equally dominant in the Roper River (1300 $\mu S\ cm^{-1}$). Bicarbonate was the dominant anion in all waters, except Salt Creek where chloride and sulphate were dominant.

Species and their relative frequencies

A total of 198 species were identified (Appendix 1). The relative abundance of most species (>90%) in a sample was less than 10%, with approximately 75% of species having relative abundances of less than 2% (Fig. 1). The distributions shown in Figure 1 were common to all substrata, at all sites. The maximum number of common species at a site was nine.

Diatom assemblages

The ordination shown in Figure 2 provides an overview of the similarity of diatom assemblages on different substrata. Overall, the similarity of replicates is generally closer when they are collected from the same substrate, compared to replicates from different substrata. Epilithic and epidendric assemblages were closest in ordination space, indicating a high degree of similarity.

Comparison of substrate species richness

Species richness at the sites ranged between 41 and 87 (Table 1), and was not related to the number of samples (Pearson correlation; $r = 0.40, p > 0.05$), indicating other factors, probably water chemistry, have a greater influence on species richness between sites. When substrate species richness is compared between sites (Table 2), the following generalisations can be made: (1) epilithic and epidendric species richness were similar with no significant pair-wise tests (Table 2); (2) epipsammic richness was either equal to or greater than epilithic richness (Table 1), and (3) the species richness on macroalgae was highly variable, relative to other substrata and between the two sample methods (Tables 1 and 2).

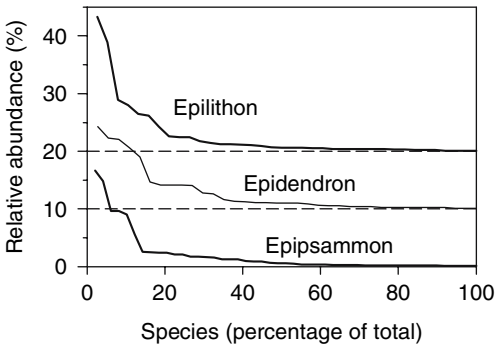

Figure 1. Frequency distribution of the relative abundances of benthic diatoms on three substrata sampled at Donkey Camp Pool, Katherine River. For clarity, the macroalgal and epipsammic plots have been raised 10 and 20 percentage points, respectively. The dotted lines equate to 0% for either macroalgae or epipsammon. The relative abundances have been calculated from the aggregated replicate data for each substrate.

Comparison of common taxa

The epilithon and epidendron supported a wide range of diatom forms. The epipsammon however supported predominantly small species of the genera *Achnanthes* (sensu lato), *Encyonema* and *Navicula* (sensu lato), as the abrasion of moving grains would detach larger taxa. The long *Synedra ulna* was universally present in this habitat however, possibly creating its own habitat on a surface film. The macroalgal samples supported more typically planktonic forms (*Aulacoseira* spp. *Cyclotella* spp. *Thalassiosira weissflogii*) than other substrata, as well as the sessile *Gomphonema* spp.

Common taxa were present on all substrata, though their relative abundances varied by up to an order of magnitude between substrata and their replicates. About one-quarter of all pair-wise comparisons were significant at the 5% level (Table 3). The most notable difference between substrata was the low abundance of common species on *Vallisneria* leaves compared to the other five substrata sampled. The abundance of common taxa on the rarer epipelic and bacterial slime substrata did not differ from other substrata. Notable also was the similar abundances of common species on epilithic and epidendronic substrata, despite being the second most numerous substrate comparison (Table 3).

Species identified on only one substrate

Species unique to a substrate approximated one-third of species richness at six of the seven sites, and 60% at the remaining site (Table 4). These species totalled between 3.7 and 16.9% of the relative abundance of all taxa at a site (Table 4), with the maximum relative abundance for a single

