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Distribution and biomass of benthic microalgae in Manukau Harbour, New Zealand

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Abstract Benthic microalgal biomass (as sediment chlorophyll *a* (Chl. *a*), by spectrophotometry) and taxonomic composition (by HPLC pigments analysis) were investigated at intertidal locations throughout Manukau Harbour, North Island, New Zealand. Benthic microalgal biomass averaged 97.5 mg Chl. *a* m^{-2} for all sediment samples. Benthic microalgal biomass was higher in sediments containing at least some sand than in muddy sediments, in contrast to previous findings from Manukau Harbour. Loading of fine sediments from erosion within the harbour's basin may, therefore, affect the amount and distribution of benthic microalgal biomass in the harbour. Average benthic microalgal biomass for the entire area of the harbour was at least 62.5 mg Chl. *a* m^{-2}. The latter value is at least 4 times higher than mean annual, spatially integrated phytoplankton biomass in Manukau Harbour, suggesting that benthic microalgae are a more important food source for estuarine consumers. High fucoxanthin:chlorophyll *a* ratios indicated that benthic microalgae were primarily diatoms. The physical characteristics of Manukau Harbour and similarity in taxonomic composition of the phytoplankton and benthic microalgae suggest that resuspended benthic microalgae are an important component of the harbour's phytoplankton biomass.

Keywords benthic microalgae; sediments; pigments; Manukau Harbour

INTRODUCTION

Benthic microalgae are recognised as important primary producers in shallow aquatic ecosystems (MacIntyre et al. 1996; Miller et al. 1996; Cahoon 1999; Underwood & Kromkamp 1999). Benthic microalgal biomass and production can equal or exceed those of phytoplankton in shallow ecosystems, e.g., Cadée & Hegeman (1974, 1977), Lukatelich & McComb (1986). Moreover, the taxonomy and ecology of benthic microalgae are distinct from those of the phytoplankton (MacIntyre et al. 1996; Miller et al. 1996). Estuarine ecosystems, with generally well-illuminated shallow bottoms and moderate to high nutrient loadings, can be optimal environments for the development of high concentrations of benthic microalgae, which can make important contributions to total ecosystem production. However, most studies of estuarine benthic microalgal ecology have been conducted in North American and European estuaries, with relatively fewer investigations in Southern Hemisphere estuaries, e.g., Lukatelich & McComb (1986); Gillespie & MacKenzie (1990); Light & Beardall (1998); Gillespie et al. (2000).

The study presented here investigated the biomass and distribution of benthic microalgae in Manukau Harbour, an estuary west of Auckland, New Zealand. Previous investigations have addressed the magnitude of phytoplankton and, to a limited degree, benthic microalgal biomass and production in this estuary (Wilkinson 1981; Vant & Budd 1993; Vant & Safi 1996; Vant et al. 1998). The aims of this study were to measure and compare benthic microalgal biomass at sites representative of different sediment types in

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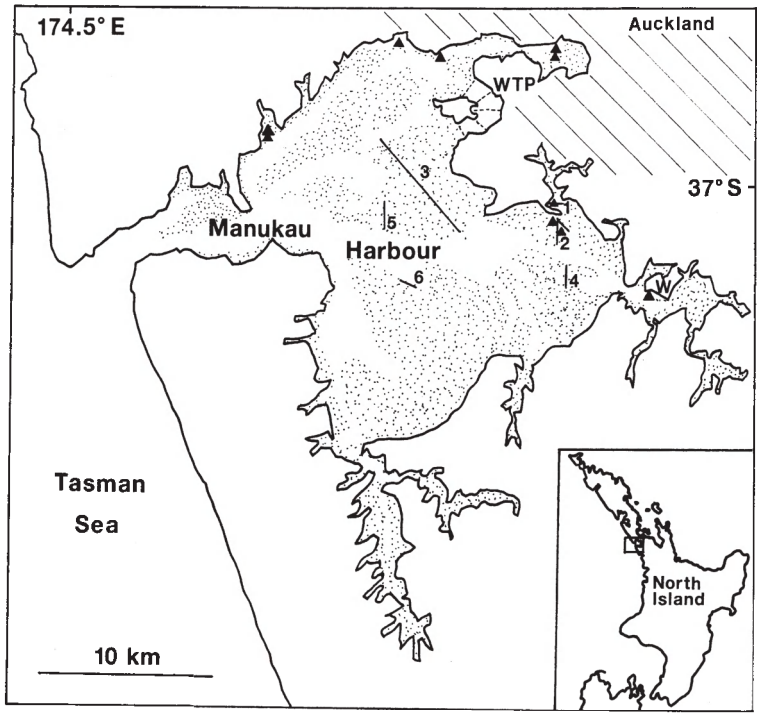

