CHAPTER 8.

Estuarine Habitats of Narragansett Bay

Malia L. Schwartz

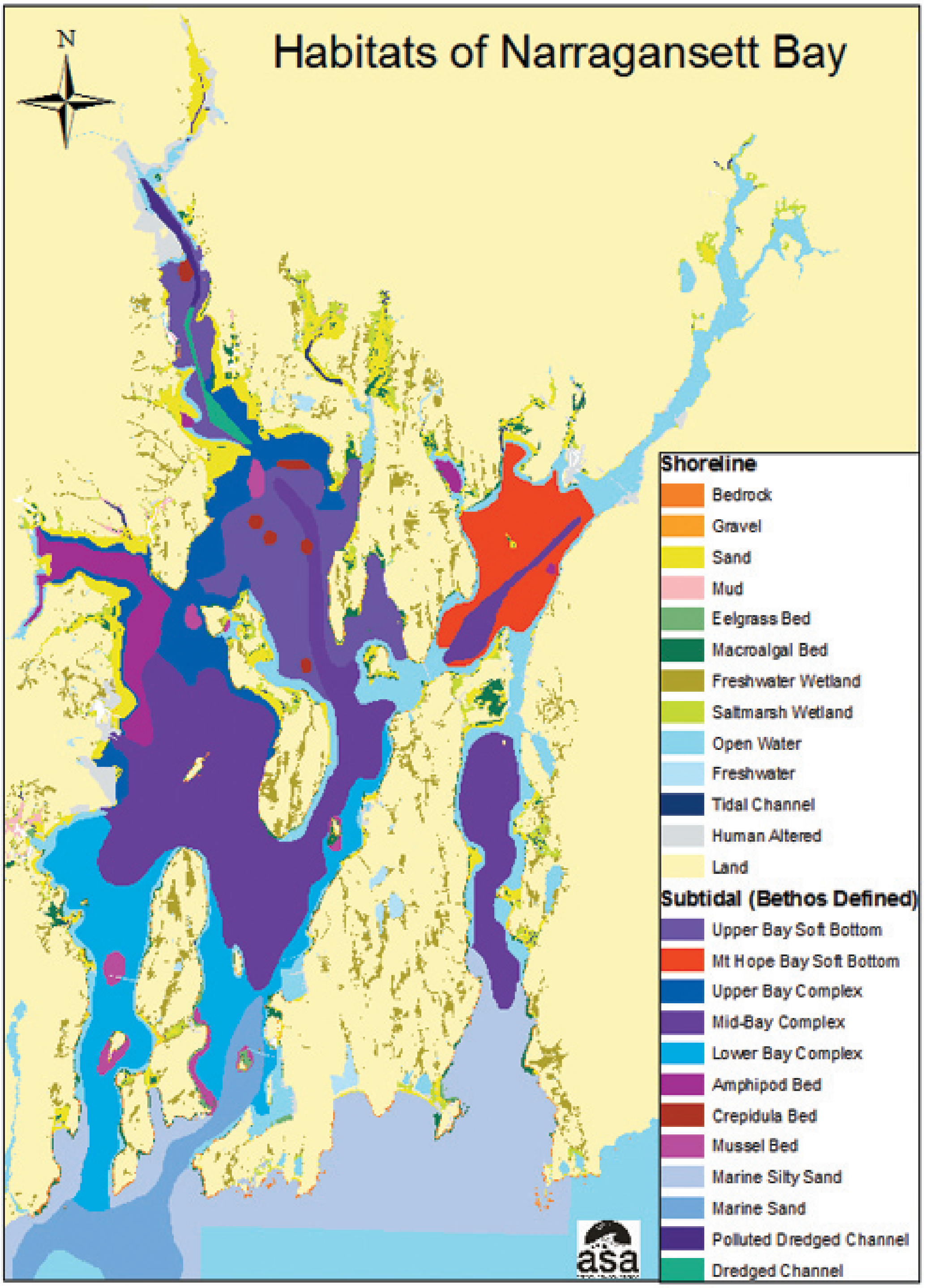


Figure 8.1. Estuarine habitats of Narragansett Bay. *Source: French et al., 1992. Image courtesy Applied Science Associates.*

Estuarine Habitats of Narragansett Bay

Introduction

Estuarine habitats support some of the most productive floral and faunal communities on Earth, and the habitats of Narragansett Bay are no exception. Many different habitat types are found in and around the Bay, including open water, salt marshes, subtidal bottom habitat, brackish waters, a complex intertidal zone of sandy beaches, mud and sand flats, and rocky intertidal areas, submerged aquatic vegetation with macroalgal and eelgrass beds, and human-modified shorelines (Fig. 8.1).

The productivity and variety of estuarine habitats foster an abundance and diversity of wildlife. Shorebirds, fish, crabs and lobsters, marine mammals, clams and other shellfish, marine worms, sea birds, and reptiles are just some of the animals that make their homes in and around estuaries. These animals are linked to one another, and to an assortment of specialized plants and microscopic organisms, through complex food webs and other interactions (EPA, 1998).

In addition to serving as important habitat for wildlife, fringing estuarine wetlands also perform other valuable services. Water draining from the uplands carries sediments, nutrients, and other pollutants. As the water flows through wetlands such as swamps and salt marshes, much of the sediments and pollutants are filtered out. This filtration process creates cleaner and clearer water, which benefits both people and marine life. Wetland plants and soils also act as a natural buffer between the land and ocean, absorbing floodwaters and dissipating storm surges. This protects upland habitats as well as economically valuable real estate from storm and flood damage. Salt marsh grasses and other estuarine plants also help prevent erosion and stabilize the shoreline (EPA, 1998).

Narragansett Bay is one of the best-studied estuaries in the world (Ely and Crist, 2001), and its habitats have been the subject of in-depth research for over 30 years. This chapter provides an overview of the major habitat types of Narragansett Bay and, where appropriate, makes specific reference to those habitats found on and around the islands of the NBNERR. It also delves into the basic life histories and ecology of the organisms found in these habitats that are then expanded on in subsequent chapters. And finally, it gives examples of habitat restoration efforts ongoing in several Bay habitats.

Figure 8.2. Salt marshes, such as Round Marsh in Jamestown, R.I., are some of the most ecologically valuable habitats in Narragansett Bay. *Photo by Malia Schwartz.*

Open Water

The open water, or pelagic, habitat is the dominant habitat in Narragansett Bay, based on area. The Bay itself is a phytoplankton-based ecosystem with relatively little salt marsh or macroalgae. The pelagic habitat is a dynamic environment with tidally and wind-driven circulation and freshwater inputs (French et al., 1992). A wide variety of plankton, benthic communities (Chapter 9), and nekton (Chapter 10) are found in and under the open water habitat of Narragansett Bay. In turn, this habitat provides food for a diverse assemblage of birds, as well as for marine mammals and occasional sea turtles (Chapter 11). The pelagic habitat also supports a number of commercial and recreational fisheries and shellfisheries.

Salt Marshes

While only covering a small surface area in Narragansett Bay, estuarine emergent wetlands, or salt marshes, are some of the most ecologically valuable habitats in the Bay (Fig. 8.2). Salt marshes protect coastal areas from erosion, remove nutrients from overenriched waters, provide sheltered habitat for key resource species, serve as nursery grounds for fish and shellfish, and are a major food source for the organisms that live there (Tiner, 1984).

A primary source of food in salt marshes is in the form of decomposing plant material, or detritus. Detritus is the base of an aquatic food web supporting higher consumers and commercial species. Animals such as shrimp, snails, clams, worms, and killifish consume plant breakdown products, graze on microscopic organisms growing on the surface of the detritus (Beck and Beck, 1998), or scour epibenthic algae off the sediments. To illustrate the interwoven nature of this food web, research by Nixon and Oviatt (1973a) in Bissel Cove reported that excretion and fecal pellets produced by foraging grass shrimp provided nutrients for enhanced development of bacteria and algae on the detritus. In turn, forage fish (e.g., anchovies, silversides, sticklebacks, mummichogs) and small invertebrates (e.g., grass shrimp and worms) are then consumed by commercial and recreational fish species, including winter flounder (*Pseudopleuronectes americanus*), striped bass (*Morone saxatilis*), and bluefish (*Pomatomus saltatrix*) (Beck and Beck, 1998).

Salt marshes are characterized by two general vegetative zones based on differences in tidal flooding—regularly flooded low marsh and irregularly flooded high marsh. In the low marsh—the area covered by each day's high tides—vegetation is dominated by a single plant, the tall form of smooth cordgrass, *Spartina alterniflora*, which typically grows 90–180 cm (3–6 feet) high (Beck and Beck, 1998). In addition, filamentous algae and diatoms are found at the base of the grasses growing in the flooded part of the marsh (Donaldson, 1995). Where the tall cordgrass meets the water's edge, the mud is home to densely packed beds of ribbed mussels, and around the plants' roots, one can find small holes that form the openings to fiddler crab burrows. Moving away from the water, at the edge of the border marked by the high-tide line, the cordgrass is short, less than 30 cm tall (Bertness, 1992).

In addition to providing food and shelter to the organisms that inhabit the low marsh, *S. alterniflora* has also been shown to be an effective nutrient sink, able to capture and hold available inorganic nutrients, such as nitrogen and phosphorus and trace elements, then slowly release them as the plants die, decay, and are carried into the estuary to serve as a rich source of detrital food (Nixon and Oviatt, 1973b).

In contrast to the low marsh, the high marsh is a mosaic of species, the occurrence of each being precisely determined by the elevation and resultant amount of tidal flooding. The high marsh is characterized by salt-marsh hay (*S. patens*), spike grass (*Distichlis spicata*), glassworts (*Salicornia spp.*), sea lavender (*Limonium nashii*), salt marsh aster (*Aster tenuifolius*), black grass (*Juncus gerardii*), and hightide bush (*Iva frutescens*). Salt marsh pools and tidal creeks can also be vegetated with widgeon grass (*Ruppia martima*), sea lettuce (*Ulva lactuca*), and other macroalgae (Beck and Beck, 1998).

In Narragansett Bay, salt marshes cover about 1,120 ha (2,800 acres). There are also roughly 80 km of narrow, fringing marshes—marshes that line the edge of rocky shores or developed areas. French et al. (1992) reported on the species composition and relative abundance of salt marsh plants in eight salt marshes around Narragansett Bay. The surveyed marshes included: 1) Watchemoket Cove, East Providence; 2) Hundred Acre Cove, Barrington; 3) Chase Cove, Warren; 4) Common Fence Point, Portsmouth; 5) Bissel Cove, North Kingstown; 6) Round Swamp, Jamestown; 7) Weaver Cove (Melville), Portsmouth; and 8) Emily Ruecker Wildlife Marsh, Tiverton. At the seven sites that could be sampled (Weaver Cove was too degraded), *S. alterniflora* dominated the low marsh and *S. patens*, the high marsh. Both species are perennial grasses, annually producing large amounts of organic matter that are exported from the marshes into the detrital

Table 8.1. Relative coverage (%) of dominant high and low marsh species for seven salt marshes within Narragansett Bay. Sp = *Spartina patens*, Ds = *Distichis spicata*, Ap = *Atriplex patula*, Sa (t) = *Spartina alterniflora* (tall), Sa (s) = *Spartina alterniflora* (short), Jg = *Juncus gerardii*, If = *Iva frutescens*, Se = *Salicornia europea*, Ss = *Solidago sempervirens*, Lc = *Limonium carolinianum*, At = *Aster tenuifolius*, Pm = *Plantago maritima. Data from French et al., 1992.*

High marsh	Sp	Ds	Ap	Sa (t)	Sa (s)	Jg	If	Se	Ss	Lc	At	Pm
Bissel Cove	53.6	14.2	0.6	0	0	17.2	0.6	0	11.2	0	0.6	1
Ruecker Wildlife Marsh	47.8	34.8	0	2.7	6.7	0.4	0.4	7.2	0	0	0	0
Round Swamp	82.7	12.5	0	2.0	0	0	0	0	0	2.0	0	0.8
Watchemoket Cove	94.1	4.7	0.6	0	0	0	0	0	0.6	0	0	0
Hundred Acre Cove	57.1	40.8	0	0	0	2.1	0	0	0	0	0	0
Common Fence Point	81.3	18.1	0.6	0	0	0	0	0	0	0	0	0
Chase Cove	72.2	27.8	0	0	0	0	0	0	0	0	0	0

Low marsh	Sa (t)	Ds	Sp	Se	Sa (s)	Ap
Bissel Cove	7.9	4.2	18.5	0	68.8	0.6
Ruecker Wildlife Marsh	100	0	0	0	0	0
Round Swamp	76.2	0	21.9	1.9	0	0
Watchemoket Cove	97.3	0.9	0	0	0	1.8
Hundred Acre Cove	80.1	8.3	9.3	2.3	0	0
Common Fence Point	98.4	0.8	0	0.8	0	0
Chase Cove	89.6	7.8	1.9	0.7	0	0

food web or deposited within the marshes, contributing to the underlying peat (Nixon, 1982; Teal and Teal, 1962). Table 8.1 shows the relative coverage of species found in the seven study sites that were examined.

Within the boundaries of the NBNERR, salt marshes are found in the North Prudence Unit (102 acres) and Barre and Little units (48 acres), on the east shore of Patience Island (13 acres), and in a small area on Dyer Island (3 acres) (see Table 4.3, page 36; Fig. 4.11, page 34). As with the previous examples, the salt marshes of the Reserve are dominated by *S. alterniflora* and *S. patens*, and are influenced by the adjoining Bay rather than landward processes. They are laced with irregular creeks, ponds, potholes, and man-made drainage ditches (Beck and Beck, 1998). Seventy-six percent of the salt marshes occurring on the islands of the Reserve are protected within NBNERR boundaries (Rosenzweig et al., 2002).

Salt Marsh Restoration

Despite their documented ecological and societal importance, over half the estuarine wetlands originally occurring in the continental United States have been destroyed, largely as a result of urbanization (Tiner, 1984; Tiner et al., 2004). But public concern, coupled with increased public awareness of the functions and values of estuarine wetlands, has provided the impetus for salt marsh restoration (Shisler, 1990). In Rhode Island, recent attempts have been made to restore once-productive salt marsh habitats.

Within Narragansett Bay, a salt marsh restoration effort was undertaken at Sachuest Point salt marsh on Aquidneck Island. In March 1998, tidal flow to the formally restricted portion of the marsh was reestablished with the construction of additional culverts, marsh pools, creeks, and ditches (Roman et al., 2002) (Fig. 8.4). One year after tidal restoration, the tidal range was equivalent to that of the unrestricted portion of the marsh, and vegetation composition had begun to return to normal unrestricted salt marsh conditions, most notably an increase in the abundance of *S. alterniflora* and *S. patens*, and decrease in the height of *Phragmites australis*. An increase in the nekton density and species richness of the restoring marsh also occurred (Roman et al., 2002). Sachuest Point is a prominent example of salt marsh restoration in Narragansett Bay; however, many other similar examples exist, including Potter Pond (Prudence Island) in the NBNERR, Gooseneck Marsh (Newport), Walker Farm (Barrington), and Silver Creek (Bristol).

Benthic Habitat

Occurring below the low-tide line, the subtidal, benthic (bottom) habitat of Narragansett Bay is composed of soft, unvegetated sediments, predominantly clayey silt and sand-silt-clay. This habitat is found throughout the mid- and upper Bay and in protected coves and embayments. Coarser, sandy sediments are found in the lower Bay (see Fig. 7.6, page 84). Sub-tidal waters support a diverse benthic community of molluscs, crabs, and worms that live in and on the sediments (Fig. 8.5). The northern quahog (*Mercenaria mercenaria*) is the most commercially important species with a smaller fishery in the Bay for the American lobster (*Homarus americanus*). Blue mussels (*Mytilus edulis*) are abundant intertidally, in shallows with hard substrates (French et al., 1992), and in two big commercial beds in the lower West Passage at depths of 12–18 m (40–60 feet) (S. Nixon, personal communication).

There are 13 benthic habitat types found in the waters of Narragansett Bay (Table 8.2, Fig. 8.1). Organisms found in the lower Bay and at depths greater than 12 m (40 feet) in the mid-Bay are adapted to true marine conditions. Evidence of this historically could be seen in sea scallop beds off Gould Island, ocean quahogs in the East Passage, and populations of surf clams off Bonnet Shores in the West Passage and in the lower reaches of the Sakonnet River. In the lower reaches of the East and West passages, much of the bottom is composed of empty oyster and quahog shells, on which live large numbers of blue mussels and slipper shells (*Crepidula fornicata*) found in densities high enough to affect the distribution of other species and sediment characteristics. (Olsen et al., 1984; French et al., 1992).

In areas of deep water in the mid-Bay, where sediments are soft and salinities high, a deposit-feeding community flourishes that is dominated by two species of small clams, *Yoldia limatula* and *Nucula annulata,* and the catworm, *Nephtys incisa*, as well as the coot clam, *Mulinia lateralis*, and a polychete worm, *Mediomastus ambiseta*. This community is widespread on soft bottom and is also found at the bottom of dredged channels. These deposit-feeding organisms constantly rework the top few centimeters as they sift organic matter from between the sediment grains and excrete it in packets called pseudofeces. This produces a soft, pelletized surface. Since the pellets clog the feeding mechanism of filter feeders, they are largely excluded from such areas. Currents occasionally sweep these nutrient-rich pellets into suspension, thus enriching the water. (Olsen et al., 1984; French et al., 1992).

Historically, the upper Bay was rich in oysters (*Crossostrea virginica*), quahogs, and soft-shelled clams (*Mya arenaria*) (Olsen et al., 1984). While quahogs are still abundant, some of the most productive shellfishing grounds, including the Providence River and Greenwich Bay (see Fig. 7.2, page 79), are often conditionally or permanently closed to harvesting due to bacterial pollution.

Parts of the "upper Bay complex" (Table 8.2, BUB), such as the habitat surrounding North Prudence and Patience Island, are characterized by various sandy sediment types. The tube-dwelling amphipod crustacean, *Ampelisca abdita*, can be found in dense mats in this habitat, as are quahog beds, which sustain lucrative commercial and recreational shellfish harvests (Fig. 8.6). In addition, the *Ampelisca* themselves are an important food source for fish, notably winter flounder (French et al., 1992; Olsen et al., 1984).

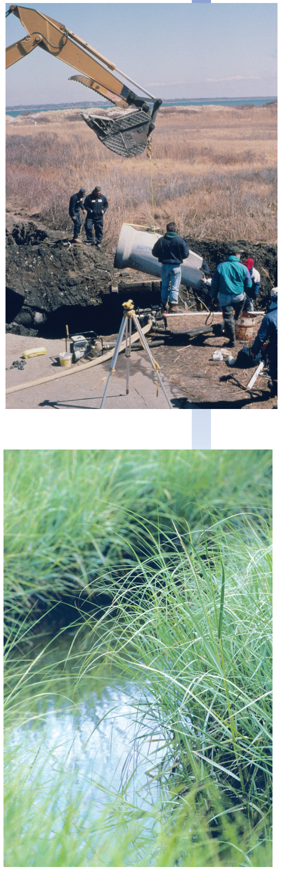


Figure 8.4. Tidal flow was restored to a previously restricted portion of Sachuest Marsh by constructing a new culvert (*top*) as well as marsh pools, creeks, and ditches (*bottom*). *Photos by John Catena, NOAA Restoration Center.*

Rocky Reefs

Narragansett Bay has few natural rocky reefs (e.g., off Hope Island), but the West Passage of Narragansett Bay near Dutch Island is home to six small artificial rocky reefs. Constructed by NOAA Fisheries with settlement money from the 1989 *World Prodigy* oil spill, the reefs—made of two different sizes of quarried cobble—were built to enhance lobster stocks in the Bay by providing new shelters created by the artificial reefs (Schwartz, 1996).

Castro (2003) examined the effects of habitat enhancement and stock enhancement on the abundance of American lobster inhabiting the artificial reefs. Reefs were monitored for six months pre-construction and five years post-construction using a combination of visual surveys by scuba divers, trap sampling, a tag-recapture program, and airlift sampling for young-of-the-year. Castro (2003) found an approximate population size of 1,250 lobsters at the reef sites, calculated from tag-recapture and visual survey information. In addition, a significant increase in the number of naturally settling young-of-the-year was noted at the reef sites compared to pre-reef conditions. While the addition of hatchery-reared lobsters (stock enhancement) did not contribute to enhancement at the reef sites, the addition of the reefs (habitat enhancement) did significantly increase the numbers of lobsters in Dutch Harbor through increased settlement and migration (Castro, 2003).

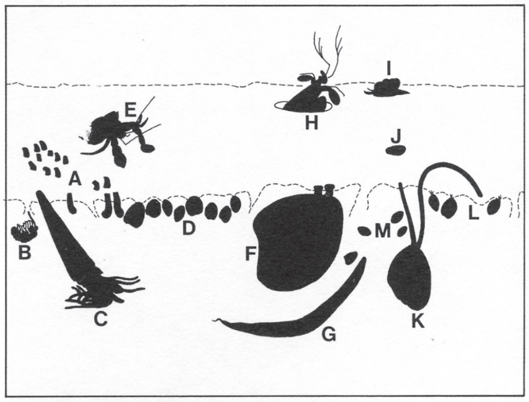
In addition to the Dutch Harbor reefs, an artificial reef-site was constructed in Mount Hope Bay as part of a Rhode Island Experimental Program to Stimulate Competitive Research (EPSCoR) project to study the role of artificial reefs in oyster enhancement and finfish habitat restoration in Narragansett Bay (EPSCoR, 2007; *www.riepscor.org/summer2007/project34.html)*. And when the R.I. Department of Transportation and Federal Highway Administration approved the demolition of the old Jamestown Bridge, artificial reefs were created with the concrete rubble from the bridge at several deep-water sites at the bottom of Rhode Island Sound (Berman, 2006).

Brackish Habitat

Portions of Narragansett Bay where salinity levels are reduced by freshwater dilution are important for supporting important resource species such as oyster, soft-shell clam, and blue crab (*Callinectes sapidus*) (Fig. 8.7). However, the value of these brackish habitats can be compromised by their location at river mouths and within coves that are often subjected to intense physical disturbance from dredging and filling, and which serve as sinks for local and watershed contaminants. Brackish areas in Narragansett Bay tend to be small since many streams enter the water from steeply sloping shores or over dams; the Tauton River is an exception, having a long tidal reach (French et al., 1992).

All brackish areas studied in Narragansett Bay supported species adapted to shallow water with low and variable salinity, extremes in temperature, and high concentrations of organic detritus. These include molluscs (*Hydrobia totteni, Illyanassa obsoleta, Macoma balthica,* and *Mya arenaria*) and polychaetes (*Neanthes succinea, Polydora ligni, Scolecolepides viridis*, and *Streblospio benedicti*). The brackish fauna of the Kickemuit River, which empties into Mount Hope Bay, R.I., included a number of species not found, or rare, in other brackish areas, such as the gastropods *Sayella fusca* and *Odostomia trifida* and the amphipod *Paraphoxus spinosus*. These may be sensitive species that have been eliminated from polluted areas (French et al., 1992).

Figure 8.5. A benthic community. Illustration by S.P. Silvia. (A) Tube-dwelling amphipods, *Ampelisca*. (B) Benthic amphipod in filter-feeding position, *Leptocheirus pinguis*. (C) Ice cream cone worm, *Pectinaria gouldii*. (D) Coot clams, *Mulinia lateralis*. (E) Hermit crab, *Pagurus longicarpus*. (F) Quahog, *Mercenaria mercenaria*. (G) Shimmy worm, *Nephtys incisa*. (H) Mantis shrimp, *Squilla empusa*. (I) Mud snail, *Ilyanassa trivittatus*. (J) Worm casting. (K) Macoma clam, *Macoma balthica*. (L) Nematodes. (M) Nut clams, *Nucula proxima*. *Source: Olsen et al., 1984*.



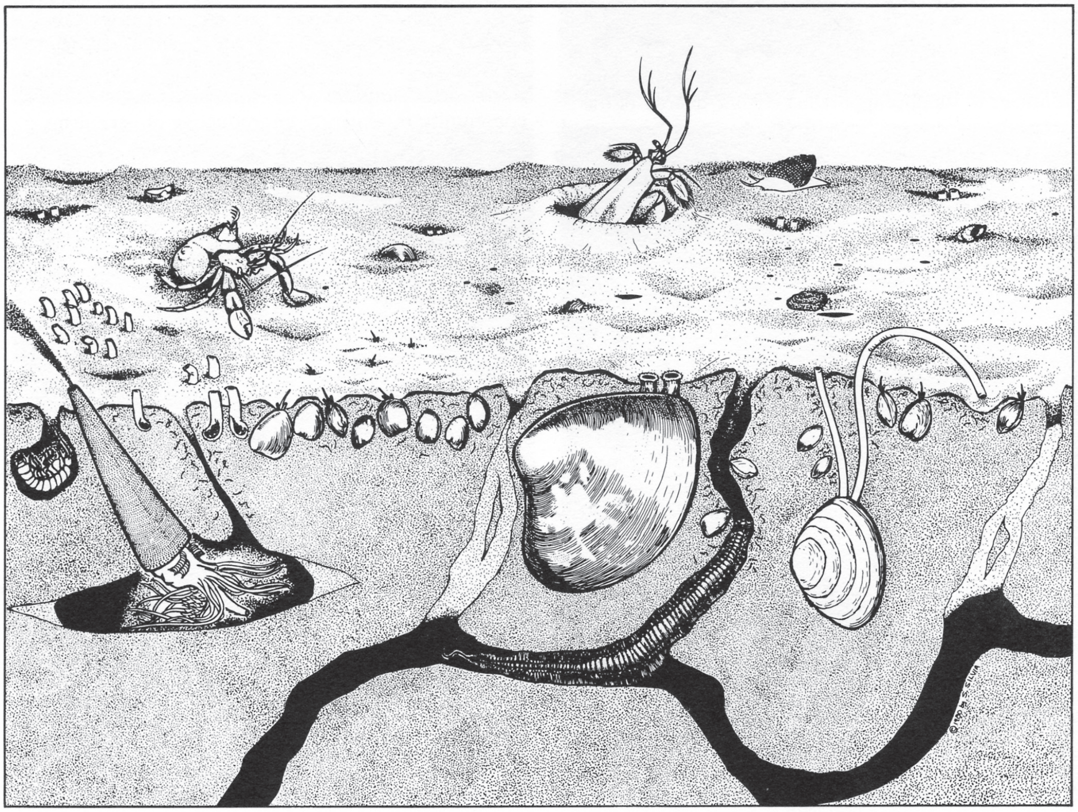


Table 8.2. Thirteen benthic habitat types indicated on the Narragansett Bay map of habitats (Fig. 8.1). *Data from French et al., 1992*.

