

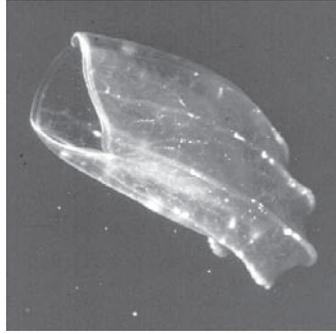


CHAPTER 9.

Plankton and Benthos

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Plankton and Benthos

Introduction

Narragansett Bay has historically been considered a phytoplankton-based estuary. In part, this is due to the geomorphology of the Bay itself; since much of the Bay is relatively deep (see Fig. 7.4, page 81), submerged aquatic vegetation (SAV; macroalgae and eelgrass, *Zostera marina*) is limited in distribution and cover. Coves, embayments, marshes, and other shallow areas typically support dense and productive SAV (primarily macroalgae), but on a Bay-wide scale, phytoplankton is the dominant primary producer (Kremer and Nixon, 1978; Kremer, 1990). Phytoplankton composition and production is variable among regions of the Bay and over different temporal cycles. It is directly grazed by zooplankton in the water column and provides a critical food source for benthic organisms. The purpose of this chapter is to provide an overview of plankton (both phyto- and zoo-) and benthic communities in Narragansett Bay by discussing spatial and temporal patterns in composition, abundance, biomass and production, plankton-benthos interactions, and long-term trends and changes.

Phytoplankton

Community Composition

Narragansett Bay supports a rich phytoplankton assemblage (Appendix 9.1) that researchers have been studying for over five decades (although some basic species composition lists date back to the early 1900s). The number of phytoplankton species present in Narragansett Bay is predictably variable among different studies. For example, an early 10-month study documented approximately 75 species of phytoplankton (Smayda, 1957), while a longer-term study from 1959–1980 identified 138 phytoplankton taxa (Karentz and Smayda, 1984). The variability in the number of phytoplankton species among different studies is due in part to differences in the timing and location of sampling and to different sampling techniques. However, one consistent result among all studies is that diatoms and, to a lesser extent, dinoflagellates overwhelmingly dominate the phytoplankton community in Narragansett Bay. Of the 138 taxa identified by Karentz and Smayda (1984), 84 were diatoms and 30 were dinoflagellates. Similarly, Smayda (1957) found that

nine diatom and four dinoflagellate species comprised 94 percent of the phytoplankton community.

Diatoms and flagellates exhibit a conspicuous alternating cycle of abundance in Narragansett Bay over the course of a year (Pratt, 1959; Durbin and Durbin, 1981). Diatoms tend to dominate during late winter through spring (January through May), when flagellate abundance is lowest. Diatoms begin to decline in the spring when flagellate numbers begin to rise, and by early summer flagellates reach their annual maximum. Diatoms again dominate at the end of the summer, but fall off again in late autumn (Pratt, 1959).

Microplankton (20–200 micrometers (μm)), primarily diatoms, are generally reported as the dominant size fraction in Narragansett Bay. However, nanoplankton in the 2–20 μm size range are typically an order of magnitude more abundant than microplankton but are not often identified to species (Oviatt, personal communication). Microplankton include the most abundant diatom in the Bay, *Skeletonema grethae* (formerly misidentified as *S. costatum* (Sarno et al., 2005)), which Smayda (1957) found during all four seasons, comprising over 81 percent of the total phytoplankton population. Similarly, over a 22-year period, Karentz and Smayda (1984) found that *S. grethae* occurred in 88 percent of all samples collected and displayed a bimodal annual abundance with the highest cell counts in late winter-early spring and mid-summer, and lower counts in June and July.

In addition to *S. grethae*, Karentz and Smayda (1984) found that several other phytoplankton species are also numerically abundant in Narragansett Bay, including *Detonula confervacea*, *Asterionella glacialis*, *Olisthodiscus lutes*, and *Thalassiosira nordenskiöldii*. From 1959–1980, *D. confervacea* ranked second most abundant behind *S. grethae* and was a characteristic member of the winter phytoplankton assemblage in Narragansett Bay, occurring between January and March (although this species is now much less abundant and even absent in some years due to warming water temperature (Paul Hargraves, personal communication)). *A. glacialis* was found to be the third most numerically dominant species in Narragansett Bay, was present throughout the year, and was most abundant in late summer and winter. The fourth most abundant species was *O. lutes*, which occurred from May through December and was most abundant when *S. grethae* abundance was low. *Thalassiosira* sp. first appeared in Narragansett Bay in 1967 and has



continually increased since then to the point where it ranked sixth in total cell abundance and fifth in frequency over the 22-year study period (Karentz and Smayda, 1984).

Biomass and Production

Phytoplankton biomass (expressed as chlorophyll *a*) generally exhibits variable seasonal patterns in Narragansett Bay. Often, the typical signature seasonal event in Narragansett Bay is the winter-spring phytoplankton bloom (Fig. 9.1) (Pilson, 1985; Li and Smayda, 1998; Oviatt et al., 2002). Winter-spring bloom inception is variable among years, but typically occurs between November and March. The time and magnitude of the bloom maximum is also highly variable; the peak can occur as early as January, when it is most frequently observed, or as late as April (Smayda, 1998). However, major blooms are not restricted to the annual winter-spring bloom and instead have been observed during most times of the year. In fact, from 1973–1990 major phytoplankton blooms occurred in January, February, March, April, June, August, September, November, and December (Li and Smayda, 1998). Li and Smayda (1998) further documented that the frequency and magnitude of blooms were higher from late autumn through spring (e.g., October to April) than during the summer, with chlorophyll levels exceeding 150 mg m⁻² in January and reaching only 80 mg m⁻² in July.

Phytoplankton dynamics in Narragansett Bay, including the winter-spring bloom, are affected by numerous, often interacting factors including light, temperature, nutrient concentrations, grazing, and competition among other phytoplankton species (Hargraves, 1988). The classic view of the winter-spring bloom holds that phytoplankton is light limited during winter and is therefore unable to bloom until water column stratification occurs. However, although temperature and irradiance, either acting independently or synergistically, have been identified as bloom triggers, so has the removal of nutrient limitation and the release of grazing pressure (Smayda, 1998). Indeed, Keller et al. (1999) has suggested that the annual winter-spring bloom in temperate areas is controlled by low temperatures that lead to a relaxation in grazing pressure. Li and Smayda (1998) further suggest that temperature may have less of a direct effect and more of an indirect effect in that it can increase zooplankton grazing. In addition, summer phytoplankton blooms may be indirectly regulated by ctenophores (*Mnemiopsis lledyii*), which directly graze upon herbivorous zooplankton (Deason and Smayda, 1982). It seems clear

that since the timing of the bloom can be highly variable in the Bay in different years, the bloom—or any bloom throughout the year—is ultimately controlled by multiple interacting factors that vary year to year (Smayda, 1998).