Fig. 1 Map of sampling sites (refer to Table 1) in Manukau Harbour on the North Island of New Zealand. Stippling denotes intertidal areas. "Manukau littoral" sites are indicated by triangles; "W" denotes Weymouth site. Transects are indicated by numbered lines: 1 = Wiroa A, nine sites sampled 31 January 1996; 2 = Wiroa B, seven sites sampled 1 February 1996, and eight sites sampled 13 February 1996; 3 = Te Tau/Karore Bank, 15 sites sampled by diver 7 February 1996; 4 = Hikihiki Bank, eight sites sampled 13 February 1996; 5 = Karore Bank, 10 sites sampled 15 February 1996; 6 = Hangore Bank, five sites sampled 15 February 1996. Sites were evenly spaced along transects. Auckland metropolitan area lies north-east of Manukau Harbour, indicated by slanted lines.

Manukau Harbour, compare benthic microalgal biomass with measured values of phytoplankton biomass in the harbour, and determine the relative abundances of major taxa in the benthic microalgae for comparison with the phytoplankton.

Sediment characteristics were recognised as a key variable likely to affect the biomass and composition of the benthic microalgae. Opinions on this issue in the literature diverge, with some reporting higher biomass associated with sandier substrates, e.g., Cahoon et al. (1999), and others reporting higher biomass associated with finer sediments, e.g., Underwood & Kromkamp (1999). Sediment characteristics reflect physical forces in the estuary and natural and anthropogenic sedimentation processes in the estuary's drainage basin. Human activities are widely considered to accelerate loadings of sediment to estuaries, particularly fine particles, in run-off water (Wanielista & Yousef 1993). Therefore, human activities might alter the distribution and concentrations of benthic microalgae in estuaries. However, previous studies in Manukau Harbour focused almost entirely on muddy substrates (Wilkinson 1981). Thus, there was a need to sample sediments of varying grain-size composition throughout the harbour at approximately the same time of year to resolve these issues.

METHODS AND MATERIALS

Study area

Manukau Harbour lies west of Auckland, emptying into the Tasman Sea by a narrow, deep channel (Fig. 1). Total area of the harbour, excluding the entrance region, is 221.4 km^2 at mean sea level (Vant & Budd 1993). Freshwater inflow is low, so that average salinities are usually above 31 ppt (Vant & Budd 1993). Manukau Harbour has a tidal range of 2–3.4 m (Vant & Budd 1993), which creates strong currents and exposes large intertidal areas (estimated at 61.7% of the total harbour area; Vant et al. 1998) of muddy and sandy bottoms at low tide. Owing partially to strong currents driven by tidal flows and wind mixing, turbidity levels are usually high; values of the light extinction coefficient, k, are in the range 0.8–2.1 m^{-1} (Vant 1991). High levels of nutrient loading are driven by discharges from the Manukau Wastewater Treatment Plant (WTP), which serves the City of Auckland and suburbs (Fig. 1; Vant & Smith 1991). The combination of high turbidity but generally shallow morphometry (areally integrated mean depth at mean sea level excluding the entrance region, is 3.67 m (Vant & Budd 1993)), and high nutrient loading levels support phytoplankton concentrations with annual mean values ranging

between 2.8 and 9.3 µg chlorophyll *a* (Chl. *a*) litre^{-1}, with values <3 µg litre^{-1} in the entrance region and adjacent Tasman Sea (Vant & Budd 1993).