Name	Abbrev.	Description
Marine sand	BSA	Silty sand typical of Rhode Island Sound and extending up into the East Passage. Fauna characterized by marine spp. such as *Astarte, Cyclocardium, Byblis serrata,* and *Arctica islandica*
Marine silty sand	BSS	Habitat found at the mouth of the Bay and in Rhode Island Sound. Characterized by fine sands with marine spp. such as *Spisula, Echinarachnius,* and *Spiophanes bambyx*
Lower Bay complex	BLB	Composed of a variety of mixed sediments containing sand. *Mytilus* and *Crepidula* shells may be locally abundant. Mid-estuarine and estuarine-offshore spp. found here include *Pherusa affinis, Aricidea* and *Ampelisca vadorum*
Mid-Bay complex	BMB	Habitat found in the deeper water of the mid-Bay, channels of Mt. Hope Bay, and the upper Bay on clayey silt and sand-silt-clay. The fauna are mid-estuarine and estuarine-offshore and include *Mulina, Mediomastus, Nucula annulata, Nephtys*, and *Yoldia*
Upper-Bay complex	BUB	Composed of various sediment types containing sand, with tidal current features and *Mytilus* and *Crepidula* beds
Mussel (*Mytilus edulis)* beds	BME	
Crepidula beds	BCF	
Amphipod beds	BAA	
Mt. Hope Bay soft bottom	BMH	Clayey-silt and sand-silt-clay habitat found in the non-channel areas of Mt. Hope Bay. Mid-estuarine spp. include *Spiochaetopterus*, while *Nucula, Nephtys, Yoldia,* and *Ampelisca abdita* are of lesser importance
Upper Bay soft bottom	BUS	Softer sediments of the upper Bay and lower Providence River. Its low diversity fauna includes mid-estuarine spp. and high levels of eutrophication indicators such as *Streblospio* and *Mediomastus*
Estuarine dredged channel	BLP	Habitat on the soft sediments of the lower Providence River channel includes a low density of mid-estuarine species, much like BMB, but fewer in number
Polluted dredged channel	BUP	Upper channel of the Providence River and Seekonk River have a fluid, non-cohesive bottom low in oxygen. Fauna consists of greatly reduced diversity and density of pollution-resistant spp.
Shallow undredged brackish	BSU	Undredged areas of the Seekonk River and other shallow brackish areas with fine sand and silt bottoms with brackish water spp. such as *Macoma balthica, Scolecoleipides, Cyathura,* and *Mya*

Intertidal Zone

The intertidal, or littoral, zone—the area above the low-water mark and below the high-tide line—of Narragansett Bay is composed largely of narrow cobble beaches. Within the NBNERR, beaches (some sand, mostly cobble) are found on Prudence, Patience, Hope, and Dyer islands; mud or sand flats can be seen in the North Prudence Unit; and rocky intertidal areas are found on Hope Island and at the southern end of Prudence Island (Beck and Beck, 1998).

Organisms that live in the intertidal zone are adapted to an environment of harsh extremes. Temperature, dessication, salinity, and wave action can vary widely depending on the area inhabited. One easily visible feature of intertidal communities is "vertical zonation," where the community is divided into distinct vertical bands of specific species going up the shore. Typically, species' ability to cope with dessication determines their upper limits, while competition with other species sets their lower limits.

In the "upper littoral" subzone, which is flooded only during the day's high tides, the environmental fluctuations are most dramatic. The duration of submersion is not long enough to sustain large amounts of vegetation, but some do survive. In Narragansett Bay, the predominant organisms in this subzone are barnacles, small gastropods, isopods, mussels, sea stars, and whelks. The upper littoral can also contain rock pools inhabited by small fish Fig. 8.8).

In contrast, the "lower littoral" subzone is mostly submerged—it is only exposed during low tides. This area is teeming with life—the most notable difference in this subzone is that there is much more marine vegetation, especially seaweeds, or macroalgae. Organisms in this subzone generally are not well adapted to periods of dryness and temperature extremes. Some of the organisms in this area include anemones, crabs, green algae, hydroids, isopods, mussels, nudibranchs, sculpins, sea cucumber, sea lettuce, sea stars, sea urchins, shrimp, snails, sponges, tube worms, and whelks. Creatures living in this subzone can grow to larger sizes because there is more productivity in the lower littoral and because marine vegetation can grow to much greater sizes due to the better water coverage—the water is shallow enough to allow light to reach the vegetation, nutrients are supplied on a regular basis, and the salinity is close to that of full seawater. This area is also protected from large predators such as large fish because of the wave action and the water still being relatively shallow (Bertness et al., 2001).

Submerged Aquatic Vegetation

Eelgrass

Eelgrass, *Zostera marina*, is a rooted, submerged flowering plant typically found in coastal and marine habitats (Fig. 8.9). Eelgrass contributes significantly to the health and productivity of these habitats (Keller et al., 1996). It plays an important role in the life cycles of scallops, crabs, finfish, geese, and ducks. The dense meadows of eelgrass provide breeding and nursery areas for young finfish and shellfish as well as a substratum for attachment in the water column and protection from predators (Thayer et al., 1984). In fact, recent studies in Rhode Island (Harris et al., 2004) have documented that eelgrass beds—even those of modest density—increase survivorship of tautog (*Tautoga onitis*), cunner (*Tautogolabrus adspersus*), and silversides (*Menidia menidia*), but do not affect predation by bluefish (*Pomatomas saltatrix*) on Atlantic menhaden (*Brevoortia tyrranus*). These findings suggest that eelgrass habitats indeed serve a functional role as refuges from predation for some prey fish.

During its life cycle, eelgrass typically breaks away from the base shoots and becomes an important component of the detrital pathway. Detritovores begin to break down the leaves into smaller particles which are then consumed by bacteria and fungi. Many invertebrates also consume the decaying eelgrass and then become food for larger life forms, such as fish and crabs (Keller et al., 1996).

Eelgrass communities are also valuable sediment traps and help stabilize bottom sediments

Figure 8.7. Brackish water habitats, such as at the mouth of the Narrow River in Narragansett, support important resource species, but are also often compromised because they serve as sinks for local and watershed contaminants. *Photo by Malia Schwartz.*

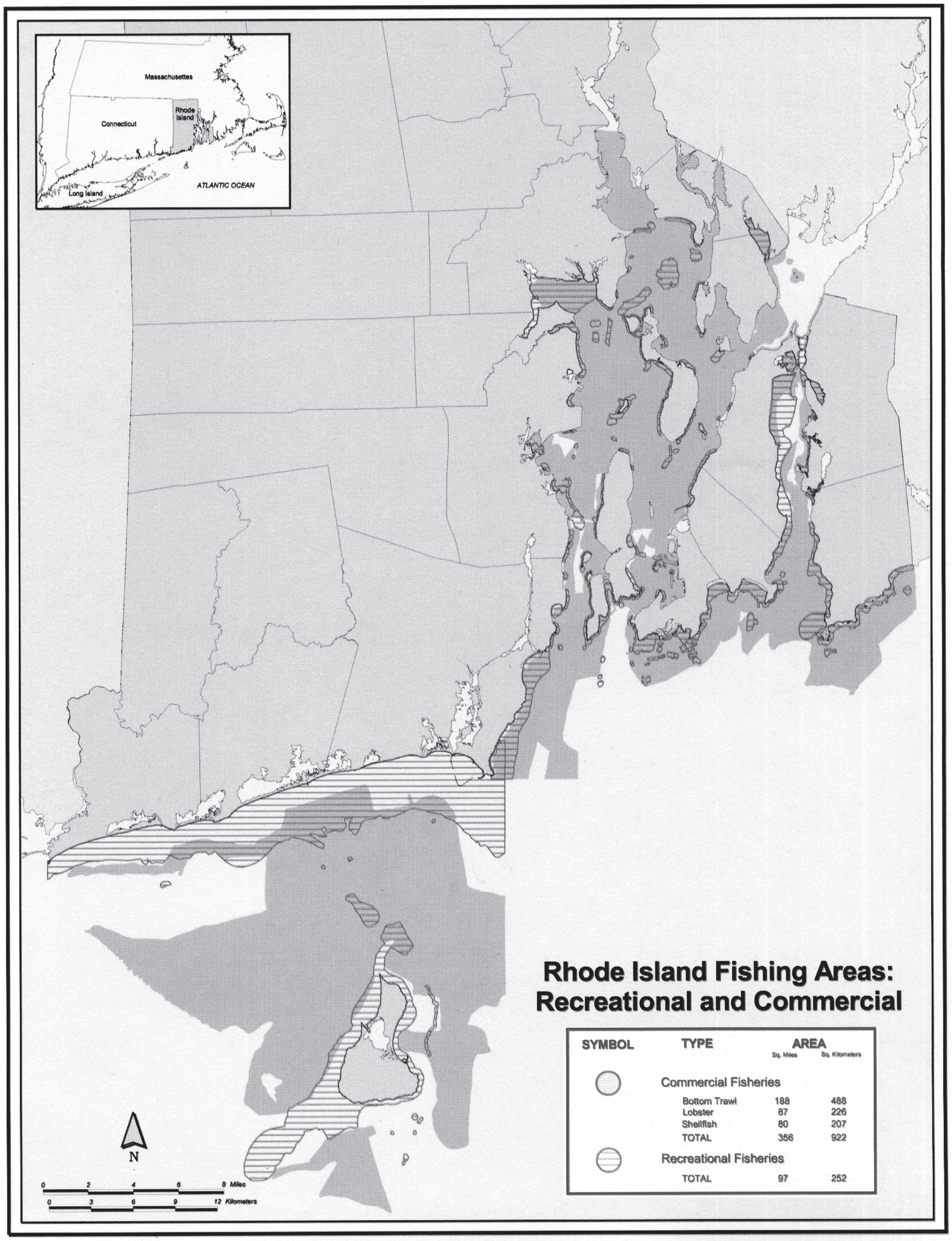


Figure 8.6. Narragansett Bay provides ideal habitat for commercial and recreational fisheries. *Source: Rhode Island Marine Resource Uses Project*.

(Thayer et al., 1975). Their leaves act as dampers in the water and reduce wave motion. Eelgrass meadows remove both suspended sediments and nutrients from the water column. High levels of nutrients entering a system from developed areas are taken up by eelgrass rather than being passed downstream where they might add to the level of pollution in a system (Keller et al., 1996). Historically, eelgrass beds could be found throughout the Bay and thrived even in the more polluted areas of the upper Bay and Providence River (Nixon et al., 2007).

The current distribution of eelgrass in Narragansett Bay is patchy (Fig. 8.10). It is limited to shallow embayments with mud-sand substrata since the rhizome is buried in the sediment and leafy shoots arise annually. Eelgrass beds have been reported in the southern East Passage around Newport (Brenton Cove and Coasters Harbor Island), on the east side of Conanicut Island (east of Beavertail State Park, Mackerel Cove, and Fort Wetherill State Park), and around Rose Island. Small patches have been reported in the West Passage north of Bonnet Point, on the east side of Dutch Island in Wickford, and in East Greenwich Cove (Keller et al., 1996). A 1989–1990 macroalgal survey (French et al., 1992) extended what was earlier limited to locations along the eastern shore of Conanicut Island to the eastern and western shores of the Sakonnet River. Within the NBNERR, lush eelgrass meadows could be found in the shallow waters of the Reserve until the 1930s. Today, only two healthy beds exist within the boundary of the NBNERR. The largest bed extends from the south end/ T-wharf area on Prudence for over 364 m (400 yards) north along the east shore. A much smaller bed exists south of Sheep Pen Cove (Beck and Beck, 1998).

Figure 8.8. Beavertail's rocky shores contain small tide pools that are home to creatures that can tolerate the extreme environmental fluctuations characteristic of the upper intertidal zone. *Photo by Malia Schwartz.*

Eelgrass Restoration

In the 1930s, a virulent fungal disease swept through eelgrass beds in North America and Europe and almost completely eliminated the plants from many areas (den Hartog, 1987). A slow recovery over the next 30 years renewed scientific interest in the ecology and reproduction of *Zostera,* and numerous studies began to reveal the importance of eelgrass habitats. Ironically, the recovery of eelgrass, at least along the U.S. East Coast, coincided with the migration of the human population to the coast, the increasing use of nitrogen fertilizer following World War II, and increasing atmospheric emissions of nitrogen from electric power generation and transportation. The increasing inputs of sediment and nutrients combined to reduce coastal water clarity. As a result, the natural recovery of eelgrass largely stopped, and the plants were lost once again from many bays and estuaries. It is estimated that from one- to two-thirds or more of the once-recovered eelgrass has been lost (Fonseca et al., 1998; Hurley, 1992; Orth and Moore, 1983; Short et al., 1996).

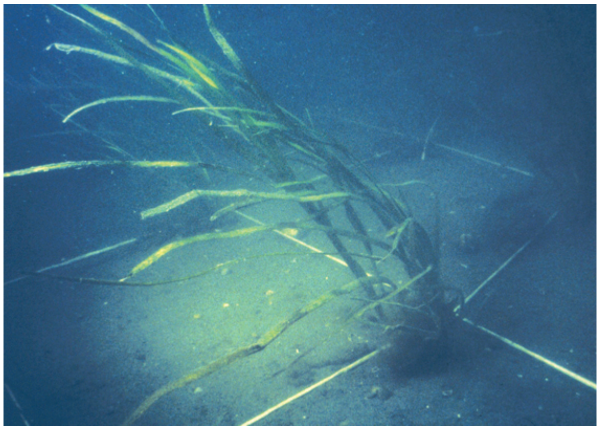


Figure 8.9. A plug of eelgrass, shown after transplant into one of 10 locations in Narragansett Bay as part of an eelgrass restoration effort. *Photo by Jerry Prezioso, NOAA.*

However, this loss of eelgrass has stimulated growth in the area of eelgrass research, restoration, and recovery. Rhode Island Sea Grant researchers used mesocosm tanks, which replicated the coastal lagoons where eelgrass grows, to examine the effects of nutrients, temperature, shoot density, and ecosystem value of eelgrass (Bintz and Nixon, 2001; Harris et al., 2004). This led not only to new understanding of eelgrass ecology, but also to new approaches to restoring eelgrass beds through the use of seeds (Granger et al., 2002).

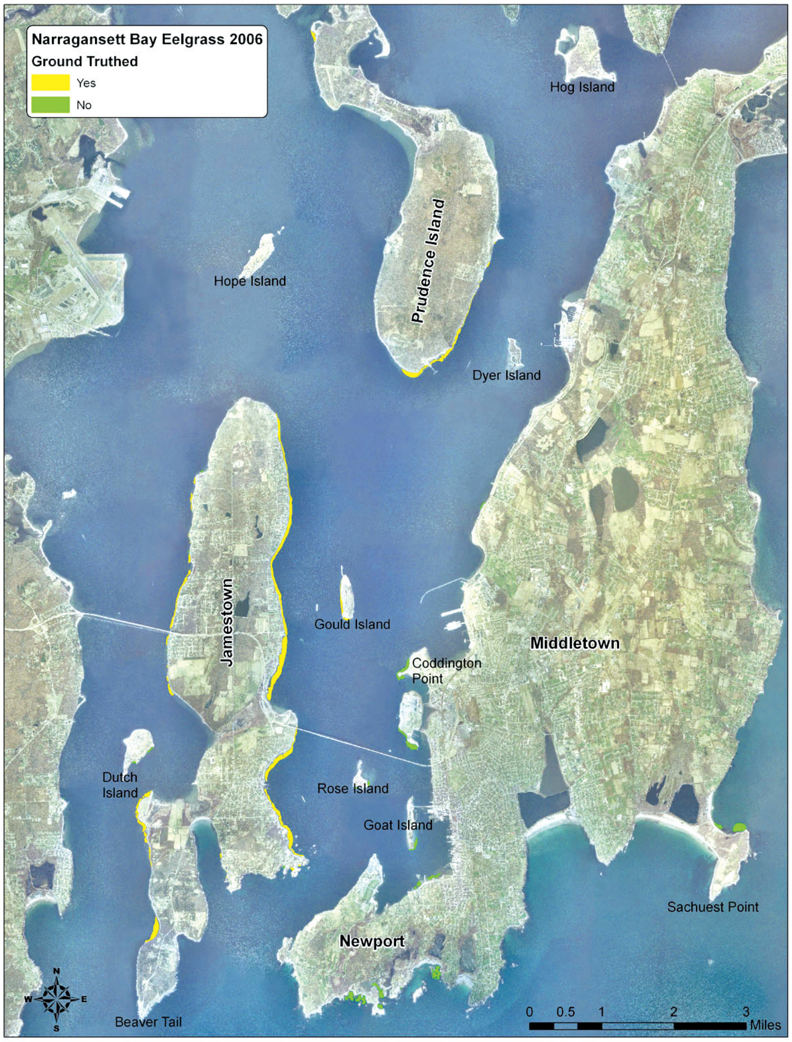


Figure 8.10. Eelgrass distribution (green/yellow) in Narragansett Bay. *Map courtesy Michael Bradley, URI Environmental Data Center.*

With funding from the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) and Rhode Island Sea Grant, Granger and colleagues developed techniques for harvesting, preparing, and storing eelgrass seed for later planting (Granger et al., 2002). The investigators went on to develop a "seeding sled"—a device towed under water that creates furrows, injects a seed-gelatin matrix into the sediments, and covers the seeds (Fig. 8.11). The researchers' mesocosm studies demonstrated 50 percent seed survival using these methods—unheard of success compared with past seed-based restoration efforts (Granger et al., 2002). This work was field-tested in Narragansett Bay in Reserve waters (see Chapter 13) and provided a link to the goals of the NBNERR to reestablish eelgrass in selected areas with a high potential for successful restoration (Beck and Beck, 1998).

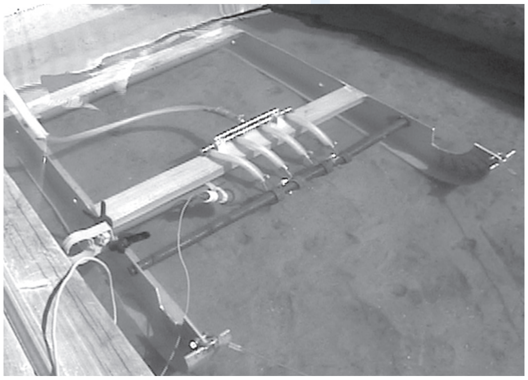


Figure 8.11. The eelgrass seeding sled, developed by URI researchers, was field-tested in NBNERR waters. *Photo by Stephen Granger, URI Graduate School of Oceanography (GSO).*

Macroalgal Beds

In shallow areas, macroalgae may contribute significantly to primary production particularly via contributions to detrital food chains (Mann, 1972; 1973) (Fig. 8.12). They provide habitat for a variety of organisms, such as bay scallop (*Argopecten irradians*) (Hicks, 1986), and when sessile, may integrate the history of a water mass. Consequently, rugged species such as *Ulva latuca, Fucus vesiculosus*, and *Chondrus crispus* serve as useful bioaccumulators of pollutants (Levine and Wilce, 1980; Sears and Battaglia, 1990), and therefore, changes in their abundance and distribution can be an indicator of degradation or recovery of an area.

But macroalgal proliferation can also cause degradation in an ecosystem. Increased nutrients, especially nitrogen and phosphorus, coming into an embayment from human sources can overstimulate plant growth—a process called eutrophication. If large amounts of seaweed accumulate, they may clog beaches and boating areas and cause odor problems when they decompose (Granger et al., 2000). More importantly, when the plants die and are decomposed by bacteria, oxygen in the water is depleted. Granger et al. (2000) conducted an assessment of eutrophication in Greenwich Bay in which they quantified the biomass of macroalgae at different times during the summer to predict the amount of oxygen consumption that might occur when the seaweeds died and decomposed in the bottom water. The major species they found were *U. lactuca* and *Gracilaria tikvahiae*, with lesser amounts of *U. linza* (Fig. 8.13). They determined that, while the macroalgae in the coves may have some impact on bottom-water dissolved oxygen if the coves became stratified, this impact was unlikely to be significant (Granger et al., 2000).

Seaweeds have been studied in Narragansett Bay since the mid-1800s (Fig. 8.14). Much of the published information as well as unpublished material was synthesized by French et al. (1992) and combined with a broad scale and semiquantitative sampling program to compile maps of macrophyte distributions within the Bay. Table 8.3 lists the macrophyte species collected during a 1989–1990 survey. Species diversity was highest where water from Rhode Island Sound entered the Bay through the East Passage and Sakonnet River. The number of macroalgal species found in the low intertidal was consistently higher than the upper subtidal. Red algae predominated in the subtidal zone (French et al., 1992).

Figure 8.12. Seaweeds, or macroalgae, contribute significantly to primary production in estuarine habitats. *Photo by Malia Schwartz.*

According to the survey, the dominant species in the Bay were *Chondrus, Codium, Fucus, Ulva, Ascophyllum*, and *Laminaria*. *Chondrus, Codium, Fucus*, and *Ascophyllum* appeared throughout the Bay, while *Ulva* also extended into the tributaries. For the most part, *Fucus* and *Ascophyllum* were restricted to intertidal zones, while *Codium* and *Ulva* were a major component of both intertidal and subtidal zones. Compared with estuaries north of Cape Cod, Narragansett Bay has fewer species but a larger proportion that extend to the tropics (French et al., 1992).

Human-Modified Shorelines

Within Narragansett Bay, over half the shoreline has been "hardened" by human-made structures (RIGIS, 2006) (Fig. 8.15). These structures include bulkheads or seawalls that were designed to prevent erosion (Fig. 8.16). However, most coastal erosion in the Bay results from major storms, such as hurricanes and nor'easters. Sometimes these structures actually hasten erosion by concentrating the wave energy in the area of the barrier (Keller, et al., 1996). Under changing climate conditions and rising sea level, this effect will be intensified. The R.I. Coastal Resources Management Council's (CRMC) webpage on "Climate Change & Sea Level Rise" offers resources for information and related links on the topic. Visit *www.crmc.ri.gov/climatechange.html*. In addition, the CRMC had adopted new shoreline maps for Rhode Island's coast, detailing erosion rates for the shoreline. The maps are available at *www.crmc.ri.gov/maps/shoreline.html*.

Marinas as Habitat

Besides those structures built along the shore to prevent erosion, another type of human-modified structure along the shoreline is marinas (Fig. 8.17). A study by Nixon et al. (1973) provided one of the first attempts to look at marinas as habitat. They made basic ecological measurements of marina system production, respiration, species diversity, and major populations for comparison with those of estuarine salt marshes and other natural communities.

Figure 8.14. Seaweeds provide habitat for a variety of organisms. Their ecology has been studied extensively in Narragansett Bay. *Photo by Malia Schwartz.*

In their study, Nixon et al. (1973) compared two coves that both open into Wickford Harbor—Wickford Cove, which has three marinas and numerous moorings, and Mill Creek, which is bordered by fringing *S. alterniflora* marsh with no boats, docks, or moorings. They found that the two ecosystems were strikingly similar in many respects. Fish species were similarly diverse in the marina and the marsh habitats, but abundance was greater in the marsh cove due to the presence of dense juvenile menhaden schools. Additionally, the fouling communities that grow on the undersurface of floats and wooden dock pilings of marinas appeared to be a food source for juvenile mummichogs (*Fundulus heteroclitus*) and likely serve as additional food sources to complement the detritus input from the salt marsh. Based on their findings, Nixon et al. (1973) concluded that in most respects, the marina cove and the marsh cove appeared not only to be similar, but also compatible ecological systems.

More recently, the concept of marinas as habitat has taken hold in the aquaculture industry. Innovative aquaculture techniques are using floating docks in marinas as platforms for the nursery culture of shellfish seed as a means to efficiently utilize valuable shoreline space (Scott et al., 2000). Shellfish seed, such as oyster, quahog, or scallop, are hung in bags on the underside of docks. There, they filter-feed on a variety of organisms in the water column, which, in addition to enhancing shellfisheries, also have the added benefit of removing excess nutrients from the Bay and improving water quality (Scott et al., 2000).

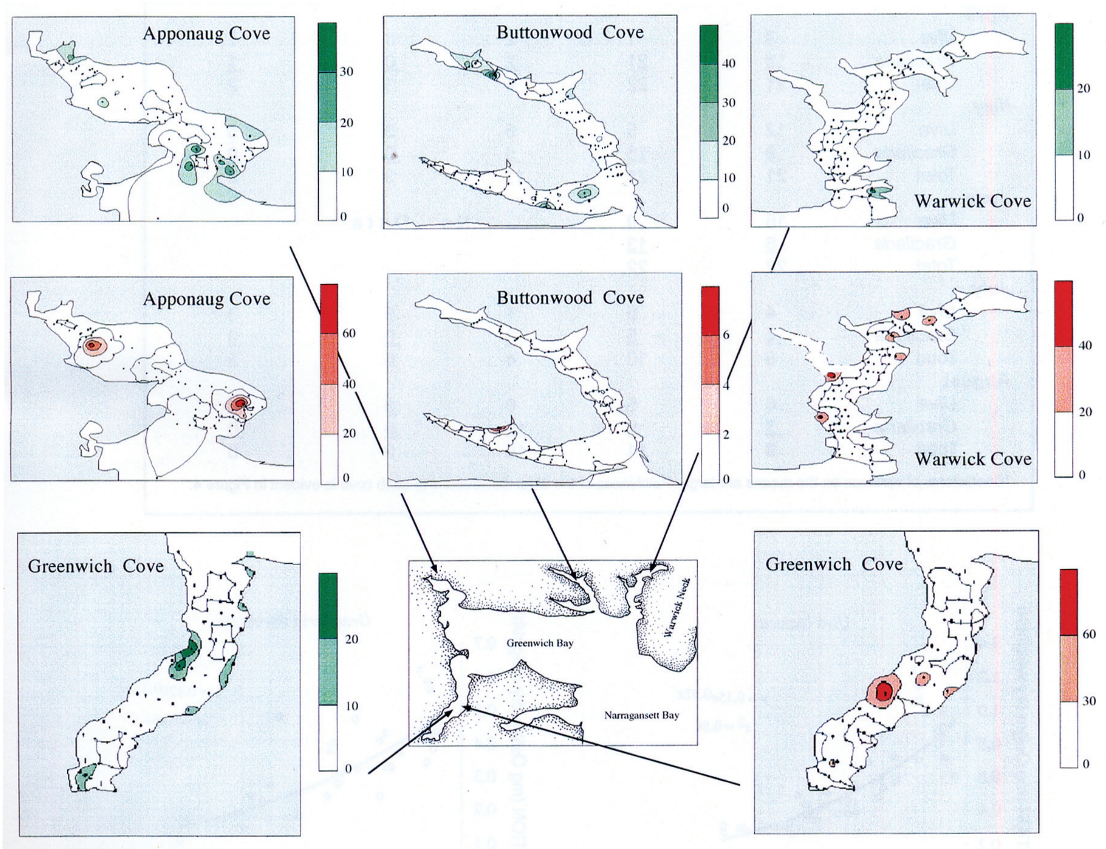


Figure 8.13. Biomass of *Ulva* (a green algae) and *Gracilaria* (a red algae) in the major coves of Greenwich Bay in July 1997. Units are in grams dry weight/m^2. Dots show sampling locations. *Source: Granger et al., 2000.*

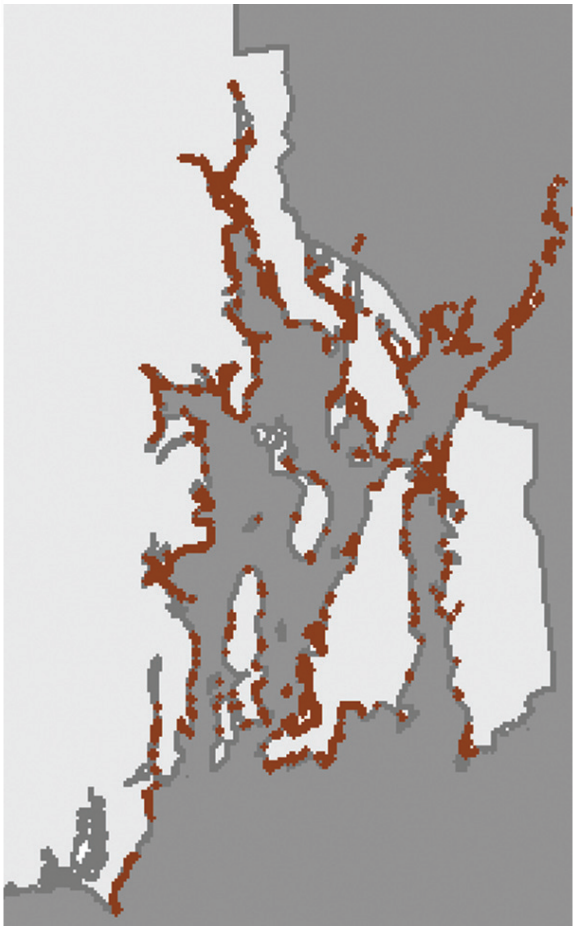


Figure 8.15. Within Narragansett Bay, over half of the shoreline is "hardened" with human-made structures (red areas). *Data source: RIGIS.*

Figure 8.16. This bulkhead at State Pier #5 in Narragansett provides a sheltered cove to tie up, launch a boat, fish, or scuba dive. Human-made structures are designed to prevent erosion and provide sheltered areas for human use. *Photo by Malia Schwartz.*

Figure 8.17. This marina in Wickford Cove provided an ideal study site to explore the role of marinas as habitat. *Photo by Malia Schwartz.*

Table 8.3. Macrophyte species collected during a 1989–1990 survey in Narragansett Bay. Species names read across, then down. *Data from French et al., 1992. Note: The genus* Enteromorpha *was recently reclassified as Ulva.*

Chlorophyta		
	Blidingia minima	*Bryopsis plumose*
	Chaetomorpha aerea	*C. linum*
	Cladophora albida	*C. sericea*
	Codium fragile	*Enteromorpha compressa*
	E. flexuosa	*E. intestinalis*
	E. linza	*E. prolifera*
	Kommannia leptoderma	*Monostroma grevillei*
	M. oxyspermum	*Protomonostroma undulatum*
	Rhizoclonium reparium	*Spongomorpha arcta*
	S. lanosa	*Ulothrix flacca*
	Ulva latuca	*Urospora penicilliformis*
Phaeophyta		
	Ascophyllum nodosum	*Chorda filum*
	Cladosiphon zosterae	*Cladostephus spongiosus*
	Desmarestia viridis	*Desmotrichum undulatum*
	Dictyosiphon foeniculaceus	*Ectocarpus siliculosus*
	Elaschista fucicola	*Fucus evanescens*
	F. spiralis	*F. vesiculosus*
	Giffordia granulosa	*Laminaria digitata*
	L. saccharina	*Leathesia difformis*
	Petalonia fascia	*Pilayella littoralis*
	Punctaria latifolia	*Ralfsia verrucosa*
	Scytosiphon lomentaria	
Rhodophyta		
	Agardhiella subulata	*Ahnfeltia plicata*
	Antithamnion cruciatum	*Audouinella* sp.
	Bangia atropurpurea	*Bonnemaisonia hamifera*
	Callithamnion baileyi	*C. byssoides*
	C. tetragonum	*Ceramium elegans*
	C. rubrum	*Champia parvula*
	Chondrus crispus	*Corallina officinalis*
	Cystoclonium purpureum	*Dasya baillouviana*
	Dumontia contorta	Encrusting corallines
	Gelidium pusillium	*Gloiosiphonia capillaries*
	Gracilaria tikvahiae	*Griffithsia globulifera*
	Grinnellia Americana	*Hildenbrandia rubra*
	Lomentaria baileyana	*Mastocarpus stellatus*
	Palmaria palmata	*Phycodrys rubens*
	Phyllophora pseudoceranoides	*P. truncata*
	Plumaria elegans	*Pneophyllum lejolisii*
	Polyides rotundus	*Polysiphonia denudata*
	P. fibrillose	*P. harveyi*
	P. lanosa	*P. nigra*
	P. nigrescens	*P. novae-angliae*
	P. urceolata	*P. umbrilicalis*
	Porphyra umbilicalis	*Pterothamnion plumula*
	Rhodomeia confervoides	*Scagelia pylaisaei*
	Titanoderma pustulatum	
Cyanophyta		
	Callothrix sp.	*Microcoleus lyngbyaceus*
Chrysophyta		
	Berkeleya rutilens	*Grammatophora angula*
	Licomorpha sp.	*Melosira* sp.
	Vaucheria sp.	

