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Review of Phytoplankton Data: Massachusetts Bay

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REVIEW OF PHYTOPLANKTON DATA:
MASSACHUSETTS BAY

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1.0 INTRODUCTION

This report provides a review of the historically observed phytoplankton species composition, chlorophyll concentration, and primary production data in Massachusetts Bay. We define Massachusetts Bay as the coastal water from Cape Ann to Cape Cod (including Cape Cod Bay) which is west of Stellwagen Bank. The report does not review data from samples taken within coastal embayments or estuaries, except for some limited data in Boston Harbor. We identified the various sources of data which characterize phytoplankton species, cell abundance, chlorophyll, and primary production in Massachusetts Bay and provide a brief comparison of some of this data to proximate nearshore and offshore areas.

Table 1 lists the reviewed data sets. These include data from collections made between 1905 to 1988. The earliest collections include work from as early as 1912 summarized in Bigelow (1926), while the latest data are from MWRA (1988; 1990). This summary does not include analysis of samples which Bigelow Laboratory, West Boothbay Harbor, Maine recently collected under contract to MWRA. The reviewed programs which were conducted for various reasons include:

> four 301(h) or 316(a) monitoring programs (a 301(h) program is a study done in support of an application for a waiver from secondary treatment; and a 316(a) study is associated with discharge of heated effluent from a power plant);
>
> NOAA's temporally limited MARMAP program (no longer extant);
>
> a doctoral thesis from the University of New Hampshire;

Bigelow's early work done as part of several Bureau of Fisheries studies;

a "one time experiment" north of Cape Ann;

a "one-time" monitoring at the "foul grounds";

a temporally limited monitoring by the New England Aquarium;

and,

the 1988 and 1990 MWRA studies.

It is significant to an understanding of the limitations of the analysis which follows that none of these studies are part of a continuous program. Most ran for only short (less than one year) periods in support of environmental permit requirements. Also, only five studies, MWRA (1988; 1990), NEA (1973; 1990), and Metcalf & Eddy (1979) sampled synoptically inshore and offshore of Deer Island. However, there is enough data to provide some perspective on long term characteristics of Mass Bay and to compare it to Boston Harbor and The Gulf Of Maine.

Table 1 also indicates that enumeration of phytoplankton species is the most commonly measured parameter and primary production is the least commonly measured parameter. Note also that there are very few measures of primary production in Boston Harbor for comparative purposes. This is expected because the earlier collections predate the routine analysis of chlorophyll or primary production.

Earlier investigations do not recognize the distinction between nannoplankton and netplankton made in later studies. In this report, we make the comparison between these two components of the plankton where possible. We use the widely accepted definition of nannoplankton as those phytoplankton which are less than 10 microns in diameter while the netplankton are those greater than ten microns in diameter.

Figure 1 is a map of the station locations by investigator. The more inshore regions of central and northern Massachusetts Bay have been sampled more frequently than other areas. Most of this sampling was for regulatory and monitoring studies in Nahant Bay, Salem Sound, and the MWRA outfall as well as a doctoral thesis (Parker, 1980). Further offshore, Bigelow occupied several stations, as did the National Oceanic And Atmospheric Administration's (NOAA) MARMAP program (the Marshall and Cohn stations on Figure 1). One station (Martin and Yentsch, 1973) occupied the "foul grounds".

Note that there is a paucity of stations in Cape Cod Bay where there were three nearshore stations sampled for monitoring associated with the Pilgrim nuclear power plant, one MARMAP station , and one Bigelow station.

In general, spatial coverage is best in central and nearshore regions. The least coverage is in Cape Cod Bay and offshore areas of Mass Bay. Synoptic coverage of various geographic areas is poor and temporal coverage is aperiodic and disjoint. However, the various data bases extend over a long enough time period to provide information concerning the general floristic composition and average seasonal trends in biomass and productivity in Massachusetts Bay phytoplankton communities.

2.0 SPECIES SUCCESSION

This section briefly describes the historically observed pattern of phytoplankton species succession in the coastal Gulf of Maine and compares it to the observed pattern in Massachusetts Bay, Cape Cod Bay, and Boston Harbor. Appendix A is a table which classifies the various species used in the text, identifies the abbreviations for these species, and provides common names for the higher taxa (e.g. Centrales = centric diatom). In terms of species succession, we addressed only the netphytoplankton. We did not address the nannoplankton as part of the discussion on species succession because generally investigators have been unable to distinguish among nannoplankton species. In Massachusetts Bay, only the most recent studies recognize the importance of nannoplankton and we discuss the observations made in them.

2.1 Species Succession In Coastal Gulf Of Maine

The seasonal succession of phytoplankton species has been well described for the coastal Gulf Of Maine, and to a lesser extent for its adjoining estuaries. A review of various works (Bigelow, 1926, Bigelow et al., 1940; Gran, 1933, Gran and Braarud, 1935; and, Lillick, 1937, 1938, 1940) allows a general description of the species succession in coastal Gulf Of Maine.

The early winter flora is sparse and the dominant species are usually *Thalassiosira eccentrica* and *Coscinodiscus centralis*. By January, *Coscinodiscus* attains the greatest percentage of the flora, although Lillick does not consider this a bloom in the sense of the later more dramatic spring blooms. In late December or January, several other species may dominate. Among these are: *Biddulphia aurita*, *Paralia sulcata*, *Thalassionema nitzschioides*, and *Thalassiosira decipiens*. At this time, *Skeletonema costatum* and several *Peridinium* species may occasionally dominate.

Thalassiosira nordenskioldii characterizes the first prominent winter-spring bloom. Several other dominant or co-dominants include *Thalassiosira decipiens*, *T. gravida*, and *Porosira glacialis*. This bloom lasts for about five weeks when a *Chaetoceros* dominated flora replaces it between the end of March and April. Although this assemblage may contain as many as thirty species of *Chaetoceros*, the dominant is often *Chaetoceros debile*. The *Chaetoceros* bloom may last from several weeks to several months.

The summer flora is mixed and not as predictable as the winter and spring flora. If diatoms dominate, they may include members of the genus *Chaetoceros*, *Rhizosolenia*, *Guinardia*, and *Thalassiosira*. In the absence of diatoms, *Peridinium* and *Ceratium* species dominate.

Skeletonema costatum, *Guinardia flaccida*, and various species of *Rhizosolenia* generally dominate the Gulf of Maine in autumn. Occasionally, *Melosira sulcata* and *Thalassionema nitzschioides* may dominate nearshore while *Prorocentrum micans* dominates in more offshore areas of the gulf.

2.2 Species Succession In Massachusetts Bay

This subsection presents our review of the various data sets which address phytoplankton species composition in Massachusetts Bay and compares these to the historically observed data for the coastal Gulf Of Maine as described in subsection 2.1.

Tables 2 and 3 provide the dominant netphytoplankton species by month in Massachusetts Bay and Cape Cod Bay as observed in the historical data. These tables represent an idealized "floristic year" in that they are monthly compilations of observations made over eighty years. Table 4 is a summary of Tables 2 and 3 by season and a comparison of species succession in the Gulf Of Maine and Boston Harbor. Each "season" contains the dominant species found in at least one study during that time. The species are derived from the thirteen individual studies listed in Tables 2 and 3. In these tables, we summarized the near surface euphotic zone data. Within the text which follows, we noted where this data does not generally represent the euphotic zone phytoplankton composition.

The data set for northern Massachusetts Bay provides greater spatial and temporal coverage than the data sets for Cape Cod Bay or Boston Harbor. Three studies from the years 1926, 1977, and 1980 (Table 2) provide data for the winter season (January and February) in Massachusetts Bay. During each of these studies, a different dominant occurred. However, each of the dominants, except for *C. closterium* are among those historically observed in the coastal Gulf Of Maine (Table 4).

Seven studies from the years 1926, 1940, 1973, 1977, 1980, 1986, MWRA 1990 (Table 2) provide spring (March and April) data for Massachusetts Bay. During three of these studies, the dominant was *T. nordenskioldii* which is the commonly observed dominant in the Gulf Of Maine. The other dominants in the Massachusetts Bay spring data are also among the historically observed dominants in the Gulf Of Maine (Table 4). These include *P. glacialis* and various *Chaetoceros* species, especially the common dominant, *Chaetoceros debile*. MWRA (1990) noted a short-lived dominance by *Phaeocystis poucheti* during March.

Ten studies from the years 1926, 1940, 1973 (two studies), 1977, 1979, 1980, 1986 (two studies) and 1987 (Table 2) provide summer phytoplankton data for Massachusetts Bay. As Table 4 demonstrates, the flora observed in northern Massachusetts Bay is similar to the flora historically observed in the coastal Gulf Of Maine during this period. In the Bay, various species of *Rhizosolenia* (*R. alata*, *R. fragilissima*, and *R. delicatula*) were among the dominants observed in six of the ten studies. Also during this period, species of *Ceratium* and *Peridinium* may dominate the flora. The coastal Gulf Of Maine displays a similar flora, but also includes coccolithophores in summer. The historical data for northern Massachusetts Bay does not reveal the presence of coccolithophores until autumn (see Tables 2 and 4).

Five studies from 1926, 1973, 1977, 1978, and 1980 (Table 2) provide phytoplankton data for the autumn in northern Massachusetts Bay. Table 3 shows that the dominant species in the autumn flora are generally similar to the summer flora with the exception of the presence of coccolithophores such as *Emiliani huxleyii* and the presence of *Guinardia flaccida*, a common autumn species in nearshore waters.

Table 3 summarizes the limited data available for Cape Cod Bay. It is a compilation of the data from the sampling stations shown on Figure 1. The data from Boston Edison (1975) represents several inshore stations. The Marshall and Cohn data is a temporally limited data set from offshore Cape Cod Bay. The Bigelow data is from an offshore station. These data sets indicate that Cape Cod Bay does not follow the general pattern of species succession observed in the coastal Gulf Of Maine as closely as does northern Massachusetts Bay. In particular, the major dominants of the spring, *T. nordenskioldii* and *C. debile*, do not appear as dominants (i.e. >5% of the cell abundance) in either the offshore or near-shore samples of Cape Cod Bay, although they do appear as subdominants in the flora. However, there is not enough sampling frequency or spatial coverage to conclude that these species do not regularly dominate the spring flora in Cape Cod Bay. Although *Phaeocystis* occurs in Bigelow's data in Cape Cod Bay, he notes that its period of dominance was short (less than two weeks). Subsequent investigations (Guillard and Hellebust, 1971) have found *Phaeocystis* blooms in the waters off Cape Cod; however, the data set is too sparse to comment upon the regularity of its occurrence.

In general, the flora of northern Massachusetts Bay appears to be quite similar to the coastal Gulf Of Maine in species composition and succession of species. Cape Cod Bay has received very limited spatial and temporal coverage.

2.3 Species Succession In Boston Harbor

Several investigators have described the phytoplankton of Boston Harbor at various times. These data sets include: Trapper (1970); New England Aquarium (1973); Fitzgerald (1980); Metcalf and Eddy (1979), and MWRA (1988). Table 4 summarizes the netphytoplankton data. Trapper (1970) who sampled over a two year period during the spring bloom found that the phytoplankton at that time (March-April) was dominated by either *T. nordenskioldii* or *S. costatum.* A major difference between Massachusetts Bay and the inner harbor stations in these studies was the local dominance of *Asterionella* (a genus common to estuarine areas) and the occasional dominance of various pennate diatoms such as *Nitzschia*, *Navicula*, *Striatella*, and *Pleurosigma* in the inner harbor. The dominance of these pennates probably reflects the shallower nature of the harbor, particularly the inner harbor. The presence of these species, particularly blooms of *Asterionella*, are commonly found in estuaries of the Gulf Of Maine (Cura, 1981; Petrie, 1975). Often the inner harbor was dominated by genera more commonly associated with fresh water such as *Scenedesmus* or by microflagellates.