Although it varies by location, phytoplankton primary production generally averages approximately 300 grams of carbon per square meter per year (g C m⁻² yr⁻¹) on a Bay-wide scale (Hargraves, 1988; Oviatt et al., 2002). However, phytoplankton primary production is also highly variable both within and among years, and different results are reported from different studies—in part a reflection of different methods of measuring production. For example, Durbin et al. (1975) reported that primary production was highest during the winter-spring bloom as well as during the summer nanoplankton (tiniest plankton) blooms. Later, Durbin and Durbin (1981) found that compared to summertime values, production was relatively low even during the winter-spring bloom due to the effects of low temperatures (Durbin and Durbin, 1981). More recently, Oviatt et al. (2002) found that production was generally highest during the summer but differences in timing were apparent depending on location within the Bay. A review of all available data at the time, however, concluded that production is generally highest during mid- to late summer, while lowest production values occur from November through January and are approximately an order of magnitude lower than summer values (Hinga et al., 1989).

Spatial Patterns

Phytoplankton abundance and biomass predictably vary among different areas of Narragansett Bay. A conspicuous pattern is that phytoplankton abundance and biomass is higher in the upper regions of the Bay, including the Providence River and Mount Hope Bay, than in the remainder of the Bay. In other words, phytoplankton exhibits changes along a north-south gradient in Narragansett Bay, and this pattern may be a result of increased nutrient input into the upper Bay from sewage plants and other inputs, and to greater mixing with nutrient-poor shelf water lower in the Bay (Durbin and Durbin, 1981). For example, Oviatt et al. (2002) found that mean nutrient concentrations decreased by 75 percent from the Providence River to Rhode Island Sound and mean chlorophyll values dropped from 13 micrograms per liter (µg L⁻¹) in the Providence River to 3 µg L⁻¹ in Rhode Island Sound. Seasonal patterns in phytoplankton also differ around the Bay; a large, distinct chlorophyll maximum is



a.
b.

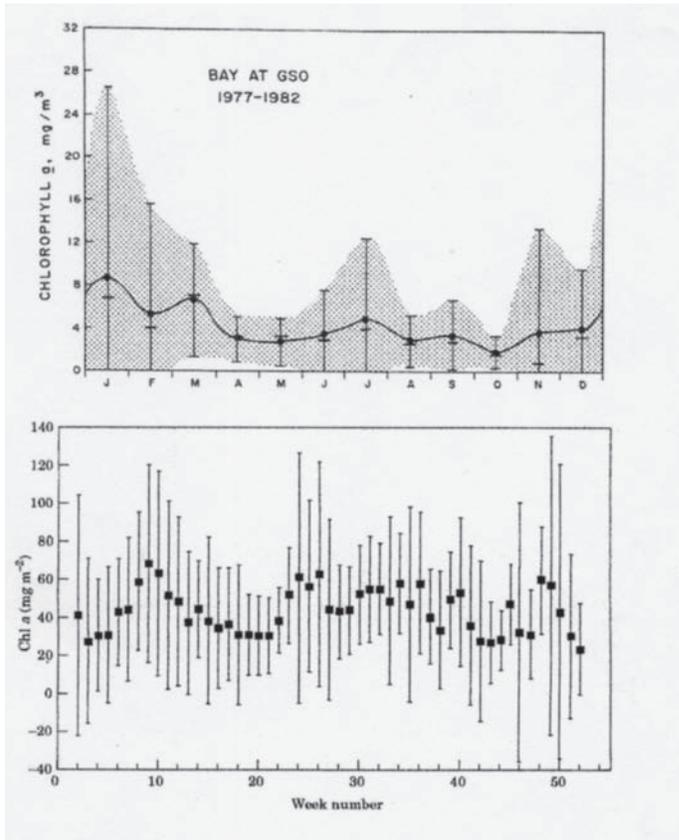


Figure 9.1. Seasonal changes in chlorophyll *a* in Narragansett Bay, Rhode Island. (a) Reproduction of Figure 7 from Pilson (1985) illustrating chlorophyll concentrations from the dock at the GSO from 1977–1982. Error bars are two standard deviations and the shaded areas represent the field where 95 percent of the observations are likely to be found. (b) Reproduction of Figure 3 from Li and Smayda (1998) showing weekly mean chlorophyll in Narragansett Bay from 1973–1990. It is clear from both figures that high chlorophyll levels occur during the winter-spring bloom and that concentrations vary throughout the year due to periodic blooms of varying intensity.

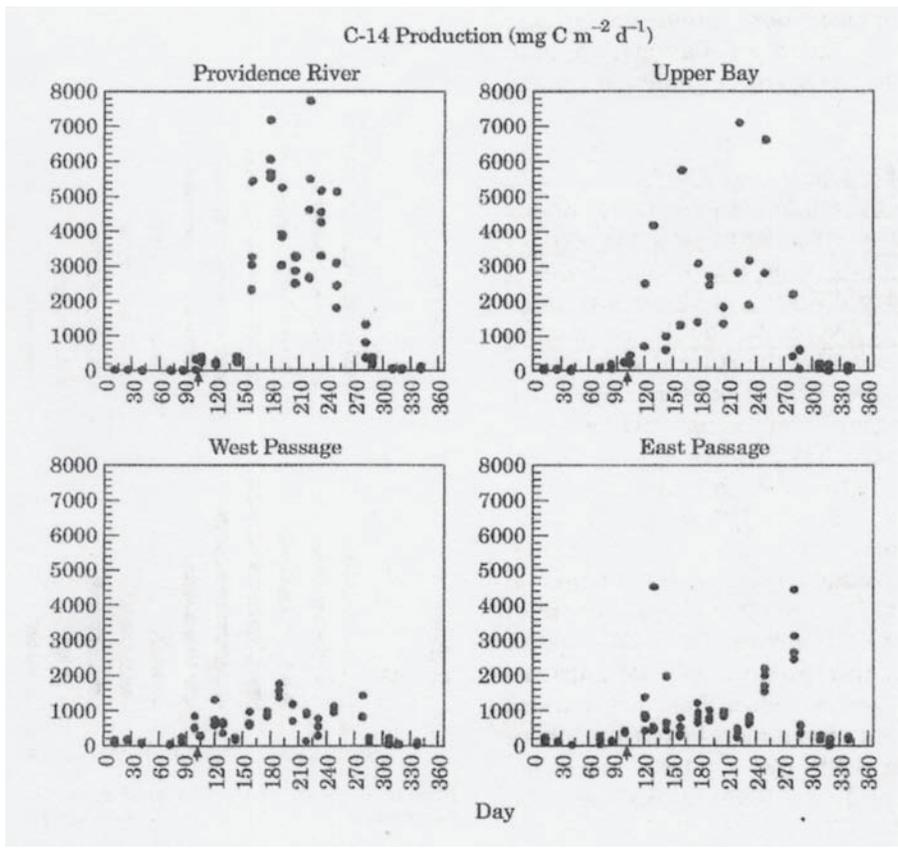


Figure 9.2. Reproduction of Figure 4 from Oviatt et al. (2002) showing phytoplankton primary production in different regions of Narragansett Bay using the C^{14} method. Data were collected every two weeks from April 1997 through April 1998. Note the very high production levels in the Providence River and upper Bay during summer and, in contrast, the two smaller production spikes in spring and early fall in the East Passage.