Literature Cited

Beck, A. and M. Beck. 1998. Narragansett Bay National Estuarine Research Reserve Revised Management Plan 1998. Prepared by R.I. Department of Environmental Management Narragansett Bay National Estuarine Research Reserve Program and NOAA Sanctuaries and Reserves Division. Rhode Island Sea Grant, Narragansett, R.I. 145pp.

Berman, D.J. 2006. Recycling from Rhodes to reefs. *Public Roads* **70(2)**:1–18. Available at: *www.tfhrc.gov/pubrds/06sep/05.htm*.

Bertness, M.D. 1992. The ecology of a New England salt marsh. *American Scientist* **80**:260–268.

Bertness, M.D., S.D. Gaines, and M.E. Hay. 2001. *Marine Community Ecology*. Sinauer Associates, Inc., Sunderland, Mass.

Bintz, J.C. and S.W. Nixon. 2001. Responses of eelgrass *Zostera marina* seedlings to reduced light. *Marine Ecology Progress Series* **223**:133–141.

Castro, K.M. 2003. Assessing the impact of habitat and stock enhancement for the American lobster (*Homarus americanus*) in Narragansett Bay, Rhode Island. University of Rhode Island Ph.D. Dissertation. Kingston, R.I.

den Hartog, C. 1987. Wasting disease and other dynamic phenomena in *Zostera* beds. *Aquatic Botany* **27**:3–14.

Donaldson, J. 1995. Salt marsh. **In**: *A Guide to Rhode Island's Natural Places*. By Gibbs, E., T. Corey, M. Schwartz, D. Grossman-Garber, C. Jaworski, and M. Bucheit. Rhode Island Sea Grant, Narragansett, R.I. 208pp.

Ely, E. and D.T. Crist. 2001. *Narragansett Bay Window: The Cooperative Bay Program—Phase 1*. Rhode Island Sea Grant, Narragansett, R.I. 16pp.

Environmental Protection Agency. 1998. Estuaries and your coastal watershed. Coastal Watershed Factsheets EPA 842-F-98-009. U.S. Environmental Protection Agency Office of Water, Washington, D.C. Available at: *www.epa.gov/owow/oceans/factsheets/fact5.html*.

Fonseca, M.S., W.J. Kenworthy, and G. Thayer. 1998. Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters. **In**: NOAA Coastal Ocean Program, Decision Analysis Series No. 12. NOAA Coastal Ocean Office, Silver Spring, Md. 222pp.

French, D.P., H. Rhines, J. Boothroyd, C. Galagan, M. Harlin, A. Keller, G. Klein-MacPhee, S. Pratt, M. Gould, M. Villalard-Bohnsack, L. Gould, and S. Porter. 1992. Habitat inventory/resource mapping for Narragansett Bay and associated coastline. Applied Science Associates Report 89-33, October 1992. Final Report, Narragansett Bay Project, Providence, R.I.

Granger, S., M. Brush, B. Buckley, M. Traber, M. Richardson, and S.W. Nixon. 2000. An assessment of eutrophication in Greenwich Bay. Paper No. 1 in: M. Schwartz (ed.) Restoring Water Quality in Greenwich Bay: A Whitepaper Series. Rhode Island Sea Grant, Narragansett, R.I. 20pp.

Granger, S., M. Traber, S.W. Nixon, and R. Keyes. 2002. A practical guide for the use of seeds in eelgrass (*Zostera marina* L.) restoration. Part I. Collection, processing, and storage. M. Schwartz (ed.), Rhode Island Sea Grant, Narragansett, R.I. 20pp.

Harris, L.A., B. Buckley, S.W. Nixon, and B.T. Allen. 2004. Experimental studies of predation by bluefish *Pomatomus saltatrix* in varying densities of seagrass and macroalgae. *Marine Ecology Progress Series* **281:**233–239.

Hicks, G.R.F. 1986. Meiofauna associated with rocky shore algae. **In**: *The Ecology of Rocky Coasts*. Pp. 36–56. Edited by Moore, P.G. and R. Seed. Cambridge University Press, Cross, N.Y.

Hurley, L. 1992. Field guide to the submersed aquatic vegetation of Chesapeake Bay. U.S. Fish and Wildlife Service Report. 51pp.

Keller, A.A., M.E.Q. Pilson, and R. Johnson. 1996. Estuarine profile of Narragansett Bay, Rhode Island. University of Rhode Island Graduate School of Oceanography Technical Report. 244pp.

Levine, H.G. and R.E. Wilce. 1980. *Ulva lactuca* as a bioindicator of coastal water quality. Pub. #119. Water Resources Research center, University of Massachusetts at Amherst.

Mann, K.H. 1972. Introductory remarks. **In**: Proceedings of the IBP-UNESCO Symposium on Detritus and its Role in Aquatic Ecosystems. Pp.13–16. Edited by Melchiorri-Santlini, U. and J.W. Hopton. Memorie dell' Istituto Italiano di Idrobiologia, Pallanza, Italy. 540pp.

Mann, K.H. 1973. Seaweeds: Their productivity and strategy for growth. *Science* **182**:975–981.

Nixon, S.W. 1982. The ecology of New England high salt marshes: A community profile. FWS/OBS-81/55. U.S. Fish & Wildlife Service, Office of Biological Services, Washington, D.C. 70pp.

Nixon, S.W., B.A. Buckley, S.L. Granger, L.A. Harris, A.J. Oczkowski, R.W. Fulweiler, and L.W. Cole. 2007. Nutrient inputs to Narragansett Bay: Past, present, and future. **In**: *Science for Ecosystem-based Management: Narragansett Bay in the 21st Century*. Edited by Desbonnet, A. and B.A. Costa-Pierce. Springer Series in Environmental Management. New York, N.Y. 430pp.

Nixon, S.W. and C.A. Oviatt. 1973a. Ecology of a New England salt marsh. *Ecological Monographs* **43(4)**:463–498.

Nixon, S.W. and C.A. Oviatt. 1973b. Analysis of local variation in the standing crop of *Spartina alterniflora*. *Botanica Marina* **16:**103–109.

Nixon, S.W., C.A. Oviatt, and S.L. Northby. 1973. Ecology of small boat marinas. Marine Technical Report Series No. 5. Rhode Island Sea Grant, Narragansett, R.I. 20pp.

Olsen, S., D.D. Robadue, Jr., and V. Lee. 1984. *An Interpretive Atlas of Narragansett Bay*. Rhode Island Sea Grant, Narragansett, R.I. 82pp.

Orth, R.J. and K. Moore. 1983. Chesapeake Bay: An unprecedented decline in submerged aquatic vegetation. *Science* **22**:51–53.

Roman, C.T., K.B. Raposa, S.C. Adamowicz, M.J. James-Pirri, and J.G. Catena. 2002. Quantifying vegetation and nekton response to tidal restoration of a New England salt marsh. *Restoration Ecology* **10(3)**:450–460.

Rosenzweig, L., R. Duhaime, A. Mandeville, and P. August. 2002. Ecological geography of Block Island. **In**: *The Ecology of Block Island*. Pp. 3–12. Edited by Paton, P.W., L.L. Gould, P.V. August, and A.O. Frost. Rhode Island Natural History Survey, Kingston, R.I.

Schwartz, M.L. 1996. Finding new homes for lobsters. **In**: *Nor'easter: Magazine of the Northeast Sea Grant Programs* **8(1)**:4.

Scott, T.M., D. Alves, R.B. Rheault, and M.A. Rice. 2000. Aquaculture in Rhode Island: Working Draft 12 April 2000. Narragansett Bay Summit 2000 Whitepaper. 18pp.

Sears, J.R. and J. Battaglia. 1990. Uses of benthic seaweeds to monitor heavy metals at selected sites in Buzzards Bay, adjacent estuaries and New Bedford Harbor, Massachusetts. Final Report 87-10. Massachusetts Department of Environmental Protection. 88pp.

Shisler, J.K. 1990. Creation and restoration of coastal wetlands of the northeastern United States. **In**: *Wetland Creation and Restoration*. Pp. 143–170. Edited by Kusler, J.A. and M.E. Kentuna. Island Press, Washington, D.C.

Short, F.T., D. Burdick, S. Granger, and S.W. Nixon. 1996. Long-term decline in eelgrass, *Zostera marina* L., linked to increased housing development. Pp. 291–298. **In**: Seagrass Biology: Proceedings of an International Workshop. Edited by Kuo, J., R. Phillips, D. Walker, and H. Kirkman. Rottnest Island, Western Australia.

Teal, J. and M. Teal. 1969. *Life and Death of the Salt Marsh*. National Audubon Society. Ballentine Books, New York, N.Y. 274pp.

Thayer, G.W., S.M. Adams, and M.V. LaCroix. 1975. Structural and functional aspects of a recently established *Zostera marina* community. *Estuarine Research* **1**:518–540.

Thayer, G.W., W.J. Kenworthy, and M.S. Fonseca. 1984. The ecology of eelgrass meadows of the Atlantic coast: A community profile. U.S. Fish & Wildlife Service FWS/OBS-84124. 85pp.

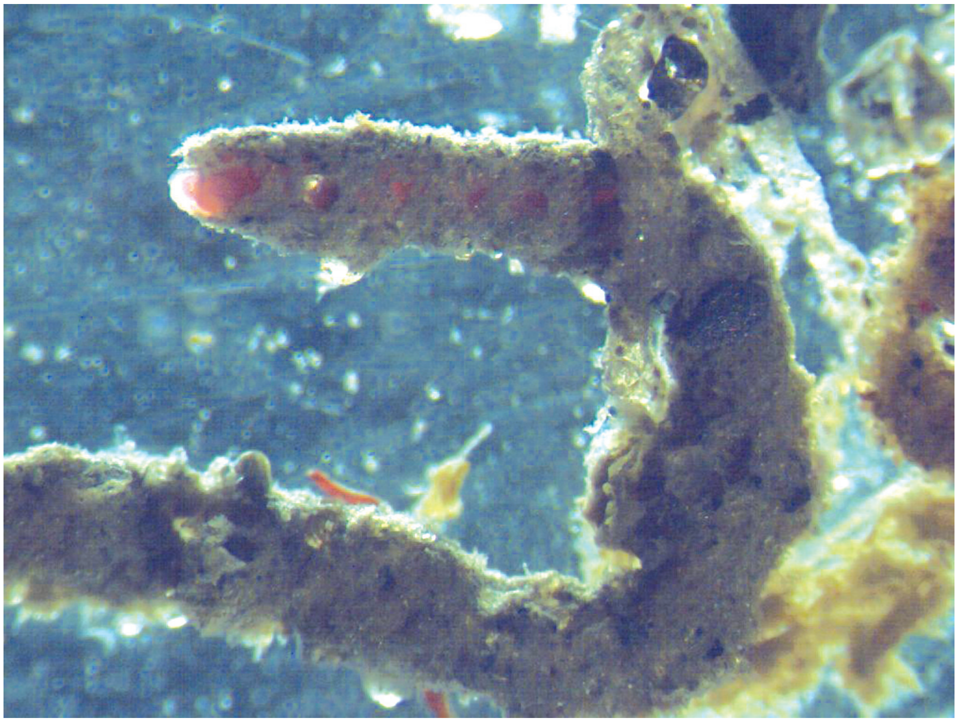
Tiner, R.W., Jr. 1984. Wetlands of the United States: Current status and recent trends. U.S. Fish & Wildlife Service, National Wetlands Inventory, Washington, D.C.

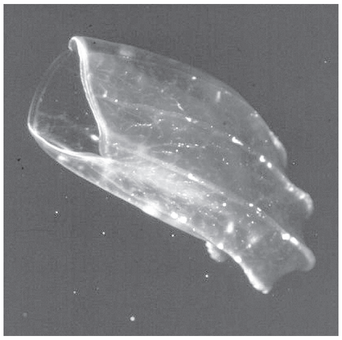
Tiner, R.W., Jr., I.J. Huber, T. Nuerminger, and A.L. Mandeville. 2004. Coastal wetland trends in the Narragansett Bay estuary during the 20th century. U.S. Fish & Wildlife Service, Northeast Region, Hadley, Mass. National Wetlands Inventory Cooperative Interagency Report. 37pp.

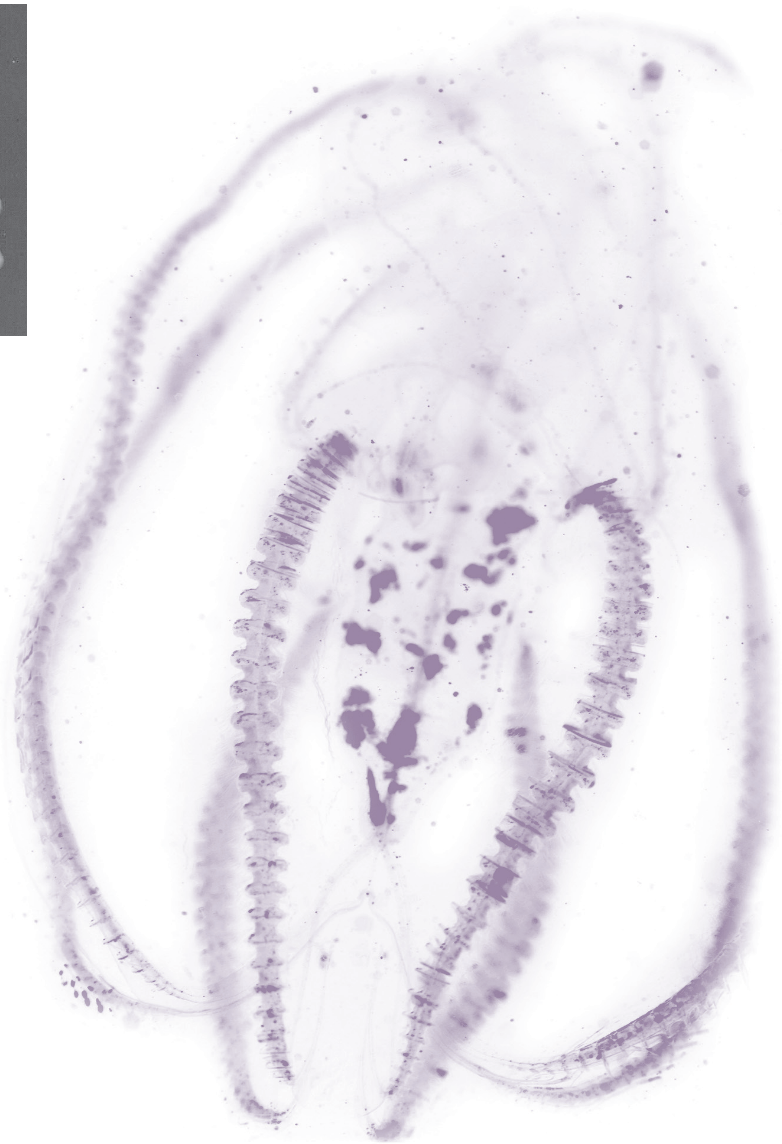
CHAPTER 9.

Plankton and Benthos

Kenneth B. Raposa and
Christine R. Comeau







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 lutues,* and *Thalassiosira nordenskioeldii*. 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. lutues*, 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 (*Mnmeiopsis 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 ($\mu g\ L^{-1}$) in the Providence River to 3 $\mu g\ L^{-1}$ in Rhode Island Sound. Seasonal patterns in phytoplankton also differ around the Bay; a large, distinct chlorophyll maximum is

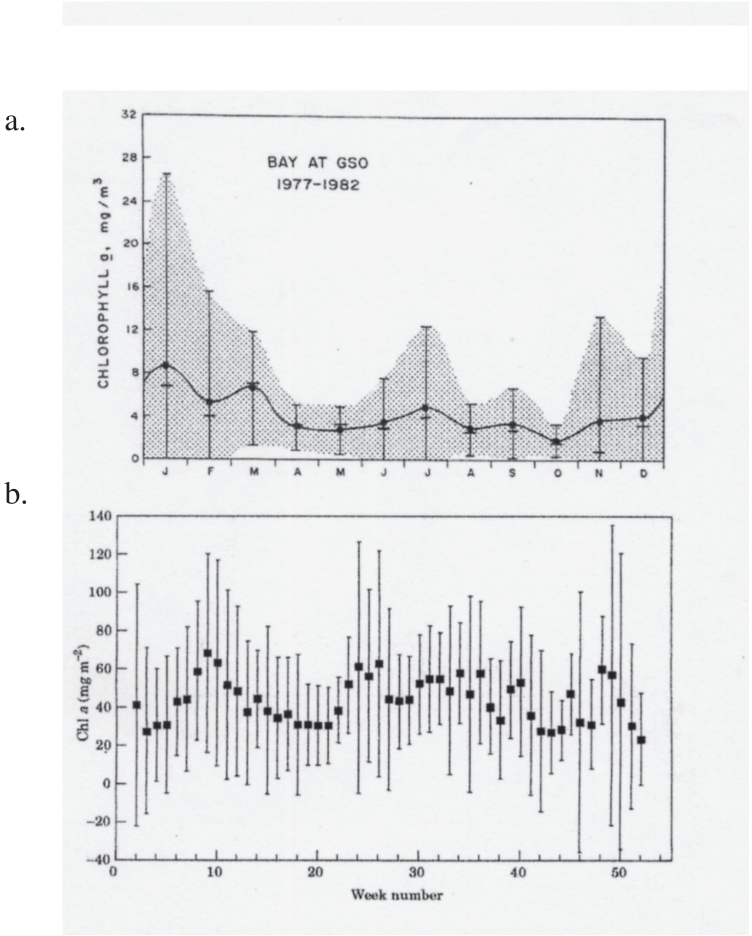


Figure 9.1. Seasonal changes in chlorophyll *a* in Narragansett Bay, Rhode Island. (a) Reproduction of Figure 7 from Pilson (1985) illustrating chlorophyll concentrations from the dock at the GSO from 1977–1982. Error bars are two standard deviations and the shaded areas represent the field where 95 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.

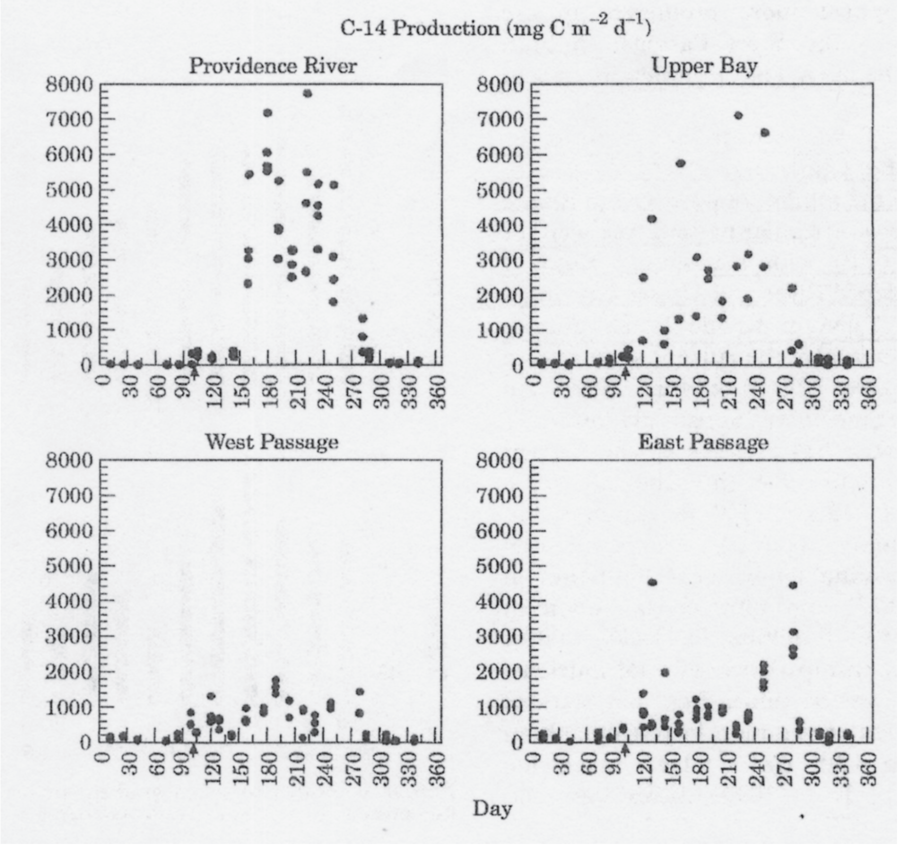


Figure 9.2. Reproduction of Figure 4 from Oviatt et al. (2002) showing phytoplankton primary production in different regions of Narragansett Bay using the C^{14} method. Data were collected every two weeks from April 1997 through April 1998. Note the very high production levels in the Providence River 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 g C m^{-2} yr^{-1} in the Providence River and a low of 152 g C m^{-2} 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 macrozoplankton (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, copepedite, 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).

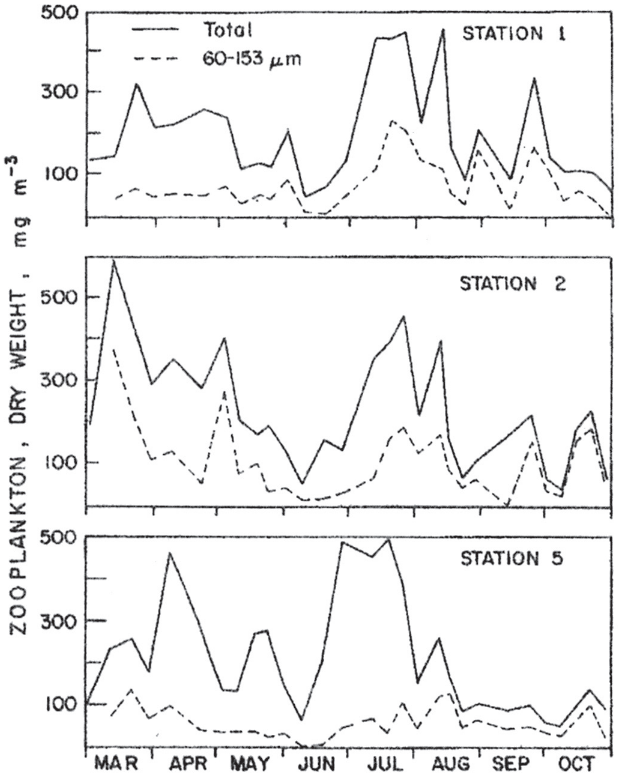


Figure 9.3. Reproduction of Figure 6 from Durbin and Durbin (1981) showing seasonal patterns of zooplankton biomass for all zooplankton combined and for the 60–153 µm size fraction. Data were collected at approximately weekly intervals from March to October 1976. Note the consistently high zooplankton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

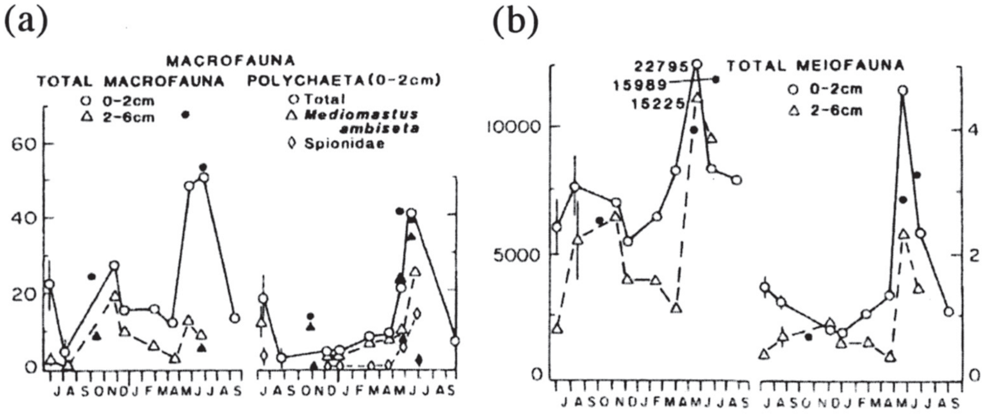


Figure 9.5. Partial reproduction of Figure 2 from Rudnick et al. (1985). (a) Abundance of total macrofauna (left panel) and polychaetes (right panel) over time. (b) Abundance (left panel) and biomass (right panel) of total meiofauna over time. Abundance is presented as number of individuals m^{-2} and 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 *Nephytes-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

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

Order Pennales

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

Class Dinophyceae

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

Appendix 9.1. Continued

Oxyrrhus marina
Paulsenella chaetoceratis
Polykrikos schwarzii
Prorocentrum balticum
P. gracile
P. micans
P. minimum
P. scutellum
P. triestinum
Protogonyaulax tamarensis
Protoperidinium bipes
P. conicum
P. depressum
P. excentricum
P. granii
P. leonis
P. minutum
P. steinii
Protoperidinium spp.
Scrippsiella trochoidea

Additional phytoplankton species

Apedinella spinifera
Aureococcus anophagefferns
Carteria sp.
Chlamydomonas sp.
Chlorella sp.
C. salina
Chroomonas spp.
Chrysochromulina ericina
C. parkae
Chrtsochromulina spp.
Coccolithus pelagicus
Cricosphaera roscoffensis
Cryptomonas spp.
Dichtyocha fibula
Dinobryon balticum
Distephanus speculum
Dunaliella sp.
Ebria tripartita
Euglena proxima
Euglena spp.
Eutreptia scotica
Eutreptiella hirudoidea
Eutreptiella sp.
Fibrocapsa japonica
Hemiselmis sp.
Hermesinum adriaticum
Heteronema acus
Isochrysis sp.
Mesocena polymorpha
Micromonas pusilla
Nannochloris sp.
Nephroselmis rotunda
Nephroselmis sp.
Ochromonas sp.
Olisthodiscus luteus
Oltmannsielloopsis virida
Paraphysomonas sp.
Pavlova gyrans
Pavlova sp.
Pedinomonas minor
Phaeocystis pouchetii
Pseudopedinella pyriformis
Pterosperma sp.
Pyramimonas amylifera
P. torta
Pyramimonas sp.
Spirulina subsalsa
Synechococcus sp.
Tetraselmis spp.
Urceolus 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
Acartia hudsonica
A. tonsa
A. longiremis
Calanus finmarchicus
Centropages hamatus
C. typicus
Coryceaus sp.
Cyclops sp.
Eurytemora sp.
Harpacticoid sp.
Hemicyclops sp.
Labidocera aestiva
Metridia lucens
Microstetella norvegica
Oithona colcarva
O. similis
Oncea sp.
Paracalanus parvus
Parvocalanus crassirostris
Pseudocalanus minutus
Pseudodiaptomus coronatus
Rhincalanus nasutus
Temora longicornis
Tortanus discaudatus

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

Appendix 9.3. Continued

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

Literature Cited

Borkman, D.G. and T.J. Smayda. 1998. Long-term trends in water clarity revealed by Secchi-disk measurements in lower Narragansett Bay. *ICES Journal of Marine Science* **55:**668–679.