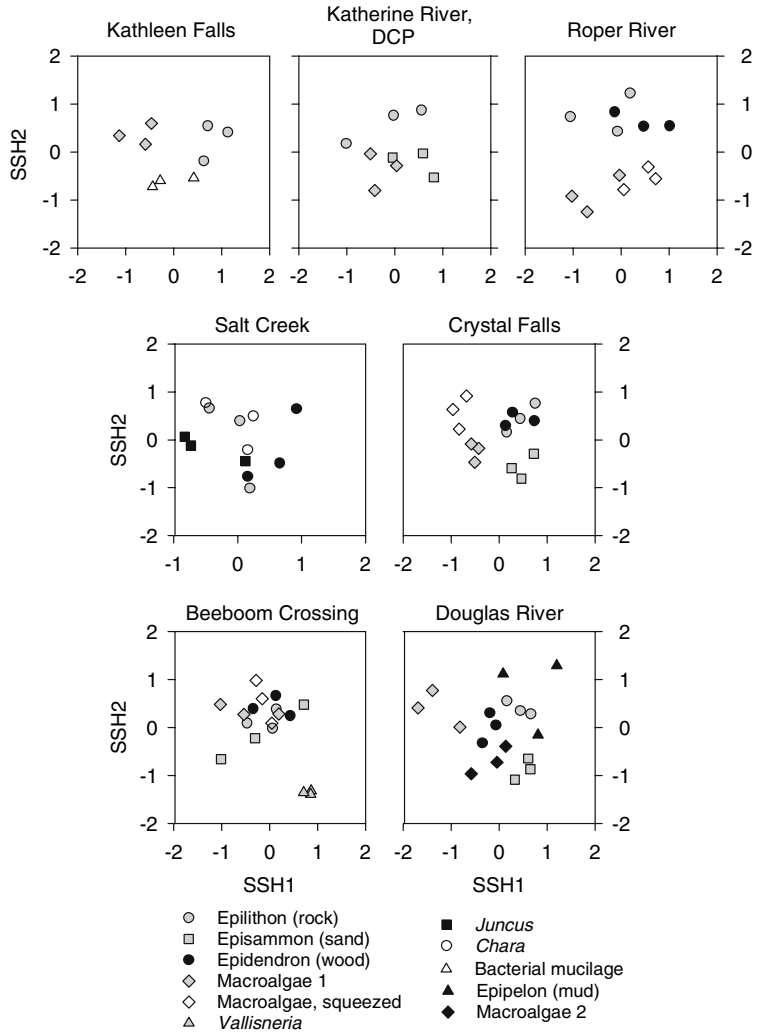

Figure 2. Ordination of diatom assemblages. Each symbol represents the assemblage for a single sample. Triplicate samples were collected from each substrate.

Table 2. Statistically significant ($p < 0.05$) pair-wise comparisons of species richness amongst the most common substrata

	Epidendron	Epipsammon	Algae	Squeezed algae
Epilithon	0 (3)	1 (3)	2 (6)	0 (2)
Epidendron	x	0 (2)	1 (5)	0 (2)
Epipsammon	x	x	0 (4)	0 (1)
Algae	x	x	1 (1)	0 (2)

The total number of tests performed is presented in parentheses. The algae–algae test compared the species richness for two species of macroalgae at Douglas River Reserve. The statistical power of these tests was >0.8.

species of 0.09–2.0%. The species unique to a substrate at a site were, with one exception, present on only one of the three substrate replicates. Moreover, approximately 30% of the 121 species unique to a substrate at a site were present at other sites and on at least one other

substrate, indicating these taxa are not substrate specific. No commonly occurring taxa were unique to a substrate.

Table 3. Summary of pair-wise comparisons of the relative abundance of commonly occurring species on substrata for all sites

Substrate Comparison	% significant
Epidendron vs. epilithon	0% (26)
Epidendron vs. squeezed macroalgae	0% (11)
Macroalgae vs. squeezed macroalgae	0% (17)
Macrophyte vs. macrophyte	0% (6)
Epidendron vs. macroalgae	13% (23)
Epilithon vs. epipsammon	13% (15)
Epilithon vs. macrophyte	17% (18)
Epipsammon vs. squeezed macroalgae	17% (12)
Epilithon vs. squeezed macroalgae	18% (17)
Epidendron vs. epipsammon	25% (12)
Epipsammon vs. macroalgae	26% (23)
Epidendron vs. macrophyte	33% (18)
Epilithon vs. macroalgae	43% (35)
Epipsammon vs. macrophyte	50% (6)
Squeezed macroalgae vs. macrophyte	83% (6)
Macroalgae vs. macrophyte	100% (6)
Total	23% (251)

The total number of tests is show in parentheses. A common species has been defined as any taxon with a relative abundance greater than or equal to 10% in a single replicate. The number of taxa with statistically significant different relative abundances may be under-estimated because the statistical power to detect differences was satisfactory for only half the tests

