

# Spatial distribution of modern dinoflagellate cysts in polluted estuarine sediments from Buzzards Bay (Massachusetts, USA) embayments

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**ABSTRACT:** Analysis of the spatial distribution of the dinoflagellate cyst assemblages in 19 surface sediment samples collected from 3 Buzzards Bay (Massachusetts, USA) embayments revealed the potential applicability of dinoflagellate cysts as biological indicators of environmental conditions in estuarine systems. Sites with the highest levels of toxic pollution and hypertrophic conditions are characterized by the lowest dinoflagellate cyst species-richness and concentrations. Among the abiotic factors influencing the distribution of dinoflagellate cysts, nutrients and toxic pollution are the major controls, as in these embayments salinity and temperature variability is low. Principal component analysis, based on the proportions of cyst taxa, indicated that cyst assemblages gradually change when moving away from the sources of nutrient pollution, sewage outfalls in particular.

**KEY WORDS:** Dinoflagellate cyst · Eutrophication · Heavy metals · Sewage · Wastewater treatment plant · PCBs · Apponagansett Bay · New Bedford Harbor

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## INTRODUCTION

Human activities such as nutrient enrichment and toxic pollution cause water-quality degradation and habitat loss. These activities are most intensive in estuaries with highly urbanized and industrialized watersheds. Concern about water-quality degradation in estuarine waters has stimulated a demand for development of indicators of nutrient enrichment and toxic contamination to examine paleo- and modern environmental conditions and trends caused by intensified anthropogenic activities in watersheds.

To be a useful biological indicator of environmental conditions, an organism has to satisfy certain criteria (Gibson et al. 2000). In general, a biological indicator should be ubiquitous, well preserved in sediments, numerous enough for statistical treatment, and reflect certain environmental parameters. Dinoflagellate cysts

have proven to satisfy all the above criteria (Fensome et al. 1996).

Dinoflagellates are single-celled organisms that constitute an important part of the phytoplankton population in aquatic ecosystems. During their life cycle some dinoflagellates produce hypnozygotes, or resting cysts, which can be preserved in sediments (Fensome et al. 1993). The assemblages of dinoflagellate cysts in sediments encode information on the dinoflagellates in the upper water column (Dale 1976, Reid & Harland 1978). In turn, the population of dinoflagellates is influenced by environmental factors such as temperature and salinity, nutrients, turbidity and pollution (Taylor 1987). Dinoflagellate cysts recovered from coastal sediments have the potential to provide substantial information on biological processes and interactions within aquatic systems.

Several studies have examined the temporal development of estuarine eutrophication and pollution by

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analyzing the dinoflagellate cyst records in sediment cores (Dale & Fjellså 1994, Sætre et al. 1997, Thorsen & Dale 1997, Dale et al. 1999, Matsuoka 1999, 2001, Dale 2001, Pospelova et al. 2002). A recent study of the historical records of dinoflagellate cysts from shallow unstratified embayments of Buzzards Bay (New Bedford Harbor and Apponagansett Bay) found that species richness (number of taxa), total cyst concentrations and fluxes, proportions of some heterotrophic species, as well as abundance of indicator species changed as a result of eutrophication and toxic pollution (Pospelova et al. 2002). In oligotrophic systems, such as New Bedford Harbor in its early history (Pospelova et al. 2002), nutrient enrichment initially increases dinoflagellate cyst species-richness. However, under highly eutrophic and polluted conditions, species diversity declines, as seen during the 20th century in New Bedford Harbor. These extreme conditions are also characterized by large fluctuations in total cyst concentrations and fluxes. The proportion of cysts of heterotrophic dinoflagellates, Polykrikaceae and Diplopsalidaceae in particular, tends to increase with increasing nutrient enrichment.

If the dinoflagellate cyst record reflects the temporal changes of the environmental conditions in an estuary, it must also show spatial change, as environmental conditions in an estuary are non-uniform. If so, dinoflagellate cyst assemblages from surface samples can be used to support or discard some of the conclusions previously made about the 'eutrophication and pollution signals' drawn from analyses of dinoflagellate cysts in the cores. No previous studies have investigated spatial distributions of dinoflagellate cysts in relation to eutrophication and toxic pollution in estuarine systems. This work represents the first analysis of this kind.

In this study we document the dinoflagellate cyst assemblages on a ~1 km scale in 3 side embayments of Buzzards Bay, Massachusetts. Comparison of these assemblages to known gradients of nutrient and toxic pollution allows us to assess the utility of cysts as indicators of plankton response.

## MATERIAL AND METHODS

**Study area.** New Bedford Harbor, Clarks Cove and Apponagansett Bay are side embayments of the north-western shore of Buzzards Bay, Massachusetts, USA (Fig. 1). The embayments are shallow, with water depths ranging from 1 to 12 m (mean 6 m), generally well mixed, and unstratified. There are no major bottom currents in Buzzards Bay, and most of the environmental energy is in tidal currents and waves (Summerhayes et al. 1985). The

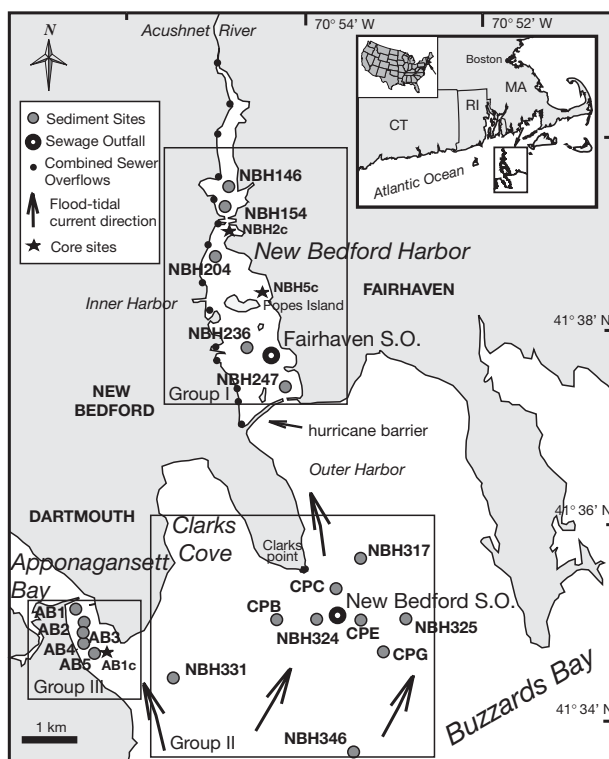


Fig. 1. New Bedford Harbor, Clarks Cove and Apponagansett Bay showing location of surface sediment samples. Direction of tidal-flood current from Howes et al. (1996), locations of 3 core sites from Pospelova et al. (2002)

tidal range is about 1 m; the direction of tidal-flood current is shown in Fig. 1.

Mean summer (June, July and August) water salinity varies from 28 to 31 and summer temperatures from 21 to 23°C (Howes et al. 1999). Concentrations of nutrients and chlorophyll *a* for the studied embayments are provided in Table 1. Ammonium is the major form of inorganic nitrogen available throughout the Bay and its concentrations are heavily influenced by the sewage outfall (Borkman & Turner 1993). A study of economic growth and environmental change in Buzzards Bay (Terkla et al. 1990) has identified population growth as the dominant factor currently affecting the environmental health of Buzzards Bay.

**New Bedford Harbor:** New Bedford Harbor, also known as the Acushnet River estuary, has a moderate

Table 1. Comparison of mean summer (June to August) concentrations of nutrients and chlorophyll *a* in embayments of Buzzards Bay

Location	Nitrate (μM)	Ammonium (μM)	Phosphate (μM)	Chlorophyll <i>a</i> (μg l <sup>-1</sup> )
Inner New Bedford Harbor	11.0	5.7	1.8	8.5
Clarks Cove	1.5	0.9	1.5	3.7
Apponagansett Bay	1.3	2.2	1.6	4.7

freshwater input (median flow  $0.54 \text{ m}^3 \text{ s}^{-1}$ ) from the river flowing into the northern part of the harbor. This harbor is heavily urbanized, as it is surrounded by 35% of the population of the entire Buzzards Bay watershed (Howes et al. 1999). As a result, ~20 combined sewer overflows (CSO) discharge into the inner part of New Bedford Harbor, in addition to the outfall of the Fairhaven Wastewater Treatment Plant (Fig. 1). From 1974 to 1996, the Fairhaven facility has continuously discharged primary-treated sewage to the harbor, resulting in a load of  $140 \text{ t N yr}^{-1}$  (SAIC 1991). A hurricane barrier greatly reduces water circulation relative to the rest of Buzzards Bay and affects water quality (Costa et al. 1996). Based on Nixon's (1995) classification, the inner New Bedford Harbor is a 'hypertrophic' or highly eutrophic system, and is one of the most eutrophic embayments in Buzzards Bay (Howes et al. 1999).

New Bedford Harbor also is one of the most contaminated sites in the United States (Nelson et al. 1996) due to polychlorinated biphenyls (PCBs) used in the manufacture of electrical capacitors. Past discharges of PCBs and other pollutants in the upper harbor have resulted in modern sediment concentrations as high as  $35\,000 \text{ ng g}^{-1}$  PCBs,  $1500 \text{ } \mu\text{g g}^{-1}$  Cu,  $600 \text{ } \mu\text{g g}^{-1}$  Pb, and  $1200 \text{ } \mu\text{g g}^{-1}$  Zn. New Bedford Harbor is listed in the US Environmental Protection Agency's National Priorities List for cleanup because of PCBs contamination (Bergen et al. 1998).

New Bedford's outer harbor, south of the hurricane barrier (Fig. 1), is expansive and well-flushed. The primary difference between the outer and inner harbor is a lower sedimentary concentration of PCBs, heavy metals and other industrial pollutants in the former. However, the surface plume of effluent from the New Bedford Wastewater Treatment Facility, located off Clarks Point, influences local water-quality conditions. The New Bedford Wastewater Treatment Plant discharges up to  $962 \text{ t N yr}^{-1}$  into the system, mostly in the form of ammonium (SAIC 1991). Elevated concentrations of nitrate ( $1.2 \text{ } \mu\text{M}$ ), ammonium ( $16.4 \text{ } \mu\text{M}$ ), and phosphorus ( $3.0 \text{ } \mu\text{M}$ ) were measured near the outfall by Borkman & Turner (1993). Despite the high sewage-effluent input, effects of the discharge on water quality are detectable only within 5 km of the outfall (Costa et al. 1999).

**Apponagansett Bay:** Similar to New Bedford Harbor, inner Apponagansett Bay is one of the most eutrophic embayments of Buzzards Bay because of its restricted geomorphology and nutrient loading from the watershed (Howes et al. 1999). The high nutrient load to the estuary originates mostly from its densely populated watershed, followed by commercial and industrial development. In contrast to the inner bay, the outer Apponagansett Bay is better flushed, with moderate nutrient levels (Howes et al. 1999).