2.4 Numerical Abundance Of Phytoplankton - Massachusetts Bay

This section reviews the numerical abundance of the major species, the total netphytoplankton abundance, and the nannoplankton abundance for the historical data base. The units for abundance are cells per liter. We recognize the potential sources of error associated with comparing cell number among studies and between seasons; however, for much of the historical data this parameter is the only measure of biomass available. The major limitations are that cell number does not account for size differences and does not reflect biomass differences (due to physiological conditions) that may occur even among cells of similar size. However, it is a legitimate comparison between studies or among seasons for a given species. Throughout the discussions which follow, note that cell abundance is not always directly proportional to biomass. In that sense, high cell abundance may clearly indicate a species bloom, but this does not necessarily indicate a proportional contribution to phytoplankton community biomass or trophic level effects.

Table 5 provides numerical data for various stations from eight studies. It shows: the five most commonly species observed on each sampling date (the table includes "ties") for each station; the total netphytoplankton abundance; and the total nannoplankton (where available).

Table 6 provides summaries of these data as monthly averages for the seven studies in northern Massachusetts Bay. These are data from surface stations only. We note in the text which follows where the phytoplankton species composition or abundance differed significantly with depth (in our judgement). Otherwise, we assumed that the surface sample adequately represented the euphotic zone. The remaining studies either did not provide numerical abundance and only identified the dominant species (e.g. Martin and Yentsch, 1973) or provided abundance in units such as chlorophyll-a or mgC/m^2).

Where comparative and synoptic data were available, it demonstrated that for most of the year, nannoplankton dominated the phytoplankton cell abundance. Also in cases where synoptic data from offshore and nearshore areas were available (e.g. MWRA, 1990) and even in making non-synoptic interstudy comparisons (e.g. compare MWRA, 1990 to CDM, 1986, 1986a) there appeared to be a trend for the nannoplankton to be more dominant or in greater abundance at nearshore rather than offshore stations.

Spring - March And April

Only four studies in the historical data base provide phytoplankton cell abundance for the usual period of the spring bloom. These include: NEA (1973); CDM (1986a); and MWRA (1990). In addition Parker (1980) provides phytoplankton abundance as estimated biomass (mgC/m^2)rather than cell abundance.

CDM (1986a) noted that the netphytoplankton cell abundance in the late spring in the offshore areas of Salem Sound averaged 225,000 cells per liter (Tables 5 and 6). Over 95% of this total is *Chaetoceros socialis* and *Chaetoceros compressus*. They do not report the nannoplankton fraction for this time period.

MWRA (1990) noted that during the observed maximum (March) of the spring bloom the total netphytoplankton cell abundance was approximately 1,000,000 cells per liter and the average nannoplankton cell abundance was nearly 20,000,000 cells per liter. Among the netphytoplankton species, the dominants, *C. debile*, *Detonula confervacea*, and *T. nordenskioldii* accounted for 80% of the netphytoplankton cell abundance. The end of the Spring bloom exhibited *Chaetoceros compressus* as the dominant netphytoplankton at 463,000 cells per liter and 64% of the netphytoplankton.

MWRA's Spring observations indicated changes in the vertical distribution of cell abundance as the bloom progressed. Early March sampling exhibited a homogenous vertical distribution of species and cell abundance. However in mid-March, MWRA noted a nannoplankton cell abundance maxima at the 3% light depth (12m). Otherwise, the nannoplankton abundance was similar to early March sampling and this maxima did not extend to their 16 meter sampling depth. By March 22, a clear diatom maxima occurred between 8 m (10% light penetration) and 16 m (1% light penetration). In this depth interval, the diatom concentration had increased 1.5 to 2.6 times its observed concentration in mid-March. By March 29, this subsurface increase in diatoms had dissipated. During this sampling period, the nannoplankton exhibited a relatively homogenous vertical distribution. Note that the water column remained well-mixed during March. By early April, there was a clear vertical gradient in cell abundance and species composition. The slightly stratified upper waters (3 m) revealed a declining diatom population (543,000 to 720,000 cells per liter) dominated by *C. compressus* and *S. costatum* while the strata below 3 m displayed *C. debile* which increased progressively with depth from 47,000 to 435,000 cells per liter (indicating a sinking community). During this sampling period, the nannoplankton fraction exhibited a strong subsurface maxima below the 1% light level. Mid-April exhibited a reversion to dominance by *C. debile* and *T. nordenskioldii* and a decreases in nannoplankton cell abundance below the euphotic zone. MWRA hypothesized that this reversion was associated with a water mass incursion rather than a species successional event. They base this opinion on synoptically observed changes in hydrographic properties which suggested a change in water type rather than a change in species composition within a water mass.

Parker notes that diatoms are the most important class of phytoplankton in Massachusetts Bay based upon estimated biomass as carbon. He found that nine species of diatoms including *P. glacialis*, *D. confervacea*, *T. nordenskioldii*, *C. debile*, and various other species of *Chaetoceros* comprised 96% of the biomass at the height of the Spring bloom.

Summer - May To September

Total cell abundance in the summer often averages in excess of 10^6 to 10^8 cells per liter (Table 6) in northern Massachusetts Bay. In most instances, 90% or more of this total is in the nannoplankton fraction. Four studies (Metcalf and Eddy, 1979; CDM 1986, 1986a; and MWRA, 1988 provide "summer" (May to September) data for nannoplankton and total netphytoplankton cell abundance. These data show that during these months, the netphytoplankton cell abundance is usually less than 10% and often less than 1% of the nannoplankton fraction. However, netphytoplankton occasionally dominate. For example, Metcalf and Eddy in their offshore station (off Graves Light) observed that the netphytoplankton cell abundance was equal to the nannoplankton cell abundance in July, 1979. Similarly, MWRA (1988) found that during one sampling period in July, 1988, the netphytoplankton fraction was about 30% greater than the nannoplankton fraction.

Table 5 shows that the nannoplankton are more likely to represent a greater proportion of the average phytoplankton cell abundance at nearshore stations even during diatom blooms. For example, during June and July, 1986, Nahant Bay exhibited a short-lived bloom of the diatom *R. delicatula.* However, even at the observed maxima for this diatom, it attained only approximately 2.3% of the nannoplankton cell abundance (CDM, 1986). A similar bloom of *R. delicatula* during approximately the same time period occurred in Salem Sound (CDM, 1986a). Similarly, the nannoplankton remained numerically dominant during the bloom; the netphytoplankton fraction of cell abundance was only 4.5% of the nannoplankton cell abundance at the height of the bloom. MWRA (1990) also noted high abundance (maxima of 1,920,000 cells per liter) of *Phaeocystis poucheti* in late March.

There is a tendency for inshore stations to exhibit a higher total nannoplankton cell abundance in summer than offshore areas. This is apparent upon comparison of different studies as well as upon comparison of nearshore and offshore stations within a single study. A comparison of the proportion of the nannoplankton fraction between the nearshore stations in Nahant Bay and Salem Sound (Tables 5 and 6) with the more offshore stations off Graves Light demonstrate that generally the offshore stations have a lower total nannoplankton and often (but not always) a higher percentage of netphytoplankton cell abundance.

Summer netphytoplankton diatom populations can be quite high. As indicated above, there were *R. delicatula* blooms observed in Salem Sound and Nahant Bay in 1986. During the summer of 1988, northern Massachusetts Bay exhibited two summer diatom blooms and an interbloom period. These included:

> high diatom cell abundance of mostly *Leptocylindrus danicus* (600,00 to 1,900,000 cells per liter) during July;
>
> approximately two weeks of low diatom abundance (4,400 to 154,000 cells per liter);

and,

> a period of high diatom cell abundance of mostly *R. fragilissima* and to a lesser extent *Ceratulina pelagica* (1,000,000 to 3,800,000 cells per liter).

during this summer period the nannoplankton cell abundance generally ranged from 10,000,000 to 90,000,000 cells per liter.

The summer dominants which Parker (1980) reports are similar to these observations, despite his measuring biomass based upon estimated cell carbon rather than cell abundance. He noted that in early summer dinoflagellate species such as *Ceratium longipies* and green algae such as *Chlamydomonas*, and *Carteria*, represented about 60% of the biomass of the flora and diatom species such as *S. costatum* and *C. closterium* represented about 40% of the flora. By late summer, the diatoms *L. danicus*, *R. fragilissima*, *R. delicatula*, and *S. costatum* represented 96% of the total biomass. These diatom species are similar to those dominants noted on a cell abundance basis.

Autumn - October To December

As indicated in Table 5, there is a paucity of quantitative phytoplankton data during the Autumn in northern Massachusetts Bay. The available data indicate a clear and expected depression in average cell abundance within the netphytoplankton ranging from 344 to 32,000 cells per liter.

The most complete autumn data set is Parker (1980) which indicates an autumn bloom of *Guinardia flaccida* which along with *Rhizosolenia faeroense* and *Coscinodiscus* comprised 93% of the total estimated biomass (as mgC/m^2). *G. flaccida* commonly dominates Gulf of Maine coastal water.

There is insufficient winter (late December-February) data to comment upon numerical abundance during this season.

Data From The Continuous Plankton Recorder

The Northeast Fisheries Center maintains a temporally and spatially rich but methodologically limited phytoplankton data set. This data derives from samples taken with a Hardy Continuous Plankton Recorder (CPR) on ships of opportunity. The major methodological limitation associated with this data is that the collection net (a long strip of continually winding silk bolting cloth) has a 240 micron mesh size. This is larger than the longest dimension of most phytoplankton species. Therefore, the CPR will capture only the largest phytoplankton species. During bloom periods, the net may clog enough to reduce the mesh size and begin capture of smaller species (J. Jossi, personal communication). Jossi and Smith (1988; 1989) summarized this data. Its advantages are that collections extend from 1961 to the present, and the sampler integrates over large spatial scales.

To date, Jossi and Smith have summarized the data based upon a "relative green" index to reflect total phytoplankton. They cut the bolting cloth into 10 nautical mile sections and before assessing taxa, identify the green-brown color by comparison to four easily distinguishable standards (no color, very pale green, pale green, and green). To plot this qualitative data, they subsequently obtained numerical values for the color categories by dilution of acetone extracts. These are relative "color" values which they plot on maps.

The data provide large scale, integrated, but relative values of phytoplankton abundance which are useful in assessing the timing of blooms and the relative abundance in space for nearly synoptically obtained samples. For example, Figure 3 (taken from Jossi and Smith, 1990) clearly demonstrates that the spring phytoplankton bloom in Massachusetts Bay occurs earlier than in the offshore Wilkinson Basin and that it tends to occur in March.

Also, the data may be useful in assessing generalizations derived from analysis of data obtained from discrete sampling events. The long term observation from the CPR data that the spring bloom occurs in March supports the data from the temporally disjoint, but discretely sampled stations in the historical data base. This provides some measure of confidence in some of the generalizations derived from the data review. On the other hand, the CPR data does not indicate an autumn bloom of the same magnitude as shown in some of the discretely obtained historical data.

2.5 Numerical Abundance Of Phytoplankton - Boston Harbor

Several studies (MWRA, 1990; Metcalf and Eddy, 1979; and NEA, 1973) included Boston Harbor stations (i.e. shoreward of Deer Island). We did not include this data for cell abundance in the summary tables and describe it here for a brief comparison only. These authors noted that summer in Boston Harbor often displayed a greater abundance of nannoplankton than was observed offshore. Also, although the inner harbor station exhibited a July *L. danicus* bloom (698,000 cells per liter) similar to the offshore stations (MWRA, 1990), *Lithodesmium undualtum* (596,000 cells per liter) was co-dominant. *Rhizosolenia fragilissima* (3,634,000 cells per liter) was dominant in the inner harbor in late summer along with a bloom of the dinoflagellate, *Massartia rotundata* (293,000 cells per liter).

Metcalf and Eddy (1979) showed that in summer, the inner harbor displayed numerical dominance by microflagellates, and that this dominance increased at the more inshore stations.

2.6 General Points Regarding Species Succession And Numerical Abundance

Phytoplankton Species Succession In Massachusetts Bay Is Similar To Species Succession In The Gulf Of Maine

Within seasons, Mass Bay holds more dominants in common with the nearby Gulf of Maine than with Boston Harbor. Also, the Gulf of Maine holds no dominants uniquely in common with Boston Harbor (that is not also held in common with Massachusetts Bay). More importantly, the major species of the spring bloom, *T. nordenskioldii*, *P. glacialis*, and *C. debile*, and occasionally *P. poucheti*, are dominant in the Gulf and Mass Bay. Boston Harbor displays spring dominance by *T. nordenskioldii*.