Discussion

Many of the taxa common in this study are cosmopolitan and have been frequently found in stream assemblages in southern Australia (Sonneman et al., 1999). These include *Achnanthidium minutissimum*, *Cocconeis placentula*, *Cyclotella meneghiniana*, *Encyonema gracile*, *Fragilaria capucina*, *Gomphonema gracile*, *Nitzschia microcephala*, *Planothidium frequentissimum*, *Synedra acus*, *Synedra ulna* and *Tabularia fasciculata*. Some species found to be common here (e.g. *Amphora strigosa*, *Encyonopsis ruttneri* and *Eunotia rhomboides*) are rarely encountered in southern Australia, while others appear so taxonomically distinct that there were not readily identified from standard taxonomic texts nor from floras from other tropical zones such as South America (Metzeltin & Lange-Bertalot, 1998). Several other species commonly encountered in southern Australia are represented in these samples although not above the 10% threshold.

The similarity of diatom assemblages was greatest amongst replicates from the same substrate, compared to replicates from different substrata. This is attributable to variation between substrata in the relative abundance of commonly occurring taxa, as well as taxa identified from only one substrate. Common species were present on all substrata at a site, though sometimes their relative abundances were statistically significantly different. This is similar to the findings of Stevenson &

Table 4. Number of species unique to a substrate, and their total relative abundances

	Kathleen Falls	Salt Creek	Roper River	Katherine River	Douglas River	Crystal Falls	Beeboom Crossing
Epilithon	20	6	5	3	0	2	5
Epidendron		3	13		2	3	3
Epipsammon				13	5	6	6
Macroalgae	5		1	11	11	10	7
Squeezed Macroalgae			7			2	2
Other	9 (1)	5 (2)			8 (3)		0 (4)
Total	34	14	26	27	26	23	23
Proportion of all species substrate unique	60%	34%	30%	39%	31%	29%	31%
Total relative abundance of substrate unique species	16.9%	5.1%	8.4%	9.4%	6.6%	3.7%	5.8%

(1) Bacterial slime; (2) *Chara* sp. , no unique taxa on *Juncus* sp.; (3) epipelon, (4) *Vallisneria*.

Hashim (1989) and Ghosh & Gaur (1991). The long period of low flows preceding sample collection, rapid reproduction, and ongoing immigration of species onto substrata may have favoured the domination by commonly occurring, presumably better adapted, diatoms. Additionally, the development of a mature, complex periphyton matrix (see Hoagland et al., 1982; Pringle, 1990), with its own biological, chemical and physical characteristics, may have mediated or even negated any substrate influence on the diatom assemblage.

The 80 species unique to a substrate were all present in low abundances (< 2%). Their low abundance and uneven distribution of these species could be due a number of reasons. These being (1) stochastic factors associated with colonisation, (2) competitive exclusion by better adapted taxa, (3) result from insufficient sample effort or (4) substrate specificity. The observation that these taxa were not present on each of the three substrate replicates suggests their limited distribution may be an artefact of insufficient sample effort, with respect to both the number of replicates and valves counted. Twenty of the taxa identified on only one substrate have been reported by Sonneman et al. (1999) on other substrata. Ghosh & Gaur (1991) also reported species from only one substrate, all with low abundance, but concluded the taxa were ubiquitous based on published reports of their occurrence on other substrata.

Species identified in this study which are widespread, with no habitat specificity, include *Craticula cuspidata*, *Gyrosigma attenuatum*, *Gyrosigma spenceri*, *Hantzschia amphioxys*, *Luticola mutica*, *Navicula bremensis*, *Navicula duerrenbergiana*, *Navicula trivialis*, *Nitzschia inconspicua*, *Nitzschia perminuta*, *Planothidium delicatulum*, *Surirella angusta*, *Thalassiosira weissflogii* and *Tryblionella levidensis*. Other factors are likely to account for the uneven distribution of these taxa amongst substrata. The only exception being species belonging to the genus *Psammothidium*, which as the name suggests, have affinities to sand habitats; *Psammothidium subexigua* and *P. subatomoides* were restricted to this habitat.