**Clarks Cove:** In contrast to New Bedford Harbor, the neighboring Clarks Cove (Fig. 1) has relatively good water quality because of the absence of major freshwater sources and a sewered watershed, with discharges located at Clarks Point (New Bedford Wastewater Treatment Plant). Clarks Cove water quality is maintained primarily by its tidal dynamics (Howes et al. 1999). Despite the fact that Clarks Cove is a comparatively deep (~9 m) and well-flushed embayment, the total nitrogen level here is higher than in the waters of outer Buzzards Bay. This enrichment of Clarks Cove waters comes from the Clarks Point outfall when its waters enter the system during periodic shifts in the outer harbor circulation, and from the tidal waters of Apponagansett Bay to the west (Howes et al. 1999).

**Sample collection.** Surface sediments were collected from 19 locations throughout New Bedford Harbor, Clarks Cove and Apponagansett Bay (Fig. 1, Table 2). For the purpose of this study, we divide all samples into 3 groups (Table 2), based on their location: Group I comprised 5 samples from the inner part of New Bedford Harbor, Group II comprised 9 samples from the outer harbor and Clarks Cove, and Group III comprises 5 samples from the outer part of Apponagansett Bay.

Sediments were collected with a van Veen or petite Ponar grab sampler during the US Environmental Protection Agency (EPA) cruises in October 1996. All samples were stored at  $-4^\circ\text{C}$  in the dark until processing in 1999. We assume that the top 2 cm of collected sediments represent ~10 yr deposition, based on the estimates of accumulation rates previously reported for the embayments (Summerhayes et al. 1985, Latimer et al. 2003). Sediments are generally characterized as fine sand and mud (Table 2).

**Sediment chemistry.** Sedimentary metal concentrations were measured by inductively-coupled plasma atomic-emission and graphite furnace atomic-absorption spectrophotometry after digestion by microwave heating in pressurized digestion vessels with a mixture of concentrated acids (for details see Latimer et al. 2003). PCBs were extracted using a microwave procedure and analyzed using gas chromatography with electron-capture detector (for details see Latimer et al. 2003). Percent organic carbon was measured by continuous-flow elemental analysis/isotope-ratio mass-spectrometry as described by Latimer et al. (2003).

**Dinoflagellate cysts.** For dinoflagellate cyst analyses, sediment samples of known volume and dry weight were processed using standard palynological preparation methods (Rochon et al. 1999). Sediment was dried at  $40^\circ\text{C}$ , weighed, sieved through  $125 \text{ } \mu\text{m}$  mesh and retained on a  $10 \text{ } \mu\text{m}$  mesh (to eliminate coarse and fine material), treated with warm HF (40%) to dissolve silicates, and HCl (10%) to remove carbonates and silicofluorides. Calibrated tablets of *Lycopodium clavatum* spores

Table 2. Surface sediment samples. Collection data

Group Station ID	Location	Latitude (°N)	Longitude (°W)	Water depth (m)	Sediment type	Sampling method
<b>Group I</b>						
NBH146	New Bedford Harbor (inner)	41.660	70.917	4.6	Sandy silt	Petite Ponar
NBH154	New Bedford Harbor (inner)	41.657	70.918	7.3	Sandy silt	Petite Ponar
NBH204	New Bedford Harbor (inner)	41.652	70.920	4	Sandy silt	Petite Ponar
NBH236	New Bedford Harbor (inner)	41.634	70.913	9.8	Mud	Petite Ponar
NBH247	New Bedford Harbor (inner)	41.627	70.905	3	Sandy silt	Petite Ponar
<b>Group II</b>						
NBH324	Clarks Cove/New Bedford Harbor (outer)	41.582	70.899	~9	Sandy silt	Petite Ponar
CPE	Clarks Cove/New Bedford Harbor (outer)	41.582	70.890	9	Mud	Petite Ponar
CPC	Clarks Cove/New Bedford Harbor (outer)	41.588	70.895	9	Fine sand	Petite Ponar
CPB	Clarks Cove/New Bedford Harbor (outer)	41.582	70.907	9.6	Mud	Petite Ponar
CPG	Clarks Cove/New Bedford Harbor (outer)	41.576	70.886	8.8	Mud	Petite Ponar
NBH317	New Bedford Harbor (outer)	41.594	70.890	9.8	Sandy silt	Petite Ponar
NBH325	New Bedford Harbor (outer)	41.582	70.881	~10	Sandy silt	Petite Ponar
NBH346	Buzzards Bay	41.545	70.891	~10	Mud	Petite Ponar
NBH331	Clarks Cove/Apponagansett Bay	41.570	70.928	7.5	Mud	Petite Ponar
<b>Group III</b>						
AB1	Apponagansett Bay	41.584	70.948	2.4	Sandy silt	Van Veen
AB2	Apponagansett Bay	41.581	70.947	4.6	Sandy silt	Van Veen
AB3	Apponagansett Bay	41.580	70.947	5.2	Silt	Van Veen
AB4	Apponagansett Bay	41.578	70.947	5.2	Sandy silt	Van Veen
AB5	Apponagansett Bay	41.576	70.945	4.9	Sandy silt	Van Veen

(Stockmarr 1977), added during processing, allowed calculation of dinoflagellate cyst concentrations. In this study, we express dinoflagellate cyst concentrations in 2 units: cysts per volume of wet sediments, and cysts per dry weight of sediments. Cyst concentrations based on dry weight of sediments facilitate comparison with core studies, whereas concentrations based on volume are often applied to study spatial cyst distributions.

Aliquots were mounted on microscope slides with glycerine jelly. Dinoflagellate cysts were counted with a transmitted light microscope (63× and 100× objectives). Identification of dinoflagellate cysts was made on the basis of published descriptions in accordance with taxonomy given by Lentin & Williams (1993) and Rochon et al. (1999). However, when species-level identification was not possible, identification was to genus level. There are different taxonomies for cysts and thecal stages of dinoflagellates because paleontological studies of cysts originally were carried out independently from biological studies of the motile forms. Here we use the paleontological nomenclature according to Head (1996), Head et al. (2001), and Pospelova & Head (2002). A list of the dinoflagellate cysts counted and their known biological name or thecal equivalent is provided in Table 3. Taxonomy is presented in Appendix 1 (available at: [www.int-res.com/journals/suppl/Pospelova\\_appendix.pdf](http://www.int-res.com/journals/suppl/Pospelova_appendix.pdf)).

*Spiniferites* spp. includes all *Spiniferites* cysts except *S. bentorii*, *S. elongatus* and *S. membranaceus*. For statistical treatment, species of the genus *Brigantedinium* (*B. cariacense* and *B. simplex*) were grouped together because cyst-folding or orientation sometimes ob-

scured the archeopyle characteristics, thus preventing identification to species level.

Species richness is used in this study as a measure of dinoflagellate cyst diversity (see discussion in Pospelova et al. 2002). To correct for non-equal cyst counts in different samples, Fisher's alpha index is often introduced (Fisher et al. 1943). This is a diversity index, defined for each sample implicitly by the formula:

$$S = \alpha \cdot \ln(1 + n/\alpha)$$

where  $S$  is number of cyst taxa,  $n$  is the cyst count and  $\alpha$  is Fisher's alpha. All statistical calculations for this work were made using SPSS 10.1 for Windows software.

## RESULTS

### Metals, PCBs and organic carbon

Samples from the inner part of New Bedford Harbor (Group I) had the highest concentrations of all metals (Table 4, Fig. 2), with average concentrations of Zn of  $372 \mu\text{g g}^{-1}$ , Cu of  $516 \mu\text{g g}^{-1}$ , and Pb of  $156 \mu\text{g g}^{-1}$ . The concentrations of metals in the outer harbor and Clarks Cove (Group II) are lower, on average, by a factor of 3, with Zn  $144 \mu\text{g g}^{-1}$ , Cu  $55 \mu\text{g g}^{-1}$ , and Pb  $49 \mu\text{g g}^{-1}$ . Apponagansett Bay (Group III) was characterized by low levels of metals pollution: Zn  $92 \mu\text{g g}^{-1}$ , Cu  $40 \mu\text{g g}^{-1}$ , and Pb  $23 \mu\text{g g}^{-1}$ . The concentration of PCBs followed the same trend (Table 4), the highest concentrations being in Group I ( $\sim 17\,000 \text{ ng g}^{-1}$ ), moderate con-

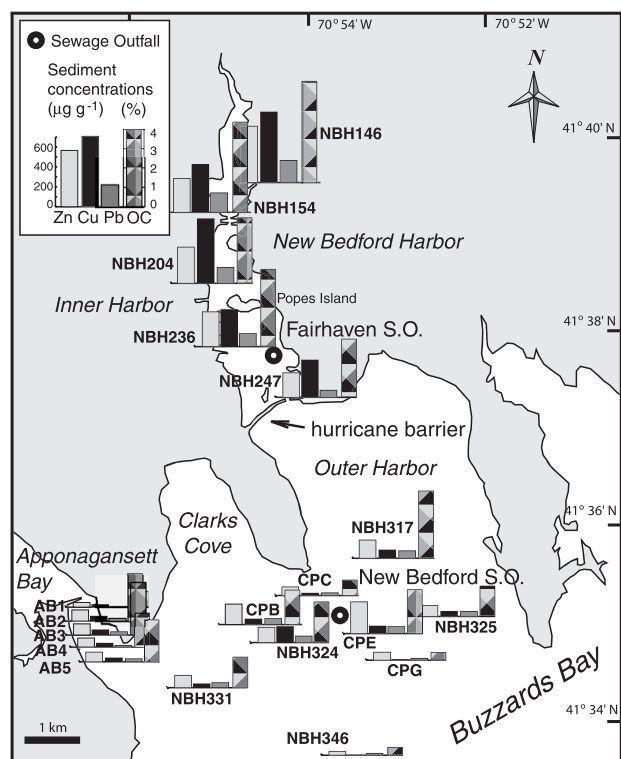


Fig. 2. Distribution of sediment concentrations of Zn, Cu, Pb ( $\mu\text{g g}^{-1}$ ) and organic carbon (OC, %) content in New Bedford Harbor, Clarks Cove and Apponagansett Bay

centrations ( $\sim 1300 \text{ ng g}^{-1}$ ) in Group II, and the lowest ( $500 \text{ ng g}^{-1}$ ) in Group III. Organic carbon content (Table 4, Fig. 2) was highest in the inner New Bedford Harbor sediments (3.0 to 5.3 %). Sediment samples from Apponagansett Bay, the outer harbor and Clarks Cove had comparable organic carbon content ranging from 0.4 to 2.7 %. Distribution of Ag and Cd did not follow the same pattern, as the highest values were found in the outer harbor, near the location of the New Bedford sewage outfall.