Chowder and Marching Society. 1967. Jiffy Cruise Report. Graduate School of Oceanography, University of Rhode Island, Kingston, R.I. 74pp.

Costello, J.H., B.K. Sullivan and D.J. Gifford. 2006. A physical-biological interaction underlying variable phenological responses to climate change by coastal zooplankton. *Journal of Plankton Research* **28:**1099–1105.

Deason, E.E. and T.J. Smayda. 1982. Ctenophore zooplankton-phytoplankton interactions in Narragansett Bay, Rhode Island, USA, during 1972–1977. *Journal of Plankton Research* **4:**203–215.

Durbin, A.G. and E.G. Durbin. 1981. Standing stock and estimated production rates of phytoplankton and zooplankton in Narragansett Bay, Rhode Island. *Estuaries* **4:**24–41.

Durbin, A.G. and E.G. Durbin. 1988. Zooplankton and ichthyoplankton in Narragansett Bay: Status and trends. Part 1: Zooplankton. Report #NBP-89-18 to the Narragansett Bay Project. 76pp.

Durbin, E.G., R.W. Krawiec, and T.J. Smayda. 1975. Seasonal studies on the relative importance of different size fractions of phytoplankton in Narragansett Bay (USA). *Marine Biology* **32:**271–287.

Ellis, G. 2002. An examination of the benthic macrofauna of Narragansett Bay and the possible implications of winter-spring bloom intensity on population size. M.S. Thesis, University of Rhode Island, Kingston, R.I. 181pp.

Frithsen, J.B. 1989. The benthic communities within Narragansett Bay. Report #NBP-90-28 to the Narragansett Bay Project. 92pp.

Frolander, H.F. 1955. The biology of the zooplankton of the Narragansett Bay area. Ph.D. Dissertation, Brown University, Providence, R.I. 94pp.

Grassle, J.F., J.P. Grassle, L.S. Brown-Leger, R.F. Petrecca, and N.J. Copley. 1985. Subtidal macrobenthos of Narragansett Bay: Field and mesocosm studies of the effects of eutrophication and organic input on benthic populations. **In:** *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms*. **Pp.** 421–434. Edited by Gray, J.S. and M.E. Christiansen. Wiley, New York, N.Y.

Hargraves, P.E. 1988. Phytoplankton of Narragansett Bay. **In:** *Freshwater and Marine Plants of Rhode Island*. **Pp.** 136–143. Edited by Sheath, R.G. and M.M. Harlin. Kendall-Hunt Publishing Company, Dubuque, Iowa. 149pp.

Hinga, K.R., N.F. Lewis, R. Rice, K. Dadey, and A. Keller. 1989. A review of Narragansett Bay phytoplankton data: Status and trends. Report #NBP-89-21 to the Narragansett Bay Project. 251pp.

Karentz, D. and T.J. Smayda. 1984. Temperature and seasonal occurrence patterns of 30 dominant phytoplankton species in Narragansett Bay over a 22-year period (1959–1980). *Marine Ecology Progress Series* **18:**277–293.

Karentz, D. and T.J. Smayda. 1998. Temporal patterns and variations in phytoplankton community organization and abundance in Narragansett Bay during 1959–1980. *Journal of Plankton Research* **20:**145–168.

Keller, A.A., C.A. Oviatt, H.A. Walker, and J.D. Hawk. 1999. Predicted impacts of elevated temperature on the magnitude of the winter-spring phytoplankton bloom in temperate coastal waters: A mesocosm study. *Limnology and Oceanography* **44:**344–356.

Keller, A.A., M.E.Q. Pilson, and R. Johnston. 1996. Estuarine profile of Narragansett Bay, Rhode Island. Unpublished Draft Final Report. University of Rhode Island, Narragansett, R.I. 115pp.

Kremer, J.N. 1990. The Narragansett Bay model—an ecological simulation of a coastal marine ecosystem: User's guide to the computer model and the Bay model analyzer. Report #NBP-90-42 to the Narragansett Bay Project. 45pp.

Kremer, J.N. and S.W. Nixon. 1978. *A Coastal Marine Ecosystem: Simulation and Analysis*. Springer-Verlag, New York, N.Y. 217pp.

Li, Y. amd T.J. Smayda. 1998. Temporal variability of chlorophyll in Narragansett Bay, 1973–1990. *ICES Journal of Marine Science* **55:**661–667.

Myers, A.C. and D. K. Phelps. 1978. Criteria of benthic health: A transect study of Narragansett Bay, Rhode Island. Final Report to the U.S. Environmental Protection Agency, Narragansett, R.I.

Nixon, S., S. Granger, and B. Buckley. 2003. The warming of Narragansett Bay. *41°N* **2:**18–20.

Oviatt, C.A. 1994. Biological considerations in marine exclosure experiments: Challenges and revelations. *Oceanography* **7:**45–51.

Oviatt, C.A. Keller, and L. Reed. 2002. Annual primary production in Narragansett Bay with no Bay-wide winter-spring phytoplankton bloom. *Estuarine, Coastal and Shelf Science* **54:**1013–1026.

Phelps, K.D. 1958. A quantitative study of the infauna of Narragansett Bay in relation to certain physical and chemical aspects of their environment. M.S. Thesis, University of Rhode Island. 56pp.

Pilson, M.E.Q. 1985. Annual cycles of nutrients and chlorophyll in Narragansett Bay, Rhode Island. *Journal of Marine Research* **43:**849–873.

Pratt, D.M. 1959. The phytoplankton of Narragansett Bay. *Limnology and Oceanography* **4:**425–440.

Pratt, S.D. 1972. Effects of spoil dumping on the benthic inverte-brates of the sound. **In:** *Dredge Spoil Disposal in Rhode Island Sound*. **Pp**. 31–42. Edited by Saila, S.B., S.D. Pratt, and T.T. Polgar. Marine Technical Report Number 2, University of Rhode Island, Kingston, R.I.

Pratt, S.D. and J.J. Bisagni. 1976. Monitoring results—Providence River dredging 1975. Submitted to the New England Division of the U.S. Army Corps of Engineers. 31pp.

Rudnick, D.T. and C.A. Oviatt. 1986. Seasonal lags between organic carbon deposition and mineralization in marine sediments. *Journal of Marine Research* **44:**815–837.

Rudnick, D.T., R. Elmgren, and J.B. Frithsen. 1985. Meiofaunal prominence and benthic seasonality in a coastal marine ecosystem. *Oecologia* **67:**157–168.

Sarno, D., W.H.C.F. Kooistra, L.K. Medlin, I. Percopo, and A. Zingone. 2005. Diversity in the genus *Skeletonema* (Bacillariophyceae). II. An assessment of the taxonomy of *S. costatum*-like species with the description of four new species. *Journal of Phycology* **41**:151–176.

Smayda, T.J. 1957. Phytoplankton studies in lower Narragansett Bay. *Limnology and Oceanography* **2:**342–354.

Smayda, T.J. 1998. Patterns of variability characterizing marine phytoplankton, with examples from Narragansett Bay. *ICES Journal of Marine Science* **55:**562–573.

Stickney, A.P. and L.D. Stringer. 1957. A study of the invertebrate bottom fauna of Greenwich Bay, R.I. *Ecology* **38:**111–122.

CHAPTER 10.

Nekton

Kenneth B. Raposa

Nekton

Introduction

Nekton generally refers to free-swimming organisms including invertebrates, fish, and marine turtles and mammals. In estuaries, however, this term typically refers to fishes and decapod crustaceans. Nekton is a critical functional component of estuarine ecosystems. Some estuarine nekton species are commercially and recreationally important, while others provide food for birds, mammals, and larger fish (Friedland et al., 1988; Sekiguchi, 1995; Smith, 1997). Some species of nekton can physically transfer organic materials between intertidal and subtidal estuarine habitats (Cicchetti, 1998), and as a guild, nekton can be used as an indicator of estuarine condition (Deegan et al., 1997). In some situations, nekton can exert substantial top-down control over estuarine system processes (Silliman and Bertness, 2002). Nekton is also a charismatic group of species that the public can easily relate to; it therefore can provide an important link between estuarine science and education or policy.

Narragansett Bay provides refuge, spawning, and foraging habitats for a diverse assemblage of nekton. Due to its location in southern New England, Narragansett Bay supports species from northern, boreal areas as well as species from subtropical and tropical climates over an annual cycle. These species include permanent and seasonal residents, seasonal and occasional visitors, anadromous and catadromous species, and accidentals and strays. Narragansett Bay provides support functions for all life history stages of nekton, including planktonic, larval, juvenile, and adult stages. When present in Narragansett Bay, these nekton have available to them a wide variety of habitats that include open water, unvegetated bottoms, intertidal beaches, salt and brackish marshes, SAVs, tidal freshwater creeks, rocky reefs, and human-modified shorelines.

Many species of nekton in Narragansett Bay support commercial or recreational fisheries (DeAlteris et al., 2000) and thus have been the focus of numerous research and monitoring programs. Based on data from several ongoing nekton monitoring programs, a great deal is known about the long-term trends in species abundance and biomass as well as distribution patterns over time. Aside from this, surprisingly little research has actually been done that specifically examines the ecology and functional role of most fish species in Narragansett Bay. For example, Keller et al. (1996) indicates that we still do not fully understand why the abundance of some species varies considerably over time independent of fishing pressure.

The goal of this chapter is to provide an ecological overview of nekton from two major zones of the Bay (open water and shore) and another overview focusing on ichthyoplankton. Open water nekton include those species that typically are found in the deepwater areas of the Bay, either in pelagic or demersal habitats, and those that are typically captured with a trawl. Shore-zone or intertidal nekton include those species that are found in shallow water habitats of the Bay that include salt marshes, eelgrass beds, coves, embayments and unvegetated shallows.

Open-water Nekton

One of the first studies that focused on fishes in the open waters of Narragansett Bay was conducted over 30 years ago by Oviatt and Nixon (1973). These authors used a trawl to sample from nine regular and 13 occasional stations in Narragansett Bay for one year. Forty-four species were documented in Narragansett Bay. Although typical of temperate estuaries, a small number of species dominated the catch (in this study, the 10 most abundant species made up 91 percent of the catch). This study also demonstrated that:

- The composition of the fish community in Narragansett Bay is comparable to those in Block Island and Long Island sounds.
- Fish abundance and biomass per unit area are comparable to other New England coastal and offshore areas, although standing crop was much less than in kelp forests, coral reefs, and salt marshes.
- Winter flounder (*Pseudopleuronectes americanus*) was easily the most abundant species, making up 36 percent of the catch.
- Spatial patterns in fish distribution were not apparent except that diversity was highest near the mouth of the Bay.
- The demersal fish in Narragansett Bay may be important in regulating the diversity and abundance of the benthos.

Oviatt and Nixon's work was limited in that it only documented the fish of Narragansett Bay at one point in time. For example, although winter flounder dominated in 1971–72, this and other

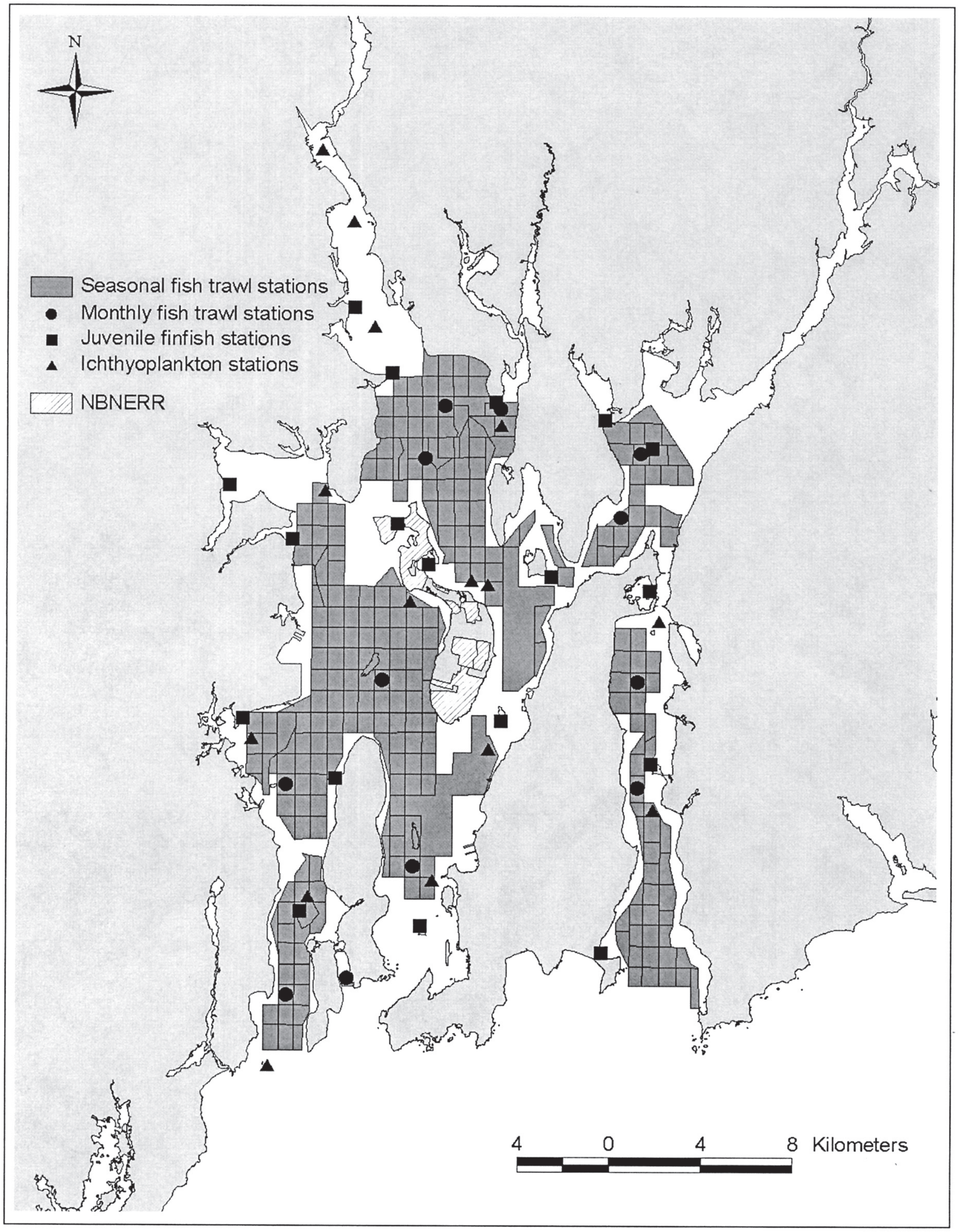


Figure 10.1. Locations of sampling stations that are part of the seasonal and monthly fish trawl survey, the juvenile finfish survey, and the Keller et al. ichthyoplankton survey that are discussed in this chapter.

demersal species have declined dramatically in subsequent decades (Oviatt et al., 2003). In recognition of the need for detailed fisheries data over time, two long-term monitoring programs were initiated in the open waters of Narragansett Bay. These programs are the RIDEM sportfish trawl survey throughout Narragansett Bay and in Rhode Island and Block Island sounds (e.g., Lynch, 2000), and the GSO fish trawl survey (Jefferies and Johnson, 1974; Jeffries and Terceiro, 1985; Jeffries et al., 1989). The GSO trawl survey is the longer running of the two, dating back to 1959; however, this survey is spatially limited since samples are only collected from two stations in the West Passage of Narragansett Bay. In contrast, the RIDEM trawl survey began 20 years later in 1979, but it samples throughout the entire Bay (Fig. 10.1) and thus provides a more comprehensive dataset in terms of combining temporal and spatial coverage. The RIDEM program has two components: a monthly survey at 12 fixed stations in the Bay that began in 1990, and a seasonal survey in spring and fall at approximately 50 stations (selected randomly from approximately 265 stations located throughout the Bay) that began in 1979.

From 1979 through 2003, 107 species (mostly fish, a few crustaceans, and one bivalve species) have been collected from the combined efforts of the RIDEM monthly and seasonal fish trawls. However, the mean number of species in any given year is much less, averaging 57 species per year from the monthly program and 45 species per year from the seasonal program (Fig 10.2). This illustrates the value of the two programs—more species are observed annually with the monthly effort, which provides a more comprehensive overall view of fish community composition and structure, while the seasonal program provides more information on the Bay-wide distribution of common species because more stations are sampled. Based on abundance from the seasonal data, five species make up greater than 90 percent of the community found in Narragansett Bay since 1979. In decreasing abundance, these species include bay anchovy (*Anchoa mitchilli*, 51 percent of total abundance), scup (*Stenotomus chrysops*, 19 percent), longfin squid (*Loligo pealei*, 8 percent), menhaden (*Brevoortia tyrannus*, 6 percent), and butterfish (*Peprilus triacanthus*, 5 percent) (Appendix 10.1). Using the same data, but considering biomass, 13 species make up over 90 percent of the total nekton biomass. In decreasing order, these species are scup (19 percent), winter flounder (18 percent), American lobster (9 percent), skates (Rajidae, 9 percent), windowpane flounder (*Scophthalmus aquosus*, 6 percent), longfin squid (6 percent), tautog (*Tautoga onitis*, 6 percent), butterfish (5 percent), summer flounder (*Paralichthys dentatus*, 4 percent), bay anchovy (3 percent), weakfish (*Cynoscion regalis*, 2 percent), Atlantic herring (*Clupea harengus*, 2 percent), and bluefish (*Pomotomus saltatrix*, 2 percent). Based on biomass, the nekton species that dominate Narragansett Bay are primarily demersal species such as flounders, lobster, and skates. However, based on abundance, the opposite is true where the dominant species are mostly small, schooling, pelagic species.

The data from the RIDEM trawl programs are particularly useful for observing trends in fish over time and at a Bay-wide scale. There is no clear trend in the annual number of species in Narragansett Bay (Fig. 10.2), nor is there a trend in total fish biomass over time (Fig. 10.3). In contrast, total abundance is tending to increase over time, mostly due to increases in small pelagic schooling fish such as Atlantic menhaden and bay anchovy. In fact, these data have documented a shift in species abundance patterns in Narragansett Bay. The Bay is undergoing a shift from a community dominated by demersal species to a system dominated by pelagic species that may be due to climate and bottom-trawl fishing (Oviatt et al., 2003). Further, data from the seasonal trawl survey illustrate that this trend is occurring on a Bay-wide scale. For example, using GIS, it is clear that the abundance of the commercially important winter flounder has been in steady decline since at least the beginning of the survey, and this decline is evident throughout Narragansett Bay (Fig. 10.4). Similar patterns have been observed for other demersal species, including those that are not exposed to fishing pressure (e.g., hogchoker, *Trinectes maculatus*) (Lynch, personal communication).

In contrast to the abundance of long-term monitoring data, surprisingly little research on open-water nekton in Narragansett Bay has been conducted, especially recently. However, there are some notable recent examples. Durbin and Durbin (1998) used a bioenergetic model to examine the effects of menhaden predation on phytoplankton in Narragansett Bay. DeAlteris et al. (2000) used monitoring and landing data to summarize the status and trends of many of Narragansett Bay's commercial fisheries. Lapolla (2001a, 2001b) examined a number of population characteristics of the bay anchovy in

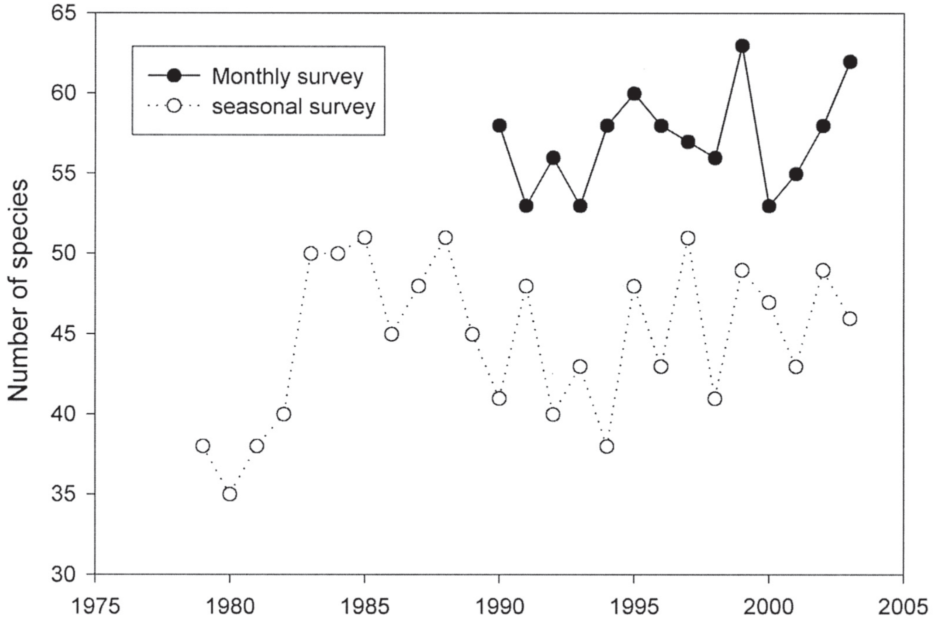


Figure 10.2. The average annual number of species of nekton in Narragansett Bay as determined from the RIDEM seasonal and monthly fish trawl program. Nearly all the species are fishes; relatively few are invertebrates.

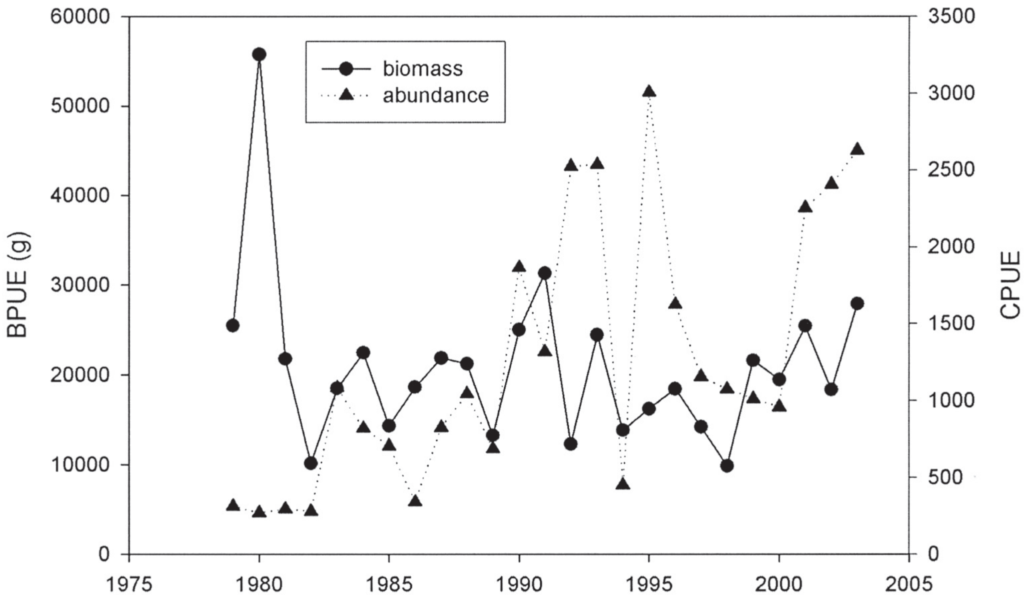


Figure 10.3. Mean catch (abundance) (number of individuals captured per trawl; CPUE) and mean biomass (biomass in grams per trawl; BPUE) between 1979 and 2003 from the RIDEM seasonal fish trawl.

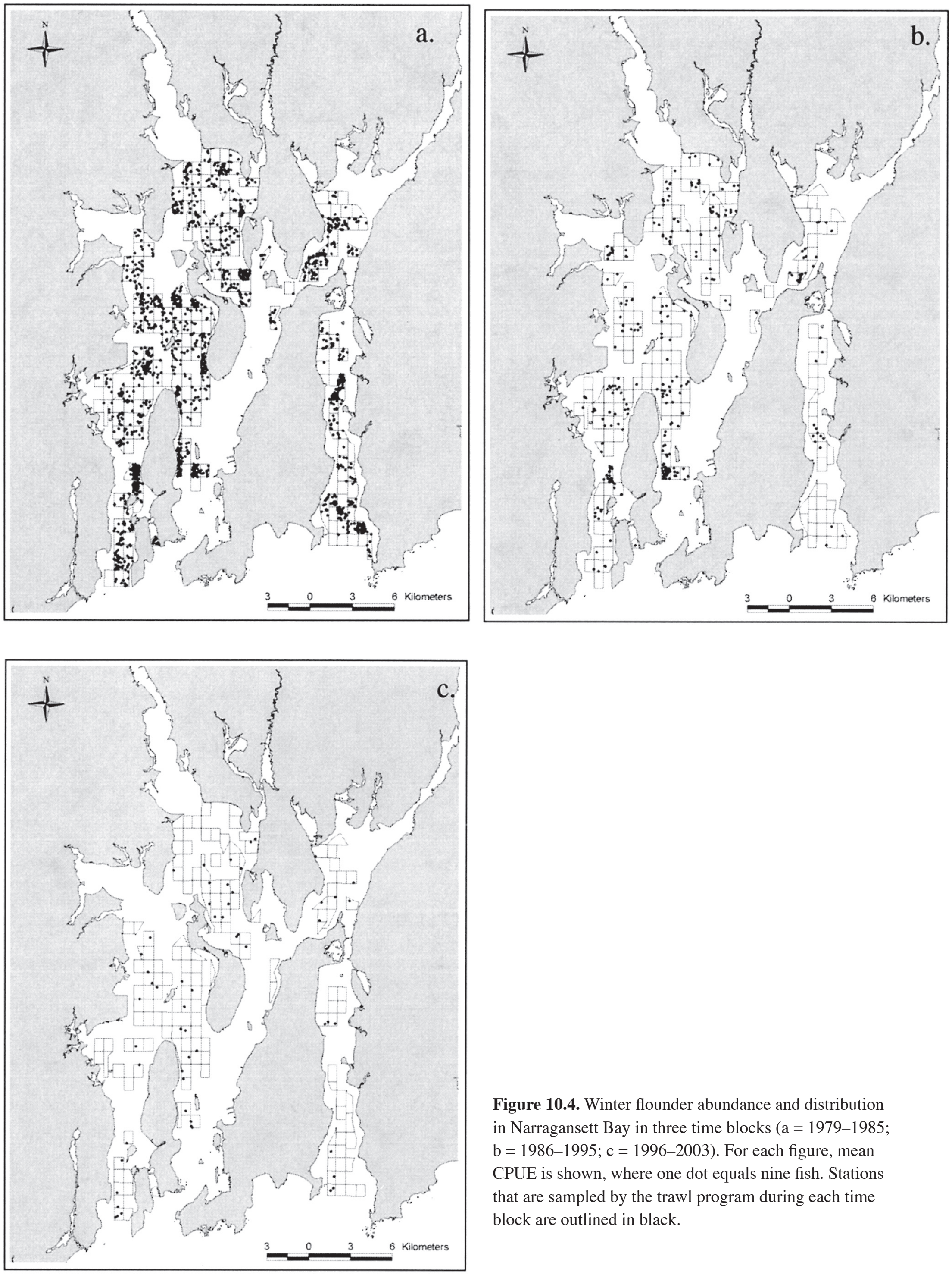


Figure 10.4. Winter flounder abundance and distribution in Narragansett Bay in three time blocks (a = 1979–1985; b = 1986–1995; c = 1996–2003). For each figure, mean CPUE is shown, where one dot equals nine fish. Stations that are sampled by the trawl program during each time block are outlined in black.