Macroalgae were a common substrate in the rivers sampled, with diatom assemblages and species richnesses that sometimes differed from other substrata, differed amongst macroalgae at a site, and differed with the method of collection. Autogenic sloughing and grazing (see Biggs, 1996) probably removed epiphytic diatoms, and at the same time exposed new algal substrate for diatom colonisation. This loss of epiphytic diatoms may account for the observed heterogeneity of diatom assemblages on macroalgae. Losses due to sloughing may vary according to species and the alga's position in a river and its exposure to currents likely to cause sloughing. The dissimilar assemblages collected from samples of complete and 'squeezed' macroalgae could reflect the heterogeneity of the macroalgae diatom assemblages, rather than inherent differences between the two methods. The 'squeezed' method introduces additional and unnecessary complexity to the interpretation of the results compared to sampling a portion of the macroalgae itself, and is not recommended.

Epiphytic assemblages have been shown to be both similar and different to other substrata (Stevenson & Hashim, 1989; Jüttner et al., 1996), and to also differ amongst plant species (Eminson & Moss, 1980; Cox, 1988; Shamsudin & Sleigh, 1994; Cazaubon, 1996), and microhabitats on the same species (Cazaubon, 1996). In this study, diatom assemblages on *Juncus* and *Chara* at one site were similar to each other and other assemblages (epilithon, epidendron), but *Vallisneria* leaves were distinctly depauperate in species compared with other substrata available. Invertebrate grazing is the most likely explanation for the low species richness on *Vallisneria*. Large populations of snails that graze on periphyton have been observed on the plant's leaves (Rea et al., 2002). Grazing probably reduced diatom species richness, with recolonisation of species, from either other parts of the plant or river water, needed to maintain species richness. Alternatively, allelopathy may have limited species richness (see Burkholder, 1996). Assemblages of epiphytic diatoms were highly variable between aquatic vegetation compared to other substrata.

Both the parametric ANOVA tests and the ordination of community abundances provide evidence that the benthic diatoms on epilithic and epidendronic substrata could not be distinguished. This is probably due to their hard and biologically inert surfaces. The sandstone and dolomite rocks sampled would not be expected

to supply phosphorous to the periphyton matrix because they lack phosphoric minerals. Comparative studies of benthic diatoms on different substrata rarely include epidendron. Indeed, only two (Stevenson, 1976 cited in Stevenson & Hashim, 1989; Mille & Lowe, 1983) of the 24 studies reviewed by the authors included epidendron. Nevertheless, epilithon and epidendron are sometimes sampled, or substituted for each other, in monitoring programmes (Gell et al., 1999; Potapova & Charles, 2002). This study provides quantitative evidence that the diatom assemblages on the two substrata are similar. The two substrata can be substituted for one another, at least in riffle and river run habitats, thereby increasing the number and choice of potential sample sites.

Monitoring programmes that aim to assess the full complement of diatom species typically collect samples from multiple substrata at a single site (e.g. Chessman, 1986; Cazaubon et al., 1995; Reavie & Smol, 1997; Lim et al., 2001), based on the assumption that some species occur more often, or are specific to, a substrate. Additional taxa may also be found by sampling more than one habitat, such as pools and riffles (Jüttner et al., 1996). In this study, there is no clear evidence of substrate specific diatoms, with the exception of *Psammothidium*, though the abundance of common species differed between some substrata. Instead, the results underpin the importance of substrate replication and counting effort to sample all species at a site. Multiple substrate sample collection, however, is a sound principle for the assessment of diatom biodiversity, as it may result in the collection of a small number of taxa that are substrate specific.

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Appendix 1

Diatom taxa present on substrates at each of the seven sites. Common species (relative abundance greater than or equal to 10% in a single sample) are indicated in bold print. The macroalgae and squeezed macroalgae substrates have been combined. The plant substrates were macrophytes *Vallisneria, Chara* and *Juncus*. Unidentified species are named and numbered as TEEF (Top End Environmental Flows). Table A1

Table A1.