We calculated Pearson's correlations to determine the degree of covariance between concentrations of contaminants and content of organic carbon (Table 5). Most correlation coefficients were higher than 0.50 ( $p \leq 0.02$ ). Thus, sedimentary concentrations of PCBs, Zn, Cu, Cr, Pb, Ni, Ag and organic carbon content were highly covariant and the effect of individual pollutants on the system could not be separated.

### Distribution of dinoflagellate cysts

An average of 317 cysts and a minimum of 102 were counted in each sample. We identified and counted 35 dinoflagellate cyst taxa in sediments from 19 sites

Table 3. Taxonomic designation of dinoflagellate cysts counted in this study. Thecal equivalents from Head (1996), except for *Islandinium brevispinosum* (from Pospelova & Head 2002) and *I. cezare* and *I. minutum* (from Head et al. 2001)

Cyst species (paleontological name)	Dinoflagellate thecate name or affinity (biological name)
<b>Autotrophic</b>	
Gonyaulacaceae	
–	<i>Alexandrium tamarense</i>
<i>Impagidinium</i> spp.	? <i>Gonyaulax</i> sp. indet.
<i>Lingulodinium machaerophorum</i>	<i>Lingulodinium polyedrum</i>
<i>Nematosphaeropsis</i> spp.	<i>Gonyaulax spinifera</i> complex
<i>Operculodinium centrocarpum</i> sensu Wall & Dale 1996	<i>Protoceratium reticulatum</i>
<i>Operculodinium israelianum</i>	? <i>Protoceratium reticulatum</i>
<i>Spiniferites bentorii</i>	<i>Gonyaulax digitalis</i>
<i>Spiniferites elongatus</i>	<i>Gonyaulax spinifera</i> complex
<i>Spiniferites membranaceus</i>	<i>Gonyaulax spinifera</i> complex
<i>Spiniferites</i> spp.	<i>Gonyaulax</i> complex
<i>Tectatodinium pellitum</i>	<i>Gonyaulax spinifera</i> complex
Peridiniaceae	
–	<i>Pentapharsodinium dalei</i>
Pyrophacaceae	
<i>Tuberculodinium vancampoe</i>	<i>Pyrophacus steinii</i>
<b>Heterotrophic</b>	
Diplopsalidaceae	
<i>Dubridinium</i> spp.	Diplopsalid group
Gymnodiniales	
–	<i>Gymnodinium</i> spp.
Polykrikaceae	
–	<i>Polykrikos schwartzii</i>
–	<i>Polykrikos kofoidii</i>
Peridiniaceae	
<i>Peridinium wisconsinense</i>	<i>Peridinium wisconsinense</i>
Proto-peridiniaceae	
<i>Brigantedinium cariacense</i>	<i>Proto-peridinium avellanum</i>
<i>Brigantedinium simplex</i>	<i>Proto-peridinium conicoides</i>
<i>Brigantedinium</i> spp.	? <i>Proto-peridinium</i> spp.
<i>Islandinium brevispinosum</i>	<i>Proto-peridinium</i> sp. indet.
<i>Islandinium? cezare</i>	<i>Proto-peridinium</i> sp. indet.
<i>Islandinium minutum</i>	<i>Proto-peridinium</i> sp. indet.
<i>Lejeunecysta oliva</i>	<i>Proto-peridinium</i> sp. indet.
<i>Lejeunecysta sabrina</i>	<i>Proto-peridinium leonis</i>
<i>Proto-peridinium minutum</i>	<i>Proto-peridinium minutum</i>
<i>Proto-peridinium</i> spp.	<i>Proto-peridinium</i> sp. indet.
<i>Quinquecuspis concreta</i>	<i>Proto-peridinium leonis</i>
<i>Selenopemphix nephroides</i>	<i>Proto-peridinium subinermis</i>
<i>Selenopemphix quanta</i>	<i>Proto-peridinium conicum</i>
<i>Stelladinium stellatum</i>	<i>Proto-peridinium stellatum</i>
<i>Trinovantedinium applanatum</i>	<i>Proto-peridinium pentagonum</i>
<i>Votadinium calvum</i>	<i>Proto-peridinium oblongum</i>
<i>Votadinium spinosum</i>	<i>Proto-peridinium claudicans</i>

(Table 6). Microphotographs of cyst taxa are shown in Figs. 3 to 7.

Dinoflagellate cysts were recovered from all the sediment samples. Total dinoflagellate cyst concentrations varied by an order of magnitude, from  $\sim 300$  to  $4200 \text{ cysts cm}^{-3}$  and  $\sim 500$  to  $9400 \text{ cysts g}^{-1}$ , averaging  $\sim 2000 \text{ cysts cm}^{-3}$  and  $\sim 4300 \text{ cysts g}^{-1}$  (Tables 7 & 8, Fig. 8). In general, the total cyst concentrations in inner

New Bedford Harbor (Group I) were 2 to 3 times lower compared to the outer harbor and Clarks Cove (Group II) and Apponagansett Bay (Group III). The highest concentrations were found in Group II, which was also characterized by the largest range of variation within the group; the total cyst concentrations ranged from ~500 to 4200 cysts cm<sup>-3</sup> and ~500 to 9400 cysts g<sup>-1</sup>. We divided the highest by the lowest value for the total cyst concentration within each group to characterize fluctuations in cyst concentrations. These fluctuations can be expressed as a ratio of 6:8:4 for Groups I, II and III if concentrations are expressed in units of cysts per volume of sediments, and as 12:20:7 if cysts per dry weight are used.

The ratio between cysts produced by autotrophic and heterotrophic dinoflagellates ranged from 0.9 to

4.9, with an average of 2.0 (Table 6). Cysts of autotrophic dinoflagellates usually comprised more than 50% of the assemblages (Fig. 9), with the exception of 3 sites—CPG, CPB and AB3 (46 to 47%). Cysts of heterotrophic dinoflagellates comprised an average of 36% of each cyst assemblage, ranging from 17 to 53% (Fig. 9). The proportion of Diplopsalidaceae and Polykrikaceae was ~12% at all sites (Fig. 9).

A total of 37 dinoflagellate cyst taxa were identified (Table 6). The number of taxa (species richness) in samples ranged from 12 to 26, with an average of 22, and Fisher's index changed from 3.5 to 6.4 (Table 6, Fig. 8). Cyst assemblages in Group I, the inner part of New Bedford Harbor, were characterized by lower diversity (an average species richness of 17,  $\alpha = 4.5$ ) compared to assemblages in Groups II (24 taxa,  $\alpha = 5.7$ )

and III (21 taxa,  $\alpha = 5.2$ ). There were significant ( $p < 0.01$ ) negative correlations between dinoflagellate cyst species-richness, Fisher's index and sedimentary concentrations of Cu, Zn, Pb, PCBs and organic carbon content (Table 7, Fig. 10). A highly significant correlation ( $R = 0.91$ ,  $p < 0.01$ ) between species richness and Fisher's alpha showed that the correction for non-uniform cyst counts in different samples was not significant.

The composition of the dinoflagellate cyst assemblages is described with respect to proportions (Table 6) and concentration by volume and dry weight, respectively (Appendices 2 & 3; [www.int-res.com/journals/suppl/Pospelova\\_appendix.pdf](http://www.int-res.com/journals/suppl/Pospelova_appendix.pdf)). The dominant taxa belonged to Gonyaulacaceae, *Spiniferites* spp. and *Operculodinium centrocarpum* sensu Wall & Dale (1966) (Table 6, Fig. 11). Cyst taxa that comprised >5% of the assemblages include *Protoperidinium* spp., *Dubridinium* spp., *Pentapharsodinium dalei*, *Islandinium brevispinosum*, *Bri-gantedinium* spp., *Polykrikos kofoidii* plus *P. schwartzii*, *Islandinium minutum* and *Spiniferites elongatus*. At 4 sites, cysts of the toxic bloom-forming *Alexandrium tamarense* were found in low proportions (<2%).

Principal component analysis (PCA) was performed on taxa percentages using Subprogram 10.1 of the Statistical Package for the Social Sciences (SPSS 10.1). The first principal component (PC1) represented 90% of the

Table 4. Concentrations of organic carbon (OC, %), PCBs (ng g<sup>-1</sup>) and metals ( $\mu\text{g g}^{-1}$ ) in sediments

Group Site	OC	PCBs	Zn	Cu	Cr	Pb	Cd	Ni	Ag
<b>Group I</b>									
NBH 146	5.3	33525	564.9	706.8	204.1	222.1	0.73	39.9	1.85
NBH154	4.7	22532	339.1	480.0	249.7	194.9	1.06	38.3	4.63
NBH204	3.4	15052	362.7	647.0	296.2	160.2	1.39	41.5	3.02
NBH236	4.0	10495	349.1	373.0	210.7	132.2	0.85	27.6	3.47
NBH247	3.0	4520	245.7	374.4	122.4	71.5	0.54	11.1	2.65
<b>Group II</b>									
NBH324	2.1	2757	153.4	161.2	121.9	64.8	0.75	29.4	2.90
CPE	2.3	1039	317.7	74.8	197.4	70.6	0.20	40.6	4.64
CPC	0.8	938	85.7	22.8	39.0	27.3	0.20	7.9	0.73
CPB	1.8	1481	205.0	55.5	92.1	60.0	0.42	24.8	2.02
CPG	0.4	138	80.2	6.9	23.4	19.4	0.06	5.8	0.22
NBH317	2.5	3885	183.5	83.3	111.8	75.5	0.78	20.9	4.42
NBH325	1.6	1205	108.7	50.6	85.3	51.0	0.24	19.4	1.36
NBH346	0.4	61	37.3	4.2	23.4	19.2	0.10	6.6	0.14
NBH331	1.6	729	123.7	37.7	78.4	50.4	0.41	23.9	1.15
<b>Group III</b>									
AB1	0.8	134	47.4	19.7	34.3	5.8	0.09	3.0	0.28
AB2	2.5	726	112.2	48.7	60.5	28.1	0.30	7.4	0.79
AB3	2.7	537	112.5	52.4	63.5	32.6	0.18	11.2	1.03
AB4	1.8	398	90.8	39.1	54.2	18.5	0.17	5.0	0.86
AB5	2.2	579	96.9	38.0	57.4	30.5	0.21	7.6	0.89

Table 5. Correlation matrix of organic carbon, PCBs and metal sedimentary concentrations. Coefficients with  $R > 0.5$  and significance at 0.01 level in bold