The sediments of Manukau Harbour include extensive areas dominated by sand (64%), muddy sand (19%), shell hash-sand (6%), sandy mud (5%), and mud (0.5%), with additional small proportions accounted for by mixtures of these types (Gregory et al. 1994). Sediments are typically sandier in the middle portions of the harbour, where currents and waves are more active, and muddier in enclosed areas. Intertidal sediments tend to have a higher frequency of muddy and sandy sediments, whereas the deeper channels have higher frequencies of shell hash and coarse sediments (Grange 1977). Mud and sand sediments observed during this study frequently exhibited a golden-brown colour indicating the presence of benthic diatoms, but layered mats of microalgae were not observed.

Methods

Sediment samples for measurements of benthic microalgal biomass were collected from locations throughout the Manukau Harbour intertidal zone (Fig. 1) chosen to represent the harbour's various sediment textures. Sediment samples were collected by hand held 2.5 cm diam. corers to a depth ≥2 cm (below the visible redox discontinuity indicative of sediment overturn) during January and February 1996. Most samples were collected at low tide; one set of samples was collected along a transect across Te Tau and Karore Banks by a diver at high tide. One to six replicate cores were collected at each sample location. Samples were stored on ice and kept dark until return to the laboratory, where they were frozen.

Benthic microalgal biomass was measured as chlorophyll *a* using the double extraction, spectrophotometric technique of Whitney & Darley (1979). Frozen sediment samples were thawed and extracted in 100% acetone for 24 h, after which the acetone-pigment solution was partitioned with 0.05% NaCl and hexane. The absorbance at 663 nm of the hexane-pigment solution was measured before and after acidification with two drops of 50% HCl. This technique minimises the interferences caused by chlorophyllides and other pigment degradation products that can otherwise yield overestimates of sediment chlorophyll *a* levels. Beretich (1992) found an average overestimate of 90% by a standard fluorometric method (90% acetone extraction and fluorescence readings before and after acidification (Parsons et al. 1984)) in comparison with the Whitney & Darley technique.

Sediment samples were also collected for analysis of grain size distribution. Samples were dried, suspended in a detergent solution, wet sieved through 500, 250, 125, and 63 µm mesh sieves, and the separated fractions dried and weighed. Results were expressed as % dry weight within each size range.

A subset of the collected sediment cores were sent to National Institute of Water and Atmospheric Research (NIWA), Christchurch for High Performance Liquid Chromatography (HPLC) analysis of pigments as a means of determining the higher level taxonomic composition of the benthic microalgae in different locations and sediment types in Manukau Harbour. Frozen core samples were freeze-dried, weighed, extracted in 100% acetone, then chromatographed on a Shimadzu HPLC system

Table 1 Summary of sediment sampling site locations and characteristics in Manukau Harbour, New Zealand, January and February 1996. Locations are indicated in Fig. 1.

Location	Date	No. sites	No. cores	No. mud	No. sandy mud	No. sand	No. muddy sand	No. shell hash
Manukau littoral	26 Jan 1996	10	60	3	2	2	2	1
Wiroa A	31 Jan 1996	9	54	8	1	–	–	–
Wiroa B	1 Feb 1996	7	41	–	–	4	3	–
Te Tau/Karore	7 Feb 1996	15	48	–	–	8	6	1
Weymouth	13 Feb 1996	2	4	2	–	–	–	–
Hikihiki	13 Feb 1996	8	22	–	3	4	1	–
Wiroa B	13 Feb 1996	8	20	–	–	5	3	–
Karore	15 Feb 1996	10	29	–	1	9	–	–
Hangore	15 Feb 1996	5	18	–	1	3	–	1
Totals		74	296	13	8	35	15	3

using an RP C-18 column with spectrophotometric detection at 440 nm and photodiode array analysis of spectral composition of eluted peaks. Peak identification and quantification were consistent with Mantoura & Llewellyn (1983). Pigment concentrations were calculated as ng/g dry sediment and expressed as pigment ratios.