found during the summer in the Providence River and upper Bay, but smaller chlorophyll maximums can also occur in spring and fall in both the East and West passages (Fig. 9.2) (Oviatt et al., 2002).

Primary production levels mirror the gradients in chlorophyll and nutrient concentrations. Production values are highest in the Providence River and upper Bay and decrease while moving south throughout the Bay towards its mouth. For example, Oviatt, et al. (2002) recorded a high production of $492 \text{ g C m}^{-2} \text{ yr}^{-1}$ in the Providence River and a low of $152 \text{ g C m}^{-2} \text{ yr}^{-1}$ at the seaward extent of sampling (the dock at GSO in the lower West Passage). This trend is consistent even among studies using different techniques for measuring productivity (see discussions in Keller et al. (1996) and Hargraves (1988)).

Zooplankton

Community Composition

The zooplankton community in Narragansett Bay (Appendix 9.2) can be grouped according to size and type. The three general size groups of zooplankton include microzooplankton (typically less than 60–80 μm in length; e.g., tintinnids), mesozooplankton (typically between 80 μm and approximately 3 mm in length; e.g., copepods, cladocerans, and rotifers), and macrozooplankton (greater than 3 mm; e.g., gelatinous zooplankton such as the ctenophore, *M. lledyii*). In addition, the two types of zooplankton include the holoplankton, which spend their entire lives as plankton, such as copepods, and meroplankton, which include planktonic larval stages of animals such as bivalves and worms. Discerning trends and spatial and temporal patterns in zooplankton is difficult in Narragansett Bay because most studies used different sampling methods and mesh sizes, and many only sampled a small number of stations or for a short period of time, depending on the question under investigation. However, some general patterns have emerged in terms of the composition of the zooplankton community and overall, large-scale spatial and temporal patterns.

By far, the most conspicuous group of zooplankton in Narragansett Bay is copepods. The Bay's zooplankton community is consistently dominated by the two species of copepods, *Acartia tonsa* and *Acartia hudsonica* (Durbin and Durbin, 1988). Their overall dominance of the zooplankton community was demonstrated by Durbin and Durbin (1981), who found that these two species

(combining the nauplii, copepedita, and adult stages) composed 74 percent and 54 percent of total zooplankton abundance in the lower and upper Bay, respectively. Other species, though less abundant, are important components of the Narragansett Bay zooplankton community, including certain meroplankton (e.g., bivalve larvae, polychaete larvae), rotifers, the cladoceran, *Podon polyphemoides*, and in the summer, *M. lledyii* (Durbin and Durbin, 1981).

Temporal and Spatial Patterns

Zooplankton in Narragansett Bay varies seasonally in terms of species composition, total abundance, and total biomass, and these changes are generally in response to temperature. The two dominant copepod species demonstrate an oscillating pattern of abundance with *A. hudsonica* being most abundant in winter and spring, and *A. tonsa* dominating in summer and fall (Durbin and Durbin, 1981). However, more recent work has demonstrated a change in *M. lledyii* abundance in response to warming temperatures, resulting in a concurrent near extirpation of *A. tonsa* in Narragansett Bay (Costello et al., 2006). Overall peaks in zooplankton biomass can occur in spring (March through May), summer (primarily July), and, to a lesser extent, in early fall (September–October) (Fig. 9.3) (Durbin and Durbin, 1981).

Unlike phytoplankton, zooplankton biomass does not appear to differ substantially between upper and lower Bay areas, except near the Bay mouth where biomass drops quickly as coastal species replace estuarine species (Durbin and Durbin, 1988). Abundance of individual species and of all zooplankton combined also does not differ significantly between upper and lower Bay stations (Durbin and Durbin, 1981). However, the abundance of some of the more abundant zooplankters is reduced while moving from the Bay into the adjacent Block Island Sound, although these patterns are generally based on samples taken from a small number of stations. For example, species such as *A. hudsonica*, *A. tonsa*, *Podon* sp., and bivalve and polychaete larvae are much more abundant in upper Bay areas as compared to Block Island Sound where coastal species are more prevalent (Frolander, 1955; Durbin and Durbin, 1988).

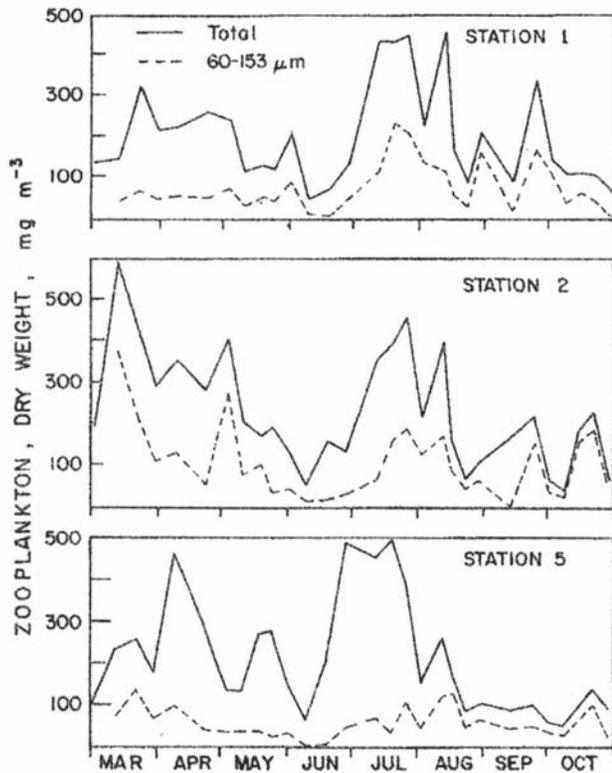


Figure 9.3. Reproduction of Figure 6 from Durbin and Durbin (1981) showing seasonal patterns of zooplankton biomass for all zooplankton combined and for the 60–153 μm size fraction. Data were collected at approximately weekly intervals from March to October 1976. Note the consistently high zooplankton biomass at all stations during summer.