	OC	PCBs	Zn	Cu	Cr	Pb	Cd	Ni	Ag
OC		<b>0.849</b>	<b>0.878</b>	<b>0.849</b>	<b>0.811</b>	<b>0.894</b>	<b>0.730</b>	<b>0.687</b>	<b>0.617</b>
PCBs	<b>0.849</b>		<b>0.879</b>	<b>0.911</b>	<b>0.742</b>	<b>0.952</b>	<b>0.686</b>	<b>0.678</b>	0.411
Zn	<b>0.878</b>	<b>0.879</b>		<b>0.891</b>	<b>0.877</b>	<b>0.936</b>	<b>0.705</b>	<b>0.837</b>	<b>0.639</b>
Cu	<b>0.849</b>	<b>0.911</b>	<b>0.891</b>		<b>0.853</b>	<b>0.930</b>	<b>0.820</b>	<b>0.694</b>	0.482
Cr	<b>0.811</b>	<b>0.742</b>	<b>0.877</b>	<b>0.853</b>		<b>0.893</b>	<b>0.868</b>	<b>0.900</b>	<b>0.788</b>
Pb	<b>0.894</b>	<b>0.952</b>	<b>0.936</b>	<b>0.930</b>	<b>0.893</b>		<b>0.824</b>	<b>0.833</b>	<b>0.627</b>
Cd	<b>0.730</b>	<b>0.686</b>	<b>0.705</b>	<b>0.820</b>	<b>0.868</b>	<b>0.824</b>		<b>0.745</b>	<b>0.693</b>
As	0.306	-0.011	0.259	-0.006	0.245	0.143	-0.466	0.497	-0.196
Ni	<b>0.687</b>	<b>0.678</b>	<b>0.837</b>	<b>0.694</b>	<b>0.900</b>	<b>0.833</b>	<b>0.745</b>		<b>0.766</b>
Ag	<b>0.617</b>	0.411	<b>0.639</b>	0.482	<b>0.788</b>	<b>0.627</b>	<b>0.693</b>	<b>0.766</b>	

variance, whereas the second and the third components explained less than 5 and 2%, respectively. Thus, only PC1 was considered for further analyses.

The first principal component (PC1) was distributed in 2 contrasting patterns. It increased from the upper part of New Bedford Harbor seaward towards the hurricane barrier, but decreased from Clarks Cove Point and inner Apponagansett Bay in the seaward direction (Fig. 12). The highest values of PC1 were near the sewage outfalls of Fairhaven and New Bedford Wastewater Treatment Plants, as well as at Site AB1, the sample from the uppermost reach of Apponagansett Bay included in our study. There was a significant ( $R^2 = 0.71$  and  $p < 0.001$ ) linear correlation between PC1 scores and the distance to the nearest locations of

the sewage outfalls (Fig. 13) for sites from Groups I and II, for which the distance from the point-sources of sewage discharge could be determined. Sites from Group III were not considered, as there is no identified point source of sewage discharge in Apponagansett Bay. Thus, this is a strong indication that PC1 is related to the discharge of sewage enriched with nutrients.

Fig. 11 shows relative abundances of the dinoflagellate cysts taxa that constituted  $>1\%$  of the assemblages. Amongst these taxa, the proportions of *Islandinium brevispinosum* and *Protoperidinium* spp. decreased as PC1 increased, i.e. towards the sewage outfalls (Fig. 11), whereas the proportions of cysts of *Quinquecuspis concreta*, *Protoperidinium minutum*, *Spiniferites elongatus* and Cyst Type E tended to increase with

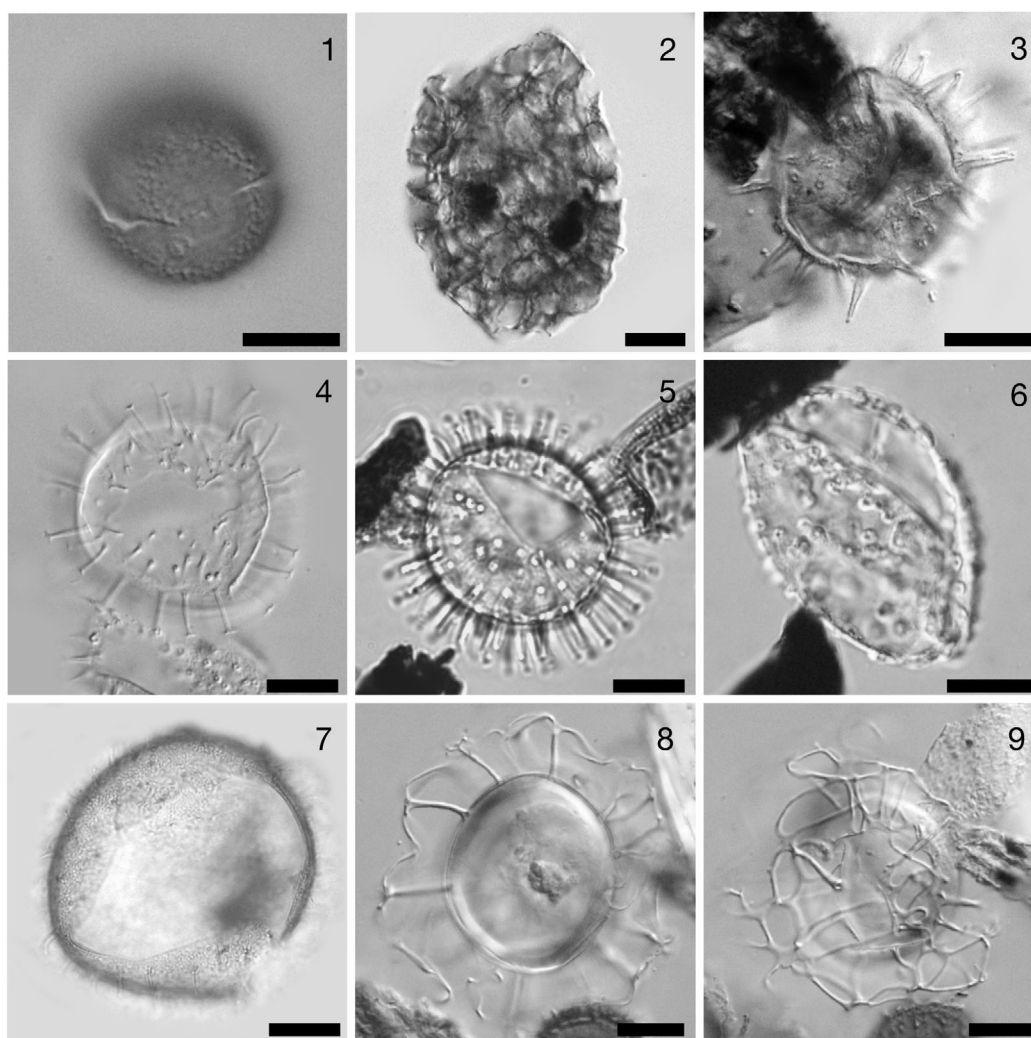


Fig. 3. Bright-field photomicrographs. **1.** *Gymnodinium* spp. indet., NBH325, Slide x, W53/2, lateral surface; **2.** *Polykrikos schwartzii*, NBH346, Slide 1, O29/3, equatorial view; **3.** *Lingulodinium machaerophorum*, NBH247, Slide 1, L391/2, orientation uncertain; **4,5.** *Operculodinium centrocarpum* sensu Wall & Dale (1966), NBH325, Slide 1, M51/4, dorsal surface (4), and NBH325, Slide 1, dorsal surface (5); **6.** *Operculodinium centrocarpum* var. *truncatum*, NBH204, Slide 2, S58/3, orientation uncertain; **7.** *Operculodinium israelianum*, AB2, Slide 1, R41/1, dorsal surface; **8,9.** *Nemosphaeropsis* spp. indet, CPE, Slide 1, V38/0, optical section (8), ventral surface (9). Scale bars = 10  $\mu$ m

increasing PC1. The abundance of *Nematosphaeropsis* spp. was greater at low (<0.91) and high values of PC1 (>0.97) than at the intermediate values.

## DISCUSSION

Our work documents the composition of dinoflagellate cyst assemblages in surface sediments and studies the cyst distribution on small spatial scales in 3 Buzzards Bay embayments. Spatial variability in cyst concentrations, species diversity and species composition of the assemblages suggest that the cyst assemblages reflect gradients of nutrients and toxic pollution in the embayments. However, prior to discussing the details of these cyst signals, we would like to highlight

the complexity of the suggested connection between the dinoflagellate cyst record in the sediments and environmental parameters. Many factors affect the multi-step process from dinoflagellate distribution in estuarine waters to cyst accumulation in sediments. Distribution of dinoflagellate cysts depends on the distribution of dinoflagellates, biological and ecological controls over cyst formation, and hydrographic conditions affecting the cyst deposition in sediments.

Spatial distribution of the motile stage of dinoflagellates is controlled by biotic and abiotic factors. These factors may substantially differ for different groups of dinoflagellates. About half of the dinoflagellates are heterotrophic and half are autotrophic, but some dinoflagellates can feed both ways, termed mixotrophic (Jacobson & Anderson 1994, Dale 1996). The distribu-