Mass Bay and the Gulf Of Maine are often dominated by a peridinian flora in summer. Bigelow noted that this peridinian flora, particularly *Ceratium*, appears earlier in Mass Bay than in the Gulf. Where synoptic data is available, the inshore stations of Mass Bay are more likely to be dominated by *R. alata*, while the offshore stations are more likely to continue dominance by *Ceratium* in late summer-early fall. Boston Harbor does not share this characteristic. Boston Harbor summer dominants are most often diatoms, and occasionally the green alga, *Scenedesmus* or the diatom, *Asterionella*. However, these species are common to the estuarine flora generally along the coastal Gulf Of Maine.

Coccolithophores appear in the Gulf Of Maine in summer. In Massachusetts Bay, the do not appear until autumn.

There Appears To Be A Difference In Species Succession Between Northern Massachusetts Bay And Cape Cod Bay

In general Mass Bay phytoplankton species succession is similar to phytoplankton in the Gulf of Maine with some differences in timing of events. Where synoptic data are available, there is a difference in species succession between northern Mass Bay and Cape Cod Bay. Bigelow noted this in 1926, and it is also apparent in the more limited MARMAP data set from 1978. A comparison of the nearshore Cape Cod Bay Boston Edison data from the summer of 1975 with the nearshore CDM 1986 data and the MWRA 1988 data also suggests some dissimilarities. In particular, the nearshore areas of Cape Cod Bay do not appear to exhibit the late summer diversity in the genus *Rhizosolenia* which occurs in northern Massachusetts Bay stations.

The Historical Data In Massachusetts Bay Does Not Indicate Prolonged Blooms Of "Nuisance" Or Novel Phytoplankton Blooms

Among those species considered "nuisance" *Phaeocystis* occurs in the historical data base on several occasions, but not in abundance for more than approximately two weeks at a time.

The only report of dominance by a "red-tide" organism in the reviewed data is the occurrence of *Gonyaulax* off coastal Cape Ann. Note however, that this review does not include nearshore estuarine areas, where there is a more concerted effort to assess the prevalence of "red-tide" organisms based upon mussel bioassays.

There Is An Uneven Temporal And Spatial Coverage Of Phytoplankton Species Succession In Massachusetts Bay

Historically, phytoplankton studies occurred most commonly in summer. For example, among the twelve studies listed in Table 2, nine covered the summer months (May to September). Only three of these studies included sampling in February or March/April when the Spring bloom is most likely to begin (February) and reach its maxima (March/April).

Nearshore areas, particularly those associated with large population centers (e.g. offshore Boston, Nahant Bay, Salem Sound) or a particular industry (e.g. power generation in Plymouth) have been most frequently sampled. The more offshore areas of northern Massachusetts Bay and in particular, central Cape Cod Bay were sampled so infrequently as to make generalizations very tenuous. As will be discussed in subsection 4.3, the paucity of data in Cape Cod Bay may be particularly critical given the emerging knowledge of the physical oceanography of this area.

The Numerical Abundance Of Phytoplankton In Massachusetts Bay Is Similar To That Observed In The Coastal Gulf Of Maine

The observed seasonal average abundances (Table 6) of phytoplankton in Massachusetts Bay are:

> $>10^5$ average netphytoplankton cells per liter (with individual observations reaching 10^6) and $> 10^7$ nannoplankton cells per liter in the spring;
>
> $>10^4$ to 10^6 netphytoplankton cells per liter and 10^5 to 10^8 nannoplankton cells per liter in the summer;

and,

> $<10^3$ to 10^5 netphytoplankton cells per liter and no observations for nannoplankton in autumn.

Individual observations do not often exceed 10,000,000 cells per liter even during periods of spring or summer blooms (Table 5). These observations clearly suggest a diminished autumn to winter abundance, a clear spring maxima and summers characterized by short periods of increased cell abundance separated by periods of low cell abundance. These cell concentrations are within the seasonal ranges commonly observed in the coastal Gulf Of Maine (Marshall, 1984).

The nannoplankton cell abundance reported for Boston Harbor is generally two to five times greater than that observed in Massachusetts Bay.

Note also that a comparison of dominant species based upon Parker's estimated carbon biomass results in a species list similar to that obtained by other investigators using cell abundance.

3.0 CHLOROPHYLL AND PRIMARY PRODUCTION

This section briefly describes the historical chlorophyll data obtained in Massachusetts Bay and Boston Harbor. These data appear only in the more recent studies.

3.1 Chlorophyll Concentrations

Tables 7 and 8 provide, for Massachusetts Bay and Boston Harbor, respectively, the average euphotic zone chlorophyll (in units of mg/m^3) by month for the listed sources as well as the average for all entries. In several instances, these numbers are the arithmetic average of chlorophyll concentrations measured at a series of discrete depths within the euphotic zone from the surface to the 1% light level. Some studies made measurements only at the surface and at a subsurface depth. In such cases we assumed that the two measures represented the euphotic zone. For some months this average derives from several studies and in some instances (e.g. MWRA in March) from several measurements within the month.

Given the averaging, there is considerable smoothing of the data, and as with the phytoplankton species data the chlorophyll data as presented provides an idealized "floristic year". This hides much of the variation between studies and even between stations within a single study (see the range in Parker's data in Table 7). Table 7 also provides summary statistics for the Massachusetts Bay data. For most months one or two outliers caused the broad ranges. The monthly standard deviations indicate that the variation increases during periods of elevated chlorophyll concentrations. This is an expected result given that the chlorophyll maxima will rise and fall on time scales of days while sampling occurred on time scales of weeks.

For Massachusetts Bay the averaged data show a distinct spring maxima (average chlorophyll approximately 7 mg/m^3) in March and a fall maxima of the same average magnitude in September. These maxima in chlorophyll biomass coincide with the periods of maximum average diatom cell abundance which occur in March and August/September (see Section 2).

The average summer euphotic zone chlorophyll ranges between 2 and 4 mg/m^3 between April and August. This is a relatively narrow range for the monthly averages. Note however, that the range of individual euphotic zone chlorophyll concentrations have a much broader range which is influenced by several outliers. The observed outliers in summer chlorophyll is consistent with the general observation that coastal areas are subject to short-lived summer blooms (e.g. Takahashi et al, 1979). The cell abundance data also reflects this summer variability.

Only four studies (MWRA 1988; 1990; CDM 1986; 1986a) distinguish between the nannoplankton fraction and total chlorophyll. For those limited studies where data is available, the fraction of chlorophyll contributed by the nannoplankton increased after the spring bloom. For example, MWRA (1988; 1990) noted that nannoplankton chlorophyll contributed 5 to 46% of the total chlorophyll during the spring bloom (March). The percentage increased toward the end of March. During the late spring and summer, 27% to 90% of total chlorophyll was in the nannoplankton fraction. Highest nannoplankton chlorophyll occurred in August (56% to 90% of total).

Figure 2 compares the average euphotic zone chlorophyll in Massachusetts Bay with that measured in Boston Harbor (note that these are averages, Tables 7 and 8 provide summary statistics which include the maxima, minima, and standard deviation for each month). Over the course of the average year, the range of chlorophyll concentrations in the two areas are similar. The obvious differences based upon the historical data are:

> The spring bloom (defined as increase in chlorophyll biomass) in Boston Harbor is on average prolonged relative to Massachusetts Bay;
>
> Average summer chlorophyll in Boston Harbor (particularly in July) is high relative to Massachusetts Bay (note that this observation derives from two separate studies which show elevated July chlorophyll in the Harbor);
>
> Massachusetts Bay displays a clear autumn bloom in terms of chlorophyll which is absent from Boston Harbor.

3.2 Primary Production

Table 9 provides primary production data in Massachusetts Bay on an areal basis from three of the five studies which measured this parameter in the bay (MWRA 1988; 1990; Parker, 1980). The other two studies (CDM, 1986; 1986a) do not provide this data on an areal basis, nor do the reports provide sufficient information concerning actual depths of light penetration levels to integrate the data on a station specific basis. However, one these reports (CDM,1986) provides the measured summer range of areal production within Nahant Bay.

Figure 4 shows the average areal primary production rate within Massachusetts Bay. On average, there is a clear and pronounced March maximum in excess of 3,000 mgC/m^2/day.

Summer production rates are generally less than 1500 mgC/m^2/day. and there is a secondary August maximum. Both studies in Table 9 indicate that March is the period of highest production, although Parker's measurements were not has high as those observed by MWRA. Primary production from May to July is generally less than 1500 mgC/m^2/day. CDM (1986) observed a June and July range of 1100 to 1600 mgC/m^2/day in Nahant Bay. We were not able to adjust measurements in Salem Sound (CDM, 1986a) to an areal basis for direct comparison. However, a relative analysis based on either a volumetric measurement or an assumed euphotic zone depth (to provide a rough estimate of areal production) reveals a similar summer pattern including a clear maxima in August.

A simple integration of the curve in Figure 4 indicates that the average annual total primary productivity in Massachusetts Bay is 350 grams C/m^2/year. This value is similar to the annual primary production, 415 gC/m^2/year, measured in the Gulf of Maine and lower than the estimate for the coastal area south of New Jersey, 726 gC/m^2/year (NOAA, 1981). Note that these NOAA estimates include total production (i.e. particulate and dissolved fixed carbon) while the estimate for Massachusetts Bay is only particulate. In general, NOAA found that dissolved production was about 10% to 15% of total. Therefore, the estimate for Massachusetts Bay is probably approximately the same as in the Gulf of Maine. NOAA also notes that particulate primary production in Block Island Sound (a nearby coastal area) is 300 gC/m^2/year. In terms of primary production, Massachusetts Bay appears within the range commonly found in temperate coastal shelf areas north of the plume of the Hudson-Raritan system. Note that Massachusetts Bay average annual production as estimated in this document is less than the NOAA estimates for Georges Bank, 665 gC/m2/year.

MWRA (1988; 1990) distinguishes between total primary production and primary production in the nannoplankton fraction. These data indicate that the nannoplankton contribution to total primary production is lowest during the spring bloom (6% to 27%). The nannoplankton fraction was lowest in early March and increased with increasing total primary production during the first three weeks of the month. During late spring (April and May), the nannoplankton fraction ranges from 13% to 38% of total production. Highest nannoplankton contribution to total primary production occurred in July and August (25% to 99%). We noted that in the MWRA summer observations, stations with highest total primary production exhibited the lowest nannoplankton fraction. Therefore, the August bloom which was most prominent at MWRA station P3 (where the nannoplankton fraction of chlorophyll was as high as 90%) had a relatively low contribution to total primary production from the nannoplankton (range 25% to 64%). During the same time, other stations with less total production, exhibited nannoplankton production at 67% to 93% of total.

3.3 General Points Regarding Chlorophyll Concentrations And Primary Production

Several general points emerge from a review of the monthly averaged and annualized historical chlorophyll and productivity data in Massachusetts Bay. These include:

> March is a period of high chlorophyll concentrations and primary production. Note that this is also the period when the classic spring diatom species appear in Massachusetts Bay;
>
> There is a secondary chlorophyll and primary production maximum in August/September. On average, this second maximum is equal to the March maximum in chlorophyll concentration, but less in terms of primary production.
>
> During the March bloom, the nannoplankton contribution to chlorophyll and primary production is lowest early in the bloom and increases as the bloom progresses. The nannoplankton contribution to both parameters is highest in summer;
>
> There are differences in timing, magnitude, and temporal pattern of the average chlorophyll concentration between Boston Harbor and Massachusetts Bay Total average annual production in Massachusetts Bay is similar to that measured in the Gulf of Maine.

4.0 DISCUSSION AND IMPLICATIONS OF THE DATA SETS FOR PHYTOPLANKTON MONITORING IN MASSACHUSETTS BAY

4.1 Potential Effects Of Increased Nutrient Loading Upon Phytoplankton Communities

One of the most immediate concerns associated with the proposed discharge of secondarily treated effluent to Massachusetts Bay is the potential effect of increased nutrients upon primary producers in the pelagic environment. This concern derives to a large degree from the well established knowledge that coastal marine systems are generally nitrogen limited. Therefore, an increase in nitrogen loading to a localized area or water mass may result in changes to the marine system. Obviously those organisms most likely to manifest the effects of nutrient enrichment are those which can make immediate use of increased concentrations of inorganic nitrogen. In a pelagic system those organisms are the phytoplankton. The potential responses of the phytoplankton community are: accelerated growth rate; increased biomass; and changes in species composition. The degree to which such changes occur in a particular coastal environment depend largely upon the rates of nutrient loading and site specific physical conditions such as basin topography, advection, and vertical mixing which affect flushing or residence times.