Benthic Communities

Used here, benthic organisms are considered to be those living within or directly on the surface of the sediments or hard-bottom substrates within Narragansett Bay (Fig. 9.4). This includes infauna and epibenthic organisms such as polychaete worms, nematodes, bivalves, and amphipods and other small crustaceans (Appendix 9.3). It does not necessarily include other epibenthic and burrowing species such as crabs and bottom fish, which are considered in more detail the nekton chapter (even though these species are intimately associated with the benthos of Narragansett Bay).

Although Narragansett Bay is a phytoplankton-based estuary, it has long been recognized that the benthos and its associated communities play an integral role in Bay-wide processes and are intimately coupled with the water column (e.g., benthic-pelagic coupling is strong in Narragansett Bay). As such, benthic communities have been intensely studied in the Bay for at least 50 years (see review in Frithsen, 1989). Unfortunately, differences among studies in terms of sampling gear, sieve size, study year, and sample location make it difficult to synthesize all available benthic data. Frithsen (1989) assessed the effects of these differences among studies and produced an excellent review of the knowledge

of the benthic communities in Narragansett Bay through the late 1980s.

The species composition of benthic communities in the Bay is difficult to generalize because of the issues mentioned above and because the different faunal groups that are considered part of the benthos (e.g., meiofauna vs. macrofauna). However, some conspicuous benthic species that are often frequent and abundant include *Nephtys incisa*, *Nucula annulata*, *Mediomastus ambiseta*, the polychaete *Streblospio benedicti*, and the tube-dwelling amphipod *Ampelisca spinipes*. Other larger species include the commercially important quahog clam, the mat-forming slipper-shell clam, and the bed-forming blue mussel. All told, Frithsen (1989) lists 546 species or groups of species as identified from the benthos of Narragansett Bay.

Spatial Patterns

Benthic communities in Narragansett Bay vary over multiple scales ranging from sub-meter to multi-kilometer as a result of the influence of a variety of independent and interacting factors, including sediment type and grain size, sediment organic content, anthropogenic inputs, salinity, and oxygen concentration. The benthos is also largely affected



Figure 9.4. *Left:* Students from the Marine Ecosystems Research Laboratory at GSO collect benthic samples in Narragansett Bay. *Below:* Tube-dwelling bamboo worm *Clymenella* sp. Photo courtesy Chris Calabretta, GSO.



by the amount of organic matter that is produced by phytoplankton in the overlying water column. For example, Rudnick and Oviatt (1986) reported that approximately 40 percent of the phytoplankton biomass that is produced during winter-spring blooms drops to the Bay bottom where it is utilized by benthic communities.

A number of studies have found that, as is the case with zooplankton, Narragansett Bay benthic communities do not generally exhibit a strong north-south gradient throughout the length of the Bay. Instead it is thought that observed spatial patterns were likely due to location-specific differences in sediment characteristics (see Fig 7.6, page 84) (Phelps, 1958; Chowder and Marching, 1967; Myers and Phelps, 1978). At a smaller scale, however, some patterns and gradients emerge. For example, multiple studies have documented an increase in benthic species richness and macrofaunal abundance while moving south within the Providence River and upper Bay away from metropolitan Providence (Pratt, 1972; Pratt and Bisagni, 1976), and have linked this trend to differences in organic loadings, oxygen levels, and phytoplankton (Frithsen, 1989).

Benthic communities have been investigated in other smaller regions of Narragansett Bay, and some of the most intense sampling (although it is largely old data) comes from Greenwich Bay (see Fig 7.2, page 79). For example, Stickney and Stringer (1957) sampled over 200 stations from within Greenwich Bay in 1951 and 1952 in an attempt to correlate benthic communities with the quahog. Although this study could not ultimately relate the quahog to benthic communities, some patterns were found. For example, the most extensive benthic community in Greenwich Bay was the one dominated by the amphipod *A. spinipes*, and this community was generally found associated with mud sediments. In contrast, sandy sediments were dominated by the slipper-shell clam and other associated species such as the jingle shell, *Anomia simplex*, and the clam worm, *Nereis succinea*.

Temporal Patterns

Benthic meiofauna and macrofauna exhibit similar patterns across the seasons and these patterns



are in part related to plankton dynamics in the overlying water column. The signature seasonal pattern is one of increased abundance and biomass in spring (i.e., May and June), followed by a decrease in both summer and fall (Fig. 9.5) (Grassle et al., 1985; Rudnick et al., 1985). It is likely that the increase in biomass and abundance in spring is primarily a response to the deposition and accumulation of organic matter from the winter-spring phytoplankton bloom (zooplankton predation during this time is largely minimal due to cold water temperatures). However, Rudnick et al. (1985) suggest that rapidly increasing sediment temperatures during this time (from 2°C to approximately 13°C by May) may also strongly affect benthic communities. It is also possible that the seasonal dynamics of Narragansett Bay benthic communities are affected by other factors (e.g., predation) (Frithsen, 1989), and ultimately these temporal patterns are probably affected by multiple factors working in concert.

Long-term Trends in Plankton and Benthos

Plankton, but not necessarily benthic, communities in Narragansett Bay are clearly changing over time. Notable patterns include changes in the timing and magnitude of the winter-spring phytoplankton bloom and an interrelated decrease in phytoplankton biomass. These changes are complex and are being driven by numerous interacting factors, including warming water temperature and increasing anthropogenic nutrient inputs over time.

Phytoplankton community structure has remained relatively similar in the mid- and lower Bay since at least the late 1950s (Hinga et al., 1989), although some recent changes have been observed due to warming water temperatures. However, phytoplankton biomass has been decreasing over time in Narragansett Bay. From 1973 to 1990, chlorophyll *a* levels have decreased by approximately half, from 60 mg m⁻² in 1973 to 30 mg m⁻² in 1990, possibly due to factors that include zooplankton grazing, warmer water temperatures, and higher wind speeds (Li and Smayda, 1998; Smayda, 1998). Further, the duration and intensity of the winter-spring bloom has been decreasing since the 1970s, and in some years the bloom has failed to occur entirely (Oviatt, 1994; Oviatt et al., 2002). This trend is probably related to warming water temperatures, since chlorophyll records show that intense winter-spring blooms occur primarily when temperatures remain less than 3.5°C (Oviatt et al., 2002), and winter water temperatures have risen about 1.5°C in Narragansett Bay since the 1890s (Nixon et al., 2003). Although water temperature may ultimately affect and control winter-spring blooms and phytoplankton dynamics, it does so indirectly through the mechanism of zooplankton grazing (Li and Smayda, 1998). Experimental studies in mesocosms with elevated winter temperatures have shown that zooplankton or benthic grazing or both may control the winter-spring diatom bloom (Oviatt et al., 2002), and during exceptionally warm winters, zooplankton may even prevent the initiation of the winter-spring bloom (Keller et al., 1999).