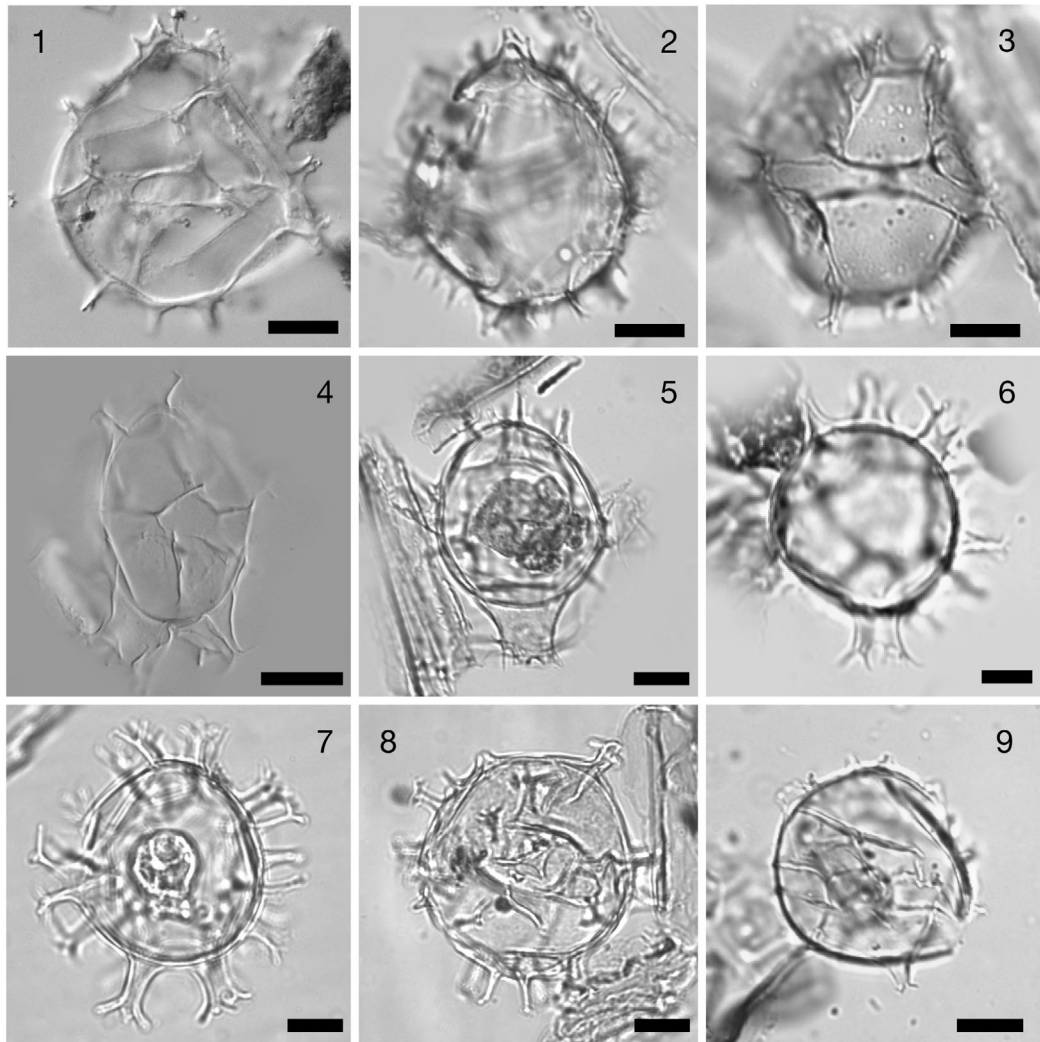


Fig. 4. Bright-field photomicrographs. 1–3. *Spiniferites bentorii*, CPC, Slide 1, V38/0, lateral surface (1), NBH317, Slide 2, optical section (2), and ventral surface (3); 4. *Spiniferites elongatus*, NBH325, Slide 1, X36/1, ventral surface; 5,6. *Spiniferites membranaceus*, NBH236, Slide 1, optical section (5) and AB5, Slide 3, optical section; 7. *Spiniferites* cf. *delicatus*, NBH324, Slide 2, optical section; 8,9. *Spiniferites* spp. indet, NBH325, Slide 1, lateral surface (8) and NBH204, Slide 1, optical section (9).

Scale bars = 10  $\mu$ m

tion of heterotrophic dinoflagellates is controlled, in part, by availability of prey (diatoms and small flagellates), whereas the distribution of autotrophic species depends on the availability of light and dissolved nutrients. Both types of dinoflagellates are common in New Bedford Harbor and Apponagansett Bay.

Observations of dinoflagellates in Buzzards Bay by Pierce & Turner (1994) over a 2 yr period revealed that the stations near the New Bedford Harbor sewage outfalls had significantly (by a factor of 2 to 10) higher dinoflagellate abundance than the other parts of Buzzards Bay. In the same study, significant temporal variability in dinoflagellate abundances caused by seasonal blooms was recorded in New Bedford Harbor. However, high abundances of dinoflagellates may not necessarily be directly reflected in high concentrations of cysts in sedi-

ments, because not all species of dinoflagellates are cyst-producing, and the process of cyst formation or encystment can also be influenced by environmental factors.

Encystment may happen spontaneously, but also can be enhanced by external factors such as depletion of nutrients—phosphorus and nitrogen in particular (Anderson et al. 1984, Ellegaard et al. 1998), light limitation (Anderson et al. 1985) and other factors. Therefore, high rates of cyst production can reflect high abundances of dinoflagellates and/or enhanced rates of encystment (e.g. caused by depletion of nutrients). However, it is important to note that even in the case of the surface sediments, the cyst record represents many years of deposition, which is approximately 10 yr in the studied embayments. Thus, much of the temporal variability in dinoflagellate abundance and the rate of

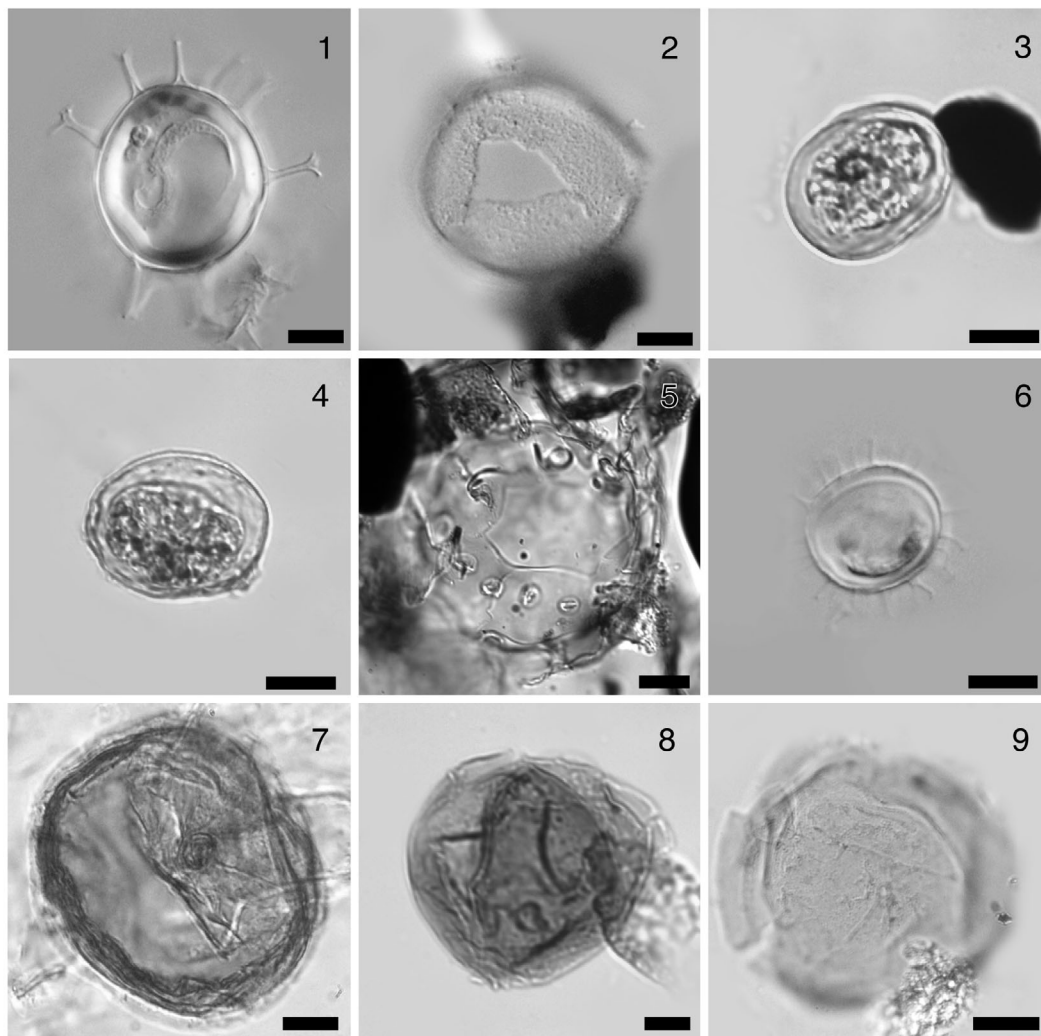


Fig. 5. Bright-field photomicrographs. **1.** *Spiniferites* spp. indet, CPG, Slide 1, optical section; **2.** *Tectatodinium pellitum*, CPE, Slide 1, X48/1, dorsal surface; **3,4.** *Alexandrium tamarense*, NBH247, Slide 1, optical section (3) and NBH247, Slide 2, optical section (4); **5.** *Tuberculodinium vancampoae*, NBH317, Slide 1, T43/1, apical surface; **6.** *Pentapharsodinium dalei*, CPE, Slide 1, F613/4, optical section; **7–9.** *Dubridinium* spp. indet, NBH324, Slide 1, D38/1, apical view (7), CPB, Slide 2, apical surface (8), and NBH236, Slide 4, apical surface (9). Scale bars = 10  $\mu$ m

encystment average out. At the same time, those environmental factors that are present on the scale of the last 10 yr may be reflected in the 'integrated' sedimentary cyst record. The correlations between dinoflagellate cyst assemblages and environmental parameters found in this study cannot reveal particular mechanisms by which environmental parameters influence the distribution of dinoflagellates and the rates of encystment. To address these mechanisms in details, one would have to tie together the studies of the motile stage of dinoflagellates in the water column, the sediment-trap studies of cyst accumulation, and simultaneous measurements of water-quality parameters (see e.g. Godhe et al. 2001) over an extended period of time. At present, such studies in Buzzards Bay do not appear to be feasible.

Hydrographic regimes in the estuary also affect spatial distribution of dinoflagellate cysts in sediments. When produced, dinoflagellate cysts behave as particles in the water column, and there are several known mechanisms of cyst accumulation in the sediments (see e.g. Harland & Pudsey 1999). The presence of strong currents may lead to systematic transport of cysts away from the place where they were produced and/or resuspension. In the studied embayments, there are no strong bottom currents, and the influence of the Acushnet River is negligible. Moreover, the inner New Bedford Harbor is almost completely enclosed by a hurricane barrier that restricts water circulation with the rest of the bay. There is no reason to expect that tidal currents in the harbor would transport cysts over significant distances. Hydrographic conditions can be