Figure 10.5. Researchers conducting the RIDEM juvenile finfish seine survey. *Photo by J. Christopher Powell, RIDEM.*

Narragansett Bay, including population structure, growth, mortality, and spawning season. Meng et al. (2001) found that winter flounder growth rates in Narragansett Bay were lower in the upper Bay, suggesting that anthropogenically lowered dissolved oxygen levels had a negative impact on this species. More recently, Oviatt et al. (2003) used historic and current data to demonstrate the dramatic effects humans have had on the fishes of Narragansett Bay through fishing pressures, and Castro and Angell (2000), Castro et al. (2005), and Cobb and Castro (2006) have examined aspects of the emergence, spread, and severity of lobster shell disease in the Bay.

Shore-zone and Intertidal Nekton

Shallow estuarine waters provide critical nursery habitats for juvenile estuarine fish and permanent habitats for some abundant forage species. These types of habitats are often at risk, however, due to their proximity to the land and thus the activities of humans. Nekton in shallow, shore-zone habitats are monitored monthly from June through October by RIDEM with a juvenile finfish seining survey at 20 nearshore stations in Narragansett Bay (Fig. 10.5). Since the inception of this program in 1990, 78 species (or undifferentiated species within the same family, e.g., gobidae, bothidae) have been collected from nearshore and shore-zone habitats as part of this monitoring program. Based on abundance, the most common species include Atlantic menhaden (62 percent of total abundance), silversides (*Menidia* spp., 8 percent), river herring species (6 percent), bluefish (*Pomotomus saltatrix*, 4 percent), winter flounder (3 percent), striped killifish (*Fundulus majalis*, 3 percent), sea herring species (3 percent), and bay anchovy (2 percent) (Appendix 10.2). Meng and Powell (1999) used these data to explore relationships between fish communities and habitats. This study found that separate analyses of fish communities and their habitats correlated well. In addition, it was found that total abundance, species richness, and the number of winter flounder were highest at an upper Bay station. This is contrary to the findings of Oviatt and Nixon (1973); however, the two studies used different gears to sample different age classes of fish, and the two studies were conducted over 25 years apart. Dorf and Powell (1997) used these same seining data to document the distribution and habitat preferences of juvenile tautog, a recreationally important species, in Narragansett Bay. More recently, DeLong et al. (2001) used data from this survey in a model to examine the effects of density and environmental conditions on the growth of juvenile winter flounder.

Nekton has also been sampled extensively from salt marsh habitats around Narragansett Bay and the south shore of Rhode Island (Fig. 10.6). As with salt marshes elsewhere, marshes in Rhode Island clearly support highly abundant and produc-

tive nekton communities (Raposa, 2002; Meng et al., 2004). Quantitative data collected from three salt marshes around Rhode Island show that these marshes are consistently dominated by very few species (i.e., species diversity is low). These species include the common mummichog (*Fundulus heteroclitus*), striped killifish, sheepshead minnow (*Cyprinodon variegatus*), Atlantic and inland silversides (*Menidia menidia* and *Menidia beryllina*, respectively), and grass shrimp (*Palaemonetes* spp.) (Appendix 10.3). Less abundant, though ecologically important, species that also use Narragansett Bay salt marshes include juvenile winter flounder, sticklebacks (e.g., three-spined *Gasterosteus aculeatus*, fourspine *Apeltes quadracus*, and nine-spined *Pungitius pungitius*), American eel (*Anguilla rostrata*), and blue crab (*Callinectes sapidus*). The data in Appendix 10.3 further indicate that while general patterns of species composition are similar among marshes, large differences in density exist (e.g., *Palaemonetes pugio*). Halpin (1997) also noted substantial differences in mummichog use among different Narragansett Bay salt marshes. The factors that contribute to differences in nekton composition and abundance among salt marshes in Narragansett Bay are largely unknown and need to be identified and examined, especially in light of ongoing and future marsh restoration efforts.

Marsh nekton species can move among and utilize multiple marsh habitats (e.g., creeks, pools, vegetated marsh surface) depending on life history stage and tide stage. Roman et al. (2003) showed that more species were found in subtidal creeks and pools when compared to intertidal marsh habitats in the Sachuest Point salt marsh in Middletown, R.I. Data from Raposa (2002) in the Galilee, R.I., salt marsh indicate that nekton tend to be more abundant in subtidal, rather than intertidal, marsh creeks. In nearby Cape Cod, Mass., Raposa (2003) showed that mummichogs moved into soft-substrate pools in fall where they burrowed into the sediments to overwinter. A given marsh is a dynamic place with multiple habitats interacting to support nekton. Threats to some of these habitats in Rhode Island marshes include the invasion of high marsh by the common reed, *Phragmites australis*, the loss of marsh pools due to historic ditching, and tidal restrictions that limit nekton access to marsh surface habitats, which are used for foraging, nursery, and refuge.

The restoration of tide-restricted salt marshes around Narragansett Bay is clearly returning natural and abundant nekton communities to marshes that supported a dysfunctional and depleted community. Studies indicate that removing tide-restricting structures results in improved nekton function, and that the more severe the restriction, the more negatively affected the nekton community is, and the more positive the response is after restoration (Raposa, 2002; Raposa, unpublished data; Raposa and Roman, 2003; Roman et al., 2003). A consortium of agencies, including the R.I. Coastal Resources Management Council, the Narragansett Bay Estuary Program, and Save The Bay, among others, has identified salt marshes around Narragansett Bay that are in need of restoration, and some of these efforts are under way. If previous results hold true, these restoration efforts should continue to return nekton communities to more natural conditions representative of unrestricted salt marshes. In addition to removing tidal restrictions, efforts should seek to restore pool habitats that were lost from ditching. Salt marsh pools can support dense nekton assemblages (Raposa and Roman, 2001), and if the pools are shallow enough, this nekton provides attractive forage for wading birds.

Ichthyoplankton

Ichthyoplankton (eggs and larvae) are early life-history stages of nekton that are useful for understanding adult spawning patterns and temporal fluctuations in the abundance of juvenile and adult nekton. Ichthyoplankton are particularly abundant in estuaries in part due to the use of these areas as spawning and nursery grounds by nekton species. In recognition of this, and to help fill a critical data gap, multiple surveys and ichthyoplankton monitoring programs were initiated in Narragansett Bay. The first survey occurred in 1957–1958 and included sampling in the lower East Passage of Narragansett Bay and in Mount Hope Bay (Herman, 1963). Another survey occurred in 1972–1973 and included 160 total stations divided among 10 sectors in Narragansett Bay (Bourne and Govoni, 1988; hereafter referred to as the MRI (Marine Research Inc.) survey). Almost 20 years later, similar methods were used by Keller et al. (1999; hereafter referred to as the Keller survey) to collect newer data from 1989–1990 and to explore changes in ichthyoplankton composition and abundance over time. The most recent effort is a partnership between URI and RIDEM to collect annual data beginning in 2002 to observe ichthyoplankton trends over an even longer time period (Klein-MacPhee et al., 2002). The combined data from these programs provide a baseline for examining trends in composition, relative abundance, distribution, and seasonal abundance of ichthyoplankton in Narragansett Bay.

Ichthyoplankton on the whole display a clear seasonal pattern in abundance, with a distinct peak in eggs in June and in larvae slightly later in July. This pattern was observed in both the MRI and Keller surveys. The total number of ichthyoplankton species was also similar between the two surveys (43 in the MRI survey; 41 in the Keller survey), but differences in the abundance of dominant species were apparent. In 1972–73 the most abundant species included cunner (*Tautogolabrus adspersus*), tautog, bay anchovy, Atlantic menhaden, scup, and weakfish; in 1989–90 the dominant species included bay anchovy, tautog, and cunner, but menhaden, scup, and weakfish were not abundant. Egg and larval (all species combined) densities were considerably lower in 1989–90 compared to the MRI survey. Abundance of some species declined substantially in the highly impacted upper Bay, Providence River, and Greenwich Bay areas. In fact, Keller et al. (1999) indicate that there was a general shift in ichthyoplankton distribution down-Bay away from these impacted areas. It was not clear whether this was due to reduced adult spawning in the upper Bay regions, or to higher mortality of ichthyoplankton while in these areas. In either case, upper Bay regions that were known as important historic spawning and nursery areas for some important nekton species now seem to have lost some of that value, perhaps due to impacts from human activities.

Summary

In addition to the impacts to ichthyoplankton outlined above, the abundance, distribution, growth, and survival of juvenile and adult nekton in Narragansett Bay are also affected by human activities. Commercial fishing has depleted many fish populations over at least a century (Oviatt et al., 2003), and fishing pressures continue to exert considerable influence. Substantial areas of important nursery habitats such as eelgrass and salt marshes have been extensively degraded or lost. Eutrophication and the resultant increase in the frequency and duration of hypoxia forces fish to either move out of the affected areas or suffer negative impacts. Meng et al. (2001) demonstrated that winter flounder growth and survival decreased in upper Bay areas where water quality and dissolved oxygen conditions are poor. In the summer of 2003, a large fish kill (over 1 million Atlantic menhaden) occurred in Greenwich Bay when excessive nutrients and physical processes combined to create an extensive anoxic event (RIDEM, 2003). However, despite all of these pressures, Narragansett Bay and its habitats continue to support an abundant and diverse nekton assemblage, albeit one whose composition appears to be shifting over time.

Figure 10.6. Using a throw trap to quantitatively sample nekton from salt marsh habitats. *Photo from NBNERR photo library.*

Appendix 10.1. Abundance and Biomass of Nekton Species

Abundance and biomass of nekton species collected during the RIDEM seasonal trawl survey. For each species, mean abundance (catch per unit effort, CPUE) and mean biomass (biomass per unit effort, BPUE) are provided as averages between 1979 and 2003. Averages for spring, fall, and all data combined are provided.

Species	**Common name**		**CPUE**			**Species**	**Common name**		**BPUE**	
		Spring	**Fall**	**Total**				**Spring**	**Fall**	**Total**
Anchoa mitchilli	Bay anchovy	11.65	1213.08	600.42		*Stenotomus chrysops*	Scup	920.29	7024.48	3911.69
Stenotomus chrysops	Scup	7.41	439.56	219.19		*Pseudopleuronectes americanus*	Winter flounder	5609.57	1812.89	3748.98
Loligo pealei	Longfin squid	4.17	178.85	89.77		*Homarus americanus*	American lobster	1641.79	2041.53	1837.69
Brevoortia tyrannus	Atlantic menhaden	0.05	144.19	70.68		*Rajidae*	Skates	2613.60	1006.83	1826.19
Peprilus triacanthus	Butterfish	2.56	129.18	64.62		*Scophthalmus aquosus*	Windowpane	1526.77	1047.50	1291.90
Pseudopleuronectes americanus	Winter flounder	40.21	20.97	30.79		*Loligo pealei*	Longfin squid	324.67	2172.53	1230.23
Clupea harengus	Atlantic herring	44.38	5.19	25.18		*Tautoga onitis*	Tautog	1465.55	965.02	1220.26
Cynoscion regalis	Weakfish	0.00	39.53	19.38		*Peprilus triacanthus*	Butterfish	148.57	1788.75	952.35
Pomatomus saltatrix	Bluefish	0.00	17.63	8.64		*Paralichthys dentatus*	Summer flounder	84.12	1634.31	843.80
Menidia menidia	Atlantic silverside	3.40	13.19	8.20		*Anchoa mitchilli*	Bay anchovy	16.13	1195.97	594.32
Scophthalmus aquosus	Windowpane	8.09	8.08	8.08		*Cynoscion regalis*	Weakfish	8.36	880.81	435.91
Homarus americanus	American lobster	5.89	8.72	7.28		*Clupea harengus*	Atlantic herring	673.32	40.93	363.41
Alosa pseudoharengus	Alewife	3.11	8.65	5.83		*Pomatomus saltatrix*	Bluefish	5.57	707.27	349.45
Selene setapinnis	Atlantic moonfish	0.00	9.13	4.47		*Mustelus canis*	Smooth dogfish	21.10	628.16	318.60
Rajidae	Skates	5.19	1.86	3.56		*Prionotus evolans*	Striped searobin	41.13	510.10	270.95
Alosa aestivalis	Blueback herring	4.37	0.88	2.66		*Brevoortia tyrannus*	Atlantic menhaden	1.80	360.91	177.79
Urophycis chuss	Red Hake	2.69	1.45	2.08		*Limulus polyphemus*	Horseshoe crab	44.60	282.14	161.01
Trinectes maculatus	Hogchoker	0.21	2.87	1.51		*Urophycis chuss*	Red Hake	165.80	123.26	144.95
Tautoga onitis	Tautog	0.91	1.26	1.08		*Trinectes maculatus*	Hogchoker	17.27	255.90	134.21
Paralichthys dentatus	Summer flounder	0.08	2.05	1.05		*Macrozoarces americanus*	Ocean pout	221.01	0.00	112.71
Paralichthys oblongus	Fourspot flounder	0.40	1.59	0.99		*Prionotus carolinus*	Northern searobin	146.76	74.03	111.12
Urophycis regia	Spotted Hake	1.05	0.64	0.85		*Alosa pseudoharengus*	Alewife	110.58	110.91	110.74
Merluccius bilinearis	Silver hake	0.74	0.66	0.70		*Alosa aestivalis*	Blueback herring	106.59	17.87	63.11
Centropristis striata	Black sea bass	0.04	1.33	0.67		*Hemitripterus americanus*	Sea raven	119.18	1.31	61.42
Prionotus carolinus	Northern searobin	0.41	0.66	0.53		*Paralichthys oblongus*	Fourspot flounder	80.74	32.43	57.07
Prionotus evolans	Striped searobin	0.12	0.94	0.52		*Opsanus tau*	Oyster toadfish	6.85	104.49	54.70
Tautogolabrus adspersus	Cunner	0.51	0.45	0.48		*Urophycis regia*	Spotted Hake	17.30	78.69	47.38
Syngnathus fuscus	Northern pipefish	0.12	0.67	0.39		*Morone saxatilis*	Striped bass	13.95	62.97	37.97
Mustelus canis	Smooth dogfish	0.01	0.58	0.29		*Centropristis striata*	Black sea bass	13.87	56.15	34.59
Macrozoarces americanus	Ocean pout	0.42	0.00	0.22		*Merluccius bilinearis*	Silver hake	29.11	22.66	25.95
Opsanus tau	Oyster toadfish	0.03	0.39	0.20		*Tautogolabrus adspersus*	Cunner	32.97	15.88	24.60
Menticirrhus saxatilis	Northern kingfish	0.00	0.38	0.19		*Selene setapinnis*	Atlantic moonfish	0.00	49.00	24.01
Alosa sapidissima	American shad	0.25	0.04	0.15		*Menidia menidia*	Atlantic silverside	18.86	22.12	20.46
Ammodytes americanus	American sand lance	0.27	0.00	0.14		*Menticirrhus saxatilis*	Northern kingfish	0.00	36.77	18.02
Trachurus lathami	Rough scad	0.00	0.20	0.10		*Squalus acanthias*	Spiny dogfish shark	13.93	2.83	8.49
Gadus morhua	Atlantic Cod	0.19	0.00	0.10		*Alosa sapidissima*	American shad	9.06	5.90	7.51
Osmerus mordax	Rainbow smelt	0.14	0.06	0.10		*Myoxocephalus octodecemspinos*	Longhorn sculpin	13.34	0.45	7.02
Hemitripterus americanus	Sea raven	0.18	0.00	0.09		*Aequipecten irradians*	Sea scallop	1.04	10.26	5.56

Appendix 10.1 Continued

Citharichthys arctifrons	Gulfstream flounder	0.07	0.10	0.08		*Leiostomus xanthurus*	Spot	1.64	6.15	3.85
Limulus polyphemus	Horseshoe crab	0.03	0.14	0.08		*Trachurus lathami*	Rough scad	0.04	7.61	3.75
Myoxocephalus aenaeus	Grubby	0.14	0.01	0.08		*Microgadus tomcod*	Atlantic tomcod	5.90	1.36	3.67
Selene vomer	Lookdown	0.09	0.06	0.07		*Urophycis tenuis*	White hake	6.21	0.23	3.28
Sphyraena borealis	Northern sennet	0.00	0.14	0.07		*Pollachius virens*	Pollock	6.11	0.00	3.12
Gobiidae	Gobies	0.01	0.13	0.07		*Anguilla rostrata*	American eel	4.85	0.58	2.75
Pholis gunnellus	Rock gunnel	0.04	0.09	0.07		*Myoxocephalus aenaeus*	Grubby	4.53	0.29	2.45
Microgadus tomcod	Atlantic tomcod	0.09	0.04	0.06		*Priacanthus arenatus*	Bigeye	0.00	4.55	2.23
Myoxocephalus octodecemspinos	Longhorn sculpin	0.09	0.01	0.05		*Enchelyopus cimbrius*	Fourbeard rockling	1.40	2.95	2.16
Aequipecten irradians	Sea scallop	0.00	0.10	0.05		*Scomber scombrus*	Atlantic mackeral	0.44	3.54	1.96
Priacanthus arenatus	Bigeye	0.00	0.09	0.04		*Osmerus mordax*	Rainbow smelt	3.43	0.30	1.89
Urophycis tenuis	White Hake	0.07	0.02	0.04		*Syngnathus fuscus*	Northern pipefish	0.67	2.50	1.57
Enchelyopus cimbrius	Fourbeard rockling	0.02	0.06	0.04		*Lophius americanus*	Goosefish	2.68	0.40	1.56
Anchoa hepsetus	Striped anchovy	0.00	0.07	0.03		*Gobiidae*	Gobies	0.07	2.78	1.40
Brosme brosme	Cusk	0.06	0.00	0.03		*Synodus foetens*	Inshore lizardfish	0.00	2.76	1.35
Morone saxatilis	Striped bass	0.03	0.03	0.03		*Sphoeroides maculatus*	Northern puffer	0.00	2.48	1.22
Scomber scombrus	Atlantic mackeral	0.00	0.06	0.03		*Citharichthys arctifrons*	Gulfstream flounder	0.68	1.33	1.00
Orthopristis chrysoptera	Pigfish	0.00	0.04	0.02		*Ammodytes americanus*	American sand lance	1.62	0.00	0.83
Sphoeroides maculatus	Northern puffer	0.00	0.04	0.02		*Sphyraena borealis*	Northern sennet	0.00	1.57	0.77
Mullus auratus	Red goatfish	0.00	0.04	0.02		*Caranx hippos*	Crevalle jack	0.00	1.48	0.72
Synodus foetens	Inshore lizardfish	0.03	0.04	0.02		*Caranx crysos*	Blue runner	0.00	1.45	0.71
Leiostomus xanthurus	Spot	0.01	0.03	0.02		*Brosme brosme*	Cusk	1.25	0.00	0.64
Gaidropsarus ensis	Threebeard rockling	0.01	0.03	0.02		*Gaidropsarus ensis*	Threebeard rockling	0.29	0.97	0.62
Caranx crysos	Blue runner	0.00	0.02	0.01		*Gadus morhua*	Atlantic Cod	0.95	0.05	0.51
Anguilla rostrata	American eel	0.01	0.01	0.01		*Etrumeus teres*	Roung herring	0.00	1.01	0.50
Caranx hippos	Crevalle jack	0.00	0.02	0.01		*Cryptacanthodes maculatus*	Wrymouth	0.87	0.00	0.44
Conger oceanicus	Conger eel	0.00	0.01	0.01		*Mullus auratus*	Red goatfish	0.00	0.76	0.37
Selar crumenophthalmus	Bigeye scad	0.00	0.01	0.01		*Conger oceanicus*	Conger eel	0.00	0.75	0.37
Synodus synodus	Red lizardfish	0.00	0.01	0.01		*Pholis gunnellus*	Rock gunnel	0.41	0.16	0.29
Lophius americanus	Goosefish	0.01	0.00	0.01		*Selar crumenophthalmus*	Bigeye scad	0.00	0.56	0.27
Pollachius virens	Pollock	0.01	0.00	0.01		*Synodus synodus*	Red lizardfish	0.00	0.53	0.26
Pristigenys alta	Short bigeye	0.00	0.01	0.01		*Scomberomorus maculatus*	Spanish mackeral	0.00	0.51	0.25
Melanogrammus aeglefinus	Haddock	0.01	0.00	0.00		*Selene vomer*	Lookdown	0.21	0.27	0.24
Monacanthus hispidus	Planehead filefish	0.00	0.01	0.00		*Cyclopterus lumpus*	Lumpfish	0.45	0.00	0.23
Fistularia tabacaria	Bluespotted cornetfish	0.00	0.01	0.00		*Peristedion miniatum*	Armored searobin	0.37	0.00	0.19
Upeneus parvus	Dwarf goatfish	0.00	0.01	0.00		*Anchoa hepsetus*	Striped anchovy	0.00	0.30	0.15
Cyclopterus lumpus	Lumpfish	0.01	0.00	0.00		*Myoxocephalus scorpius*	Shorthorn sculpin	0.28	0.00	0.14
Myoxocephalus scorpius	Shorthorn sculpin	0.01	0.00	0.00		*Monacanthus hispidus*	Planehead filefish	0.00	0.28	0.14
Lepophidium profundorum	Fawn eelpout	0.01	0.00	0.00		*Pristigenys alta*	Short bigeye	0.00	0.28	0.13
Squalus acanthias	Spiny dogfish shark	0.00	0.00	0.00		*Morone americana*	White perch	0.24	0.00	0.12
Cryptacanthodes maculatus	Wrymouth	0.01	0.00	0.00		*Orthopristis chrysoptera*	Pigfish	0.00	0.24	0.12
Lutjanus campechanus	Red snapper	0.00	0.00	0.00		*Aluterus schoepfi*	Orange filefish	0.00	0.17	0.09
Petromyzon marinus	Sea lamprey	0.00	0.00	0.00		*Fistularia tabacaria*	Bluespotted cornetfish	0.00	0.17	0.08
Scomberomorus	Spanish	0.00	0.00	0.00		*Petromyzon marinus*	Sea lamprey	0.11	0.00	0.06

Appendix 10.1. Continued

maculates	mackeral									
Peristedion miniatum	Armored searobin	0.00	0.00	0.00		*Pleuronectes ferrugineus*	Yellowtail flounder	0.10	0.00	0.05
Decapterus macarellus	Mackeral scad	0.00	0.00	0.00		*Lepophidium profundorum*	Fawn eelpout	0.08	0.00	0.04
Aluterus schoepfi	Orange filefish	0.00	0.00	0.00		*Upeneus parvus*	Dwarf goatfish	0.00	0.09	0.04
Ulvaria subbifurcata	Radiated shanny	0.00	0.00	0.00		*Decapterus macarellus*	Mackeral scad	0.00	0.08	0.04
Etropus microstomus	Smallmouth flounder	0.00	0.00	0.00		*Lutjanus campechanus*	Red snapper	0.00	0.07	0.04
Gasterosteus aculeatus	Stickleback threespine	0.00	0.00	0.00		*Decapterus punctatus*	Round scad	0.00	0.02	0.01
Apeltes quadracus	Fourspine stickleback	0.00	0.00	0.00		*Apeltes quadracus*	Fourspine stickleback	0.02	0.00	0.01
Decapterus punctatus	Round scad	0.00	0.00	0.00		*Epinephelus niveatus*	Snowy grouper	0.00	0.02	0.01
Etrumeus teres	Roung herring	0.00	0.00	0.00		*Melanogrammus aeglefinus*	Haddock	0.02	0.00	0.01
Cyprinodon variegatus	Sheepshead minnow	0.00	0.00	0.00		*Cyprinodon variegatus*	Sheepshead minnow	0.01	0.00	0.00
Epinephelus niveatus	Snowy grouper	0.00	0.00	0.00		*Gasterosteus aculeatus*	Stickleback threespine	0.01	0.00	0.00
Morone Americana	White perch	0.00	0.00	0.00		*Etropus microstomus*	Smallmouth flounder	0.00	0.00	0.00
Pleuronectes ferrugineus	Yellowtail flounder	0.00	0.00	0.00		*Ulvaria subbifurcata*	Radiated shanny	0.00	0.00	0.00
Total		150.17	2256.47	1182.36		Total		16331.13	25235.62	20694.83

Appendix 10.2. Species Composition and Abundance of Fishes

Species composition and abundance of fishes collected between 1990 and 2003 during the RIDEM juvenile finfish seining survey. For each species, the average number per seine (across all 20 stations and all years) is shown for each month of the survey and for the entire survey (across all months).