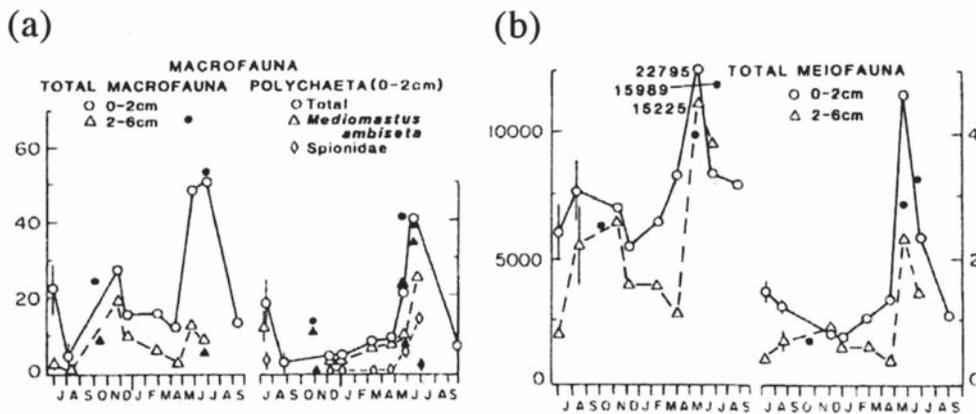


Figure 9.5. Partial reproduction of Figure 2 from Rudnick et al. (1985). (a) Abundance of total macrofauna (left panel) and polychaetes (right panel) over time. (b) Abundance (left panel) and biomass (right panel) of total meiofauna over time. Abundance is presented as number of individuals m⁻² and biomass is presented as grams of ash-free dry weight m⁻². All data were collected between 1977 and 1980 from the top 2 cm of sediment from a station located to the north of Jamestown, R.I. Note the rapid summertime increase in benthic fauna in all cases followed by an equally rapid decrease later in the same season.



It appears that phytoplankton bloom dynamics underwent a dramatic change between the 1960s and 1970s. Specifically, the warm spring temperatures of 1969 may have initiated profound changes in the biology of Narragansett Bay by stimulating a shift in the timing of the annual phytoplankton maximum (Karentz and Smayda, 1998). From 1959 to 1969, the annual phytoplankton maximum generally occurred in winter (January through March); in the following decade, the maximum switched and occurred primarily during the summer (June–September). Severe differences in sampling methodologies make discerning long-term trends in benthic assemblages difficult. Based on earlier research, it seemed clear that benthic community composition and the abundance of dominant benthic species underwent dramatic changes over the last 50 years. Conspicuous among the supposed changes was the dramatic shift around the 1970s from a *Nephtyes-Nucula* dominated community to one that was dominated by *Mediomastus* and *Nucula* (Frithsen, 1989). This switch would appear to have resulted in a dramatic increase in the overall benthic faunal abundance, due mostly to exceptionally high densities of *Mediomastus*. If true, the timing and ecological response of this switch would suggest a benthic response to higher inputs of anthropogenic organic matter, since *Mediomastus* has been shown experimentally to rapidly increase in abundance and biomass in response to increased nutrient enrichment (Frithsen, 1989). However, recent work indicates that earlier workers likely failed to discern the thread-like *Mediomastus* from detritus, suggesting that there probably has not been a change in dominant benthic species assemblages over time (Ellis, 2002; Oviatt, personal communication).

It is apparent that many of the changes in plankton and benthic communities in Narragansett Bay are directly linked to changes in the Bay that are, in part, a result of human activities, including increases in water temperatures and nutrient concentrations. As a plankton-based estuary, any changes to the plankton-benthic food web can have subsequent changes to Narragansett Bay as a whole. For

example, concurrent with the long-term decrease in chlorophyll has been an increase in water clarity as measured by secchi depths (Borkman and Smayda, 1998), which should ultimately affect the production and distribution of light-limited SAV species, such as eelgrass.

These resources must continue to be studied and monitored, especially over the long term as further human-induced changes are inevitable. For example, the planned decrease in nutrient inputs to the Bay from some of the major sewage treatment plants in the watershed will potentially have a dramatic effect on phytoplankton dynamics, and thus, whole Bay processes. There is a need for comprehensive monitoring programs that focus on high spatial coverage throughout Narragansett Bay and frequent sampling intervals. Long-term chlorophyll monitoring at multiple stations by the NBNERR, RIDEM, GSO, and others should ultimately provide an excellent record of phytoplankton biomass in Narragansett Bay over time, including any responses to further human-induced changes to the estuary.



Appendix 9.1 Phytoplankton of Narragansett Bay

List of phytoplankton species known to occur in Narragansett Bay. Species names read across, then down.
Compiled in Keller et al. (1996) using data from Hargraves (1988) and Hinga (1989).