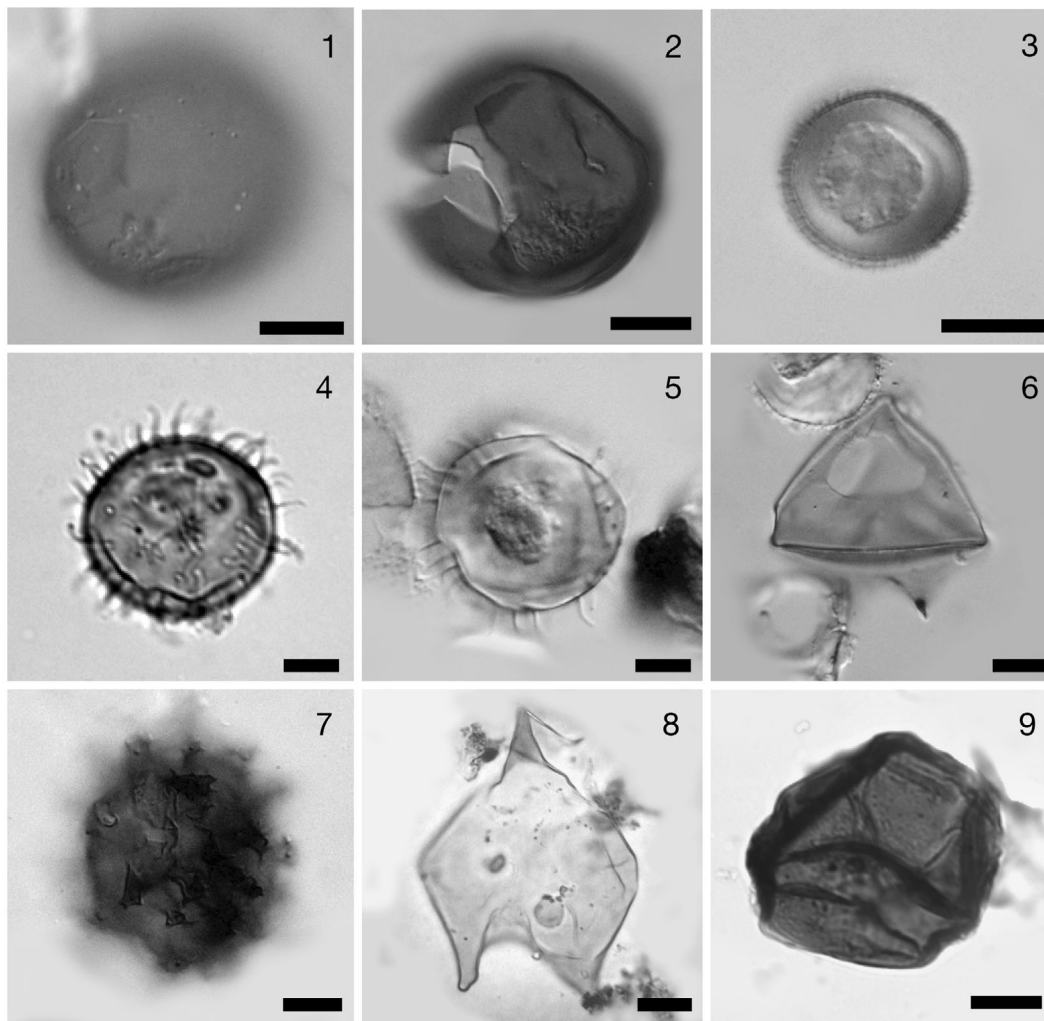


Fig. 6. Bright-field photomicrographs. **1.** *Brigantedinium cariacense*, CPG, Slide 1, F55/4, lateral surface; **2.** *Brigantedinium simplex*, NBH325, Slide 1, L51/1, dorsal surface; **3.** *Islandinium brevispinosum*, CPG, Slide 1, D48/4, orientation uncertain; **4.** *Islandinium? cezare*, NBH204, Slide 1, orientation uncertain; **5.** *Islandinium minutum*, NBH317, Slide 1, F41/4, optical section; **6.** *Lejeunecysta oliva*, CPC, Slide 1, V56/4, dorsal surface; **7.** *Protoperidinium minutum*, CPE, Slide 1, T46/2, orientation uncertain; **8.** *Protoperidinium oblongum*, CPG, Slide 2, dorsal surface; **9.** *Protoperidinium* spp. indet, NBH325, Slide 2, orientation uncertain. Scale bars = 10  $\mu$ m

also assessed by studying the spatial distribution of pollutant concentrations in the sediments. High concentrations of metals and other pollutants are found in much greater concentrations near the sources of contamination (in the upper New Bedford Harbor and near the sewage outfalls), suggesting that the sediment transport is not substantial. However, we cannot discount the possibility that effects of short-distance transport are also encoded in our data.

Below we discuss the particular characteristics of the dinoflagellate cyst assemblages in the studied embayments and their relation to environmental conditions, and compare spatial cyst distribution with the temporal cyst records from the sediment cores taken in New Bedford Harbor and Apponagansett Bay (Pospelova et al. 2002).

### Total dinoflagellate cyst concentrations

Despite a number of factors affecting dinoflagellate cyst concentrations in sediments, the total cyst concentration has been regarded as a proxy of dinoflagellate production (e.g. Dale 2001). A potential problem with this approach is that the change in sediment accumulation rate affects dinoflagellate cyst concentrations. In this study, we observe large fluctuations in the total cyst concentrations in the surface sediment samples that could be attributable to varying dinoflagellate production and encystment rates and/or sedimentation rate. However, it is difficult to determine the sedimentation rates station by station. Estimates show that they typically vary between 0.2 and 0.6 cm yr<sup>-1</sup> in the inner New Bedford Harbor and between 0.1 and 0.5 cm yr<sup>-1</sup>

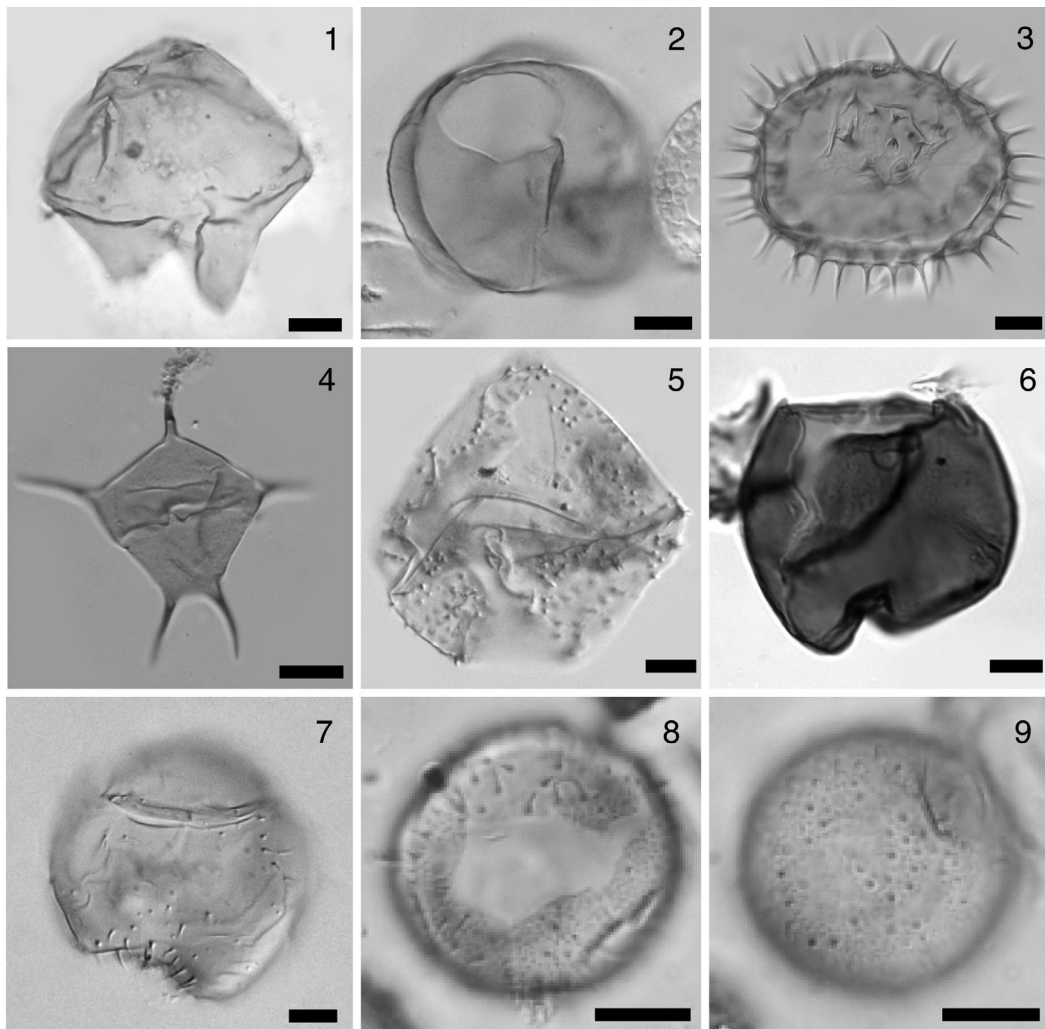


Fig. 7. Bright-field photomicrographs. **1.** *Quinquecuspis concreta*, NBH324, Slide 2, N51/1, ventral surface; **2.** *Selenopemphix nephroides*, CPE, Slide 1, C49/0, apical surface; **3.** *Selenopemphix quanta*, NBH346, Slide 1, X58/4, apical surface; **4.** *Stelldinium stellatum*, CPC, Slide 1, Y59/2, dorsal surface; **5.** *Trinovantedinium applanatum*, CPG, Slide 1, O62/3, dorsal surface; **6.** *Votadinium calvum*, NBH317, Slide 1, dorsal surface; **7.** *Votadinium spinosum*, CPG, Slide 1, O62/3, dorsal surface; **8, 9.** Cyst type E, CPC, Slide 2, dorsal surface (8), and ventral surface (9). Scale bars = 10  $\mu$ m



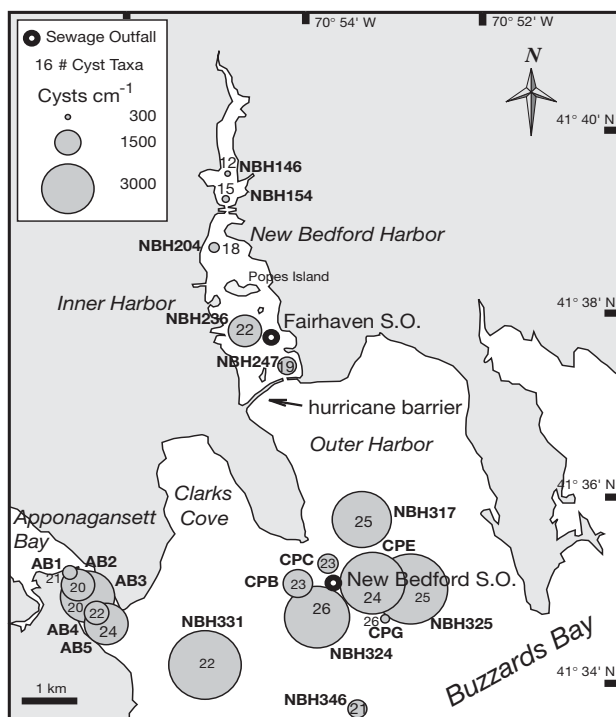


Fig. 8. Distribution of dinoflagellate cyst species-richness and total dinoflagellate cyst concentration in surface sediments of New Bedford Harbor, Clarks Cove and Apponagansett Bay