Species	**Common Name**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Average**
Brevoortia tyrannus	Atlantic menhaden	1.69	4.35	1060.21	74.32	310.31	293.31
Menidia spp.	Silverside	18.12	44.17	49.85	47.77	31.05	38.44
River herring spp.	River herring	27.29	81.24	9.94	17.75	1.11	27.48
Pomotomus saltatrix	Bluefish	0.68	16.39	40.17	25.81	0.32	16.85
Pseudopleuronectes americanus	Winter flounder	25.81	29.01	14.92	5.39	4.68	15.67
Fundulus majalis	Striped killifish	6.71	12.67	23.60	19.91	14.55	15.59
Sea herring spp.	Sea herring	62.90	1.05	0.27	4.91	0.04	13.25
Anchoa mitchilli	Bay anchovy	34.51	7.94	0.16	4.01	14.84	11.84
Fundulus heteroclitus	Mummichog	7.38	12.02	13.47	9.53	7.85	10.09
Tautoga onitis	Blackfish	1.65	8.13	14.97	8.04	2.24	7.10
Menticirrhus saxatilis	Northern kingfish	0.03	3.30	11.33	3.18	0.09	3.61
Tautogolabrus adspersus	Cunner	0.47	3.18	5.71	4.69	1.33	3.13
Stenotomus chrysops	Scup	0.01	1.43	10.25	0.80	< 0.01	2.54
Ammodytes spp.	Sandlance	7.26	0.27	0.36	0.06	0.70	1.67
Cynoscion regalis	Weakfish	< 0.01	3.18	3.69	0.02	< 0.01	1.40
Microgadus tomcod	Tomcod	3.87	1.28	0.35	0.37	0.13	1.16
Gasterosteidae	Stickleback	1.38	1.59	0.86	0.39	1.43	1.13
Syngnathus fuscus	Northern pipefish	1.78	1.35	1.27	0.58	0.56	1.10
Myoxocephalus aenaeus	Grubby sculpin	0.78	0.77	0.97	1.92	0.65	1.02
Cyprinodon variegatus	Sheepshead minnow	0.03	0.43	0.31	1.79	1.29	0.78
Prionotus spp.	Searobin	0.08	1.91	1.46	0.06	< 0.01	0.71
Mugilidae	Mullet	0.03	0.47	0.83	0.49	0.07	0.38
Morone saxatilis	Striped bass	0.32	0.24	0.35	0.24	0.15	0.26
Caranx hippos	Crevalle jack	< 0.01	0.03	0.94	0.21	< 0.01	0.24
Cyprinodontidae	Killifish spp.	0.28	0.58	0.18	0.08	0.08	0.24
Trachinotus falcatus	Permit	< 0.01	0.02	0.57	0.35	0.12	0.22

Appendix 10.2. Continued

Sphoeroides maculatus	Northern puffer	< 0.01	0.44	0.50	0.08	< 0.01	0.21
Anguilla rostrata	American eel	0.24	0.23	0.43	0.08	0.01	0.20
Pollachius virens	Pollock	1.01	< 0.01	< 0.01	< 0.01	< 0.01	0.19
Scomber scombrus	Atlantic mackeral	0.04	0.75	< 0.01	< 0.01	0.02	0.16
Scopthalmus aquosus	Windowpane flounder	0.20	0.28	0.10	0.11	0.08	0.15
Merluccius bilinearis	Silver hake	0.78	0.01	< 0.01	< 0.01	< 0.01	0.15
Gobiidae	Goby	0.25	0.25	0.12	0.04	0.07	0.14
Centropristis striata	Black sea bass	< 0.01	< 0.01	0.46	0.20	< 0.01	0.13
Caranx bartholomaei	Yellow jack	< 0.01	< 0.01	0.02	0.56	< 0.01	0.11
Osmerus mordax	Smelt	0.31	0.06	0.01	0.01	< 0.01	0.08
Opsanus tau	Toadfish	0.04	0.09	0.14	0.03	0.02	0.06
Peprilus triacanthus	Butterfish	< 0.01	0.22	0.06	0.01	< 0.01	0.06
Caranx spp.	Jack spp.	< 0.01	0.02	0.07	0.20	< 0.01	0.06
Synodontidae	Lizardfish	< 0.01	0.02	0.07	0.16	0.01	0.05
Lucania parva	Rainwater killifish	0.02	0.06	0.06	< 0.01	0.07	0.04
Urophycis regia	Spotted hake	0.16	0.01	< 0.01	< 0.01	0.02	0.04
Etropus microsromus	Smallmouth flounder	0.02	< 0.01	< 0.01	0.05	0.05	0.02
Bothidae	Lefteye flounder	0.01	< 0.01	0.01	0.03	0.06	0.02
Alosa sapidissima	American shad	< 0.01	0.09	< 0.01	< 0.01	0.01	0.02
Leiostomus xanthurus	Spot	0.02	0.02	0.03	< 0.01	0.03	0.02
Paralichthys dentatus	Fluke	0.02	0.04	0.01	0.01	0.01	0.02
Urophycis chuss	Red hake	0.08	0.02	< 0.01	< 0.01	< 0.01	0.02
Fundulus diaphanus	Banded killifish	0.09	< 0.01	< 0.01	< 0.01	< 0.01	0.02
Caranx crysos	Blue runner	< 0.01	0.01	0.07	< 0.01	< 0.01	0.02
Strongylura marina	Needlefish	< 0.01	< 0.01	< 0.01	0.07	< 0.01	0.02
Pholis gunnellus	Rock gunnel	< 0.01	0.01	0.01	0.01	0.01	0.01
Fistularia tabacaria	Bluespotted coronetfish	< 0.01	< 0.01	0.02	0.01	0.01	0.01
Lutjanus griseus	Gray snapper	< 0.01	0.01	0.02	0.01	< 0.01	0.01
Hippocampus erectus	Seahorse	< 0.01	0.01	0.01	0.02	0.01	0.01
Clupeidae	Herring	0.02	0.02	< 0.01	< 0.01	< 0.01	0.01
Sphyraena borealis	Northern sennet	< 0.01	< 0.01	0.03	< 0.01	< 0.01	0.01
Enchelyopus cimbrius	Fourbeard rockling	0.03	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Gadus morhua	Cod, Atlantic	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Citharichthys arctifrons	Gulfstrseam flounder	0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01
Raja erinacea	Little shad	< 0.01	< 0.01	< 0.01	0.01	0.01	< 0.01
Decapterus macarellus	Scad	0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01
Mullidae	Goatfish	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Selene vomer	Lookdown	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01
Balistidae	Filefish	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Eucinostomus argenteus	Spotfin mojarra	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01
Ostraciidae	Boxfish	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Paralichthys oblongus	Fourspotted flounder	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01
Dactylopterus volitans	Gurnard	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Engraulis eurystole	Silver anchovy	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Chaetodon spp.	Butterflyfish	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Trinectes maculatus	Hogchoker	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Chilomycterus spp.	Burrfish	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Dorosoma cepedianum	Gizzard shad	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Lophius americanus	Monkfish	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Morone Americana	White perch	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Naucrates doctor	Pilotfish	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Scomber japonicus	Chub mackeral	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

Appendix 10.3. Nekton Density in Salt Marshes

Nekton density in the Sachuest Point, Coggeshall, and Galilee salt marshes in Rhode Island. All data were collected with the same methods (with a 1 m² throw trap when the marsh surface was drained), in similar habitats (e.g., creeks and pools), and are thus comparable. Galilee data are from restricted, restoring, and unrestricted marsh areas from June through September 1997–1999. Sachuest Point data are from restricted, restoring, and unrestricted marsh areas from June through October 1997–1999. Coggeshall is an unrestricted marsh and these data are from July and September 2000, 2003, and 2004.

Species	Common name	Galilee	Sachuest Point	Coggeshall	Average
Palaemonetes pugio	Daggerblade grass shrimp	15.30	4.29	136.60	52.06
Fundulus heteroclitus	Mummichog	12.70	12.46	18.05	14.40
Pagurus spp.	Hermit crab	0.01	0.00	8.36	2.79
Cyprinodon variegates	Sheepshead minnow	4.30	1.52	0.89	2.24
Fundulus majalis	Striped killifish	3.14	0.23	1.29	1.55
Menidia menidia	Atlantic silverside	3.54	0.18	0.22	1.31
Crangon septemspinosa	Sand shrimp	0.15	0.01	2.18	0.78
Menidia beryllina	Inland silverside	0.31	0.34	0.45	0.37
Carcinus maenas	Green crab	0.27	0.07	0.42	0.25
Lucania parva	Rainwater killifish	0.12	0.01	0.23	0.12
Anguilla rostrata	American eel	0.02	0.12	0.19	0.11
Callinectes sapidus	Blue crab	0.22	0.06	0.01	0.10
Mugil curema	White mullet	0.05	0.20	0.01	0.08
Panopeus herbstii	Black-fingered mud crab	0.00	0.00	0.19	0.06
Brevoortia tyrannus	Atlantic menhaden	0.08	0.02	0.03	0.04
Apeltes quadracus	Fourspine stickleback	0.01	0.00	0.10	0.04
Centropristis striata	Black sea bass	0.00	0.08	0.00	0.03
Gobiosoma ginsburgi	Seaboard goby	0.00	0.07	0.00	0.02
Pseudopleuronectes americanus	Winter flounder	0.01	0.00	0.07	0.02
Ovalipes ocellatus	Lady crab	0.00	0.00	0.05	0.02
Pungitius pungitius	Ninespine stickleback	0.02	0.01	0.01	0.01
Syngnathus fuscus	Northern pipefish	0.00	0.00	0.02	0.01
Notropis sp.	Shiner	0.00	0.01	0.00	< 0.01
Tautoga onitis	Tautog	0.00	0.00	0.01	< 0.01
Limulus polyphemus	Atlantic horseshoe crab	0.01	0.00	0.00	< 0.01
Alosa aestivalis	Blueback herring	0.00	< 0.01	0.00	< 0.01

Literature Cited

Bourne, D.W. and J.J. Govoni. 1988. Distribution of fish eggs and larvae and patterns of water circulation in Narragansett Bay 1972–1973. *American Fisheries Society Symposium* **3:**132–148.

Castro, K.M. and T.E. Angell. 2000. Prevalence and progression of shell disease in American lobster, *Homarus americanus*, from Rhode Island waters and the offshore canyons. *Journal of Shellfish Research* **19:**691–700.

Castro, K.M., T.E. Angell, and B. Somers. 2005. Lobster shell disease in Southern New England: Monitoring and research. **In**: Lobster Shell Disease Workshop Forum Series 05-1. Pp. 165–172. Edited by Tlusty, M.F., H.O. Halvorson, R. Smolowitz, and U. Sharma. New England Aquarium, Boston, Mass.

Cicchetti, G. 1998. Habitat use, secondary production, and trophic export by salt marsh nekton in shallow water. Ph.D. Dissertation, The College of William and Mary, Williamsburg, Va. 276pp.

Cobb, J.S. and K.M. Castro. 2006. *Shell Disease in Lobsters: A Synthesis*. Edited by Somers, B. and M.L. Schwartz. Rhode Island Sea Grant, Narragansett, R.I. 16pp.

DeAlteris, J.T., M. Gibson, and L.G. Skrobe. 2000. Fisheries of Rhode Island. White paper for the Narragansett Bay Summit 2000. 48pp.

Deegan, L.A., J.T. Finn, S.G. Ayvasian, C.A. Ryder-Kieffer, and J. Buonaccorse. 1997. Development and validation of an estuarine biotic integrity index. *Estuaries* **20:**601–617.

DeLong, A.K., J.S. Collie, C.J. Meise, and J.C. Powell. 2001. Estimating growth and mortality of juvenile winter flounder, *Pseudopleuronectes americanus*, with a length-based model. *Canadian Journal of Fisheries and Aquatic Science* **58:**2233–2246.

Dorf, B.A. and J.C. Powell. 1997. Distribution, abundance, and habitat characteristics of juvenile tautog (*Tautoga onitis*, Family Labridae) in Narragansett Bay, Rhode Island, 1988–1992. *Estuaries* **20:**589–600.

Durbin, A.G. and E.G. Durbin. 1998. Effects of menhaden predation on plankton populations in Narragansett Bay, Rhode Island. *Estuaries* **21:**449–465.

Friedland, K.D., G.C. Garman, A.J. Bejda, and A.L. Studholme. 1988. Interannual variation in diet and condition in juvenile bluefish during estuarine residency. *Transactions of the American Fisheries Society* **117:**474–479.

Halpin, P.M. 1997. Habitat use patterns of the mummichog, *Fundulus heteroclitus*, in New England. 1. Intramarsh variation. *Estuaries* **20:**618–625.

Herman, S.S. 1963. Planktonic fish eggs and larvae of Narragansett Bay. *Limnology and Oceanography* **8:**103–109.

Jefferies, H.P. and W.C. Johnson. 1974. Seasonal distributions of bottom fishes in the Narragansett Bay area: Seven-year variations in the abundance of winter flounder (*Pseudopleuronectes americanus*). *Journal of the Fisheries Research Board of Canada* **31:**1057–1066.

Jeffries, H.P. and M. Terceiro. 1985. Cycle of changing abundances in the fishes of the Narragansett Bay area. *Marine Ecology Progress Series* **25:**239–244.

Jeffries, P., A. Keller, and S. Hale. 1989. Predicting winter flounder, *Pseudopleuronectes americanus,* catches by time series analysis. *Canadian Journal of Fisheries and Aquatic Sciences* **46:**650–659.

Keller, A.A., M.E.Q. Pilson, and R. Johnston. 1996. *Estuarine Profile of Narragansett Bay, Rhode Island*. 244pp.

Keller, A.A., G. Klein-MacPhee, and J. St. Onge Burns. 1999. Abundance and distribution of ichthyoplankton in Narragansett Bay, Rhode Island, 1989–1990. *Estuaries* **22:**149–163.

Klein-MacPhee, G., A. Keller, and D. Erkan. 2002. Monitoring ichthyoplankton abundance in Narragansett Bay and Rhode Island territorial waters. Annual report to the R.I. Department of Environmental Management, Providence, R.I. 32pp.

Lapolla, A.E. 2001a. Bay anchovy *Anchoa mitchilli* in Narragansett Bay, Rhode Island. I. Population structure, growth and mortality. *Marine Ecology Progress Series* **217**:93–102.

Lapolla, A.E. 2001b. Bay anchovy *Anchoa mitchilli* in Narragansett Bay, Rhode Island. II. Spawning season, hatch-date distribution and young of the year growth. *Marine Ecology Progress Series* **217:**103–109.

Lynch, T. 2000. Assessment of recreationally important finfish stocks in Rhode Island waters. Coastal fishery resource assessment trawl survey. R.I. Department of Environmental Management Division of Fish and Wildlife, Government Center, Wakefield, R.I.

Meng, L. and J.C. Powell. 1999. Linking juvenile fish and their habitats: An example from Narragansett Bay, Rhode Island. *Estuaries* **22:**905–916.

Meng, L., J.C. Powell, and B. Taplin. 2001. Using winter flounder growth rates to assess habitat quality across an anthropogenic gradient in Narragansett Bay, Rhode Island. *Estuaries* **24:**576–584.

Meng, L., G. Cicchetti, and M. Chintala. 2004. Nekton habitat quality at shallow water sites in two Rhode Island coastal systems. *Estuaries* **27:**740–751.

Oviatt, C.A. and S.W. Nixon. 1973. The demersal fish of Narragansett Bay: An analysis of community structure, distribution and abundance. *Estuarine and Coastal Marine Science* **1:**361–378.

Oviatt, C., S. Olsen, M. Andrews, J. Collie, T. Lynch, and K. Raposa. 2003. A century of fishing and fish fluctuations in Narragansett Bay. *Reviews in Fisheries Science* **11:**221–242.

Raposa, K.B. 2002. Early responses of fishes and crustaceans to restoration of a tidally restricted New England salt marsh. *Restoration Ecology* **10:**665–676.

Raposa, K. 2003. Overwintering habitat selection by the mummichog, *Fundulus heteroclitus,* in a Cape Cod (USA) salt marsh. *Wetlands Ecology and Management* **11:**175–182.

Raposa, K.B. and C.T. Roman. 2001. Seasonal habitat-use patterns of nekton in a tide-restricted and unrestricted New England salt marsh. *Wetlands* **21:**451–461.

Raposa, K.B. and C.T. Roman. 2003. Using gradients in tidal restriction to evaluate nekton community responses to salt marsh restoration. *Estuaries* **26:**98–105.

R.I. Department of Environmental Management. 2003. The Greenwich Bay fish kill—August 2003: Causes, impacts and responses. 34pp.

Roman, C.T., K.B. Raposa, S.C. Adamowicz, M.J. James-Pirri, and J.G. Catena. 2003. Quantifying vegetation and nekton response to tidal restoration of a New England salt marsh. *Restoration Ecology* **10:**450–460.

Sekiguchi, K. 1995. Occurrence, behavior and feeding habits of harbor porpoises (*Phocoena phocoena*) at Pajaro Dunes, Monterey Bay, California. *Aquatic Mammals* **21:**91–103.

Silliman, B.R. and M.D. Bertness. 2002. A trophic cascade regulates salt marsh primary production. *Proceedings of the National Academy of Science* **99:**10500–10505.

Smith, J.P. 1997. Nesting season food habits of four species of herons and egrets at Lake Okeechobee, Florida. *Colonial Waterbirds* **20**:198–220.

CHAPTER 11.

Aquatic Birds, Marine Mammals, and Sea Turtles

Kenneth B. Raposa

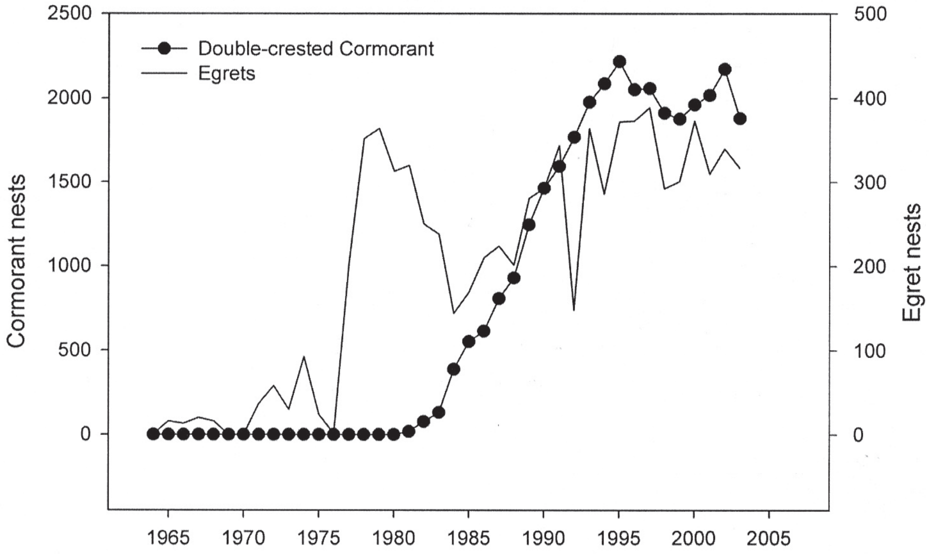


Figure 11.1. Long-term increase in the number of double-crested cormorant and egret (great and snowy egrets combined) nests in Narragansett Bay and Rhode Island. Totals for each year are sums of all the nests at all sites counted by RIDEM.

Figure 11.2. Double-crested cormorants in the waters around Prudence Island, R.I. *Photo from NBNERR photo library.*

Aquatic Birds, Marine Mammals, and Sea Turtles

Aquatic Birds

Narragansett Bay and its associated habitats provide foraging, nesting, and resting habitat for a variety of bird species. According to French et al. (1992), approximately 40 percent of all breeding bird species in Rhode Island, and 57 percent of wintering birds, use coastal habitats along Narragansett Bay for nesting. In all, 187 species of birds are considered to be associated with Narragansett Bay and its coastal habitats (French et al., 1992). Among the more frequent and abundant guilds are waterfowl (geese and ducks); shorebirds (e.g., plovers and sandpipers); wading birds (e.g., herons and egrets); raptors, gulls and terns; and songbirds. Research focusing on the ecology of most of these groups in Narragansett Bay is largely lacking, although Ferren and Myers (1998) and Trocki (2003) provide excellent data for understanding population trends and habitat use of colonial wading and nesting birds, and McKinney (2005) provides some excellent initial data on waterfowl community composition, distribution, and habitat use in Narragansett Bay.

Colonial Nesting Birds

In 1964, Ferren and Myers (1998) began monitoring the number of nests of selected coastal bird species along the entire Rhode Island coast, including Narragansett Bay (see Chapter 6 for NBNERR-specific results from this survey). These species include gulls (primarily herring gull (*Larus argentatus*) and great black-backed gull (*Larus marinus*)), terns (common tern (*Sterna hirundo*) and least tern (*Sterna albifrons*)), waders (great egret (*Casmerodius albus*), snowy egret (*Egretta thula*), cattle egret (*Bubulcus ibis*), little blue heron (*Florida caerulea*), and glossy ibis (*Plegadis falcinellus*)), piping plover (*Charadrius melodus*), double-crested cormorant (*Phalacrocorax auritus*), and American oystercatcher (*Haematopus palliates*). To date, approximately 90 nesting locations have been identified along the Rhode Island coast (see Fig. 6.6, page 62). All of these sites are not necessarily used simultaneously in a given year, however, since the nesting patterns of most species change over time (Ferren and Myers, 1998). Many of the undeveloped Narragansett Bay islands support abundant and sometimes diverse nesting bird communities. In particular, Hope, Rose, and Little Gould islands support rich heronries (mixed-species aggregations of nesting herons and egrets), while gulls/cormorants are abundant on Hope, Dyer, Little Gould, and West islands, among others. The monitoring program initiated by Ferren and Myers (1998) has been critical for documenting the dramatic return and subsequent increase in abundance of formerly displaced species, including cormorants and long-legged waders that responded, in part, to measures taken to directly protect these species and their nesting habitats (Fig 11.1).

The double-crested cormorant (Fig. 11.2; hereafter cormorant since the great cormorant (*Phalacrocorax carbo*) is generally much less abundant in Narragansett Bay) is now a conspicuous and abundant seasonal component of the estuarine bird fauna in Narragansett Bay. Cormorants are present throughout the year in Narragansett Bay, but are much more common in summer and are especially abundant during the spring and fall migrations (Conway, 1992). Cormorants can be seen foraging and resting throughout most areas of the Bay, including open water, coves, embayments, and marinas. Based on RIDEM surveys, the number of cormorant nests in Narragansett Bay has risen from zero as late as 1980 to 1,880 in 2003, with a peak of 2,217 nests in 1995 (Fig. 11.1) (Ferren and Myers, 1998; Raithel, unpublished data). Abundant nesting colonies are generally found on only a handful of islands, including Little Gould, West, and East islands (all of which are found in the Sakonnet River) and Hope Island in the West Passage. The abundance of cormorants has risen to such a degree that there is now concern about their potential impacts to commercial fishery stocks (e.g., winter flounder, *Pseudopleuronectes americanus*) in Narragansett Bay. To examine this objectively, French McCay and Rowe (2004) conducted a bioenergetic analysis of cormorant feeding in Narragansett Bay, based on cormorant abundance, foraging area, and feeding requirements. They determined that cormorants probably consume less than 10 percent of the winter flounder young-of-the-year annually in Narragansett Bay and suggest—in agreement with similar studies conducted in other locations—that cormorant predation generally has a much lower impact on fishery species than does human fishing.

Wading bird colonies, composed of species such as great egret, snowy egret, cattle egret, little

blue heron, and glossy ibis, are found on a few of Narragansett Bay's islands including Hope, Little Gould, and Rose islands. Hope Island is considered to be one of the most important heronries in the Bay, to the point where the state now restricts human activities on the island throughout the nesting season. The species composition of the Hope Island heronry is variable among years, but can include great egret, snowy egret, black-crowned night heron (*Nycticorax nycticorax*), glossy ibis, cattle egret, and little blue heron—all of which nest among abundant gull and cormorant populations. However, even though Hope and other Bay islands currently support substantial heronries, events recorded by Ferren and Myers (1998) illustrate that this was not always the case, and that other islands that do not currently support heronries may do so in the future. For example, in 1983–84 the heronry on Hope Island was almost completely abandoned. The emigrating birds moved to nest on Big Gould, Dyer, and Rose islands, with Hope remaining mostly unutilized throughout the mid-1980s (Ferren and Myers, 1988). After 1989, the heronry, along with newly returning cormorants, began to reestablish itself on Hope Island. The exact cause of the Hope Island abandonment is unclear, and may be due to bird-inflicted damage to nesting vegetation from guano, as suggested by Ferren and Myers (1988), or possibly to the presence of red fox on the island (Raithel, personal communication). A similar abandonment of the heronry from Little Gould Island in the 1970s illustrates that this was not an isolated incident. These events clearly indicate that the spatially and temporally dynamic nesting patterns of herons, egrets, and associated nesting birds necessitates the protection and preservation of natural habitats on other Narragansett Bay islands. This is true even if a particular island does not currently support a heronry or other nesting birds; if another heronry abandonment occurs in the future, displaced birds will need other islands to colonize and nest.

Although wading bird nesting areas on Bay islands are well known and many are protected, the factors that affect selection and use of foraging habitats in Narragansett Bay are less clear. Herons and egrets are commonly observed foraging in fringing and meadow salt marshes around Narragansett Bay, and it is generally accepted that marshes provide important foraging habitat for these birds. A recent study (Trocki, 2003) provides some of the first information about how and why wading birds use salt marshes in Narragansett Bay as foraging habitat. Trocki (2003) found that the number of birds foraging in a marsh correlates well with marsh area, but bird density does not (i.e., as marsh area increases, so does the number of foraging birds but not bird density). Trocki (2003) also found that wading birds strongly preferred isolated salt marsh pools as foraging microhabitat within a marsh, and concluded that the lack of marsh pools (often resulting from ditching) is the primary factor limiting the abundance of these birds on a Bay-wide scale (e.g., the number of wading birds nesting in Rhode Island has remained stable in recent years even though not all potential nesting areas are used in any given year (Ferren and Myers, 1998)). Thus, Trocki's study suggests that future marsh restoration should also consider marsh pool creation if increasing wading bird numbers is a primary goal of restoration.

Waterfowl

Narragansett Bay is used extensively by a variety of waterfowl that includes diving and dabbling ducks and swans and geese (Fig. 11.3). While some of these species (e.g., Canada goose (*Branta canadensis*), American black duck (*Anas rubripes*), and mallard (*Anas platyrhynchos*)) utilize Bay waters throughout the year, many others use the Bay primarily for overwintering (Conway, 1992). Based on annual winter surveys conducted from 2002 to 2004, 23 of the 55 native species of North American waterfowl (42 percent) use Narragansett Bay in winter (McKinney, 2005). The most abundant species according to these surveys are scaup (*Aythya* spp.), Canada goose, common goldeneye (*Bucephala clangula*), common eider (*Somateria mollissima*), and brant (*Branta bernicla*) (Table 11.1). Twelve additional waterfowl species were considered to be regular winter inhabitants. Densities of winter waterfowl in Narragansett Bay average 39 birds km^{-1}, which is comparable to nearby Boston Harbor but less than in Chesapeake Bay (36 and 55 birds km^{-1}, respectively) (McKinney, 2005).

Waterfowl species do not appear to be randomly located around Narragansett Bay; instead, these birds may select for specific habitats that have certain landscape characteristics. For example, specific groups of waterfowl in Narragansett Bay were found to be associated with salt marsh–dominated coves or rocky headland habitats near the mouth of the Bay (McKinney, 2005). Waterfowl using salt marsh and shallow cove habitats favored sites that were abutted by forest and residential land-use types. McKinney (2005) suggests that species select these areas within Narragansett Bay because trees and/or houses reduce wind velocity and because hunting is not permitted near residential areas (McKinney also found that waterfowl species richness decreased with increasing hunting activity). By design, McKinney's work was exploratory in nature

Table 11.1. Relative abundance of waterfowl and associated species in winter in Narragansett Bay and around Prudence Island. Data were collected in 2004 and 2005 by volunteers coordinated by the EPA in Narragansett, R.I. All data were provided by Richard McKinney (unpublished).

		Prudence Island		Narragansett Bay	
Species	**Common name**	**2004**	**2005**	**2004**	**2005**
Anas americana	American wigeon	0	2	1060	123
Anas platyrhynchos	Mallard	5	4	1320	1478
Anas rubripes	American black duck	139	276	983	1474
Anas strepera	Gadwall	0	3	395	61
Aythya affinis	Lesser scaup	0	0	0	368
Aythya marila	Greater scaup	4	0	3576	7889
Branta bernicla	Brant	60	468	1911	1434
Branta canadensis	Canada goose	53	390	2037	4008
Bucephala albeola	Bufflehead	74	11	718	470
Bucephala clangula	Common goldeneye	695	70	2323	849
Clangula hyemalis	Old-squaw	0	0	0	1
Cygnus olor	Mute swan	7	0	523	677
Gavia immer	Common loon	1	0	47	25
Histrionicus histrionicus	Harlequin duck	0	0	105	66
Larus spp.	Gulls	570	518	4015	3789
Lophodytes cucullatus	Hooded merganser	0	0	33	70
Melanitta deglandi	White-winged scoter	0	3	411	3
Melanitta nigra	Black scoter	0	0	198	99
Melanitta perspicillata	Surf scoter	0	2	3	33
Mergus merganser	Common merganser	0	5	0	23
Mergus serrator	Red-breasted merganser	21	11	824	404
Phalacrocorax spp.	Cormorants	0	1	1	5
Podiceps auritus	Horned grebe	6	0	127	19
Somateria mollissima	Common eider	0	0	941	2465

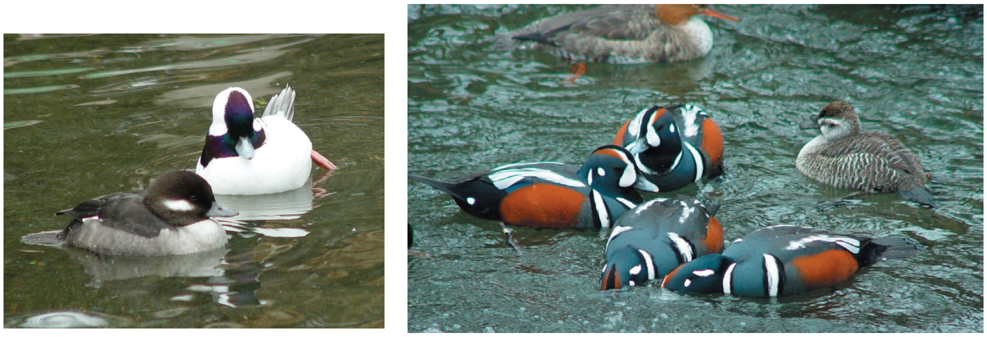


Figure 11.3. Examples of common waterfowl in Narragansett Bay, including bufflehead (*far left*), harlequin duck (*left*), and hooded merganser. *Photos by R. McKinney, EPA.*

and has raised some important questions about winter waterfowl use of microhabitats in Narragansett Bay that should be investigated. In particular, the effects of human disturbance, including coastal development and shoreline modification, hunting, and eutrophication and its resultant biotic changes, need scientific attention.