Potential Effect Of Nutrient Loading Upon Phytoplankton Growth Rate

There is considerable debate within the oceanographic community regarding the response of growth rate or primary productivity to increased nutrient concentrations. The classic view is that there is a proportional increase in growth rate (with some physiologically imposed maximum) in response to increasing nutrient concentrations (e.g. Dugdale and Goering 1967; Eppley and Strickland, 1968). Goldman (1980; 1979) summarized an alternative view of the relationship which holds that (at least for oceanic species) marine phytoplankton may be growing near their maximum growth rates and are not nutrient limited. In a more recent summary of this debate, Howarth (1988) noted that Goldman's definition of nutrient limitation is the limitation on the growth rate of the phytoplankton populations currently in the water. He speculated that if nutrient supply were increased, these phytoplankton species would be replaced by others which are better competitors in the new situation. However, we note that beyond a long recognized shift at high level taxa, often more closely related to size than phylogeny, (e.g. Margalef, 1958; 1967) there is essentially no body of theory or modelling which would allow prediction of how this hypothesized replacement might occur or what would be the resulting phytoplankton community structure. There is limited experimental evidence to show that nutrient levels and ratios may regulate species succession and community structure (Ignatiades and Smayda, 1970; Smayda, 1980; and Sommer, 1987).

Note also that an increase in growth rate per se is not necessarily obvious to a casual observer nor does it necessarily translate to general ecological impact. Various other specified and unspecified ecosystem properties commonly called "assimilative capacity" may buffer immediate or observable changes caused by increased phytoplankton growth. We note however that assimilative capacity is somewhat nebulously defined and has perhaps been the subject of as much debate as nutrient limitation (e.g. NOAA, 1979).

Potential Effect Of Nutrient Loading Upon Biomass

Of little debate is that the most commonly observed result of increased nutrient loading is an increase in biomass often expressed as chlorophyll. Marine biologists generally believed that there is a proportional response of biomass to increased nutrient availability and that the Redfield ratio expresses this proportion. That is, as the limiting nutrient, nitrogen, becomes more available, other elements such as carbon and phosphorous within the tissue of phytoplankton will increase proportionally. Under balanced growth, the result will be an increase in biomass which is measurable as chlorophyll, phytoplankton cell carbon, or perhaps cell number. There are numerous examples of nearshore systems which have experienced such measurable biomass increases associated with nutrient loading. These systems are generally nearshore, enclosed coastal embayments. For example, Curl et al. (1979) summarized some of the observed effects associated with nutrient enriched systems upon biomass in Chesapeake Bay, New York Bight, San Pedro Bay, San Francisco Bay, Kaneohe Bay, the Baltic Sea, Aegean Sea, Adriatic Sea, Oslo Fjord, and several Bays in Japan.

On the east coast of the United States, the effects of nutrient enrichment upon biomass are most often observed in enclosed or semi-enclosed bays (e.g. Ryther and Dunstan, 1971). Elevated chlorophyll levels associated with elevated concentrations of nitrogen are most commonly observed within the plumes of river discharge as observed in the New York Bight and off Delaware Bay (e.g. NOAA, 1988) or within the plume of Chesapeake Bay (NOAA, 1981). These observations which suggest coastal eutrophication are limited to the coastal areas affected by the generally southerly flow of water from east coast rivers. In more offshore areas of these shelf environments, the biomass and productivity are apparently more strongly influenced by nutrient input from deeper water (Walsh, 1981).

Potential Effect Of Nutrient Loading Upon Species Composition

The third potential change associated with increased nutrient loading is a potential change in species composition. As indicated earlier, for some time, theorists have recognized that the changes of high order taxonomic groups in the phytoplankton apparently relates to various combinations of nutrient concentrations and vertical mixing characteristics. These studies recognize that certain general groups of phytoplankton are more likely to occur under conditions of high nutrient concentration.

There are various field examples which demonstrate a dramatic species shift associated with nearshore eutrophication in coastal embayments and, recently, in more open coastal waters. These studies do not demonstrate a subtle shift in phytoplankton species composition or community structure. Rather, nearly all observations indicate a dramatic bloom which results in an essentially monospecific phytoplankton community. The species which characterize these blooms are not limited in terms of taxonomic category, size, or morphology. They may include diatoms, dinoflagellates, microflagellates, "mat formers", or toxic species and nuisance species.

On the northeast coast of the United States, these blooms have historically been observed in the enclosed bays and inlets associated with the Hudson/Raritan Estuary. For example, Ryther (1954) observed the small coccoid chlorophyte, *Nannochloris atomus* in Moriches Bay associated with increased nutrient input. Although this species was originally most commonly observed at bloom levels in the Hudson/Raritan estuary, in more recent years, it has occurred in extensive blooms in the New York Bight and southward along the New Jersey coast (EPA, 1986). The relatively open waters off the New Jersey coast have exhibited various nuisance blooms in recent years. These include:

> A discoloration off Atlantic City caused by *Dinophysis acuta* (Figley, 1979):
>
> A bloom of *Coscinodiscus wailesii* which caused clogging of fishermen's nets off Delaware Bay (Mahoney and Steimle, 1980);
>
> A similar clogging of nets along the New Jersey coast caused by a bloom of *Cerataulina pelagica* (EPA, 1987 ; 1989);
>
> "Green tides " caused by blooms of the dinophycean, *Gyrodinium aureolum* (EPA, 1986);

an extensive bloom of *Ceratium tripos* which caused an anoxic event in the offshore area of New York Bight in 1976 (Swanson and Sinderman, 1976).

The occurrence of nuisance blooms in the New York Bight and associated coastal waters maybe expanding phylogenetically as well as geographically. A previously unidentified species, *Aureococcus anophagefferens* caused the recently observed "brown tides" in Rhode Island and eastern Long Island embayments (Cosper et al., 1987; Sieburth et al., 1988).

There has been general concern regarding the occurrence of novel or nuisance phytoplankton blooms in coastal areas. There is significant empirical evidence for the increased occurrence of such blooms, although as indicated above, there is little experimental data or theoretical consideration which establishes a clear mechanism or a direct cause and effect between increased nutrient loading and the appearance of coastal blooms. A small body of empirical evidence (e.g. Frey and Small, 1979) indicates that taxonomic composition may be more affected by micronutrients (vitamins and trace metals) than by macro-nutrients (nitrogen, phosphorous, silicon). In large scale outdoor cultures, these investigators were able to control successional events with micronutrient additions and correlate these events to observations in situ.

Smayda (1989) reviewed various observations of nuisance blooms along coastal waters worldwide and has suggested that increased nutrient loading may be responsible. He reviewed the significant evidence for increased loading of nutrients to the coastal area worldwide and noted for example, that nitrate loadings to the United States northeast coast increased 34% during 1974 to 1981. Smayda argues in this paper that not only has phytoplankton growth rate and biomass increased due to nutrient loading, but also there have been observable changes to succession, competition, and species distribution. Upon establishing increased observations of toxic blooms, he noted that these may not be due to new introductions, but rather to the proliferation of indigenous populations which were previously part of the"hidden" flora.

There are acknowledged weaknesses in some of these arguments. For example:

> the increased frequency of blooms may be an artifact of increased monitoring for outbreaks of toxic shellfish;
>
> he attempts to explain the absence of novel blooms along the Dutch and German coasts (where there are reliable long term records or phytoplankton species composition) as due to chemical modification by riverine input and essentially argues that some riverine input may cause blooms while other input

> may prevent them (Smayda acknowledges that this cannot be established from the data at hand).

Smayda's review clearly establishes however that long term records indicate a remarkable correlation among increased nutrient loading, increased primary production and increased incidence of novel phytoplankton blooms in relatively (to Massachusetts Bay) restricted coastal waters such as the Skagerakk, Kattegat, Dutch Wadden Sea, and Baltic Sea. He also notes that somewhat weaker data sets (in terms of long term measurements) indicate that the more open areas of the North Sea may also exhibit an increase in novel blooms. The bloom species in these areas included such examples as:

> earlier seasonal appearance, increased persistence, and increased abundance of the historically occurring species such as *P. poucheti* in Dutch coastal waters;
>
> first appearances and subsequent spreading of *Gyrodinium aureolum* and *Prorocentrum minimum* in Norwegian waters;

and,

> dense net clogging blooms of *Coscinodiscus wailesii.*

Finally, Smayda hypothesized that the changing ratio of nutrients, especially the Si:N ratio determines which and whether diatoms will dominate in nutrient rich waters.

4.2 Implications For Monitoring In Massachusetts Bay

The discussion in subsection 4.2 has implications for the development of a monitoring program in Massachusetts Bay. There is clear potential for coastal systems including relatively open areas outside enclosed estuaries and bays to exhibit effects associated with nutrient loading. These may include increases in biomass, production, and phytoplankton species composition during blooms. At present, the Massachusetts Bay historical data set does not appear to exhibit the gross effects of nutrient loading commonly observed in some other coastal systems. Specifically:

> biomass measured as chlorophyll is not elevated to the extent observed in east coast areas influenced by plumes from the Hudson/Raritan, Delaware Bay, or Chesapeake Bay;

annual primary production is within the range observed generally for the Gulf of Maine and nearby Block Island Sound and less than the productivity observed in coastal areas affected by large riverine plumes from urban or large scale agricultural areas;

the average annual cycle of chlorophyll concentration and primary production displays the classic seasonal pattern observed in temperate coastal areas;

the succession of Massachusetts Bay netphytoplankton species is similar to that observed in the Gulf of Maine in terms of dominant species and the general timing of their appearance;

the historical data set does not exhibit the appearance of nuisance or novel species (*Phaeocystis* does appear in the historical record as a short lived dominant in spring, but short blooms of this species are apparently common to coastal Gulf of Maine and other shelf areas).

In general, the historical phytoplankton record and a review of related literature from other coastal areas indicate that Massachusetts Bay (exclusive of nearshore restricted areas) does not exhibit the characteristics of a eutrophic system. However, the historical record and literature review do not imply that relatively open water areas such as Massachusetts Bay are immune from exhibiting such characteristics based on purely physical oceanographic or morphological parameters. Open coastal areas (e.g. coastal New Jersey; the North Sea; New York Bight) have variously experienced symptoms of eutrophy such as increased biomass, elevated productivity, and novel or nuisance blooms.

In some cases, there is the opinion within the scientific community that the increased frequency of novel blooms associated with enhanced primary production is due to the increased frequency of observations. However, this argument is weaker in areas where a substantial historical data base exists. The phytoplankton data base in Massachusetts Bay is temporally and spatially restricted. Legitimate and relatively non-controversial comparisons of pre and post discharge phytoplankton properties within Massachusetts Bay will require a more temporally and spatially robust data set.

The literature review indicates that changes associated with nutrient loading are not subtle. The response of the phytoplankton community is increased production and biomass which probably follows some dose-yield relationship. Dominance of the phytoplankton by a single species not normally associated with the expected successional pattern often accompanies this increased production. The important observation here, in terms of implications for future monitoring, is that the literature indicates a gross change in community characteristics. This change is not a gradual shift in species richness or a subtle shift in diversity. It is an easily observable, transient monopoly of the netphytoplankton community by a species which exhibits an intense and prolonged appearance. The species may be a "new" species or a previously observed but numerically subordinate species. For example, we currently observe a species such as *Phaeocystis* an occasional dominant in Massachusetts Bay and consider it a normal part of the flora. However, a change in the timing or duration of its appearance (as observed in the North Sea) may constitute a novel bloom.

Finally, the relationship between the nannoplankton and netphytoplankton under changing nutrient conditions is not clear or predictable from the literature. There is a seasonal pattern of nannoplankton influence upon chlorophyll concentrations, productivity, and cell abundance.