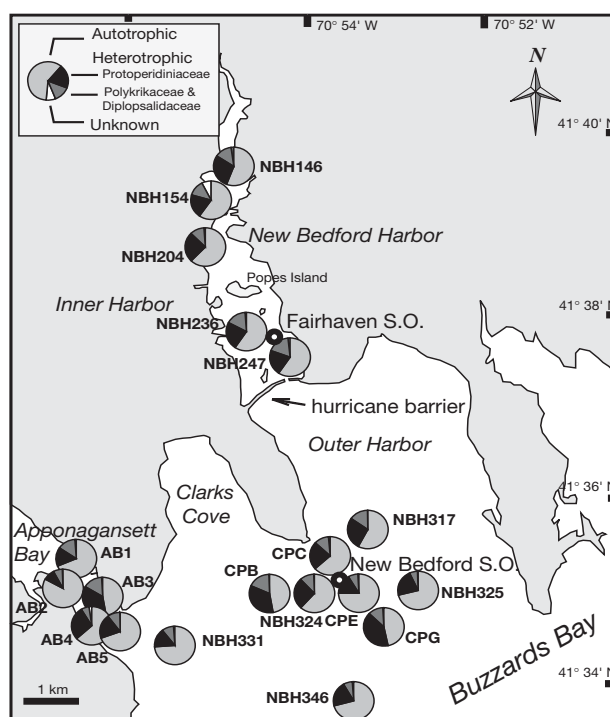


Fig. 9. Relative abundance (%) of cysts of heterotrophic (Protoperidiniaceae, Polykrikaceae and Diplopsalidaceae) and autotrophic dinoflagellates in assemblages from New Bedford Harbor, Clarks Cove and Apponagansett Bay

in the outer harbor, and Apponagansett Bay (Summerhayes et al. 1985, Latimer et al. 2003). Low cyst concentrations ( $\sim 400$  cysts  $\text{cm}^{-3}$ ,  $\sim 900$  cysts  $\text{g}^{-1}$ ) in the inner part of New Bedford Harbor, north of the Popes Islands (Sites NBH 146, 154 and 204), are one-fifth those at the other sites, which is probably too large a difference to be explained by variation in the sedimentation rate. Thus the low dinoflagellate cyst concentration in the upper part of inner New Bedford Harbor is likely to be the result of reduced dinoflagellate production. We suggest that the suppressed production is caused by high levels of toxic pollutants in the upper part of inner New Bedford Harbor and possibly by the reduction of the photic zone. Extremely high concentrations of metals and other pollutants found in the sediments indicate toxic water conditions that may affect the dinoflagellate population. Limited light penetration in this part of the harbor was supported by 1 measurement of Secchi depth in August 1993, which showed a very low

value of 0.2 m (Howes et al. 1999). The reduction of the photic zone may result from high levels of organic carbon in the water column.

### Species diversity

A decline in species richness of phytoplankton has been noted as a possible response to eutrophication (Sommer 1995, Tsirtsis & Karydis 1998). A decrease in richness of dinoflagellate cyst taxa has been suggested as a general indicator of polluted and highly eutrophic estuarine systems (Pospelova et al. 2002). Sediment samples from the upper part of the inner harbor (Group I) that had lower cyst concentrations also had lower species richness and a lower Fisher index. Species diversity is independent of variation in sedimentation rates and is a more robust indicator

Table 7. Correlation matrix of dinoflagellate cyst species richness (Richness) and the Fisher's diversity index (Fisher's) versus organic carbon, PCBs and metal sedimentary concentrations. Coefficients with  $R > 0.5$  and significance at 0.01 level in bold

	OC	PCBs	Zn	Cu	Cr	Pb	Cd	Ni	Ag	Richness	Fisher's
Richness	<b>-0.713</b>	<b>-0.813</b>	<b>-0.649</b>	<b>-0.761</b>	-0.509	<b>-0.704</b>	0.264	<b>-0.492</b>	0.190		<b>0.911</b>
Fisher's	<b>-0.755</b>	<b>-0.783</b>	<b>-0.661</b>	<b>-0.750</b>	-0.537	<b>-0.696</b>	0.036	-0.440	-0.041	<b>0.911</b>	

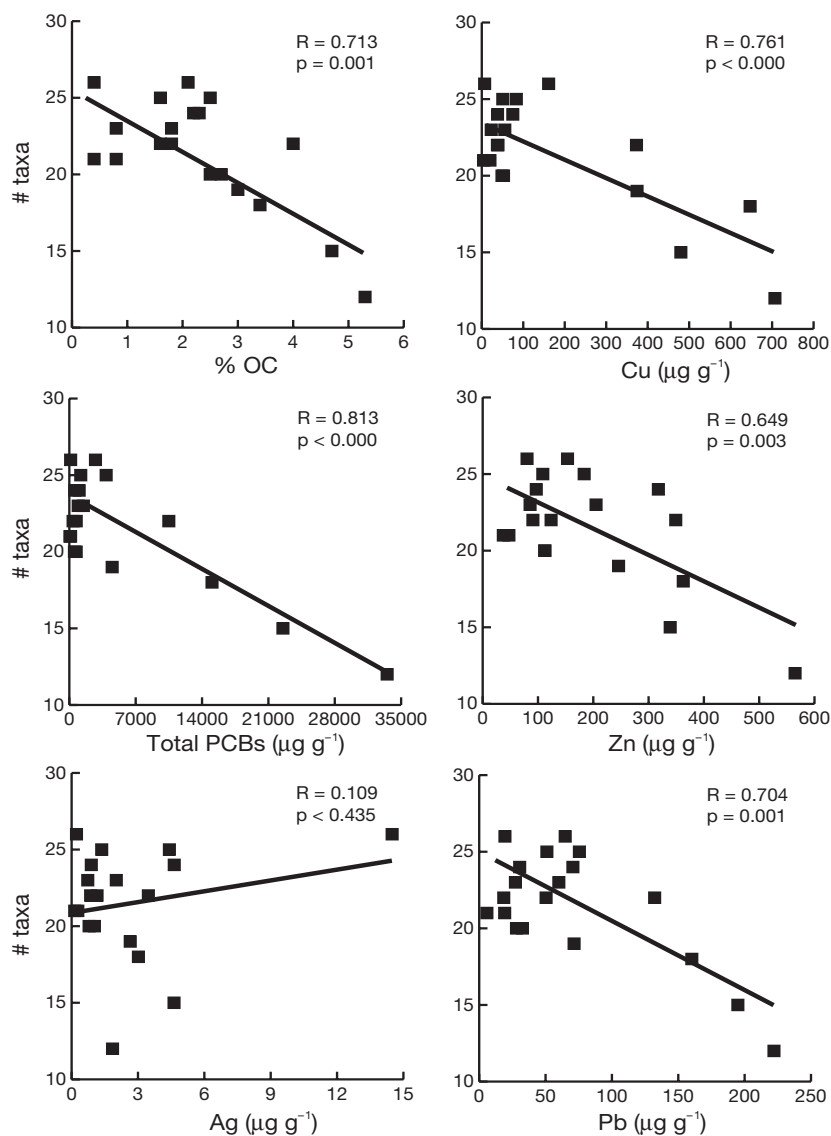


Fig. 10. Relationship between dinoflagellate cyst species-richness and sedimentary concentrations of Cu, Zn, Ag, Pb, PCBs and % organic carbon (OC)

that the environmental conditions north of Popes Island are less suitable for dinoflagellate population compared to conditions south of the island. In particular, we found that in the upper part of inner New Bedford Harbor the following cyst taxa were absent or highly suppressed in proportions relative to proportions of the same taxa in the rest of the samples: *Spiniferites elongatus*, *Pentapharsodinium dalei*, *Polykrikos schwartzii* plus *P. kofoidii*, *Islandinium minutum*, *Protopteridinium minutum*. The absence of these species from this part of the harbor is probably due to the same adverse conditions that are responsible for the suppression of the total cyst concentrations e.g. high levels of toxins and hypertrophic conditions. The decrease in Fisher's index and the species richness of

dinoflagellate cysts may be regarded as a combined signal of organic and toxic pollution in the harbor. Further support of this explanation is found in the negative linear relationship between dinoflagellate cyst species-richness and sedimentary concentrations of Cu, PCBs, Zn, and Pb, as well as % organic carbon (OC). Fisher's index shows similar correlations. Although the effects of each constituent may differ, their covariances prevent us from determining more detailed relationships.

### Spatial distribution of PCA

At our study sites, the gradients of salinity and temperature are short compared to those examined in marine and oceanic studies (Wall et al. 1977, Dale 1996, Mudie & Harland 1996, de Vernal et al. 1997, Rochon et al. 1999). They are also smaller than gradients of temperature and salinity found in the coastal lagoons from the same region (Pospelova et al. 2004). Water temperature and salinity, commonly identified as 2 major factors controlling distribution of dinoflagellate cysts, did not vary with the first principal component in this study. New Bedford Harbor and Apponagansett Bay showed similar patterns, with minor increases in salinity and slight decreases in temperature in the seaward direction, but with opposite trends in the PC1 scores (Fig. 12).

The availability of nutrients has been identified as an important factor controlling the distribution of phytoplankton, and dinoflagellates in particular (Taylor 1987). Unfortunately, there are no data on the concentrations of nitrogen or other nutrients on the scale of our sample stations. Nevertheless, we can assume that nutrient concentrations decrease with increasing distance from the sewage outfalls.

Previous studies have identified Ag as a marker of sewage effluents (MacKay et al. 1972, Abu-Hilal & Badran 1990, Bothner et al. 1994). In our study, those sites with high sediment silver-content ( $\geq 3.5 \mu\text{g g}^{-1}$ ) were NBH324, CPE, NBH317, NBH236, and NBH154. Indeed, all these sites except NBH154 are in close proximity to the sewage outfalls and also had the highest PC1 scores based on the proportions of dinoflagellate cysts in the assemblages.

The correlation between PC1 scores and proximity to sewage outfalls (Fig. 13) suggests that PC1 mainly reflects nutrient gradients, and that cyst assemblages