Marine Mammals

The mammals that use Narragansett Bay and its associated coastal habitats include those that are facultative terrestrial species as well as true marine mammals such as cetaceans and pinnipeds. According to French et al. (1992), at least 33 land-based mammals use Narragansett Bay coastal habitats (including coastal shrublands and forests); approximately half directly use shore-zone areas of the Bay. The Bay's beaches, salt marshes, and other shoreline types provide ample foraging opportunities for species such as white-tailed deer (*Odocoileus virginianus*), coyote (*Canis latrans*), red fox (*Vulpes vulpes*), raccoon (*Procyon lotor*), American mink (*Mustela vison*), striped skunk (*Mephitis mephitis*), northern river otter (*Lontra canadensis*), Norway rat (*Rattus norvegicus*), muskrat (*Ondatra zibethica*), and multiple species of bats. Mice (white-footed *Peromyscus leucopus*, meadow jumping *Zapus* *hudsonius* and house *Mus musculus*), meadow voles (*Microtus pennsylvanicus*), and masked shrews (*Sorex cinereus*) may also nest in the upper portions of salt marshes around the Bay (Nixon, 1982).

Among the marine mammals that are found in Narragansett Bay, the harbor seal (*Phoca vitulina*) is the only regular, abundant species (Fig. 11.4). The most comprehensive research focusing on harbor seals in Narragansett Bay was a study conducted by Schroeder (2000) who examined trends in population size and haul-out use. According to Schroeder (2000), harbor seals typically arrive in Narragansett Bay in late September or early October, increase in numbers through March, and leave the Bay by early May (Fig. 11.5). While they are in Narragansett Bay, harbor seals forage in subtidal areas and use rocky outcrops as haul-out sites for resting. Schroeder (2000) identified 27 sites that are used as haul-outs by harbor seals in Narragansett Bay and on Block Island. Twelve of these were considered primary sites (based on the number of seals and also monitoring effort), and among these, Rome Point in North Kingstown consistently supported some of the highest numbers of seals. Other primary haul-out sites include Brenton Point (off Newport), Citing Rock (off Rose Island), and Cold Spring Rock (north of Rome Point, near Wickford Harbor) (Fig. 11.6). Other sites, including Seal Rock (off Hope Island) and Cormorant Cove (on Block Island) also support large numbers of hauled out seals, but these sites are monitored too infrequently to assess true haul-out patterns, and are thus not considered primary. Over the last 13 years, the number of harbor seal haul-out sites in Narragansett Bay has more than tripled (Schroeder, 2000). This is a direct result of an expanding harbor seal population in Narragansett Bay that has increased by a factor of 10 in the last 40 years, and has quadrupled since 1987 (Schroeder, 2000).

A smaller, unpublished study that examined nocturnal behaviors of harbor seals in the NBNERR was conducted by Norris (2005), then an undergraduate at Roger Williams University in Bristol, R.I. Norris (2005) observed seals in the winter of 2004 at the T-wharf haul-out site on the south end of Prudence Island and found that seals hauled out in similar numbers at this site during the day and at night (average of 22 during the day; 16 at night). She also found that temperature and wind speed had no effect on the numbers of seals that were hauled out and that the number of seals exhibiting scanning behavior depended on the size of the group that was hauled out. Two to four scanners were used when the number of hauled out seals ranged from 10 to 40; however, only one seal scanned if the number hauled out was less than seven. This pattern was the same during the day and at night.

Figure 11.4. A harbor seal in Narragansett Bay. *Photo from NOAA's Estuarine Research Reserve Collection.*

Harbor seal populations have been increasing throughout much of the northwest Atlantic (Waring et al., 2004), including in Narragansett Bay, where a steadily increasing population uses an increasing number of haul-out sites. Higher numbers of seals have prompted concern over the resultant effects on commercially important fish stocks in the region (Baraff and Loughlin, 2000). However, recent research shows that these concerns may be largely unwarranted in Narragansett Bay. Nicotri and Webb (unpublished data) have used bioenergenic models to estimate that the winter seal population in the Bay consumes only 0.15 to 0.40 percent of the total commercial landing for all species, which suggests that the effects of seal foraging on fish stocks is minimal, at least in Narragansett Bay.

Other than harbor seals, Narragansett Bay is not commonly frequented by marine mammals. As such, published scientific accounts or marine mammal sighting lists specific to Narragansett Bay are rare. The best available information is a list of strandings and live sightings of marine mammals in Narragansett Bay and along coastal Rhode Island (Robert Kenney, personal communication). This list includes 15 additional species of marine mammals sighted (dead or alive) at some point in Narragansett Bay or along the south shore of Rhode Island. These species include the gray seal (*Halichoerus grypus*), harp seal (*Pagophilus groenlandicus*), hooded seal (*Cystophora cristata*), North Atlantic right whale (*Eubalaena glacialis*), humpback whale (*Megaptera novaeangliae*), fin whale (*Balaenoptera physalus*), northern minke whale (*Balaenoptera acutorostrata*), dwarf sperm whale (*Kogia sima*), long-finned pilot whale (*Globicephala melas*), Risso's dolphin (*Grampus griseus*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*), bottlenose dolphin (*Tursiops truncates*), striped dolphin (*Stenella coeruleoalba*), harbor porpoise (*Phocoena phocoena*), and West Indian manatee (*Trichechus manatus*).

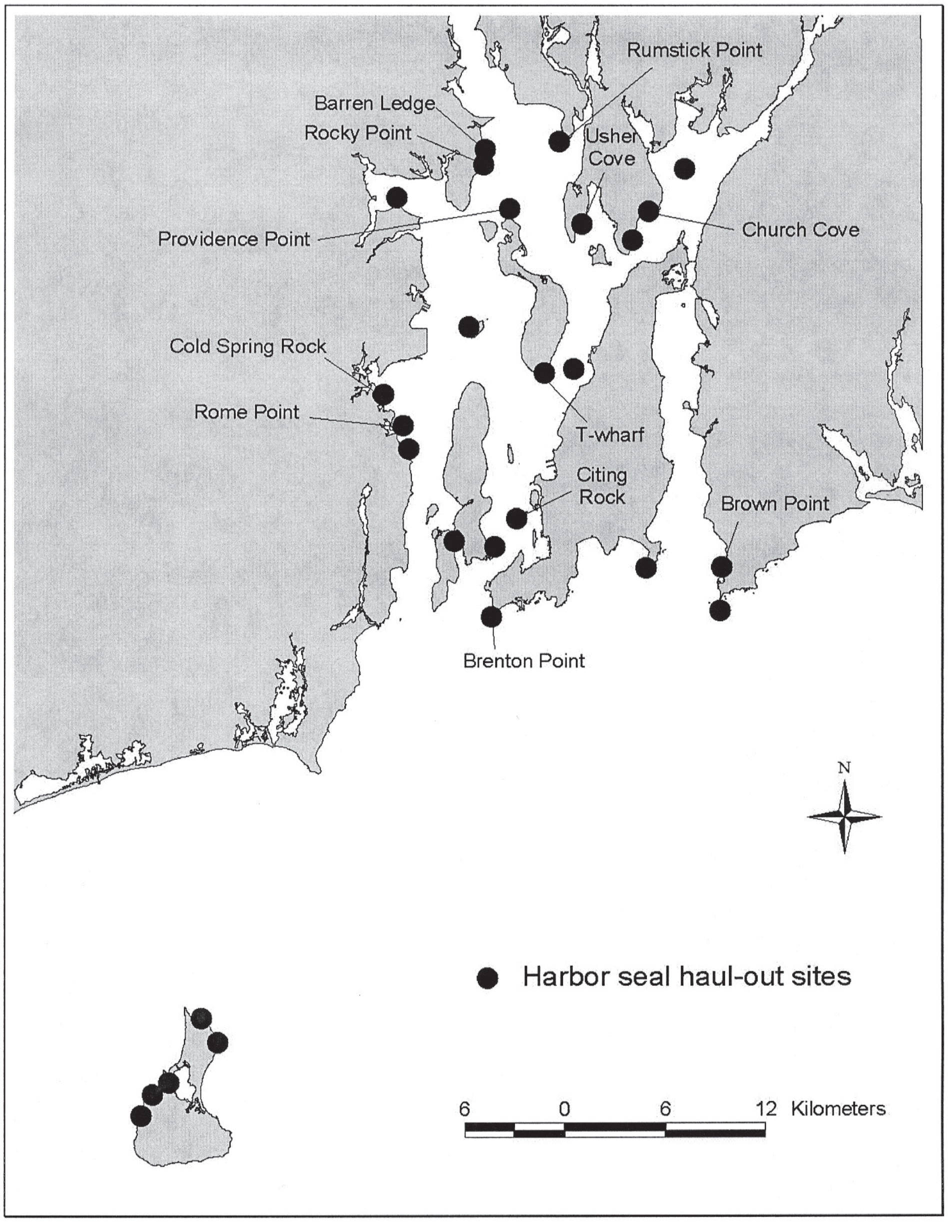


Figure 11.6. Locations of seal haul-out sites in Narragansett Bay and on Block Island, according to Schroeder (2000). Locations that are considered as primary haul-out sites by Schroeder are labeled.

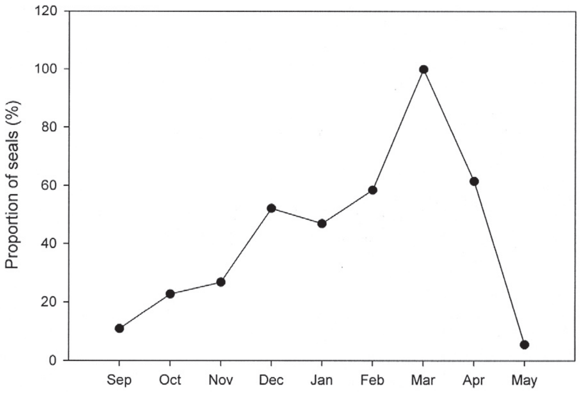


Figure 11.5. The relative abundance of harbor seals observed from September through May, expressed as a percentage of maximum abundance in March. Data are from 1993 to 2002, and were derived from monitoring efforts coordinated by Save The Bay and Schroeder (2000).

Sea Turtles

While not often thought of as local residents, sea turtles are regular summer visitors to Rhode Island waters—some making their way into Narragansett Bay. They are sighted in state waters from late June through October, when they migrate south to their wintering grounds. Data from NOAA's Sea Turtle Stranding and Salvage Network (STSSN) and from the newly created R.I. Sea Turtle Disentanglement Network (RISTDN) document the occurrence of leatherback (*Dermochelys coriacea*), loggerhead (*Caretta caretta*), and Kemp's ridley (*Lepidochelys kempi*) sea turtles in the Bay (Schwartz and Beutel, 2006; Wynne and Schwartz, 1999; H. Medic, personal communication). The leatherback is highly pelagic, traversing Rhode Island Sound but not usually venturing into the Bay farther north than its mouth. Nevertheless, in 2007, a leatherback was successfully disentangled from a buoy line off Hope Island, part of the NBNERR (M. Schwartz, personal communication) (Fig. 11.7). The loggerhead and Kemp's ridley sea turtles have been sighted (dead and alive) in the Bay around Conanicut and Aquidneck islands and likely make their way to the NBNERR as well (Schwartz and Beutel, 2006; Schwartz, personal communication; Medic, personal communication).

Figure 11.7. A leatherback sea turtle was successfully disentangled from a buoy line near Hope Island, part of the NBNERR. *Photo courtesy RISTDN.*

Literature Cited

Baraff, L.A., and T.R. Loughlin. 2000. Trends and potential interactions between pinnipeds and fisheries of New England and the U.S. west coast. *Marine Fisheries Review* **62:**1–39.

Conway, R.A. 1992. Field-checklist of Rhode Island birds. Bulletin No. 1. Rhode Island Ornithological Club. 57pp.

Ferren, R.L. and J.E. Myers. 1998. Rhode Island's maritime nesting birds. R.I. Department of Environmental Management Final Report. Providence, R.I. 222pp.

French, D.P., H. Rhines, J. Boothroyd, C. Galagan, M. Harlin, A. Keller, G. Klein-MacPhee, S. Prett, M. Gould, M. Villalard-Bohnsack, L. Gould, and S. Porter. 1992. Habitat inventory/resource mapping for Narragansett Bay and associated coastline. Applied Science Associates Report 89-33. Final Report, Narragansett Bay Project.

French McCay, D.P. and J.J. Rowe. 2004. Estimating fish predation by cormorants in the Narragansett Bay estuary. *Rhode Island Naturalist* **11:**1–3.

McKinney, R.A. 2005. Habitat use by waterfowl wintering in Narragansett Bay, Rhode Island. Ph.D. Dissertation, University of Rhode Island, Kingston, R.I. 199pp.

Nixon, S.W. 1982. The ecology of New England high salt marshes: A community profile. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C.; FWS/OBS-81/55. 70pp.

Norris, A. 2005. Nocturnal behavior for the Harbour Seal (*Phoca vitulina*) from Prudence Island, Rhode Island. Undergraduate Research Project, Roger Williams University, Bristol, R.I. 15pp.

Schroeder, C.L. 2000. Population status and distribution of the harbor seal in Rhode Island waters. M.S. Thesis, Graduate School of Oceanography, University of Rhode Island, Narragansett, R.I. 197pp.

Schwartz, M.L. and D.L. Beutel. 2006. R.I. Sea Turtle Disentanglement Program 2005 Final Report. Prepared for NOAA Fisheries Northeast Region, Gloucester, Mass.

Trocki, C.L. 2003. Patterns of salt marsh and farmland use by wading birds in southern Rhode Island. M.S. Thesis, University of Rhode Island, Kingston, R.I. 97pp.

Waring, G.T., R.M. Pace, J.M. Quintal, C.P. Fairfield, and K. Maze-Foley. 2004. U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2003. NOAA Technical Memorandum NMFS-NE-182. NOAA Fisheries, Woods Hole, Mass.

Wynne, K. and M. Schwartz. 1999. *Guide to Marine Mammals & Turtles of the U.S. Atlantic & Gulf of Mexico*. Rhode Island Sea Grant, Narragansett, R.I. 120pp.

CHAPTER 12.

Human Impacts on Narragansett Bay

Thomas E. Kutcher

Figure 12.1. Circa 1920 penny postcard depicting Slater Mill and subsequent industrialization on the Blackstone River. *Photo from USGenWeb Archives*.

Human Impacts on Narragansett Bay

Once considered the most industrialized estuary in the world, Narragansett Bay has endured a long history of human impacts—some transient, some dynamic, some chronic, and some historic yet persistent. Human impacts are numerous and vary widely temporally, spatially, and functionally. It may be safe to say that every ecological function of Narragansett Bay has been directly or indirectly impacted by human activity. To list and provide detailed information on every historic impact to the Bay is well beyond the scope of this chapter, and would certainly fill an entire book. What follows, therefore, is a brief history of consequential human activities on Narragansett Bay and a discussion of the major anthropogenic impacts that affect the present ecology, value, and aesthetics of the Bay.

Prehistoric Human Use

The first evidence of post-glacial human occupation in the Narragansett Bay watershed is located on Conanicut Island and dates back roughly 5,000 years. Two Algonquin tribes, the Narragansetts of the West Bay and the Wampanoags of the East Bay, subsisted off of the resources within and surrounding the Bay. Natives numbered approximately 8,000 in total. The Algonquins may have had a minor ecological impact on Narragansett Bay and the surrounding upland habitats, harvesting fish and shellfish, hunting keystone species, and clearing land for subsistence farming by burning. However, from an ecological perspective, influences of native peoples were relatively minor and the precolonial environment is thus generally considered to be the natural background condition (e.g., King et al., 1995; Nixon, 1995).

Preindustrial Use

European colonists first settled the Narragansett Bay watershed in 1636 along the shores of the Providence River (Keller, 1996). Colonization spread quickly south along the East Bay to Aquidneck Island, and down the West Bay to Wickford. The temperate climate, long growing season, and loamy soils along the immediate coast of Rhode Island and southern Massachusetts were ideal for farming, and coastal land along the upper Bay was extensively cleared for agriculture and lumber production during the 17th and 18th centuries. Agriculture was the dominant coastal land use in the Narragansett Bay watershed until population growth and demand for labor housing associated with industrialization and urbanization became prevalent in the early 1900s. Land clearing and agriculture have historically and presently affected the water column and benthic quality of the Narragansett Bay and its tributaries by contributing to nutrient loading and siltation.

Finfish and shellfish fisheries have historically been major sources of sustenance and income for inhabitants of the Narragansett Bay watershed from early colonial times until present. Narragansett Bay was a rich fishing ground until the mid-1800s, when pelagic and anadromous fish stocks succumbed to the pressures of trap fishing and industrialization, respectively (Oviatt et al., 2003). Heavy, persistent fishing pressure and practices have, in part, caused many Bay stocks to dwindle, and the finfishery has shifted primarily to coastal waters outside of the estuary. Today, the shellfishery is the most important commercial fishery in the Bay (DeAlteris et al., 2000).

The natural deep channels and protected harbors of Narragansett Bay were ideally suited to support the shipping trades. As early as the 1700s, Rhode Island ports were involved in a lucrative shipping trade of crops, slaves, and rum with Europe, South America, Africa, and the West Indies (Childress et al., 1996). In 1853, the Army Corps of Engineers dredged a 3 m (10-foot) deep, 30 m (100-foot) wide channel into the Port of Providence to allow for the entry of large freight vessels. By 1965, Providence was the fourth largest port in New England. Regular marine shipping continues with the present importation of fossil fuels and automobiles (Harrington, 2000). Presently, approximately 13 million tons of cargo are imported into Narragansett Bay each year (U.S. Army Corps of Engineers, 2005). Shipping has led to modifications of the shoreline, driven the dredging of deepwater channels, and introduced invasive marine species from foreign bilge water and bottom fouling.

Industrialization

Historians often credit Slater Mill as being the birthplace of the Industrial Revolution in America. This textile mill was constructed by Samuel Slater in 1793 on the Blackstone River—one of the two main tributaries to Narragansett Bay—and was powered by damming the river to create a millpond that reserved the potential energy of the descending water for controlled and constant availability (Fig. 12.1). The success of the mill spawned 19th century entrepreneurs to build small and large mills on nearly every tributary to the Bay. Metal milling operations arose to supply the demand for textile machinery, followed by the manufacture of items of precious metals. As mill dams were constructed, they constricted water flow and fish passage on virtually all tributaries to the Bay, which has had numerous ecological effects, including the decimation of anadromous fish populations. By 1900, hundreds of Narragansett Bay watershed textile and metal mills were using Bay tributary waters for power, processing, and washing of materials, and for direct waste discharge. And, with the invention of the steam turbine, many industries replaced hydropower with more flexible fossil fuel power, which introduced various hydrocarbon-derived pollutants into the Bay system. Overall, the numerous consequences of industrialization to Narragansett Bay included severely polluted waters and sediments and greatly debilitated hydrologic and biological processes.

Figure 12.2. Military installation on Gould Island in the lower East Passage. This site housed a torpedo testing facility during the mid-20th century and is now largely reclaimed by vegetation. *Photo from the National Archives.*

Population Growth and Sprawl

During the 1800s, the population of Rhode Island was growing faster than any other New England state. The livelihood of residents that once depended largely on the exploitation of local resources was shifting to manufacturing and export. Between 1860 and 1920, the population of Rhode Island tripled, and industrial employment doubled (Harrington, 2000). During that period, immigrants came to America to labor on public works projects or in the textile mills and metals factories. Meanwhile, agriculture declined as the work force shifted from fields to factories and urbanization began.

As commerce and population grew with the industrialization and urbanization of the watershed so did the need for infrastructure, in the form of streets, dredged waterways, railroads, and urban sewage systems. In 1870 the city of Providence constructed a sewer system that conveyed the city's sewage through a series of 65 sewer outfalls directly into Providence's rivers and harbor. Processing of Providence sewage by chemical precipitation began in 1901 at Field's Point, but the plant was already inadequate to keep up with the growing population by 1910 (Nixon, 1995). The city then began dumping large quantities of precipitated sludge into Narragansett Bay, just east of Prudence Island, which continued until 1950 (Nixon, 1995).

Military Occupation

Since the establishment of the Continental Navy in 1775, the U.S. military has occupied various key strategic areas within Narragansett Bay—mostly prominent coastal points and nearly every Bay island—to protect the security of the Bay's civilians as well as valuable resources. Many of these outposts began as forts to house cannons and guns to stop penetration of Bay waters by enemy ships. Over time, the Navy developed numerous in-Bay sites as huge military ports, torpedo development facilities, shipbuilding operations, and naval air stations

(U.S. Navy, 2005, Fig. 12.2). Military operations modified coastal lands and shorelines as necessary to meet their changing needs. During the early and mid-1900s, the Navy developed at least 6,000 acres of coastal lands along 31 miles of the Narragansett Bay shoreline, which included the filling of at least 400 acres of the Bay to expand Quonset Point Air Station (U.S. Navy, 2005). Military waste, including hazardous pollutants, was routinely disposed of in coastal landfills and salt marshes, which at that time were generally considered valueless. Navy dumpsites are responsible for at least seven identified superfund sites in Rhode Island (EPA, 2005). The Navy also used the Bay waters extensively as a training ground and as a testing site for maritime weaponry, including torpedoes and mines, some of which remain on the seafloor.

Anthropogenic Impacts to Narragansett Bay

Physical and Hydrologic Modifications

The physical structure, hydrology, temperature, and chemistry of Narragansett Bay have been greatly affected since colonization of the watershed in the 1700s. Development of the watershed and industrialization of the tributaries were and are the basic anthropogenic forces altering the natural physical processes that drive the Bay's estuarine functions. Modifications to the watershed for transportation, industry, residence, and infrastructure, in the forms of damming of tributaries, impoundment of salt marshes, construction of hard shoreline and roadways, dredging, canalization and diversion of waterways, filling of wetlands and shorelines, withdrawal of fresh water, massive inputs of effluent, and removal of vegetative coastal and riparian buffers all contribute to changes in Bay flow patterns, salinity, temperature, and tidal influence.

Physical modifications have been directly imposed on virtually all systems of Narragansett Bay, including the tributaries, coastal wetlands, and the seafloor. Over 1,100 dams have been constructed on virtually every tributary to the Bay, mostly to support numerous small and large mills within the watershed (Hale, 1988). Most of these delinquent dams remain as relics. Over 680 ha (1,700 acres) (48 percent) of estuarine marshes have been ditched and/or impounded, and over one-third of all coastal wetland buffer area (150 m buffer zone) has been developed (Tiner et al., 2004). In total, 52 percent (214.5 km) of Narragansett Bay's shoreline has been developed into hardened shoreline (derived from RIGIS, 2006). From 1950 to 1990, 15 percent of estuarine wetlands were lost (mostly due to filling), including 124 ha of coastal marshes (Tiner et al., 2004). In deepwater habitats, three major dredged channels are maintained to connect the deep river valleys of the Bay with major ports on the Providence and Taunton rivers and in Quonset Point. The Providence River channel, the largest of the three, is 27 km long and at the time of construction it was 183 m (600 feet) wide and 12 m (40 feet) deep, running through surrounding waters ranging from zero to 12 m (1 to 40 feet) deep.

Water withdrawals from the Bay and its tributaries for residential, industrial, and power production uses have affected temperatures, salinities, and flow patterns in the Bay. Most notably, the Brayton Point Station, the largest coal-fired power plant in the Northeast, has been extracting, warming, and reintroducing seawater to the Mount Hope Bay (the northeast sub-embayment of Narragansett Bay) since 1986. The plant has been permitted to cycle up to 1.45 billion gallons per day (BGD) through a once-through cooling system with a maximum output temperature of 95 F and a maximum change in temperature of +22 F (Massachusetts Department of Environmental Protection (MADEP), 2002). The current average discharge plume of the plant (0.98 BGD) causes a rise of over 1.5 F (MADEP maximum standard) over background temperature to 2,350 ha (60 percent) of Mount Hope Bay (MADEP, 2002). In total, Brayton Point Station cycles the equivalent of the entire contents of Mount Hope Bay approximately every 21 days (J. Quinn, personal communication).

Physical anthropogenic changes in the surrounding watershed further impact Narragansett Bay by affecting the natural hydrography. By 1995 over 30 percent of the watershed was developed including nearly 6,000 miles of public roads. Several of the urbanized subwatersheds within Narragansett Bay contain more than 15 percent impervious surface, which is an EPA benchmark for ecologically impaired watersheds (Crawley, 2000). Due to the relatively small natural input of fresh water to Narragansett Bay (2.4 billion gallons, less than 1 percent of total Bay volume, entering daily), wastewater inputs comprise a relatively large percentage (more than 4 percent) of the total freshwater inputs.

In effect, physical development of the surrounding watershed contributes to the pollution of the Narragansett Bay in nearly every aspect, but most directly it creates urban runoff. Urban runoff is the flash runoff of surface water from a watershed due to highly impervious surfaces quickly channeling water off of the watershed and into the receiving water body. With the high velocity and lack of impounding structure in urban areas, any pollutants entrained in the runoff are carried, usually through specifically designed conduits, directly into the receiving water bodies without natural filtration processes offered by vegetated riparian areas (Fig. 12.3). Urban runoff contributes to pathogen, toxic metal, and hydrocarbon pollution in the Bay.

In addition to contributing indirectly to pollution impacts, physical changes to the hydrology and structure of the Bay's tributaries, coastlines, and bottom have had several direct impacts on Narragansett Bay's ecology. Loss of estuarine wetlands directly reduces critical habitat for a variety of nekton and avian species and reduces the filtering effect on watershed runoff. Impoundment of Narragansett Bay wetlands has been found to lead to the widespread establishment of invasive vegetation due to lowering marsh salinities (Bertness, 1999). From 1950 to 1990, 97 ha of marsh were overtaken by the invasive reed *Phragmites australis* (Tiner et al., 2004). Impoundment also often results in degraded nekton assemblages within marshes (Raposa and Roman, 2003). The damming of tributaries has led to the downfall of anadromous fish stocks, beginning with the extirpation of Atlantic salmon (*Salmo salar*) by 1830, and continuing with a chronic demise in once robust river herring (*Alosa* spp.) runs (NBEP, 2006). Currently, only 18 of the historic 45 runs still support anadromous fish. Damming also raises the temperature of waters entering the Bay, traps and concentrates polluted sediments, buffers natural flow variations, and alters the compositions of riverine flora and fauna (Erkan, 2002). The ongoing maintenance of miles of dredged deepwater channels also affects the Bay's ecosystem health. Dredging causes a direct loss of benthos and also reintroduces buried toxins, such as heavy metals and synthetic organic compounds, to the living water column and aerobic benthic zones.

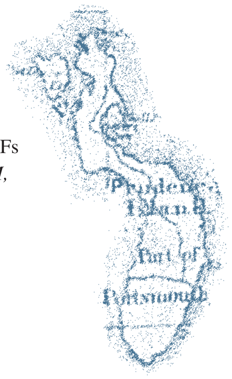
Nutrient Loading

For over a century, Narragansett Bay has been receiving a substantial loading of anthropogenic nutrients, most notably in various forms of nitrogen and phosphorus. Nutrient inputs are specifically correlated with the widespread use of running water, which began in the late 1800s (Nixon et al., 2005). The two major sources of nutrient inputs to Narragansett Bay are the major public wastewater treatment facilities (WWTFs) that discharge directly into the Bay and the major tributaries (riverine input), which act to combine nutrients from upstream WWTFs, individual sewage disposal systems (ISDSs), and runoff from their respective contributing sub-watersheds. Total riverine input is the major source of nitrogen entering the Bay (Nixon et al., 2005). However, if all WWTFs are taken into account, including those discharging into rivers, WWTFs currently contribute approximately 70 percent of the total nitrogen load entering the Bay, while runoff carrying nutrients from atmospheric deposition and agriculture contributes most of the balance (22 percent and 6 percent, respectively; Nixon et al., 2005). Direct atmospheric and groundwater sources are thought to be minor (Carey et al., 2005).