RESULTS

Sediments

A total of 296 sediment cores from 74 intertidal sampling locations and times throughout Manukau Harbour (Fig. 1) in January and February 1996, were analysed for chlorophyll *a* content by spectrophotometry (Table 1). Another 14 cores collected at the same times were analysed for pigment content by HPLC. Eighteen percent of the locations had "muddy" (>50% weight < 125 µm grain size) sediments, 11% had "sandy mud" (20–50% weight < 125 µm) sediments, 47% had "muddy sand" (10–20% weight < 125 µm) sediments, 20% had "sandy" (<10% weight < 125 µm) sediments, and 4% had "shell hash" (>10% weight > 500 µm) sediments. This sediment type frequency distribution has relatively more samples from mud, sandy mud, and muddy sand substrates and relatively fewer from sand substrates than the distribution obtained by Gregory et al. (1994), but reflects an effort to sample each substrate type and region in the intertidal portions of the harbour representatively.

Sediment chlorophyll *a*

Sediment chlorophyll *a* concentrations ranged from 11.8 to 340 mg Chl. *a* m^{-2}, with an average concentration of 97.5 mg Chl. *a* m^{-2} for all samples analysed. Variability ((SD/mean) × 100) in chlorophyll *a* concentrations among replicate cores averaged 36.4%, reflecting the natural patchiness of benthic microalgae at cm scales. However, there were statistically significant differences among the chlorophyll *a* concentrations associated with different substrate types (Table 2). Chlorophyll *a* levels were generally higher in sandier sediments, i.e., sediments with lower weight proportions of particles <125 µm grain size (Fig. 2). Muddy sediments, as defined above, had the lowest average chlorophyll *a* concentrations of all sediment types. The weighted average sediment chlorophyll *a* concentration for sediments of Manukau Harbour, calculated as the average sediment chlorophyll *a* concentration for each sediment type weighted by the areal frequency of each sediment type found by Gregory et al. (1994), is 101.7 mg Chl. *a* m^{-2}. This weighted average represents samples taken from the intertidal zone and neglects sediment chlorophyll *a* in subtidal habitats, which may be very low, owing to high turbidity and low light flux in Manukau Harbour (Vant & Budd 1993), in contrast to other neritic ecosystems where water clarity and microalgal biomass are high, e.g., Cahoon & Cooke (1992); Gillespie et al. (2000). A conservative estimate of average benthic microalgal biomass for the entire harbour, excluding the deeper entrance region, calculated by dividing the weighted average chlorophyll concentration for the intertidal zone by the percentage of intertidal bottom in the harbour (61.7%; Vant et al. 1998) (assuming that subtidal bottom areas support negligible autochthonous benthic microalgae populations), yields a harbour-wide average value of 62.5 mg Chl. *a* m^{-2}.

Sediment pigments

HPLC pigment analyses yielded estimates of sediment chlorophyll *a* concentrations ranging from

Table 2 Average sediment chlorophyll *a* (Chl. *a*) concentrations, mg m^{-2} (± SD) for major sediment types in Manukau Harbour, New Zealand. Differences in average chlorophyll concentrations were significant by 1-way ANOVA (F = 23.75, d.f. = 4, 291, P < 0.001). *A posteriori* comparisons (Student-Neuman-Keuls, (SNK)) showed that sediments containing some sand had significantly (α = 0.05) higher chlorophyll *a* levels than mud sediments.