4.3 Recommendations For A Phytoplankton Monitoring Program

Massachusetts Bay should have a phytoplankton monitoring program. The literature indicates that even open waters such as Massachusetts Bay may experience the characteristics associated with increased nutrient loading. At present, neither the experimental nor theoretical state of the art allow prediction concerning assimilative capacity. Therefore, a reasonable option is to maintain a sufficient site specific empirical data base.

Hydrographic measures should accompany any phytoplankton monitoring program. This is particularly true in light of MWRA's observation in March, 1988 in which a change in species dominance over a two week period was actually an incursion of a water mass and not an abnormality in biological succession. A sufficient monitoring program should be able to distinguish a biological change from a physical change.

A monitoring program should include measurement of the nannoplankton contribution to chlorophyll, cell abundance and production. It is nearly impossible to distinguish (at a practical level) among nannoplankton species. However, it is possible for the nannoplankton fraction to respond to increasing nutrient conditions. Therefore, the practical course is to treat them as a distinct group.

The design of a phytoplankton monitoring program should include the recent physical, chemical, and biological oceanographic investigations currently conducted under the Mass Bays and MWRA programs. In particular, the significance of such observations as the flow of water to Cape Cod Bay from northern Massachusetts Bay; the absence of drifter tracks over Stellwagen Bank; the relatively long residence time for drifters in Cape Cod Bay (R. Geyer, NEERS 1990) and the depleted nutrient and chlorophyll pool observed in Cape Cod Bay (Loder, NEERS 1990) should be assessed by a joint meeting of the principal investigators and several biologists familiar with phytoplankton in Massachusetts Bay and the Gulf of Maine. The results of such a focussed and interdisciplinary meeting should provide the details of the spatial and temporal scales for monitoring.

A monitoring program should not be limited to the spring and fall blooms. The summer chlorophyll and cell abundance data as well as the literature indicate that summer may be a period of short lived blooms. For example, the data from CDM (1986; 1986a) suggests that *R. delicatula* is a fairly widespread but temporally limited dominant species in summer. Such short-lived but "normal" summer dominants should be identified by a baseline program.

A pre-operational baseline monitoring program should be several years long if possible. This is important in establishing year to year variation. For example, there is considerable variation in primary production between the Parker (1980) and MWRA (1988; 1990) studies. Also Matta and Marshall (1984) in an analysis of variation among phytoplankton assemblages in the western North Atlantic (including the Gulf of Maine) noted year-to-year variation was the largest component of variation in his data.

A phytoplankton monitoring program probably does not have to address subtle changes in diversity and species richness. The literature indicates that changes to species composition associated with nutrient loading occurs at a gross level. Identification of major species, total netphytoplankton, and total nannoplankton is probably sufficient if coupled with analysis of small mesh net tows to provide a species "inventory".

MWRA should explore the use of Continuous Plankton Recorder data. The Northeast Fisheries Center is contemplating an upgrade of its current system to include CDT and chlorophyll data (J. Jossi, personal communication). Mr. Jossi believes it may be possible to use a smaller mesh size, although he is concerned with clogging in the spring which would bias the zooplankton data. Perhaps MWRA could run a "small mesh" CPR in tandem with Fisheries Center's CPR. This data is currently obtained on ships of opportunity. This is a relatively inexpensive sample collection method if the data return justifies it (yet to be determined).

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TABLES

TABLE 1 LIST OF STUDIES WHICH ADDRESS VARIOUS ESTIMATES OF PHYTOPLANKTON BIOLOGY IN MASSACHUSETTS BAY

	Year of Study	Phyto-Plankton	Produc-tivity	Chloro-phyll	Nutrients
Bigelow, 1926	1912	1			
Lillick, 1940	1936				
Martin and Yentsch, 1973 "Foul Ground"	1973	1		1	
Boston Edison, 1975 Off Plymouth	1975	1			
Yentsch et al., 1977 Cape Ann	1977	1		1	1
Marshall and Cohn, 1978a,b Off Provincetown	1978	1			
Marshall and Cohn, 1978a,b Off Cape Ann		1			
Parker, 1980 Offshore Graves	1978	1	1	1	
CDM, 1986 Nahant Bay	1986	1	1	1	1
CDM, 1986a Offshore Salem Sound	1986	1	1	1	1
MWRA, 1988 Offshore Graves	1987	1	1	1	1
MWRA, 1990 Offshore Graves	1988	1	1	1	1
New England Aquarium, 1973 Offshore Deer Island	1973	1		1	1
Metcalf and Eddy, 1979 Offshore Graves	1977	1			1
TOTAL		13	5	8	7

TABLE 2. Summary of phytoplankton species dominants by month in northern Mass Bay as described in the historical data base. Note that these data do not include the recently generated Bigelow Laboratory data

	Jan	Feb	March	April	May	June
Bigelow, 1926		T. nordenskioldii		P. pouchetti		Peridinians
West of Stellwagen						
Lillick, 1940			T. nordenskioldii	T. nordenskioldii		Peridinians
Off Gloucester				C. debile		
Martin & Yentsch,1973						
"Foul Ground"						
New England			Chaetoceros	S. costatum	S. costatum	
Aquarium, 1973						
Seaward of Deer Island						
Yentsch et al., 1977		Coscinodiscus		Chaetoceros		
Cape Ann						
Marshall & Cohn, 1978						
Off Cape Ann						
Metcalf & Eddy						
1979						
Off Graves						
Parker, 1980	C. closterium	C. closterium	P. glacialis	P. glacialis	S. costatum	S. costatum
Offshore Graves	T. decipiens	T. decipiens	T. nordenskioldii	T. nordenskioldii		
			Thalassiosira sp.	Thalassiosira sp.		
CDM, 1986						R. delicatula
CDM, 1986a				C. compressus	L. minimus	S. costatum
Offshore Salem Sound				C. socialis		
MWRA, 1988						
Offshore Graves						

TABLE 2. Summary of phytoplankton species dominants by month in northern Mass Bay as described in the historical data base. Note that these data do not include the recently generated Bigelow Laboratory data

	Jan	Feb	March	April	May	June
MWRA, 1990			C. debilis	C. compressus		
Offshore Graves			D. confervacea	C. debilis		
			P. pouchetti	S. costatum		
			T. nordenskioldii	T. nordenskioldii		

TABLE 2. Summary of phytoplankton species dominants by month in northern Mass Bay as described in the historical data base. Note that these data do not include the recently generated Bigelow Laboratory data

	July	August	September	October	November	December
Bigelow, 1926		R. alata	S. costatum	Ceratium	R. alata	
West of Stellwagen		S. costatum				
Lillick, 1940		Ceratium	S. costatum			
Off Gloucester		R. alata				
		S. costatum				
Martin & Yentsch,1973			S. costatum			
"Foul Ground"						
New England				Chaetoceros	Coscinodiscus	Coscinodiscus
Aquarium, 1973						
Seaward of Deer Island						
Yentsch et al., 1977	S. costatum		Gonyaulax		Thalassiosira	
Cape Ann						
Marshall & Cohn, 1978				R. delicatula	E. huxleyii	
Off Cape Ann				R. setigera	N. atomus	
					P. depressum	
Metcalf & Eddy	Dinoflaggelate					
1979	Peridinium					
Off Graves						
Parker, 1980	R. delicatula	L. danicus	L. danicus	R. delicatula	G. flaccida	G. flaccida
Offshore Graves	R. fragilissima	S. costatum	S. costatum	R. fragilissima		
				S. costatum		
CDM, 1986	R. delicatula					
CDM, 1986a	R. delicatula	L. danicus				
Offshore Salem Sound		S. costatum				
MWRA, 1988	L. danicus	C. pelagica	R. fragilissima			
Offshore Graves	L. minimus	R. fragilissima				

		TABLE 2. Summary of phytoplankton species dominants by month in northern Mass Bay				
		as described in the historical data base. Note that these data do not				
		include the recently generated Bigelow Laboratory data				
	July	August	September	October	November	December
MWRA, 1990						
Offshore Graves						

TABLE 3. SUMMARY OF PHYTOPLANKTON SPECIES DOMINANTS BY MONTH IN CAPE COD BAY AS DESCRIBED IN THE HISTORICAL DATA BASE. NOTE THAT THESE DATA DO NOT INCLUDE THE RECENTLY GENERATED BIGELOW LABORATORY DATA

	Jan	Feb	March	April	May	June
Bigelow, 1926 Cape Cod Bay		R. alata		P. poucheti	Peridinians	Perdinians
Boston Edison, 1975 Off Plymouth	S. costatum	S. costatum	S. costatum	Chaetoceros S. costatum	Chaetoceros S. costatum	L. minimus
Marshall & Cohn, 1978a,b Off Provincetown						

TABLE 3. SUMMARY OF PHYTOPLANKTON SPECIES DOMINANTS BY MONTH IN CAPE COD BAY AS DESCRIBED IN THE HISTORICAL DATA BASE. NOTE THAT THESE DATA DO NOT INCLUDE THE RECENTLY GENERATED BIGELOW LABORATORY DATA

	July	August	September	October	November	December
Bigelow, 1926 Cape Cod Bay		S. costatum R. alata		S. costatum	R. alata	R. alata
Boston Edison, 1975 Off Plymouth	S. costatum Chaetoceros sp. C. closterium	L. danicus S. costatum		L. minimus	L. minimus S. costatum	S. costatum Thalassiosira sp.
Marshall & Cohn, 1978a,b Off Provincetown				coccolithophore	N. atomus	

Table 4. A SUMMARY OF THE DOMINANT SPECIES OBSERVED IN NORTHERN MASSACHUSETTS BAY, CAPE COD BAY, AND BOSTON HARBOR COMPARED TO THE GENERAL SUCCESSION OF SPECIES OBSERVED FOR THE COASTAL GULF OF MAINE

	WINTER (Jan to Feb)	SPRING BLOOM (March to April)	LATE SPRING/SUMMER (May to Sept)	AUTUMN (Oct to Dec)
Northern Massachusetts Bay	Coscinodiscus C. closterium T. decipiens	C. compressus C. debile C. socialis D. confervacea P. glacialis P. pouchetti Thalassiosira sp. T. nordenskioldii	Ceratium Chaetoceros sp. C. pelagica Gonyaulax L. danicus L. minimus Peridinians R. alata R. delicatula R. fragilissima S. costatum	coccolithophore Coscinodiscus E. huxleyii G. flaccida N. atomus P. cerasus R. alata R. delicatula R. fragilissima R. setigera S. costatum
Cape Cod Bay	R. alata S. costatum	Chaetoceros sp. Peridinians Phaeocystis S. costatum	Chaetoceros sp. C. closterium R. alata S. costatum	coccolithophore L. minimus N. atomus R. alata S. costatum
Coastal Gulf Of Maine	Coscinodiscus R. alata B. aurita P. sulcata T. nitzschioides T. decipiens	C. convolutus C. debile T. decipiens T. nordenskioldii T. gravida P. glacialis	Ceratium Coccolithophore C. convolutus G. flaccida Peridinians R. alata	Ceratium Coscinodiscus
Boston Harbor	Coscinodiscus Navicula Nitzschia Rhizosolenia	A. japonica C. decipiens S. costatum Thalassiosira sp. T. nordenskioldii	Coscinodiscus L. danicus L. minimus L. undulatum M. rotundata R. fragilissima Scenedesmus	Coscinodiscus Distephanus sp. Nitzschia S. costatum

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

CDM, 1986 - Swampscott

	JUNE		JULY 9		JULY 23	
STATION (surface)	1	2	1	2	1	2
NANNOPLANKTON	1.3E+08	4.4E+07	1.0E+07	2.1E+07	5.2E+07	1.9E+07
TOTAL NON-NANNOPLANKTON	79,400	69,200	429,200	489,300	56,000	65,200
SPECIES						
Rhizosolenia delicatula	19,000	26,000	384,000	430,000		4,000
Leptocylindrus minimus	10,000	7,000	16,000		5,600	
Gymnodiniaceans	8,000	9,000		8,000	8,000	11,000
Cerataulina pelagica				27,000		
Nitzschia delicatissima	5,000	6,000	4,400			
Massartia rotunda	5,000					
Dinophysis acuminata						
Peridinum brevipes			3,800			
autotrophic peridinians		6,000	9,800	10,000	7,400	19,000
Leptocylindricus danicus	4,000			9,000	4,200	5,000
Thalassiosira gravida					9,000	13,000