Class Bacillariophyceae

Order Centrales

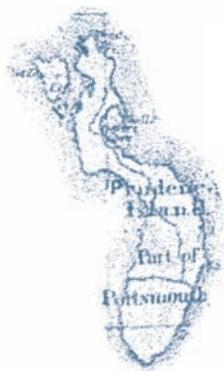
<i>Actinoptychus senarius</i>	<i>Attheya decora</i>
<i>Bacteriastrum delicatulum</i>	<i>B. hyalinum</i>
<i>Biddulphia alternans</i>	<i>Cerataulina pelagica</i>
<i>Chaetoceros affinis</i>	<i>C. amanita</i>
<i>C. atlanticus</i>	<i>C. borealis</i>
<i>C. brevis</i>	<i>C. ceratosporus</i>
<i>C. compressus</i>	<i>C. constrictus</i>
<i>C. convolutus</i>	<i>C. coronatus</i>
<i>C. costatus</i>	<i>C. crinitus</i>
<i>C. curvisetus</i>	<i>C. danicus</i>
<i>C. debilis</i>	<i>C. decipiens</i>
<i>C. densus</i>	<i>C. diadema</i>
<i>C. didymus</i>	<i>C. eibenii</i>
<i>C. fallax</i>	<i>C. gracillis</i>
<i>C. holsaticus</i>	<i>C. ingolfianus</i>
<i>C. lacinosus</i>	<i>C. lauderi</i>
<i>C. lorenzianus</i>	<i>C. pelagicus</i>
<i>C. perpusillus</i>	<i>C. pseudocurvisetus</i>
<i>C. radicans</i>	<i>C. rostratus</i>
<i>C. seiracanthus</i>	<i>C. septentrionalis</i>
<i>C. similis</i>	<i>C. simplex</i>
<i>C. socialis</i>	<i>C. subtilis</i>
<i>C. tenuissimus</i>	<i>C. teres</i>
<i>C. tortissimus</i>	<i>Chaetoceros</i> spp.
<i>Corethron criophilum</i>	<i>Coscinodiscus asteromphalus</i>
<i>C. centralis</i>	<i>C. concinnus</i>
<i>C. granii</i>	<i>C. oculus-iridis</i>
<i>C. wailesii</i>	<i>Cyclotella caspia</i>
<i>C. meneghiniana</i>	<i>C. striata</i>
<i>Detonula confervacea</i>	<i>D. delicatula</i>
<i>D. pumila</i>	<i>Ditylum brightwelli</i>
<i>Eucampia zoodiacus</i>	<i>Guinardia flaccida</i>
<i>Hemiaulus sinensis</i>	<i>Lauderia annulata</i>
<i>Leptocylindrus danicus</i>	<i>L. mediterraneus</i>
<i>L. minimus</i>	<i>Lithodesmium undulatum</i>
<i>Minidiscus trioculatus</i>	<i>Minutocellus polymorphus</i>
<i>Odontella sinensis</i>	<i>Paralia sulcata</i>
<i>Porosira glacialis</i>	<i>Rhizosolenia alata</i>
<i>R. calcar-avis</i>	<i>R. delicatula</i>
<i>R. fragilissima</i>	<i>R. imbricata</i>
<i>R. pungens</i>	<i>R. setigera</i>
<i>R. stolterfothii</i>	<i>R. styliformis</i>
<i>Roperia tessellata</i>	<i>Skelotenema costatum</i>
<i>Stephanopyxis palmeriana</i>	<i>S. turris</i>
<i>Thalassiosira anguste-lineata</i>	<i>T. binata</i>
<i>T. bioculata</i>	<i>T. constricta</i>
<i>T. decipiens</i>	<i>T. delicatula</i>
<i>T. eccentrica</i>	<i>T. gravida</i>
<i>T. mala</i>	<i>T. nordenskioldii</i>
<i>T. oestrupii</i>	<i>T. profunda</i>
<i>T. pseudonana</i>	<i>T. rotula</i>
<i>T. solitaria</i>	<i>T. weissflogii</i>
<i>Thalassiosira</i> spp.	

Order Pennales

<i>Asterionella bleakleyi</i>	<i>A. glacialis</i>
<i>A. notata</i>	<i>Cylindrotheca closterium</i>
<i>Nitzschia pseudodelicatissima</i>	<i>N. pungens</i>
<i>N. seriata</i>	<i>Thalassionema nitzschiodes</i>
<i>Thalassiothrix frauenfeldii</i>	

Class Dinophyceae

<i>Amphidinium carteri</i>	<i>A. sphenoides</i>
<i>Amphidinium</i> sp.	<i>Ceratium furca</i>
<i>C. fuscus</i>	<i>C. ineatum</i>
<i>C. longipes</i>	<i>C. minutum</i>
<i>C. tripos</i>	<i>Cochlodinium</i> spp.
<i>Dinophysis acuminata</i>	<i>D. caudata</i>
<i>D. norvegica</i>	<i>D. rotundata</i>
<i>Dissodinium pseudolunula</i>	<i>Gonyaulax digitale</i>
<i>G. polyedra</i>	<i>Gonyaulax</i> sp.
<i>Gymnodinium abbreviatum</i>	<i>G. splendens</i>
<i>Gymnodinium</i> spp.	<i>Gyrodinium aureolum</i>
<i>G. spirale</i>	<i>G. uncatenum</i>
<i>Gyrodinium</i> spp.	<i>Helogolandinium subglobosum</i>
<i>Heterocapsa triquetra</i>	<i>Katodinium rotundatum</i>



Appendix 9.1. Continued

<i>Oxyrrhus marina</i>	<i>Paulsenella chaetoceratis</i>
<i>Polykrikos schwarzii</i>	<i>Prorocentrum balticum</i>
<i>P. gracile</i>	<i>P. micans</i>
<i>P. minimum</i>	<i>P. scutellum</i>
<i>P. triestinum</i>	<i>Protogonyaulax tamarensis</i>
<i>Protoperdinium bipes</i>	<i>P. conicum</i>
<i>P. depressum</i>	<i>P. excentricum</i>
<i>P. granii</i>	<i>P. leonisi</i>
<i>P. minutum</i>	<i>P. steinii</i>
<i>Protoperdinium</i> spp.	<i>Scrippsiella trochoidea</i>

Additional phytoplankton species

<i>Apedinella spinifera</i>	<i>Aureococcus anophagefferis</i>
<i>Carteria</i> sp.	<i>Chlamydomonas</i> sp.
<i>Chlorella</i> sp.	<i>C. salina</i>
<i>Chroomonas</i> spp.	<i>Chrysochromulina ericina</i>
<i>C. parkae</i>	<i>Chrysochromulina</i> spp.
<i>Coccolithus pelagicus</i>	<i>Cricosphaera roscoffensis</i>
<i>Cryptomonas</i> spp.	<i>Dichtyocha fibula</i>
<i>Dinobryon balticum</i>	<i>Distephanus speculum</i>
<i>Dunaliella</i> sp.	<i>Ebria tripartita</i>
<i>Euglena proxima</i>	<i>Euglena</i> spp.
<i>Eutreptia scotica</i>	<i>Eutreptiella hirudoidea</i>
<i>Eutreptiella</i> sp.	<i>Fibrocapsa japonica</i>
<i>Hemiselmis</i> sp.	<i>Hermesinum adriaticum</i>
<i>Heteronema acus</i>	<i>Isochrysis</i> sp.
<i>Mesocena polymorpha</i>	<i>Micromonas pusilla</i>
<i>Nannochloris</i> sp.	<i>Nephroselmis rotunda</i>
<i>Nephroselmis</i> sp.	<i>Ochromonas</i> sp.
<i>Olisthodiscus luteus</i>	<i>Oltmannsielloopsis virida</i>
<i>Paraphysomonas</i> sp.	<i>Pavlova gyrans</i>
<i>Pavlova</i> sp.	<i>Pedinomonas minor</i>
<i>Phaeocystis pouchetii</i>	<i>Pseudopedinella pyriformis</i>
<i>Pterosperma</i> sp.	<i>Pyramimonas amyliifera</i>
<i>P. torta</i>	<i>Pyramimonas</i> sp.
<i>Spirulina subsalsa</i>	<i>Synechococcus</i> sp.
<i>Tetraselmis</i> spp.	<i>Urceolus</i> sp.