Sediment type	Mud	Sandy mud	Muddy sand	Sand	Shelly sand
Chl. *a*	32.7	61.2	121.2	98.6	82.6
(SD)	±30.5	±54.6	±85.9	±39.5	±36.6
n	71	31	126	55	13
SNK group	C	B	A	A, B	A, B, C

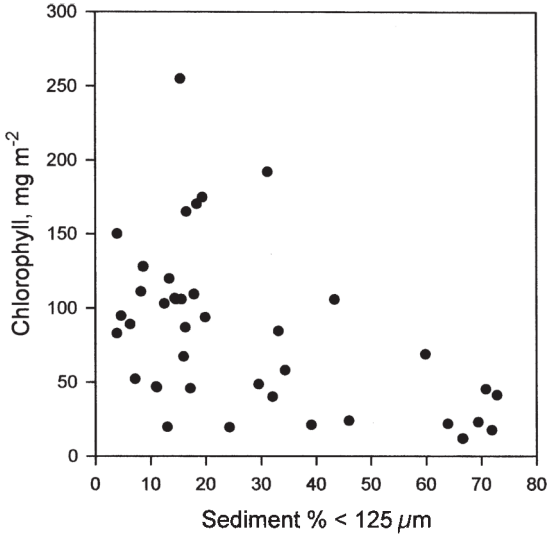

Fig. 2 Relationship between sediment chlorophyll *a* content and sediment grain size (as weight % <125 μm grain size). Pearson's product-moment correlation coefficient, $r = -0.52$ (d.f. = 1, 38, $P < 0.01$) for cube-root transformed *x* and *y* variables.

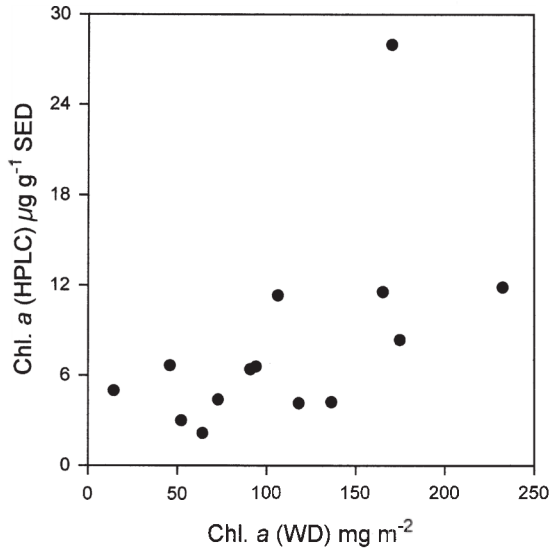

Fig. 3 Plot of chlorophyll *a* (Chl. *a*) measured by High Performance Liquid Chromatography (HPLC) (μg Chl. *a* g^{-1} sediment) versus Chl. *a* measured by Whitney & Darley (1979) method (mg Chl. *a* m^{-2}) for sediment samples collected simultaneously from the same locations. Pearson's product-moment correlation coefficient, $r = 0.56$ (d.f. = 1, 12, $P < 0.05$); without outlying data point correlation coefficient = 0.76 (d.f. = 1, 11, $P < 0.01$).

Table 3 Microalgal pigments extracted, identified, and quantified from sediments of Manukau Harbour, New Zealand, by High Performance Liquid Chromatography (HPLC) analysis. Pigment quantities, calculated as ng (g sediment)$^{-1}$, are expressed as ratios of pigment:chlorophyll *a* (Chl. *a*). Sample locations are shown in Fig. 1. (Fuco. = fucoxanthin, Zea. = zeaxanthin, Per. = peridinin.)