TABLE 5. Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

CDM, 1986a Offshore Salem Harbor

	APRIL		MAY			JUNE		
STATION (surface)	4	5	4	5	6	4	5	6
NANNOPLANKTON			8.7E+07	6.4E+07	1.0E+08	2.2E+07	1.6E+08	2.4E+08
TOTAL NON-NANNOPLANKTON SPECIES	2.1E+05	2.4E+05	6.2E+06	5.9E+06	5.3E+06	8.0E+04	3.8E+05	1.6E+04
Chaetoceros socialis	161,500	184,100						
Chaetoceros compressus	45,500	51,900	6,000	19,000	10,000			
Chaetoceros teres			8,100	18,000	141,300			
Chaetoceros eibenii	900							
Chaetoceros sp.			12,000		14,000			
Dinophysis acuminata								
Nitzschia seriata								
Skeletonema costatum		1,200	4,000	19,000	16,000	4,400	251,000	
autotrophic peridinians		1,000						2,000
Rhizosolenia delicatulata		400				13,000	31,000	
Gyrodinium spirale		400						
Gymnodiniaceans			3,000	9,000		15,000	19,300	5,000
Nitzschia delicatissima			10,000	5,000	10,000	15,000	16,000	
Heterocapsa triquetra						4,800		6,000
Leptocylindricus minimus			6.1E+06	5.9E+06	5.1E+06		20,000	
Scrippsiella trochoidea								
Peridinium brevipes								
Leptocylindricus danicus						4,000		
Thalassiosira pseudonana								
Thalassiosira gravida								1,000
Ceratium longipes								1,400
Rhizosolenia fragilissima								
Prorocentrum micans								
Prorocentrum redfieldii								
Lithodesmium undulatum								
Prorocentrum scutellum								

TABLE 5. Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

CDM, 1986a Offshore Salem Harbor

	JULY 9			JULY 23			AUGUST		
STATION (surface)	4	5	6	4	5	6	4	5	6
NANNOPLANKTON	3.0E+07	1.3E+07	2.4E+07	3.8E+07	1.9E+07	2.4E+07			
TOTAL NON-NANNOPLANKTON	6.3E+05	6.5E+05	1.2E+06	5.9E+04	1.8E+04	2.3E+04	1.5E+06	6.4E+05	5.3E+05
SPECIES									
Chaetoceros socialis									
Chaetoceros compressus									
Chaetoceros teres									
Chaetoceros eibenii									
Chaetoceros sp.								11,300	
Dinophysis acuminata									
Nitzschia seriata									
Skeletonema costatum						1,800	509,000	65,600	124,000
autotrophic peridinians	16,900		3,000		1,200	3,000	8,600		
Rhizosolenia delicatulata	593,000	630,000	1.12E+06						
Gyrodinium spirale									
Gymnodiniaceans	8,000		14,000	9,400	7,000	10,000			
Nitzschia delicatissima	1,600	4,000		3,000	2,000				
Heterocapsa triquetra	4,100	2,600	7,000						
Leptocylindricus minimus				8,000				43,100	28,100
Scrippsiella trochoidea			7,000						
Peridinium brevipes		2,600							
Leptocylindricus danicus				8,000		2,000	284,000	105,000	35,600
Thalassiosira pseudonana				9,400	3,000	3,000			
Thalassiosira gravida									
Ceratium longipes									
Rhizosolenia fragilissima				6,000				22,500	9,400
Prorocentrum micans		1,200							
Prorocentrum redfieldii							41,200		
Lithodesmium undulatum							664,000	334,000	311,000
Prorocentrum scutellum					2,000				

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

MWRA,1990,
Station P2

Plankton at surface.

	MARCH 2	MARCH 15	MARCH 22	MARCH 29	APRIL 5	APRIL 18	MAY 4
NANNOPLANKTON	1.2E+07	2.6E+07	2.0E+07	1.0E+07	2.1E+07	2.3E+07	1.5E+07
TOTAL NON-NANNOPLANKTON	7.4E+05	1.0E+06	7.7E+05	6.2E+05	7.2E+05	3.5E+05	4.6E+04
SPECIES							
Chaetoceros debilis	300,000	698,000	414,000	353,000	43,000	104,000	16,000
Detonela confervacea	155,000						
Thalassiosira nordenskioeldii	90,000	111,000	66,000		20,000	105,000	
Thalassionema nitzschioides	79,000	80,000	85,000	30,000			6,000
Chaetoceros diadema	38,000						
Chaetoceros spp.		35,000				23,000	
Thalassiosira rotula		27,000					
Chaetoceros compressus			75,000	106,000	463,000		
Chaetoceros sociale			35,000	96,000	58,000	28,000	
Thalassiothrix frauenfeldianum				16,000			
Skeletonema costatum					117,000	19,000	12,000
Massartia rotundatum							5,000

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

MWRA, 1988	JULY 15			JULY 21			JULY 28		
STATION	P1	P2	P3	P1	P2	P3	P1	P2	P3
NANNOPLANKTON	5.9E+07	2.2E+07	6.4E+07	2.5E+07	8.0E+06	4.0E+07	7.6E+07	3.9E+07	3.3E+07
TOTAL NON-NANNOPLANKTON	1.1E+06	6.9E+05	2.3E+06	5.7E+04	4.4E+03	6.9E+04	1.7E+05	1.5E+05	8.2E+04
SPECIES									
Leptocylindricus danicus	849,000	624,000	1.9E+06	37,000	900	20,000	25,000	80,000	22,000
Leptocylindricus minimus	151,000	42,000	274,000						
Lithodesmium undulatum	17,000		36,000						3,000
Thalassiosira pseudonana	17,000					1,000	20,000	15,000	11,000
Heterocapsa triquetra	15,000	9,000	20,000			1,000			1,000
Cerataulina pelagica		7,000							
Rhizosolenia fragilissima		5,000		3,000		43,000	57,000	24,000	36,000
Cheatoceros sp.			60,000	4,000					
Pennate diatoms									
Gymnodiniaceans				5,000			21,000	20,000	4,000
Skeletonema costatum				4,000					
Massartia rotunda					1,000	4,000			
Rhisosolenia alata					500				
Thalassionema nitzschoides					400				
Prorocentrum scutellum					400				
Autotrophic peridinians							33,800	3,400	
Rhisosolenia delicatula									
Nitzschia closterium									
Thalassiosira gravida									
Rhizosolenia setigera									

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

MWRA, 1988

	AUG 5			AUG 12			AUG 25		
STATION	P1	P2	P3	P1	P2	P3	P1	P2	P3
NANNOPLANKTON	2.6E+07	2.6E+07	4.9E+07	4.4E+07	6.1E+07	3.4E+07	1.9E+07	1.8E+07	3.1E+07
TOTAL NON-NANNOPLANKTON	2.3E+06	1.1E+06	3.4E+06	2.0E+06	7.0E+06	2.0E+06	1.7E+06	1.7E+05	3.8E+06
SPECIES									
Leptocylindricus danicus	27,000							7,000	113,000
Leptocylindricus minimus		21,000	191,000	90,000		70,000	444,000	26,000	546,000
Lithodesmium undulatum									
Thalassiosira pseudonana	64,000	6,000	49,000	45,000	10,000	19,000			
Heterocapsa triquetra									
Cerataulina pelagica	17,000	568,000		79,000	6.9E+06	180,000			
Rhizosolenia fragilissima	2.1E+06	467,000	788,000	1.7E+06	10,000	1.7E+06	1.2E+06	75,000	3.08E+06
Cheatoceros sp.	16,000	13,000	158,000						
Pennate diatoms									
Gymnodiniaceans					10,000				
Skeletonema costatum									
Massartia rotunda									
Rhisosolenia alata									
Thalassionema nitzschoides									
Prorocentrum scutellum									
Autotrophic peridinians									
Rhisosolenia delicatula						16,000	8,000		
Nitzschia closterium			135,000	23,000	1,000				4,000
Thalassiosira gravida							21,000	9,000	58,000
Rhizosolenia setigera							16,000	21,000	

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

MWRA, 1988

	SEPT 8		
STATION	P1	P2	P3
NANNOPLANKTON	8.4E+07	7.4E+07	9.8E+07
TOTAL NON-NANNOPLANKTON	1.0E+06	1.5E+06	6.5E+05
SPECIES			
Leptocylindricus danicus			
Leptocylindricus minimus		6,000	3,000
Lithodesmium undulatum			
Thalassiosira pseudonana			
Heterocapsa triquetra			
Cerataulina pelagica			
Rhizosolenia fragilissima	821,000	1.22E+06	458,000
Cheatoceros sp.			
Pennate diatoms			
Gymnodiniaceans	2,000	6,000	2,000
Skeletonema costatum	13,000		
Massartia rotunda			
Rhisosolenia alata			
Thalassionema nitzschoides			
Prorocentrum scutellum			
Autotrophic peridinians			
Rhisosolenia delicatula		47,000	86,000
Nitzschia closterium			
Thalassiosira gravida	195,000	165,000	94,000
Rhizosolenia setigera			

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

Marshall and Cohn, 1978a,b Cape Cod Bay (station 97) and Northern Massachusetts Bay (station 98)

	October		November	
STATION	97	98	97	98
NANNOPLANKTON	3744			
TOTAL NON-NANNOPLANKTON	304	6944	4040	344
SPECIES				
Nannochloris atomus			3704	56
coccolithophores	48	584		
Coccolithus pelagicus	24			
Gyrodinium sp.	24			
Scrippsiella trochoidea	24			
haptophycean	16			
Melosira hummi	16			
Coscinodiscus nitidus	16			
Prorocentrum micans	16			
Protoperidinium depressum	16			
Rhizosolenia delicatula		1192		
Rhizosolenia setigera		792		
Prorocentrum balticum				
Thalassionema nitzschioides		424		
Distephanus speculum		352		
Rhizosolenia stolterfothii			456	
Katodinium rotundatum			360	
Coscinodiscus wailesii			104	
Prorocentrum minimum			160	
Emiliana huxleyii				48
Protoperidinium depressum				48
Ampnidoma				32
Bidullphia regia				
Hymenomonas carteri				32

TABLE 5 . Numerical abundance of the five most abundant phytoplankton species (including ties) by station and month. Abundance is in cells per liter.

Metcalf & Eddy, 1979 Offshore Graves Light

STATIONS	DW1 JULY
NANNOPLANKTON	1.9E+06
TOTAL NON-NANNOPLANKTON	1.9E+06
SPECIES	
Dinophycae	1.7E+06
Peridinium sp.	49,600
Skeketonema costatum	49,600
Coscinodiscus centralis	44,100
Thalassiosira sp.	44,100

TABLE 6. Summary of average phytoplankton species abundance (cells/l) in northern Mass Bay as described in the historical data base. These data do not include the recently generated Bigelow Laboratory data.