	Rock	Sand	Wood	Macroalgae	Plant	Mud	Bacterial slime
Achnanthes exigua Grunow		2	1	1		1	
Achnanthes exilis Kuetzing	5	4	3	5	2		1
***Achnanthes imperfecta* Schimanski**		1		1			
Achnanthidium minutissimum Kützing	7	3	4	5	2	1	1
Adlafia aff. *minuscula* var. *muralis* Lange-Bertalot	1	3	1	4			
Adlafia bryophila (J.B.Peterson) Gerd. Moser, Lange-Bertalot & Metzelin	1		1				1
Amphora coffeaeformis (Agardh) Kützing	1		1	2	1		
Amphora libyca Ehrenberg	1		1	3			
Amphora strigosa Ehrenberg	2	1	2	1	1		
Amphora veneta Kützing	1		1		1		
Aulacoseira ambigua (Grunow) Simonsen				1			
Aulacoseira granulata (Ehrenberg) Simonsen	1	1		1			
Bacillaria paxillifer (O.F.Müller) Hendey	1		1	1			
Brachysira vitrea (Grunow) Ross in Hartley	1	1	1	1	1		
Caloneis bacillum (Grunow) Cleve	2	1	1	2			1
Caloneis silicula (Ehrenberg) Cleve		1		1			
Caloneis TEEF 1 (Cleve)	3		1				
Chaetoceros sp. Ehrenberg					1		
Cocconeis placentula Ehrenberg	4	1	3	4	1		
Craticula cuspidata (Kützing) D.G.Mann		1					
Craticula halophila (Grunow) D.G.Mann	2	2	1	3			
Craticula molestiformis (Hustedt) Lange-Bertalot	1	2	1	2		1	
***Cyclotella meneghiniana* Kützing**	2	1	2	4	1		1
Cyclotella atomus Hustedt		1	1				
Cyclotella pseudostelligera Hustedt	3	1		3			1
Cymbella affinis Kützing	3	1	2	3		1	
Cymbella aspera (Ehrenberg) Cleve			1	2			
***Cymbella cymbiformis* Agardh**	4	2	3	5	1		1
Diadesmis confervaceae Kützing	2	1		1		1	
Diploneis elliptica (Kützing) Cleve	2		1				
Diploneis modica Hustedt	1						
Diploneis oblongella (Naegeli) Cleve-Euler	2	1	1	3			
Diploneis parma Cleve	2	2	1	1			
Diploneis pseudovalis Hustedt	4	1	1	2		1	
Diploneis smithii (Brébisson)	1		2	3	1		1
***Encyonema gracile* Rabenhorst**	4	3	3	5		1	1
Encyonema mesiana (Cholnoky) D.G.Mann	3	3		1			
Encyonema minutum (Hilse in Rabenhorst) D.G.Mann		1					
***Encyonema minutum* coarse str. (Hilse ex Robenhorst) D.G.Mann**	4	3	3	4			
Encyonema silesiacum (Bleisch in Rabenhorst) D.G.Mann	1	4	1	4		1	
***Encyonopsis perborealis* Krammer**	5	1	4	5	2		1
***Encyonopsis ruttneri* Krammer**	4	2	3	4	2		1
Entomoneis alata (Ehrenberg) Ehrenberg		1	1		1		

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Table A1. (Continued)

	Rock	Sand	Wood	Macroalgae	Plant	Mud	Bacterial slime
Eolimna minima (Grunow) Lange-Bertalot			1				
Epithemia adnata (Kützing) Brébisson	1		1				
Epithemia cistula (Ehrenberg) Ralfs	3		1				
Eunotia bilunaris (Ehrenberg) Mills	1	1	1	1		1	
Eunotia camelus Ehrenberg				1			
Eunotia diodon Ehrenberg	1		1				
Eunotia fallax A. Cleve				1			
Eunotia incisa Gregory			1	2		1	
Eunotia minor (Kützing) Grunow	1			1		1	
Eunotia naegelii Migula	2	3	1	2		1	
Eunotia pectinalis (Dillwyn) Rabenhorst		1		1			
Eunotia rhomboides Hustedt	2	2	1	2		1	
Eunotia soleirolii Kützing Rabenhorst		1		1			
***Eunotia* TEEF3** Ehrenberg				1		1	
Eunotia TEEF4 Ehrenberg						1	
Fallacia TEEF1 Ehrenberg	1	1	1	2			1
Fallacia tenera (Hustedt) Stickle & D.G.Mann	2	2	3	2			
***Fragilaria capucina* Desmazières**	5	3	4	4		1	
Fragilaria delicatissima (W.Smith) Lange-Bertalot	1	1		1			
Frustulia rhomboides (Ehrenberg) De Toni	1	2	1	2		1	
Gomphonema affine Kützing	1			2			
Gomphonema angustum Agardh	1	3	2	4	1		
Gomphonema clavatum Ehrenberg		1		1		1	
Gomphonema excilissimum (Grunow) Lange-Bertalot &Reichardt	1	2		1		1	
***Gomphonema gracile* Ehrenberg**	2	3	2	4	1	1	1
Gomphonema lagenula Kützing	5	2	3	4			
Gomphonema minuta (Agardh) Agardh		1		2			
Gomphonema parvulum (Kützing) Kützing	4	2	3	6	1	1	1
Gomphonema pseudoaugur (small) Lange-Bertalot			1	2			
Gomphonema TEEF1 Agardh	3		1	3		1	
Gomphonema TEEF2 Agardh	1	1	1	1		1	
Gyrosigma acuminatum (Kützing) Rabenhorst	1	1	1	1			
Gyrosigma attenuatum (Kützing) Rabenhorst				2			
Gyrosigma spenceri (W.Smith) Cleve		1					
Hantzschia amphioxys (Ehrenberg) Grunow			1				
Hantzschia distinctepunctata (Hustedt) Hustedt		2					
Haslea spicula (Hickie) Lange-Bertalot	2		2	1	1		
Luticola goeppertiana (Bleisch) D.G.Mann			1	4			
Luticola mutica (Kützing) D.G.Mann		1					
Mastogloia recta Hustedt	3		2	2	1		
Mastogloia smithii Thwaites	2		2	1	1		
Melosira varians Agardh				1	1		
Navicella pusilla (Grunow) Krammer		1			1		
Navicula begeri Krasske			1	1			