Location	Date	Fuco.:Chl. *a*	Chl. *b*:Chl. *a*	Zea.:Chl. *a*	Per.:Chl. *a*
Karore	7 Feb 1996	0.69	0	0.012	0.0013
Karore	7 Feb 1996	0.86	0.043	0.060	0.0524
Wiroa	13 Feb 1996	0.62	0	0.062	0.0013
Wiroa	13 Feb 1996	0.49	0.040	0.113	0.0063
Wiroa	13 Feb 1996	0.55	0.034	0.036	0.0030
Hikihiki	13 Feb 1996	0.61	0	0.067	0.0059
Hikihiki	13 Feb 1996	0.68	0.061	0.067	0.0049
Hikihiki	13 Feb 1996	0.55	0.062	0.141	0.0186
Weymouth	13 Feb 1996	0.63	0.041	0.134	0.0298
Karore	15 Feb 1996	0.62	0.00004	0.0026	0.0009
Karore	15 Feb 1996	0.62	0	0.035	0.0041
Karore	15 Feb 1996	0.54	0	0.039	0.0022
Karore	15 Feb 1996	0.54	0.102	0.045	0.0016
Hangore	15 Feb 1996	0.65	0.040	0.062	0.0099
Mean		0.62	0.030	0.062	0.010

2.15 to 27.9 μg Chl. *a* g^{-1} dry sediment. These values were positively and significantly correlated with values obtained using the Whitney/Darley method (mg Chl. *a* m^{-2}) from replicate samples collected simultaneously at the same locations (Fig. 3). Chlorophyll *a* was the most abundant pigment in all sediment samples, but relatively large amounts of fucoxanthin, a diatom marker pigment, were also found in all samples (Table 3). Chlorophyll *b*, a pigment characteristic of chlorophytes and

euglenoids, was present in most sediment samples but in much smaller proportions. Marker pigments for other taxa, such as echinenone, myxoxanthin, and zeaxanthin for cyanobacteria and peridinin for dinoflagellates (Wright et al. 1991), were present in even smaller proportions if detectable at all.

DISCUSSION

Benthic microalgal biomass versus sediment type

Sediment chlorophyll *a* levels measured by spectrophotometry in this study (mean ± SD = 97.5 ± 58.5 mg Chl. *a* m^{-2} for all samples, range = 0–483) are similar to average values for shallow, temperate waters worldwide tabulated by Cahoon (1999) (128 ± 101 mg Chl. *a* m^{-2}). Gillespie et al. (2000) report a similar average and range of values for chlorophyll *a* in sediments at several subtidal locations in Tasman Bay on the north shore of the South Island of New Zealand. The range of sediment chlorophyll *a* values measured by HPLC in this study (mean ± SD = 8.11 ± 6.53 µg Chl. *a* (g sediment)$^{-1}$, range = 2.15–27.99) is also similar to values reported from other shallow marine ecosystems (Cahoon 1999). However, this study and others report a wide range of values for benthic microalgal biomass. For example, some studies report values well above 100 mg Chl. *a* m^{-2}, e.g., the Peel-Harvey Estuary in Australia (Lukatelich & McComb 1986), the Dutch Wadden Sea (Cadée & Hegeman 1974, 1977), while others report much lower levels (<100 mg Chl. *a* m^{-2}), e.g., Loch Ewe in Scotland (Steele & Baird 1968), Laholm Bay in Sweden (Sundbäck 1986; Sundbäck & Jönsson 1988). This variability likely reflects the effects of many factors that interact to control benthic microalgal biomass. These factors may include substrate characteristics, light flux patterns, nutrient availability, physical disturbance, and grazing, among others. This variability must be considered in efforts to sample benthic microalgae representatively and to evaluate the importance of benthic microalgae in aquatic ecosystems.