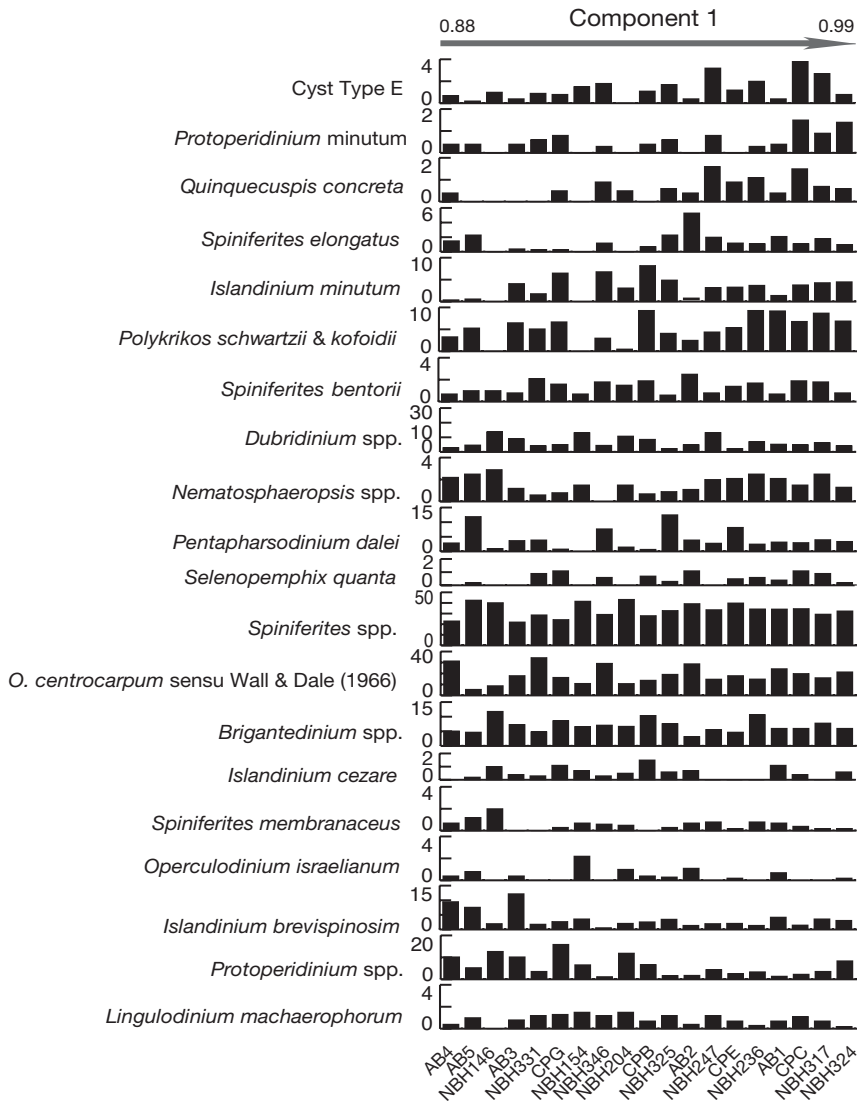


Fig. 11. Proportions of selected dinoflagellate cysts in assemblages from surface sediment samples ordered by first principal component (PC1)

change with distance from point-sources of nutrient pollution. We infer that dinoflagellate cyst assemblages in Apponagansett Bay also reflect a nutrient signal, because nutrient gradients decrease in the seaward direction (Fig. 12). Since ammonia is the main form of nitrogen from sewage effluent (Borkman & Turner 1993), it is likely to be a critical parameter affecting the distribution of the dinoflagellate cyst assemblages in the studied embayments.

### Comparison of spatial and temporal cyst records

Dinoflagellate cyst assemblages in surface sediments from New Bedford Harbor and Apponagansett Bay can be compared to the assemblages from the upper parts

of the cores from the same embayments analyzed by Pospelova et al. (2002). Surface and core assemblages have the same ranges for cyst concentration and diversity, and are dominated by the same taxa.

Large fluctuations in the total cyst concentration have been proposed (Pospelova et al. 2002) as a signature of stressed environments. These fluctuations can be seen both in the core and surface assemblages, and the range of the fluctuations in New Bedford Harbor is larger than in Apponagansett Bay. We consider this as a signal of stressed environmental conditions in New Bedford Harbor. However, we understand that a large range of fluctuations in surface sediments is also a reflection of rather large differences in the sediment accumulation rates from site to site as a result of different hydrological conditions.

Another important characteristic of the cyst assemblages in both the temporal and spatial records is the cyst diversity that can be expressed as species richness or Fisher's index. Species richness in the surface samples and in top samples from the cores had similar values. Species richness in the top samples of Core NBH2c from New Bedford Harbor had 15 to 18 taxa (Pospelova et al. 2002) and the closest surface sites (NBH154 and NBH204) in this study had correspondingly 15 and 18 taxa. Top samples from Core AB1c (Apponagansett Bay) had 21 to 23 taxa, while the surface sites AB4 and AB1 had 22 and 24 taxa. Thus, both in surface and core sediments, species richness in inner New Bedford Harbor is lower than in Apponagansett Bay. Comparison of the Fisher index values reveals the same trend. Similar to temporal records, species richness and the Fisher index were negatively correlated to sedimentary concentrations of toxic metals and organic carbon content. The decrease in species diversity is a response to hypertrophic conditions and/or high levels of inorganic pollutants in the inner part of New Bedford Harbor. The determination of the relative importance of each of these 2 factors on the decline in cyst diversity does not appear to be feasible with the current data set. The increase in species richness in outer Apponagansett Bay was noted as a possible response to eutrophication

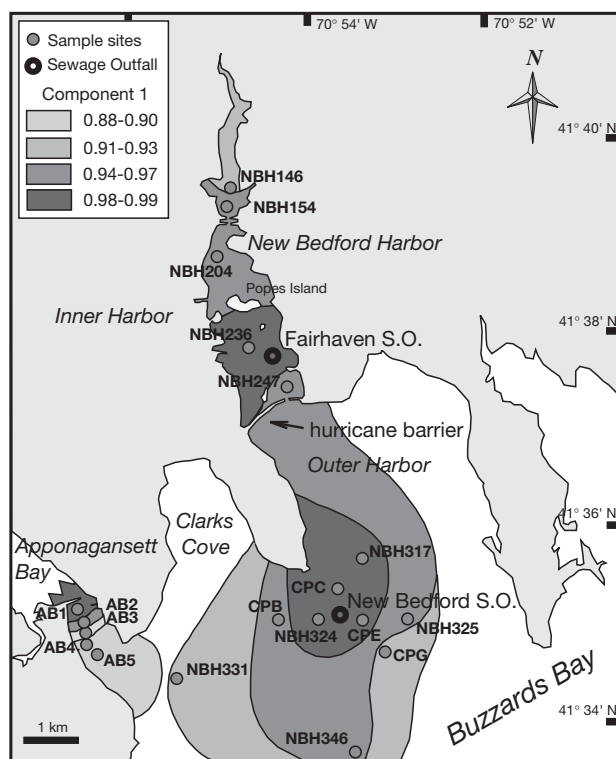


Fig. 12. Spatial distributions of first principal component (PC1) in surface sediments from New Bedford Harbor, Clarks Cove and Apponagansett Bay

when a system changes from oligotrophic/mesotrophic to eutrophic conditions by Pospelova et al. (2002). In surface samples, the highest species richness was recorded in the outer New Bedford Harbor and Apponagansett Bay, which have mesotrophic to eutrophic conditions (Howes et al. 1999).

The increased abundance of cysts of heterotrophic dinoflagellates, particularly Polykrikaceae and Diplopsalidaceae, in temporal records, was seen as a signal of nutrient enrichment of embayment waters by Matsuoka (1999) and Pospelova et al. (2002). Cysts of heterotrophic dinoflagellates constitute a large proportion of the cyst assemblages (~36%) in surface sediments, indicating a substantial role of dinoflagellates in modern secondary production. These proportions are twice as high as the maximum abundances of cysts of heterotrophic dinoflagellates that existed in the pre-settlement period (Pospelova et al. 2002). The abundance of cysts of Polykrikaceae and Diplopsalidaceae remained below 6% throughout the cores in the study of Pospelova et al. (2002) but exceeded this value in the core sediments accumulated during nutrient-enrichment periods. Dinoflagellate cyst assemblages in the surface sediments also contain high (6 to 18%) proportions of Polykrikaceae and Diplopsalidaceae cysts, indicating nutrient-rich environments.

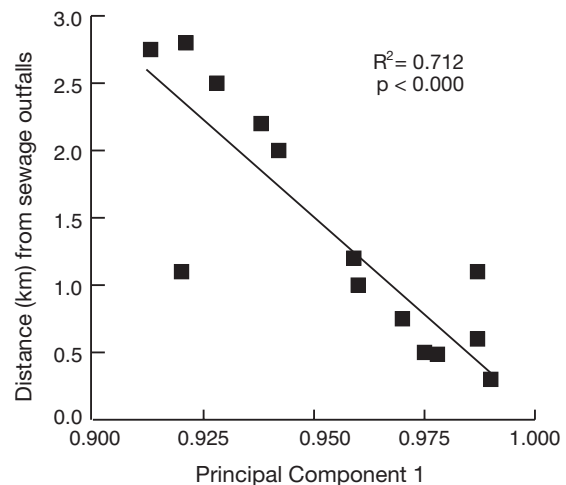


Fig. 13. Relationship between Principal Component 1 and distance from municipal sewage outfalls

*Spiniferites* spp. seem to be the most tolerant taxa, and they were encountered in high abundances in both studies in the core and surface sediments. Temporal cyst records show that certain rare and common cyst taxa, *Dubridinium* spp., *Islandinium minutum* plus *I. cezare*, *Spiniferites bentorii* and cysts of *Polykrikos schwartzii* plus *P. kofoidii*, increased in abundance with increasing nutrient enrichment as the system shifted from mesotrophic to eutrophic or highly eutrophic conditions (Pospelova et al. 2002). In most surface sediments of New Bedford Harbor, these taxa are present in proportions similar to those observed in sediments concurrent with periods of eutrophication and toxic pollution (~7% of *Dubridinium* spp., ~3% of *I. minutum* plus *I. cezare*, ~1.5% of *S. bentorii*, and ~5% of *P. schwartzii* plus *P. kofoidii*). The spatial distribution of cysts of *P. schwartzii* plus *P. kofoidii* showed that these taxa are absent from the most polluted sites in the inner part of New Bedford Harbor. This may indicate that *P. schwartzii* & *kofoidii* is suppressed in hypertrophic and highly polluted environments. Temporal studies have shown that *Lingulodinium machaerophorum*, *Operculodinium israelianum* and *Selenopemphix quanta* decline when conditions in the embayments change from oligotrophic to mesotrophic (Pospelova et al. 2002, Chmura et al. 2004); these species were absent or contributed  $\leq 1\%$  to most of the cyst assemblages in surface sites. This does not contradict our temporal studies, since all modern sites have mesotrophic to eutrophic conditions.

To conclude, this study has demonstrated that spatial distribution of dinoflagellate cysts reflects environmental conditions in polluted estuaries. Sites with hypertrophic conditions and the highest levels of toxic pollution were characterized by the lowest dinoflagel-

late cyst diversity (species richness and Fisher's diversity index), confirming patterns observed in the temporal records. We also found that at small spatial scales, where salinity and temperature variability were low, the distribution of dinoflagellate cysts reflected the proximity to the major sources of nutrient enrichment such as sewage outfalls.

In addition, our study of dinoflagellate cysts from surface sediments revealed dinoflagellate species previously not recorded in the phytoplankton population of Buzzards Bay waters. In this study, we found *Gonyaulax digitalis*, *G. spinifera*, *Lingulodinium polyedrum*, *Protoceratium reticulatum*, *Pentaparsodinium dalei*, *Polykrikos schwartzii*, *P. kofoidii*, Diplopsalidaceae and multiple species of the Protoperidiniaceae group that have never been reported in previous phytoplankton surveys conducted in Buzzards Bay (Pierce & Turner 1994, Turner et al. 2000). This underscores the usefulness of studying the dinoflagellate cyst records in sediments as a source of complementary information on phytoplankton composition, especially on species that are either rare and/or have a short motile stage (Dale 1983).

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