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Table A1. (Continued)

	Rock	Sand	Wood	Macroalgae	Plant	Mud	Bacterial slime
Navicula bremensis Hustedt			1				
Navicula broetzii Lange-Bertalot & E. Reichardt	3	1	1	4	1	1	1
Navicula cryptocephala Kützing		1		1			
Navicula difficillima Hustedt	4	2	1	3		1	1
Navicula duerrenbergiana Hustedt				1			
Navicula erifuga Lange-Bertalot	1	1	1	1			
Navicula gallica var. *perpusilla* (Grunow) Lange-Bertalot				1			
Navicula gerloffii Schimanski		2					
Navicula gregaria Donkin	1	1	2	4			1
Navicula heimansioides (large) Lange-Bertalot	2	2	1	2		1	
Navicula incertata Lange-Bertalot	1		2	1			
Navicula indifferens Hustedt	2			1		1	
Navicula pseudosubtilissima Manguin in Bourelly & Manguin	2		1	3	1		1
Navicula recens (Lange-Bertalot) Lange-Bertalot	1	1					
Navicula salincola (aff. vol. 7) Hustedt	1		1	1			
Navicula schadei Krasske	3	3	1	4			
Navicula schroeteri Meister	4	3	3	5		1	1
Small Navicula TEEF1	2	2	1	2		1	
Navicula TEEF1 (aff. *radiosa* Kützing)	3	3	3	5		1	
***Navicula* TEEF2 (small)**	3	2	2	2		1	
***Navicula* TEEF3 (aff. notha)**	5	4	3	6		1	1
Navicula TEEF4		1					
Navicula tenelloides Hustedt		1		1			
Navicula tenerrima Hustedt	3	2	1	2	1	1	
Navicula tridentula Krasske	2	1	2	3			
Navicula trivialis Lange-Bertalot	1						
Navicula vandamii Schoeman & Archibald		1	1	2			
Navicula variostriata Krasske				1			
Navicula viridula (Kützing) Ehrenberg	2	2	2	4			
Naviculadicta TEEF1	1	2	1	2			
Naviculadicta TEEF2 sensu Lange-Bertalot in Lange-Bertalot & G. Moser		2		2			1
Neidium affine (Ehrenberg) Pfitzner		1					
Neidium ampliatum (Ehrenberg) Krammer		2		1			
Neidium dubium (Ehrenberg) dubium			1	2			
Nitzschia aff. *laevis* Hustedt			1	1			
Nitzschia aequorea Hustedt	3		2	3	1		
Nitzschia aff. *agnita* Hustedt	2	1	2	3			
Nitzschia amphibia Grunow	1	2	2	3			
Nitzschia angustata Grunow	3	1	2	4			1
Nitzschia angustatula Lange-Bertalot		1		1			
Nitzschia archibaldii Lange-Bertalot	1	1	1	1	1		
Nitzschia bacillum Hustedt		1	1	2			
Nitzschia dissipata (Kützing) Grunow	2	1	2	3			
Nitzschia frustulum (Kützing) Grunow	1		1	1			

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Table A1. (Continued)