Appendix 9.2. Zooplankton of Narragansett Bay

List of dominant zooplankton known to occur in Narragansett Bay. Names of zooplankton read across, then down. Data from Keller et al. (1996).

Copepods

<i>Acartia hudsonica</i>	<i>A. tonsa</i>
<i>A. longiremis</i>	<i>Calanus finmarchicus</i>
<i>Centropages hamatus</i>	<i>C. typicus</i>
<i>Corycaeus</i> sp.	<i>Cyclops</i> sp.
<i>Eurytemora</i> sp.	<i>Harpacticoid</i> sp.
<i>Hemicyclops</i> sp.	<i>Labidocera aestiva</i>
<i>Metridia lucens</i>	<i>Microsetella norvegica</i>
<i>Oithona colcarva</i>	<i>O. similis</i>
<i>Oncea</i> sp.	<i>Paracalanus parvus</i>
<i>Parvocalanus crassirostris</i>	<i>Pseudocalanus minutus</i>
<i>Pseudodiaptomus coronatus</i>	<i>Rhincalanus nasutus</i>
<i>Temora longicornis</i>	<i>Tortanus discaudatus</i>

Cladocera

<i>Evadne nordmanni</i>	<i>E. spinifera</i>
<i>Penilla avirostris</i>	<i>Podon</i> sp.

Meroplankton

Balanus larvae	Bivalve larvae
Bryozoan larvae	Decapod larvae
Gastropod larvae	Polychaete larvae

Other Holoplankton

Chaetognaths	Ctenophores
Medusae	Oikopleura
Rotifers	



Appendix 9.3. Benthic Species of Narragansett Bay

Benthic species known to occur in Narragansett Bay listed by group and family. Species names read across, then down. List compiled in Keller et al. (1996) using data from Frithsen (1990).

Polychaeta		
Flabelleridae	<i>Pherusa affinis</i>	<i>G. capitata</i>
Glyceridae	<i>Glycera americana</i> <i>G. dibranchiata</i>	<i>Glycera</i> spp. <i>Goniada maculata</i>
Goniadidae	<i>Glycinde solitaria</i> <i>Goniadella gracilis</i>	<i>Ophioglycera gigantea</i> <i>Microphthalmus aberrans</i> <i>Microphthalmus</i> spp.
Hesionidae	<i>Gyptis vittata</i> <i>M. szcelkowi</i> <i>Podarke obscura</i>	<i>L. tenuis</i> <i>Ninoe nigripes</i>
Lumbrineridae	<i>Lumbrineris fragilis</i> <i>Lumbrineris</i> spp. <i>Magelona</i> spp.	
Magelonidae	<i>Asychis carolinae</i> <i>Asychis</i> spp. <i>C. torquata</i> <i>Clymenella</i> spp. <i>Euclymene</i> spp. <i>Macroclyme zonalis</i> <i>Microclymene zonalis</i>	<i>A. elongata</i> <i>Clymenella mucosa</i> <i>C. zonalis</i> <i>Euclymene reticulata</i> <i>Gravierella</i> spp. <i>Maldane sarsi</i> <i>Rhodine attenuata</i> <i>A. verrilli</i> <i>N. ciliata</i> <i>N. ingens</i> <i>Nephtys</i> spp. <i>Nereis acuminata</i> <i>Paranaitis speciosa</i> <i>P. groenlandica</i> <i>P. mucosa</i>
Maldanidae	<i>Aglaophamus</i> sp. <i>Nephtys caeca</i> <i>N. incisa</i> <i>N. picta</i>	
Nephtyidae	<i>Nephtys caeca</i> <i>N. incisa</i> <i>N. picta</i>	
Nereidae	<i>Neanthes virens</i>	
Phyllococeidae	<i>Eumida sanguinea</i> <i>Phyllococe arenae</i> <i>P. maculata</i> <i>Phyllococe</i> spp. Unknown	
Poecilochaetidae	Unknown	
Polygordiidae	<i>Polygordius</i> spp. <i>Gattyana cirrhosa</i> <i>H. imbricata</i> <i>Lepidametria</i> spp. <i>L. sublevis</i> <i>Sabellaria vulgaris</i>	<i>Harmothoe extenuata</i> <i>Harmothoe</i> spp. <i>Lepidonotus squamatus</i>
Polynoidea	<i>Chone americana</i> <i>Euchone</i> spp. <i>Lanonome kroyen</i> <i>Potamilla myriops</i> <i>Pseudopotamilla reniformis</i> <i>Sabella</i> spp. <i>Scalibregma inflatum</i> <i>Hydroides dianthus</i> <i>Spirorbis</i> spp.	
Sabellariidae	<i>Chone americana</i> <i>Euchone</i> spp. <i>Lanonome kroyen</i> <i>Potamilla myriops</i> <i>Pseudopotamilla reniformis</i> <i>Sabella</i> spp.	<i>Euchone incolor</i> <i>Jasmineira</i> spp. <i>Manayunkia</i> spp. <i>P. neglecta</i> <i>Sabella microphthalma</i>
Sabelludae	<i>Chone americana</i> <i>Euchone</i> spp. <i>Lanonome kroyen</i> <i>Potamilla myriops</i> <i>Pseudopotamilla reniformis</i> <i>Sabella</i> spp.	
Scalibregmidae	<i>Scalibregma inflatum</i>	
Serpulidae	<i>Hydroides dianthus</i> <i>Spirorbis</i> spp.	<i>H. uncinata</i>
Sigalionidae	<i>Pholoe minuata</i> <i>S. limicola</i>	<i>Sthenelais boa</i> <i>Sthenelais</i> spp. <i>Sphaerodorium gracilis</i> <i>Boccardia hamata</i> <i>Minuspio</i> spp. <i>P. ciliata</i>
Sphaerodoridae	<i>Ephesiella minuata</i>	
Spionidae	<i>Anaspio</i> spp. <i>Dispio uncinata</i> <i>Polydora caulleri</i>	
Archiannelida		
Nerillidae	Unknown	
Oligochaeta		
Tubificidae	<i>Limnodriloides medioporus</i> <i>Tubificoides</i> spp.	<i>Peloscolex gabriellae</i>
Bivalvia		
Arcidae	<i>Anadara transversa</i>	
Astartidae	<i>Astarte undata</i>	<i>Astarte</i> spp.
Cardiidae	<i>Cardium pinnulatum</i> <i>Laevicardium mortoni</i>	<i>Cerastoderma pinnulatum</i>
Carditidae	<i>Cardita borealis</i>	
Corbulidae	<i>Corbula contracta</i>	
Hiatellidae	<i>Hiatella arctica</i>	
Leptonidae	<i>Rochefortia cunata</i>	
Lyonsiidae	<i>Lyonsia arenosa</i>	<i>Lyonsia hyalina</i>
Mactridae	<i>Mulinia lateralis</i>	<i>Mercenaria mercenaria</i>
Montacutidae	<i>Mysella</i> spp.	
Myidae	<i>Mya arenaria</i>	
Mytilidae	<i>Crenella decussata</i> <i>Crenella</i> spp. <i>Modiolus demissus</i> <i>Mytilus edulis</i> <i>Yoldia limatula</i>	<i>C. glandula</i> <i>Modiolaria lateralis</i> <i>Modiolus</i> spp. <i>Mytilus</i> spp. <i>Y. sapotilla</i> <i>N. delphinodonta</i>
Nuculanidae	<i>Nucula annulata</i> <i>N. proxima</i>	
Nuculidae	<i>Nucula annulata</i> <i>N. proxima</i>	
Ostreidae	<i>Crassostrea virginica</i>	
Pandoridae	<i>Pandora gouldiana</i>	
Pectinidae	<i>Aequipecten irradians</i>	
Periplomatidae	<i>Periploma fragilis</i>	<i>P. papyratium</i>