	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
New England Aquarium, 1973 Seward of Deer Island												
DOMINANT SPECIES ONLY			1.1E+04	1.8E+05	1.8E+08					6.0E+03	1.1E+04	3.2E+04
Marshall & Cohn, 1978 Off Cape Ann												
NETPLANKTON										6.9E+03	3.4E+02	
NANNOPLANKTON												
Metcalf & Eddy 1979 Off Graves												
NETPLANKTON							1.9E+06					
NANNOPLANKTON							1.9E+06					
CDM, 1986 SWAMPSCOTT												
NETPLANKTON						7.4E+04	2.6E+05					
NANNOPLANKTON						8.7E+07	2.5E+07					
CDM, 1986a Offshore Salem Sound												
NETPLANKTON				2.3E+05	5.8E+06	1.6E+05	4.2E+05					
NANNOPLANKTON					8.4E+07	1.4E+08	2.5E+07	9.0E+05				
MWRA, 1988 Offshore Graves												
NETPLANKTON							7.0E+05	1.9E+06	1.0E+06			
NANNOPLANKTON							4.0E+07	3.4E+07	8.6E+07			
MWRA, 1990 Offshore Graves												
NETPLANKTON			7.9E+05	3.7E+05								
NANNOPLANKTON			1.7E+07	2.0E+07								

Table 7. Chlorophyll-a in surface stations in Mass Bay
(units in mg/m3)

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Martin & Yentsch,1973								0.40	4.42			
"Foul Ground"												
New England			0.26	1.75		5.02	1.02		0.67	5.10	0.37	
Aquarium, 1973									2.15	0.10	0.56	
Seaward of Deer Island												
CDM, 1986a						2.88	4.39		2.26			
Offshore Salem Sound							12.63					
						4.52	4.80	0.72	4.08	3.35		0.85
Parker, 1980												
Offshore Graves												
StaA2	0.51	0.64	10.36	2.90	1.03	3.70		1.07	6.01	3.46		
					2.20	2.23			6.40	3.52		
	0.83	2.73	6.32	4.23	2.70	2.21						
			7.79	1.43	3.02							
StaA4	0.57	0.47	5.59	1.18	0.49	2.22	1.63	1.09	6.61	2.51		
			9.96		1.04	3.50			7.37	7.29		
	0.90	1.25	5.98	4.45	3.59	1.75						
			6.50	0.81	0.98							
StaB3	0.49	0.51	6.03	6.60	0.91	2.85	2.21	1.10	16.01	4.63		0.70
			6.80	2.70	1.95	3.07			3.69	4.71		1.06
	0.60	1.14	8.22	4.25	1.52	1.97						
			8.51	0.86	2.02							
StaC2	0.58	0.63	8.80	5.15	1.57	0.79	10.85	2.48	29.34	10.46		

Table 7. Chlorophyll-a in surface stations in Mass Bay												
(units in mg/m3)												
	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
			21.48		5.21	2.52			12.64	3.30		
	0.98	1.16	6.88	9.95	5.00	2.59						
			10.73	3.20	6.95							
StaC4	0.66	0.46	9.93	1.35	0.72	1.69				5.39		
			11.69							3.79		
	0.66	1.29	7.65	5.88	2.86	1.48						
			6.71	1.11	2.10							
MWRA, 1987												
P1			2.34	1.47	0.53		6.78	5.21	6.10			
			4.23	1.44			1.39	9.95				
			3.77				6.12	4.53				
			2.13									
P2							1.24	3.03	5.79			
							0.43	1.15				
							1.74	0.77				
P3							5.95	9.39	3.78			
							1.66	4.32				
							0.78	10.12				
Massachusetts Bay Data Summary												
Average Mass Bay	0.68	1.03	7.44	3.20	2.32	2.65	3.98	3.69	7.33	4.48	0.47	0.87
Minimum	0.49	0.47	0.26	0.81	0.49	0.79	0.43	0.40	0.67	0.10	0.31	0.70
Maximum	0.98	2.73	21.48	9.95	6.95	5.02	12.63	10.12	29.34	10.46	0.56	1.06

Table 8. Chlorophyll-a in surface stations in Boston Harbor
(units in mg/m3)

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
MWRA 1988,							15.85	18.20	7.48			
Boston Harbor Station N1							10.20	13.19				
							8.21	8.19				
NEA, 1990			7.31	1.40	0.37	5.81	2.80	5.00	2.55	8.10	0.52	
Boston Harbor				12.88	7.38	2.03	0.59	0.82	0.41	3.08	0.17	
			0.23	5.90	1.86	3.22	3.09	2.64	2.88	0.04	0.36	
							14.91					
							10.42					
							8.25					
New England Aquarium, 1973												
President Roads												
St. 3	1.12		9.00	6.80								
Boston Harbor Data Summary												
Average Mass Bay	1.12		5.51	6.75	3.20	3.69	6.68	2.82	1.95	3.74	0.35	
Minimum	0.45		0.26	1.40	0.37	2.03	0.59	0.82	0.41	0.04	0.17	
Maximum	1.12		9.00	12.88	7.38	5.81	14.91	5.00	2.88	8.10	0.52	

Table 9. Primary Production In Massachusetts Bay In mgC/m2/day

	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPT	OCT	NOV	DEC
MWRA, 1988; 1990			2361	1711	1020		1739	1520	1268			
			5581	1706			520	934	2224			
			6853				2268	5155	1800			
			3582				578	899				
							151	146				
							623	2013				
							1623					
							1481					
							1754					
Parker, 1980	160	214	1383	1202	284	881	757	607	839	615		337
			1170	332	963	764			240	672		382
			1555	533	456							
			1915	360	940							
Average	160	214	3050	974	733	823	1149	1611	1274	644		360