	Rock	Sand	Wood	Macroalgae	Plant	Mud	Bacterial slime
Nitzschia graciliformis Lange-Bertalot & Simonsen		1		1			
Nitzschia gracilis Hantzsch	1	2	1	3			1
Nitzschia hantzschiana Rabenhorst	4	1	1	2			
Nitzschia incognita Krasske	1		1				
Nitzschia inconspicua Grunow	2						
Nitzschia lacuum Lange-Bertalot	3		1	2			
Nitzschia liebetruthii Rabenhorst	4	1	3	4			1
Nitzschia linearis (Agardh) W. Smith	1	2	2	2		1	
***Nitzschia microcephala* Grunow**	3		2	1	1		
Nitzschia obtusa (*filiformis*) W. Smith	1		1		1		
Nitzschia palea Kützing W. Smith	6	3	4	5	2	1	1
Nitzschia paleaeformis Hustedt	1						
Nitzschia pararostrata (Grunow) M. Peragallo			1				
Nitzschia perminuta (Grunow) M. Peragallo				1			
Nitzschia pseudofonticola Hustedt		2	1	2			
Nitzschia reversa W. Smith			1	1	1		
Nitzschia rosenstockii Lange-Bertalot	1			1			
Nitzschia siliqua Archibald	1	1					
Nitzschia subacicularis Hustedt				1			
Nitzschia subcohaerons var. *scotia* (Grunow) Var Huerck			1	1			
Nitzschia TEEF1			2	3			
Nitzschia TEEF2	1			2			
Nitzschia TEEF3		1		1			
Nitzschia TEEF4	3		2	3			
Nitzschia tropica Hustedt			1				
Opephora species 1 Petit		1		1		1	
Pinnularia braunii Grunow		2	1	2		1	
Pinnularia gibba Ehrenberg	1	1					
Pinnularia intermedia Zargerstedt				1			
Pinnularia subcapitata Gregory		1	1				
Pinnularia viridis Ehrenberg	1						
Planothidium delicatulum Kützing			1				
***Planothidium frequentissimum* Lange-Bertalot**	4	2	3	4		1	
Planothidium lanceolatum Brébisson		1	1	1			
Pleurosigma salinarum Grunow	1		2		1		
Psammothidium subatomoides (Hustedt) Burkhof & Round		1					
Psammothidium subexigua Krammer & Lange-Bertalot		2					
Rhopalodia brebissonii Krammer	1			1			
Rhopalodia constricta (W. Smith) Krammer	1	1	1	1		1	
Rhopalodia gibba (Ehrenberg) O. Müller	2	1	1	2		1	
Rhopalodia musculus (Kützing) O.Müller	2		2	1	1		
Sellaphora bacillum (Ehrenberg) D.G.Mann		2					
Sellaphora pupula (Kützing) Mereshkowsky	3	3	1	4		1	
Simonsenia delognei (Grunow) Lange-Bertalot	2		1	1			
Stauroneis TEEF1 Ehrenberg	2		2	3			1

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Table A1. (Continued)

	Rock	Sand	Wood	Macroalgae	Plant	Mud	Bacterial slime
Stenopterobia aff. *panctonica* Metzelin & Lange-Bertalot	2	2	1	2			
Stenopterobia curvula (W.Smith) Krammer	2	2	1	2		1	
Stenopterobia delicatissima (Lewis) Brébisson	1	1		1			
Stenopterobia densistriata (Hustedt) Krammer				1			
Stephanocostis chantiacus Genkal & Kuzmin	1						1
Surirella angusta Kützing				1			
Surirella biseriata var. *parallela* Brébisson	1			1			
Surirella linearis W.Smith		2	1	3		1	
Surirella robusta Ehrenberg	2	1	1				
Surirella (round) Turpin		1		1			
Surirella species (aff. *elegans*) Ehrenberg	1	1		1			
Synedra acus (Kützing) Lange-Bertalot	4	1		3	1		1
Synedra ulna Ehrenberg	7	4	5	6	2	1	1
Tabularia fasciculata D.M. Williams & D.G. Mann	2	1	2	1	1		
Thalassiosira weissflogii (Grunow) Fryxell & Hasle				1			
Tryblionella apiculata Gregory	1		1	1			
Tryblionella calida W.Smith	1		1	1			
Tryblionella debilis Arnott	2	1	2	1			
Tryblionella hungarica (Grunow) D.G.Mann			1	2	1		
Tryblionella levidensis W.Smith			1				
Tryblionella punctata W.Smith	1		1	1			
Tryblionella species 1 W.Smith			1				