Appendix 9.3. Continued

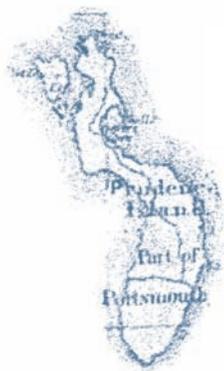


	Petricolidae	<i>Petricola pholadiformis</i>	
	Pinnidae	Unknown	
	Solecurtidae	<i>Tagelus</i> spp.	
	Solemyacidae	<i>Solemya velum</i>	
	Solenidae	<i>Ensis directus</i>	<i>Solen viridis</i>
Gastropoda			
	Pyramidillidae	<i>Odostomia trifida</i>	<i>Sayella fusca</i>
		<i>Turboinna elegantula</i>	<i>T. interrupta</i>
		<i>Turbonilla</i> spp.	
	Retusidae	<i>Retusa canaliculata</i>	<i>R. obtusa</i>
	Rissoidae	<i>Alvania excrata</i>	
	Scaphandridae	<i>Acteocina canaliculata</i>	<i>Cylichna oryza</i>
		<i>Cylichna</i> spp.	<i>Tomatina canaliculata</i>
		<i>Tagelus divisus</i>	
	Solecurtidae	<i>Trichotropis conica</i>	
	Trichotropidae	<i>Turritella</i> spp.	
	Turritellidae		
Arachnida			
	Pellenidae	<i>Callipallene brevirostris</i>	
	Tanystylidae	<i>Tanystylum orbiculare</i>	
Pycnogonida			
	Unknown	Unknown	
Merostomata			
	Limulidae	<i>Limulus polyphemus</i>	
Insecta			
	Unknown	Unknown	
Crustacea			
	Unknown	Unknown	
Amphipoda			
	Ampeliscidae	<i>Ampelisca abdita</i>	<i>A. agassizi</i>
		<i>A. macrocephala</i>	<i>A. spinipes</i>
		<i>A. vadorum</i>	<i>A. verrilli</i>
		<i>Ampelisca</i> spp.	<i>Byblis serrata</i>
	Ampithoidae	<i>Ampithoe valida</i>	<i>Ampithoe</i> spp.
	Acridae	<i>Lembos websteri</i>	<i>Leptocheirus pinguis</i>
		<i>L. plumulosus</i>	<i>Microdeutopus anomalus</i>
		<i>M. gryllotalpa</i>	<i>Uniciola irrorata</i>
	Argissidae	<i>Argissa hamatipes</i>	
	Bateidae	<i>Batea catharinensis</i>	
	Caprellidae	<i>Aiginina longicomis</i>	<i>Caprella penantis</i>
		<i>C. septentrionalis</i>	<i>C. unica</i>
		<i>Luconacia incerta</i>	<i>Paracaprella tenuis</i>
	Corophiidae	<i>Corophium acherusicum</i>	
Cumacea			
	Unknown	Unknown	
Mysidacea			
	Mysidae	<i>Heteromysis formosa</i>	<i>H. odontops</i>
		<i>Mysis stenolepsis</i>	<i>Neomysis americana</i>
		<i>Neomysis</i> spp.	
Decapoda			
	Axiidae	<i>Axius serratus</i>	
	Callinassidae	<i>Callinassa atlantica</i>	
	Cancridae	<i>Cancer irroratus</i>	<i>Cancer</i> spp.
	Crangonidae	<i>Crangon septemspinosa</i>	
	Hippolytidae	<i>Eualus pusiulus</i>	
	Majidae	<i>Libinia dubia</i>	<i>L. emarginata</i>
		<i>Libinia</i> spp.	
	Paguridae	<i>Pagurus longicarpus</i>	<i>Pagurus</i> spp.
	Palaemonidae	<i>Palaemonetes pugio</i>	<i>P. vulgaris</i>
	Pinnotheridae	<i>Pinnixa chaetoptera</i>	<i>P. sayana</i>
		<i>Pinnotheres maculatus</i>	<i>P. ostreum</i>
	Portunidae	<i>Carcinus maenas</i>	<i>Ovalipes ocellatus</i>
	Opogebiidae	<i>Upogebia affinis</i>	
	Xanthidae	<i>Neopanope texanasyi</i>	
Cirripedia			
	Balanidae	<i>Balanus balanoides</i>	<i>B. crenatus</i>
Ostracoda			
	Unknown	<i>Cylindroleberis mariae</i>	
Stomatopoda			
	Leuconidae	<i>Eudorella pusilla</i>	
	Squillidae	<i>Squilla empusa</i>	
Turbellaria			
	Leptoplanidae	<i>Leptoplana</i> spp.	
	Sylochidae	<i>Stylochus ellipticus</i>	
Hydrozoa			
	Campanulariidae	<i>Obelia</i> spp.	
	Hydractiniidae	<i>Hydractinia</i> spp.	
	Tubulariidae	<i>Tubularia</i> spp.	
Anthozoa			
	Astrangiidae	<i>Astrangia danae</i>	
	Cereianthidae	<i>Cerianthopsis americanus</i>	
	Edwardsiidae	<i>Edwardsia sipunculoides</i>	



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