The results of this study demonstrate a distinct sediment grain size relationship with sediment chlorophyll *a* levels in Manukau Harbour. Muddy sediments supported lower chlorophyll *a* levels than sediments with some sand content (Table 2, Fig. 2). This relationship is documented more thoroughly by Cahoon et al. (1999), who show that muddier sediments have lower sediment chlorophyll *a* concentrations than sandier sediments in several estuarine ecosystems. Miles & Sundbäck (2000) also found this effect in their review of a larger number of studies. There are several factors that may account for this pattern, including reduced interstitial space volumes, nutrient fluxes, and light penetration in muddier sediments, any combination of which might support lower microalgal biomass. It is also possible that muddy substrates support a taxonomically different assemblage of benthic microalgae than sandier substrates (Round 1971), and that this different assemblage has different growth rates, maximal standing crop, or susceptibility to dislodgement or grazing. This pattern of lower microalgal biomass associated with muddier sediments should be considered in evaluating the importance of benthic microalgae in estuarine ecosystems with different substrate types.

There are also circumstances, such as reduced grazing pressure or nutrient enrichment, that can support high benthic microalgal biomass in muddy substrates. A previous study of sediment chlorophyll *a* and related parameters in Manukau Harbour by Wilkinson (1981) found much higher chlorophyll *a* levels (mean = 540 mg Chl. *a* m^{-2}) than those reported here, primarily in muddy sediments in the north-eastern part of Manukau Harbour near the outfall of the Manukau WTP. This discrepancy might result from a variety of factors, including differences in time of sampling, nutrient availability, and analytical methodology. The Whitney/Darley method used in this study tends to give somewhat lower chlorophyll *a* estimates from sediment samples than other methods (Beretich 1992), but other explanations for the discrepancy cannot be ruled out, particularly the possibility that nutrient-enriched discharges from the WTP stimulated production. Gillespie & MacKenzie (1990) found chlorophyll *a* levels 5 times higher in nutrient-enriched mud substrates than in other mud and sand substrates in intertidal habitats in the South Island of New Zealand. Thus, location-specific factors can mask or alter a relationship between sediment composition and benthic microalgal biomass.

The association we found between lower benthic microalgal biomass and predominantly muddy sediments also suggests a potentially significant but poorly appreciated relationship between anthropogenic impacts and estuarine ecology. Land disturbing activities are known to cause elevated loading of sediments, particularly fine-grained materials, to receiving waters, causing accumulation of fine sediments in estuaries (Wanielista & Yousef 1993). Anthropogenic sedimentation may, therefore, reduce the total microalgal biomass, as well as possibly

altering the taxonomic composition of the microalgal communities, in estuarine ecosystems. If so, there may be additional need to consider sedimentation and erosion control efforts.

Benthic microalgal biomass versus phytoplankton biomass

Benthic microalgal biomass measured as sediment chlorophyll *a* substantially exceeds integrated mean phytoplankton biomass in Manukau Harbour. Data from Vant & Budd (1993) describing the mean annual phytoplankton standing stock for Manukau Harbour (calculated using the mean depth and area at mean sea level, but excluding the entrance region) yield an annual mean integrated biomass of 15.3 mg Chl. *a* m^{-2}. Benthic microalgal biomass calculated for the entire harbour area by extrapolating from measurements made in this study (62.5 mg Chl. *a* m^{-2}) is over 4 times higher than estimates reported for phytoplankton. The concentration of microalgal biomass at the sediment-water interface creates a rich food resource for benthic grazers and deposit feeders and, via resuspension, for suspension feeders. These trophic groups are well represented in the macrobenthos reported from Manukau Harbour (Pridmore et al. 1990).

Several lines of evidence suggest that the phytoplankton in Manukau Harbour include a significant contribution via resuspension from the benthic microalgae. The relatively large tidal range in Manukau Harbour creates strong tidal currents. The long fetches in Manukau Harbour (>10 km in most directions for the central portion, Fig. 1) at high tides permit winds to generate waves that can resuspend sediments in the shallow harbour, thereby creating the high turbidity described by Vant (1991). The diatom genera reported in plankton samples by Vant & Budd (1993) are large centric or pennate forms that may be considered "tychopelagic" (Cahoon & Laws 1993). These species are easily resuspended by tidal currents and waves, as opposed to more firmly attached benthic species. If we consider that subtidal benthic microalgae probably make some additional contribution to the microalgal biomass reported in this study, and that benthic microalgae may also contribute significantly to planktonic biomass, the relative contribution of benthic microalgae to total system biomass is accentuated further. Similar conclusions have been reached for other estuarine ecosystems where physical forces are strong (De Jonge & van Beusekom 1992; Lucas et al. 2000; Rusch et al. 2001).