FIGURES

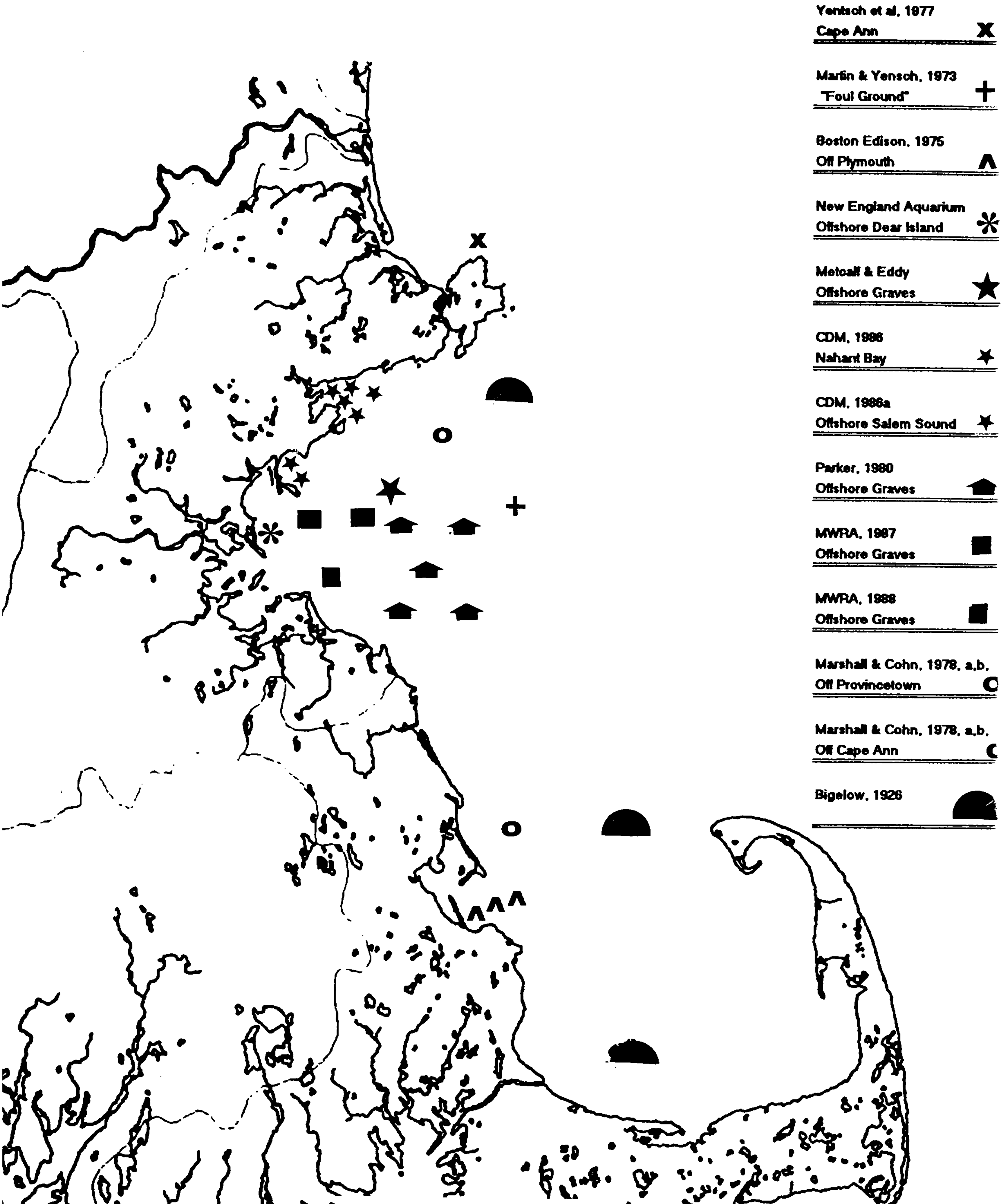

FIGURE 1.
SAMPLING LOCATIONS
FROM VARIOUS STUDIES IN
MASSACHUSETTS BAY

FIGURE 2: AVERAGE EUPHOTIC ZONE CHLOROPHYLL
IN MASSACHUSETTS BAY AND BOSTON HARBOR

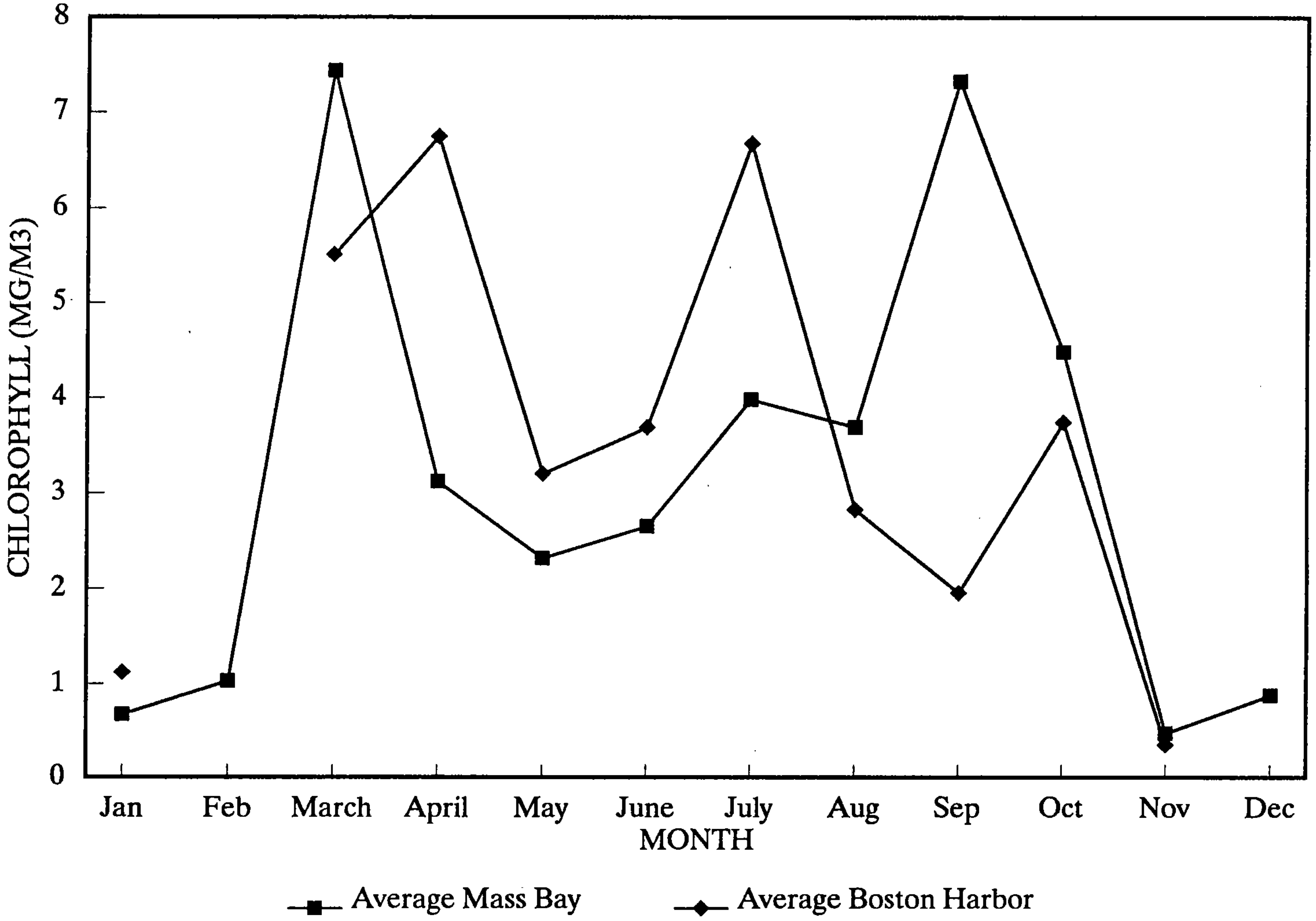

FIGURE 3. REPRODUCTION OF FIGURE 2 FROM JOSSI AND SMITH, 1990

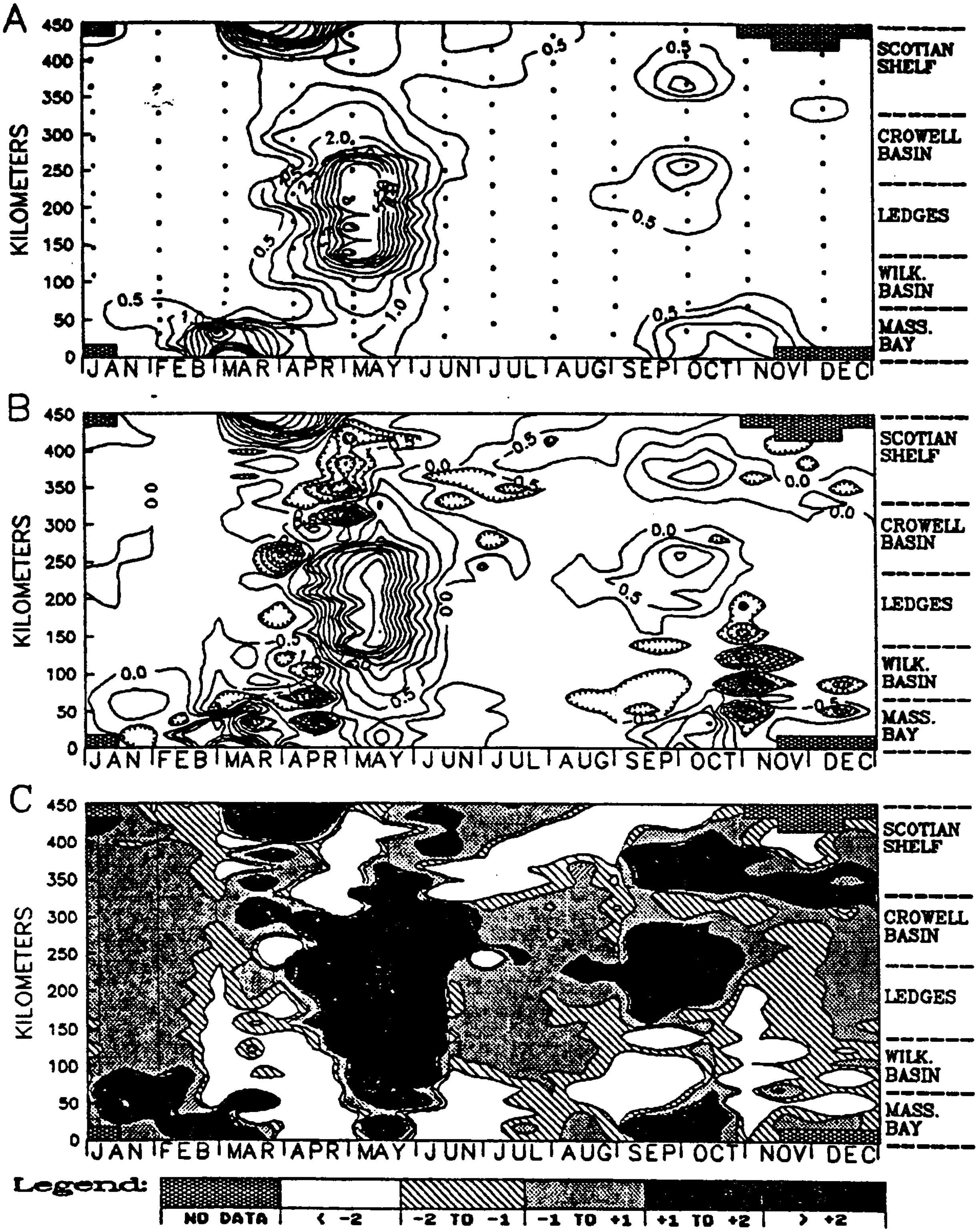

Figure 2. "Total phytoplankton" along the Gulf of Maine transect during 1989. A. Relative green color values in time and space. Dots indicate sampling locations. B. Color anomalies in time and space based on 1961 through 1987 means. C. Standardized color anomalies (standard deviations) in time and space based on 1961 through 1987 means and variances. In panels A and B values decline on those sides of contour lines with hachures.

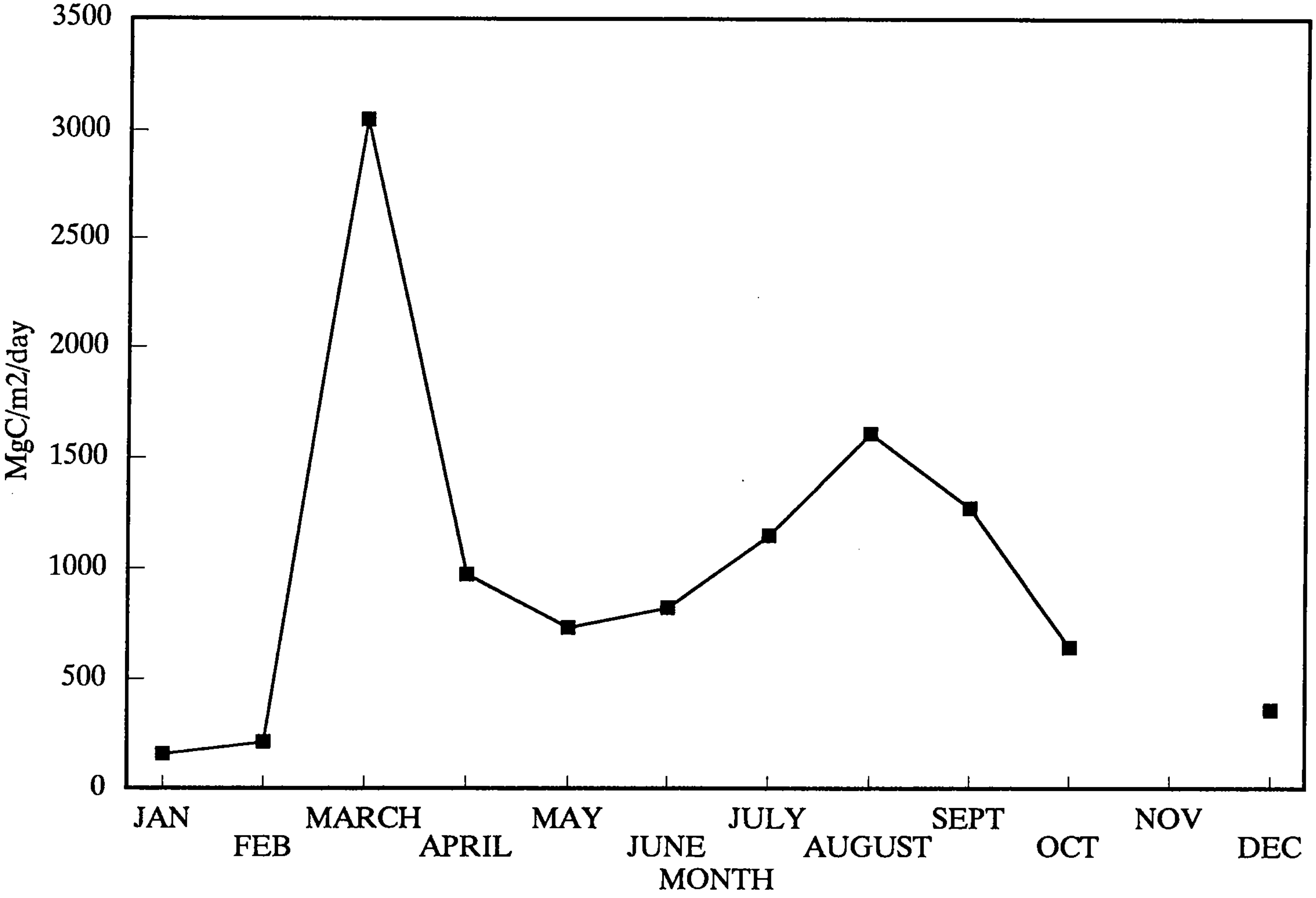

Figure 4. PRIMARY PRODUCTION

IN MASSACHUSETTS BAY

APPENDIX A

Table A1. List of species referred to in text and tables with taxonomic position
and common name where applicable
Species are alphabetized within lowest taxon for ease of use.

Latin Name	Common Name	Abbreviation Used In Text
CLASS BACILLARIOPHYCEAE	Diatoms	
Order: Centrales	Centric Diatoms	
Asterionella japonica		A. japonica
Biddulphia aurita		B. aurita
Biddulphia regia		B. regia
Cerataulina pelagica		C. pelagica
Chaetoceros compressus		C. compressus
Chaetoceros debile		C. debile
Chaetoceros diadema		C. diadema
Chaetoceros eibenii		C. eibenii
Chaetoceros socialis		C. socialis
Chaetoceros teres		C. teres
Coscinodiscus centralis		C. centralis
Coscinodiscus convolutus		C. convolutus
Coscinodiscus nitidus		C. nitidus
Coscinodiscus wailesii		C. wailesii
Detonula confervacea		D. confervacea
Guinardia flaccida		G. flaccida
Leptocylindrus danicus		L. danicus
Leptocylindrus minimus		L. minimus
Paralia sulcata		P. sulcata
Porosira glacialis		P. glacialis
Melosira hummi		M. hummi
Rhizosolenia alata		R. alata
Rhizosolenia delicatula		R. delicatula
Rhizosolenia faeroense		R. faeroense
Rhizosolenia fragilissima		R. fragilissima
Rhizosolenia setigera		R. setigera
Rhizosolenia stolterfothii		R. stolterfothii
Skeletonema costatum		S. costatum
Thalassionema nitzschioides		T. nitzschioides
Thalassiosira decipiens		T. decipiens
Thalassiosira eccentrica		T. eccentrica
Thalassiosira gravida		T. gravida
Thalassiosira nordenskioldii		T. nordenskioldii
Thalassiosira psuedonana		T. psuedonana
Thalassiosira rotula		T. rotula
Thalassiothrix frauenfeldianum		T. frauenfeldianum

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Species are alphabetized within lowest taxon for ease of use.

Latin Name	Common Name	Abbreviation Used In Text
Order: Pennales	Pennate Diatoms	
Cylindrotheca closterium		C. closterium
Lithodesmium undualtum		L. undualtum
Navicula spp		Navicula
Nitzschia spp.		Nitzschia
Nitzschia delicatissima		Ni. delicatissima
Nitzschia seriata		N. seriata
CLASS: DINOPHYCEAE	Dinoflagellates	
Order: Peridiniales	Peridinians	
Ceratium longipies		C. longipies
Ceratium tripos		C. tripos
Gyrodinium aureolum		G. aureolum
Gyrodinium spirale		G. spirale
Gonyaulax spp.		Gonyaulax
Heterocapsa triquetra		H. triquetra
Peridinium cerasus		P. cerasus
Peridinium brevipes		P. brevipes
Protoperidinium depressum		P. depressum
Order: Dinophysiales	Dinophytes	
Dinophysis acuta		D. acuta
Dinophysis acuminata		D. acuminata
Massartia rotundata		M. rotundata
Order: Prorocentrales		
Prorocentrum balticum		P. balticum
Prorocentrum minimum		P. minimum
Prorocentrum micans		P. micans
P. redfieldii		P. redfieldii
Prorocentrum scutellum		P. scutellum
CLASS: HAPTOPHYCEAE		
Order: Prymnesiales		
Family: Phaeocystaceae		
Phaeocystis poucheti		P. poucheti
Family: Coccolithaceae	Coccolithophores	
Emiliani huxleyii		E. Huxleyii

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and common name where applicable
Species are alphabetized within lowest taxon for ease of use.

Latin Name	Common Name	Abbreviation Used In Text
CLASS: CHLOROPHYCEAE	Green Algae	
Nannochloris atomus		N. atomus
Scenedesmus spp		Scenedesmus
Hymenomonas carteri		H. carteri
CLASS: CHRYSOPHYCEAE	Brown Algae	
Aureococcus anophagefferens		A. anophagefferens
Distephanus speculum		D. speculum
Scrippsiella trochoidea		S. trochoidea
Katodinium rotundatum		K. rotundatum

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