Benthic microalgal taxonomic composition

Microscopic examination of sediment samples from Manukau Harbour and other New Zealand estuaries (L. B. Cahoon & R. Laws unpubl. data) showed the presence of large numbers of pennate diatoms along with some centric forms. The composition of these samples is qualitatively similar to samples from other marine habitats where benthic diatoms were an important fraction of the benthic microalgae and where benthic microalgal biomass was large compared with phytoplankton biomass (Siqueiros-Beltrones et al. 1991; Cahoon & Laws 1993).

HPLC analyses of pigments in sediment samples from Manukau Harbour showed high ratios of the diatom marker pigment, fucoxanthin, to chlorophyll *a* (averaging 0.62, Table 2), compared with ratios reported from sediments in other estuarine ecosystems. For example, fucoxanthin:chlorophyll *a* ratios of 0.39 were reported by Cariou-Le Gall & Blanchard (1995), a range of 0.21–0.73 by Klein & Riaux-Gobin (1991) and 0.22–0.29 by Riaux-Gobin et al. (1987), all from European estuaries. Thus diatoms represent a relatively high proportion of the microalgae in the sediments sampled here. The occurrence of chlorophyll *b* in sediments from Manukau Harbour indicates the presence of chlorophytes or euglenoids, but the chlorophyll *b*:chlorophyll *a* ratios found here (mean = 0.03) are lower than those reported from sediments in other estuarine ecosystems by Klein & Riaux-Gobin (1991) or Riaux-Gobin et al. (1987), indicating that these taxa are less abundant in the Manukau sediments. The presence of small amounts of the cyanobacterial marker, zeaxanthin, averaging 0.06 × (chlorophyll *a*) and the dinoflagellate marker, peridinin, at concentrations averaging 0.01 × (chlorophyll *a*), suggest a very low relative proportion of these kinds of microalgae in the sediments of Manukau Harbour.

The taxonomic composition of the benthic microalgae indicated by HPLC pigment analysis, showing dominance by diatoms and lesser concentrations of chlorophytes and/or euglenoids, cyanobacteria, and dinoflagellates, is qualitatively similar to the composition of the phytoplankton reported in Manukau Harbour (Vant & Budd 1993; Vant & Safi 1996). They reported dominant taxa including members of the diatom genera *Coscinodiscus*, *Ditylum*, *Nitzschia*, *Odontella*, *Pleurosigma*, and *Rhizosolenia*, various dinoflagellates, and, occasionally near the Manukau WTP, the chlorophyte, *Scenedesmus*, and the euglenoid, *Euglena*. The relatively low concentrations of chlorophyte and euglenoid marker pigments in sediment samples suggest that nutrient enrichment effects of the

Manukau WTP on benthic microalgae are minor for the harbour as a whole.

The similarity of the taxonomic compositions of the benthic microalgae and phytoplankton indicated by pigment ratios suggest that either sediment pigments in Manukau Harbour accumulated from sinking phytoplankton, as found by Sun et al. (1994) in Long Island Sound (United States), or that some fraction of the "phytoplankton" were resuspended benthic microalgae (Baillie & Welsh 1980; Shaffer & Sullivan 1988). The dynamic physical processes at work in this shallow estuary probably limit net deposition rates. Thus, the flux of microalgal biomass into the water column by resuspension of benthic microalgae is probably greater than the flux of biomass into the sediments by sinking of phytoplankton. Therefore, the considerable benthic microalgal biomass indicated to exist in Manukau Harbour by sediment chlorophyll *a* values probably makes an important contribution to the previously reported phytoplankton biomass.

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