Figure 12.3. A highly modified and industrialized upper reach of the Providence River in Narragansett Bay. Note highway storm drain pipes discharging directly into the river. *Photo from NBNERR photo library.*

Currently, total inputs from Narragansett Bay's five major tributaries contribute 1.5 times the nitrogen and 2.7 times the phosphorus to the Bay as the three combined largest WWTFs (Field's Point, Bucklin Point, and East Providence), dispensing an estimated 2,590 metric tons (MT) of total nitrogen and 271 metric tons of total phosphorus per year into the Bay (Nixon et al., 2005). Nitrogen enters the Bay from rivers mainly in the form of dissolved inorganic nitrogen, mostly derived from WWTF discharges during high river flow periods in spring and in fall storms (Carey et al., 2005). Phosphorus enters from rivers mostly in the forms of inorganic phosphate and particulate phosphorus (Nixon et al., 2005).

Over 290,000 cubic meters per day of effluent enter Narragansett Bay directly from the three large sewage treatment facilities. Nixon et al. (2005) estimated that, combined, the three big WWTFs contribute 1,650 MT and 120 MT per year of total nitrogen and phosphorus, respectively. Nitrogen inputs from major WWTFs have changed little since



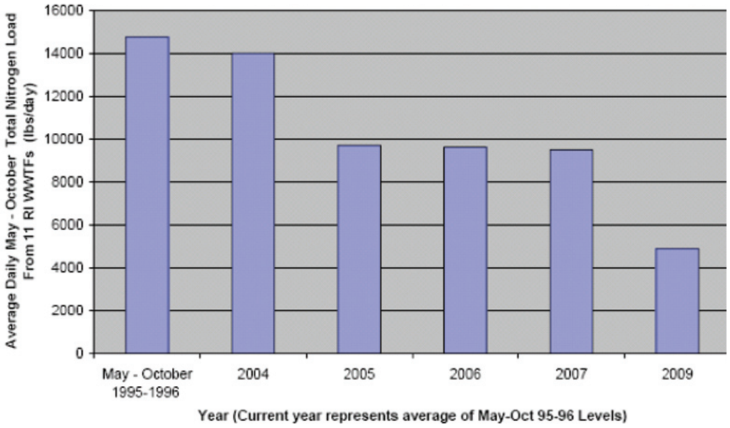


Figure 12.4. Projected yearly reductions in nitrogen loads from major Rhode Island WWTFs on Narragansett Bay. *Reproduced from RIDEM, 2005.*

the mid-1970s, with reduced inputs from the Field's Point facility being offset by increased inputs from the Bucklin Point facility, while phosphorus inputs have decreased significantly during that time. Nitrogen enters mainly in the form of ammonia (approximately 60 percent) followed by organic nitrogen and nitrites/nitrates, while the state of phosphorus entering has not been determined for sewage effluent (Nixon et al., 2005).

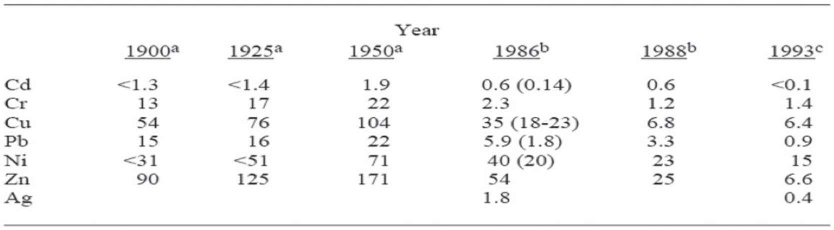
Nutrient loading is considered by some ecologists to be the most serious and widespread pollution impact currently occurring in Narragansett Bay, decreasing benthic biodiversity and altering valuable ecosystem functions (e.g., Deacutis, 1998; Carey et al., 2005). Nitrogen is considered the limiting nutrient to primary production in the Bay, while phosphorus and other nutrients may have lesser effects on certain ecosystem processes (Carey et al., 2005). Overloading the Bay with these nutrients has led to widespread eutrophication (over-production in primary producers such as phytoplankton and macroalgae, especially *Ulva* sp.), primarily in the upper reaches. This has ultimately impacted the ecology of much of the Bay ecosystem. One impact is high turbidity, which remains a primary cause in the stress or complete elimination of eelgrass (*Zostera marina*) from historic areas (visit *www.edc.uri.edu/restoration/html/intro/sea.htm*). Eelgrass forms an important Bay habitat type that provides cover for many juvenile and adult marine species and thus its decline has had ascending trophic effects on the ecosystem.

Another effect of eutrophication on Narragansett Bay is the regular seasonal occurrence of hypoxic and anoxic events, especially in areas of the upper Bay near the sources of nutrients. Middle and lower Bay segments are subject to periodic and infrequent hypoxic events, respectively (Carey et al., 2005). Habitats subjected to regular oxygen depletion have been degraded, with shifts in benthos from expected diverse faunal assemblages of large species such as American lobster (*Homarus americanus*), crabs, and mantis shrimp (*Squilla empusa*) to depauperate assemblages of small, short-lived worms and clams (Deacutis, 1998; Carey et al., 2005). Hypoxic and anoxic events have also been responsible for recent fish kills in the Bay (e.g., RIDEM, 2003; RIDEM, 2004).

The Rhode Island Governor's Commission enacted a "Plan for Managing Nutrient Loadings to Rhode Island Waters" (RI General Law 46-1-3(25)) in 2004 to reduce, by 50 percent, dissolved nutrients entering the Bay from 11 major WWTFs by 2009 (RIDEM, 2005; Fig. 12.4). This is expected to result in a 48 percent reduction in total summertime nitrogen loads to the Bay (Carey et al., 2005). Reduction of nutrients has been shown to restore expected ecological functions to estuarine systems (Mallin et al., 2005). Scientists expect a recovery of diversity and productivity in the degraded benthos of the upper Bay in response to lower nutrient loads, but are uncertain whether it will lead to a rebound in eelgrass abundance (Carey et al., 2005).

Toxic Metals

The sediments and waters of Narragansett Bay have been contaminated with a variety of anthropogenic metals contributed by numerous sources over the course of developed history. Significant inputs of metals to Narragansett Bay began as industrialization led to prevalent machinery and jewelry base-metal industries on Narragansett Bay tributaries during the mid-1800s. Metal-rich manufacturing wastes from these and other industries were dumped directly into the Bay and its tributaries until about 1910, when the Field's Point treatment facility began treating combined household, street runoff, and industrial effluent (Nixon, 1995). From 1909 to 1950, metal-laden solids were precipitated from the Field's Point effluent and dumped directly into the mid-Bay, just south of Prudence Island (Nixon, 1995). As a result, various anthropogenic metals are known to exist throughout the Bay in various levels of concern. These include arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, and zinc. All facets of industrialization and subsequent urbanization of the



	Year					
	1900[a]	1925[a]	1950[a]	1986[b]	1988[b]	1993[c]
Cd	<1.3	<1.4	1.9	0.6 (0.14)	0.6	<0.1
Cr	13	17	22	2.3	1.2	1.4
Cu	54	76	104	35 (18-23)	6.8	6.4
Pb	15	16	22	5.9 (1.8)	3.3	0.9
Ni	<31	<51	71	40 (20)	23	15
Zn	90	125	171	54	25	6.6
Ag				1.8		0.4

Table 12.1. Partial reproduction from Nixon (2005) presenting a comparison of estimated inputs of various metals to Narragansett Bay from the Fields Point WWTF in metric tons per year.

watershed, including fossil fuel use, the widespread use of automobiles, construction, street paving, and indoor plumbing, contributed to a snowballing of metal inputs, peaking around the 1950s when environmental regulations began to be implemented (Table 12.1).

Metals have entered Narragansett Bay through several interconnected modes: riverine inputs, WWTF discharges, direct point and nonpoint discharges, and direct atmospheric deposition. Rivers and WWTFs have historically been, and remain, the main sources of metal inputs into Narragansett Bay, while direct atmospheric deposition has been a significant source of only lead, mostly during the leaded gas era (Nixon, 1995). River and upstream inputs increased with urbanization of the watershed, as metals from atmospheric deposition and automobile byproducts were efficiently and quickly transported from the roofs, streets, and sidewalks of urban areas into the tributaries in the form of urban runoff. Narragansett Bay tributaries also carry the discharges of some 22 WWTFs and numerous industries (RIDEM, 2003). Rivers currently contribute the most cadmium, lead, zinc, copper, nickel, and chromium, while WWTFs contribute the highest amount of silver (Nixon, 1995).

Due to environmental regulations imposed in recent decades, metal inputs to Narragansett Bay have diminished, but high concentrations of these contaminants remain buried in Bay sediments. Decreases in inputs have resulted from air and water pollution legislation, the shift from wood and coal to oil and natural gas, application of stack emission reduction devices, removal of lead from gasoline, termination of sludge-dumping in the Bay, upgrading of WWTFs, and the loss of primary metal industries in the watershed (King et al., 1998; Greene and Deacutis, 2000; Nixon, 1995). In fact, Nixon (1995) estimated that fewer metals were entering the Bay from watershed discharges than from the open ocean. However, high concentrations of persistent metals remain within bottom sediments in many areas of the Bay and its tributaries. King et al. (1995) found the dam-impounded sediments of the Bay's major tributaries often exceeded the "effects range–median" (ERM) sediment quality guidelines (EPA Sediment Effect Concentrations: "a level above which indicates frequent adverse biological effects") for cadmium, chromium, copper, lead, nickel, silver, and zinc. Some of these concentrations were among the highest ever observed in the United States. They also noted that large areas of the upper Bay also exceeded sediment quality guidelines. Overall, the National Status and Trends Program, conducted by NOAA in 1989, found Narragansett Bay to rank among the top 20 most contaminated embayments in the country for mercury, selenium, and silver, as well as ranking sixth of 72 for copper, eighth of 45 for lead, and 21st of 145 for nickel contamination in *M. edulis* flesh concentrations (Keller et al., 1996). In more recent studies, King et al. (2003) found concentrations of several metals to be above "effects range–low" (ERL) values in the sediments around a remediated military superfund site near Quonset Point, while Hanson et al. (2002) found similar results in the sediments at Potter Cove in the NBNERR North Prudence Unit.

In general, the highest concentrations of metals in the sediments of Narragansett Bay are located near historic sources in the upper Bay and decrease exponentially with distance down-Bay (King et al., 1995). Core samples collected by King et al. (1995) suggest that as sediments are disturbed by such processes as bioturbation or dredging, metals are resuspended and transported down the Bay with the net flow of the estuary; thus, areas away from the source are becoming more contaminated, while upstream areas are becoming less contaminated (Ely and Trew Crist, 2001).

Sediments contaminated with metals can have harmful effects on marine and human life, but knowledge of the extent of direct effects on Bay life is limited, due to confounding factors such as nutrient loading, Bay warming, and the complex nature of effective bioavailability. Metals vary widely in toxicity, bioavailability, and the degree in which they are bioaccumulated, depending on various physical factors such as temperature, salinity, and sediment composition. Because metal inputs have dramatically declined, most Bay metals are remnants of historic sources, buried in the sediments in reduced states and are not readily bioavailable. In general, metals in the sediments most directly affect

shellfish and other burrowing fauna. King et al. (1995) found a weak relationship between sediment concentrations and flesh concentrations in *M. mercenaria* for copper and cadmium, and no relationship for nickel, chromium, or lead, but they observed a stronger correlation between *M. mercenaria* tissues and effective water-column metal concentrations (likely due to increased bioavailability of oxidized metals), which has implications for dredging and dam remediation projects. RIDEM (2004) does not consider current levels of toxic metals buried in Bay sediments to pose an immediate public human health threat, primarily because contaminated areas exist mostly in the upper reaches of the Bay where shellfishing is already banned due to sewage contamination.

Petroleum Hydrocarbons and Polycyclic Aromatic Hydrocarbons

Petroleum hydrocarbons (PHCs) encompass the total suite of hydrocarbon compounds derived from petroleum oil, while polycyclic aromatic hydrocarbons (PAHs) are toxic constituents of PHCs, created during PHC combustion. PHCs and PAHs enter Narragansett Bay primarily through chronic urban runoff that is introduced to Bay waters via combined WWTFs and rivers, although direct atmospheric deposition and direct industrial discharge may also be significant contributors (Latimer and Quinn, 1998; Hartmann et al., 2004). Large accidental spills only constitute about 2 percent of all oil entering the Bay (Keller et al., 1996). Major chronic sources of PHCs are thought to originate primarily from used crankcase oil, either being illegally discharged directly into the environment or from runoff carrying roadway oil into storm drains (Latimer and Quinn, 1998). In addition to pervasive crankcase oil, Latimer and Quinn (1998) also found a high incidence of No. 2 and No. 6 fuel oil constituents in riverine samples, as well as gasoline or kerosene-like components in the Moshassuck River, which likely result from leaking tanks or spillage. Significant PAH inputs currently originate in the Bay's watershed as both petrogenic (from petroleum) and pyrogenic (from combustion) hydrocarbons. Creosote (from treated piles and bulkheads), coal combustion (possibly from two power plants on the Taunton River in Massachusetts), and diesel exhaust are thought to be the major contributors (Hartmann et al., 2003). Higher molecular weight species are most likely to settle in Bay sediments.

Annual loads of total PHCs to Narragansett Bay are estimated to be 420 MT, including approximately 240 MT dry-season chronic inputs (150 MT from WWTF, 64 MT from rivers, and 27 MT from other surface water sources) and approximately 180 MT of wet-weather and other event-driven inputs (Latimer and Quinn, 1993). Total input is roughly the equivalent 128,000 gallons of oil per year, but, due to considerable pyrogenic sources, contains a much higher aromatic (PAH) fraction (Latimer and Quinn, 1993). Hartmann et al. (2006) ran sediment grab-sample transects (41 samples total) down both the East and West passages and found that PAH concentrations were highest at the industrialized head of the Bay and lowest toward the mouth, suggesting urban runoff and WWTF sources, with the Barrington, Taunton, and Seekonk/Providence rivers having the highest values.

In 1993, annual loads of total PHCs in Narragansett Bay were estimated to be 37±17 micrograms per liter (μg l^{-1}) in the Bay's main-stem rivers—substantially higher than the reference level of 10 μg l^{-1} reported in prior studies to be harmful to certain biota, including the American lobster—a locally valuable commercial species. Eighty-six percent of samples were above that value. Hartmann et al. (2006) found a mean concentration of PAHs in the sediments of the Narragansett Bay of 21 micrograms per gram (μg g^{-1}), which was well above ERL (4.02 μg g^{-1}) sediment quality guidelines. Overall, 73 percent (30) of their stations exceeded ERL values, while 12 percent (5) were above the ERM guideline of 44.8 μg g^{-1}. Toxicity of each hydrocarbon component varies, but chronic exposures to total hydrocarbons have shown effects in winter flounder physiology at concentrations of 1 μg g^{-1} and on benthic macrofauna communities at 0.09–0.18 μg g^{-1} (Keller et al., 1996).

The various components of PHCs contain a wide range of compounds that are highly toxic to marine and human life, with aromatic and mid-weight components (such as diesel due to its high aromatic fraction and persistent physical properties) being the most toxic (Clark, 2001). Pruell et al. (1984) found that *M. mercenaria* samples purchased at Rhode Island commercial seafood stores—which the authors presumed were locally caught—were contaminated with levels of biogenic hydrocarbons that exceeded levels found in samples from a control site in the lower Bay. King et al. (1993) found a strong correlation between sediment concentrations and tissue concentrations of PAHs among Narragansett Bay *M. mercenaria*. Although PAHs are considered to be carcinogenic, no state—Massachusetts or Rhode Island—or federal standards are set for concentrations of any PHCs in seafood (Pruell et al., 1984; J. Migliore, personal communication).

Synthetic Organic Compounds

Synthetic organic compounds are anthropogenic, potent, and generally highly conservative pollutants that are composed of a wide range of organochlorines and other halogenated hydrocarbons. They include industrial solvents, chlorofluorocarbons (CFCs), flame-retardants, polychlorinated biphenyls (PCBs), and pesticides such as DDT, '-drins', lindane, hexochlorobenzene (HCB), toxophene, and dioxins (Clark, 2001). Synthetic organic contaminants enter Narragansett Bay from a wide range of sources, including rivers, point sources, atmospheric deposition and spills, and adsorb to particulate matter that settles to the seafloor, where it can remain in the sediments almost indefinitely (Quinn and King, personal communication). Many of these compounds were extensively produced and utilized in and around the Narragansett Bay watershed in support of modern agriculture and infrastructure systems during the mid-1900s. In response to worldwide environmental and human health impacts brought to light mostly during the 1960s, production and use of most of these compounds has been highly regulated or halted since the 1970s and 1980s (Clark, 2001). Although PCBs and DDT have been banned from sale in the United States, they both remain measurable in Narragansett Bay waters (Keller et al., 1996).

The most notable suite of synthetic organic compounds currently affecting Narragansett Bay is PCBs, which were produced mainly for use in electrical capacitors and transformers. The Blackstone River is by far the greatest contributor of PCBs, carrying 93 percent of total PCBs entering the Bay from rivers (Latimer et al., 1990; J.G. Quinn, personal communication). Latimer et al. (1991) and Quinn and King (personal communication) found that PCB levels in sediments were highest in the industrialized source areas in the extreme upper Bay and decreased in a linear fashion down-Bay due to sediment transport, with 90 percent of contaminants accumulated in the Providence River (Latimer and Quinn, 1996, Fig. 12.5). King et al. (1995) found that sediments in the Seekonk River and northern and middle sections of the Providence River contain concentrations exceeding ERM quality guidelines. Mid-bay areas situated near point sources such as in Newport and Quonset Point also contain elevated levels of PCBs. Latimer et al. (1996) found mean PCB concentrations in Narragansett Bay sediments of 390 ppm, ranging from about 1,000 ppm in the Providence River to less than 10 ppm near the mouth of the Bay. Total annual flux to the sediments of the Bay is approximately 0.1 MT (J.G. Quinn, personal communication). Quinn and King (personal communication) also found high concentrations of the flame suppressant polybrominated diphenyl ether (PBDE) in the sediments in Pawtuxet Cove and at Bucklin Point in the Upper Bay. PBDE is structurally similar to PCBs and is believed to have similar function and toxicity.

Synthetic organic compounds are considered the most highly toxic and mutinogenic of all marine pollutants. They are a particular threat to species in higher trophic levels, as they tend to bioaccumulate and biomagnify in fatty tissues (Clark, 2001). However, because their effects are not typically acute, little is known about their direct impacts on Bay or human life. King et al. (2005) found a strong correlation between surface sediment concentrations and tissue concentrations in *M. mercenaria* for five organic compounds including benzotriazoles and PCBs. Jeon and Oviatt (1991; in Keller et al., 1996) assessed concentrations of toxic contaminants in Narragansett Bay blue mussel, quahog, and winter flounder and found that PCB concentrations were generally higher in tissues of animals in the upper Bay. Of 42 coastal sites ranked for contamination by NOAA in 1989, Narragansett Bay ranked 14th for PCB concentrations in flounder. Strong correlations between PCB burdens and liver disease in winter flounder have since been revealed (Keller et al., 1996).

Another notable environmental consequence of synthetic organic pollution is that it limits riverine restorations, specifically the removal of relic dams, due to high concentrations in impounded sediments. High costs of removing and disposing of contaminated sediments are often prohibitive to riparian restoration efforts in the Narragansett Bay watershed (T. Ardito, personal communication).

Aquatic Nuisance Species

Historically, nonindigenous marine species (or aquatic nuisance species) have entered Narragansett Bay mainly through passive introduction via the shipping trades. The primary vector has been bilge water effluence, although ship fouling, aquaculture importation, and ornamental escape may have been instrumental for certain species (Narragansett Bay Estuary Program (NBEP), 2005; Cute and Hobbs, 2000; Massachusetts Invasive Species Working Group (MAISWG), 2002). Estuaries are generally considered the most vulnerable waters to invasion of aquatic nuisance species due to the extended time international ships spend in estuarine ports. Narragansett Bay, as a net importer of goods, supports less ballasted incoming international shipping traffic than many major ports, and is thus considered by some to have a relatively low risk of invasion

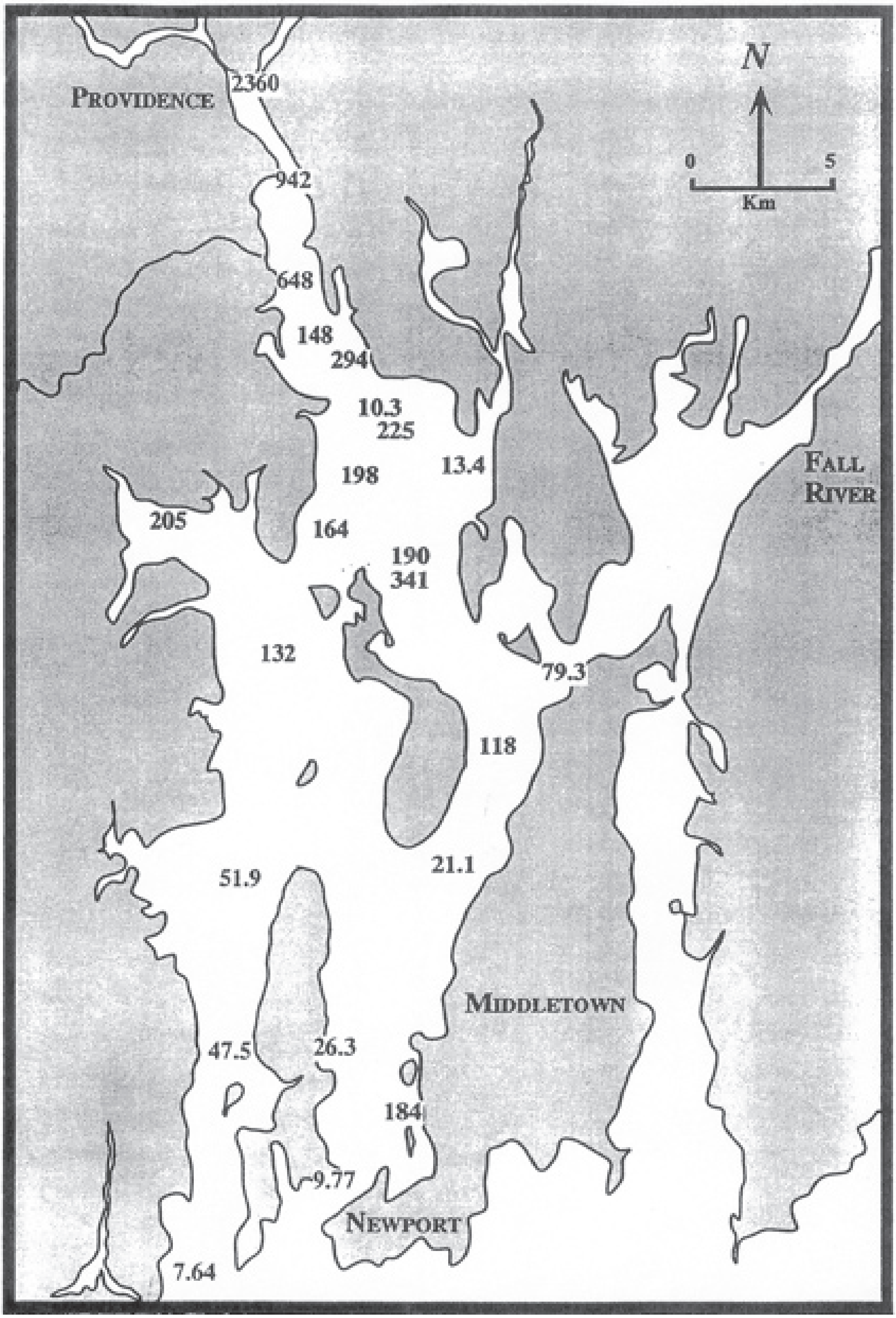


Figure 12.5). A reproduction from King et al. (1995) depicting concentrations of total PCBs (ng/g) in the surface sediments of Narragansett Bay. Note that the concentrations are highest in the industrialized upper Bay and diminish while moving down the Bay (a trend that holds for most contaminants in the Bay).

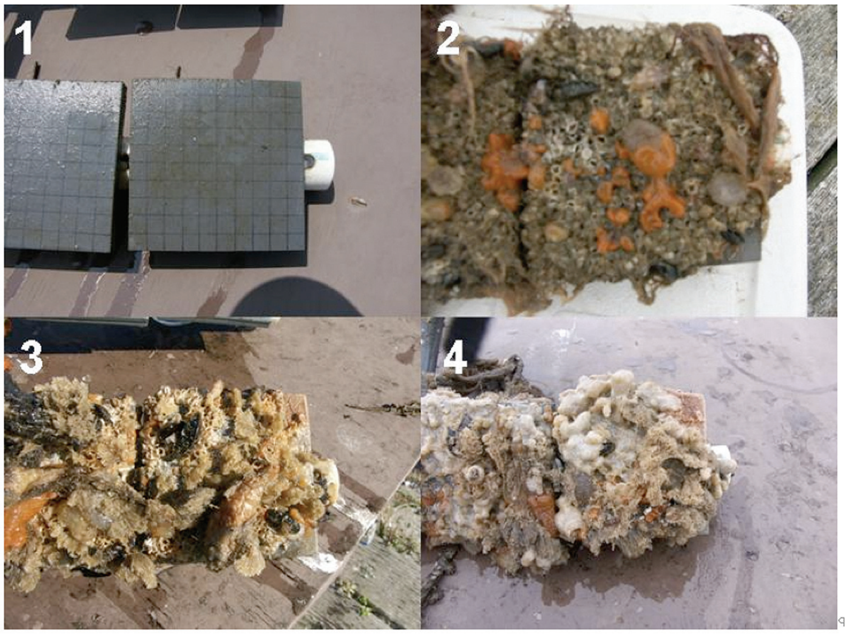


Figure 12.6. A time-series account of species recruitment on a Whitlatch settling plate set off the T-wharf in the NBNERR in 2005 by URI graduate student Linda Auker. Note how expected species such as barnacles (*Semibalanus balanoides*) and blue mussels (*Mytilus edulis*) are almost entirely overtaken by invasive tunicates. *Photo from NBNERR photo library.*

(NBEP, 2005). Others consider the Bay ecosystem to be at a high risk of invasion due to recent glacial history resulting in an under-saturated ecosystem (e.g., Bertness, 1999). Cute and Hobbs (2000) found that rates of invasion within Narragansett Bay have generally been increasing since 1900, which follows regional and global trends (NBEP, 2005).

Several aquatic nuisance species are widespread and abundant in Narragansett Bay. These include long-time invasives such as the common periwinkle (*Littorina littorea*), which was introduced from Europe circa 1840, and the green crab (*Carcinus maenas*), which was introduced from Europe circa 1841; and recent introductions such as the red seaweed *Grateloupia turuturu*, which was introduced from the West Pacific circa 1996, and the Asian shore crab (*Hemigrapsus sanguineus*), which was introduced from the West Pacific circa 1988 (Cute and Hobbs, 2000) and currently is showing rapid growth around Prudence Island (NBEP, 2005).

The only known formal inventory of aquatic nuisance species in Narragansett Bay is a rapid assessment of floating dock fouling communities that was conducted over a four-day period in 2000 (Cute and Hobbs, 2000). Of 149 species catalogued during that assessment, 22 species in 11 phyla were determined to be nonindigenous, while 17 species in four phyla were determined to be cryptogenic (of undetermined origin). Due to the nature of the assessment, all nonindigenous species found were either seaweeds or sessile invertebrates, with the exceptions of the green crab and the Asian shore crab.

The MAISWG (2002) compiled a list of problematic marine invaders and marine species of concern for the Massachusetts Aquatic Invasive Species Management Plan. Problematic invaders occurring in Narragansett Bay include green crab; Asian shore crab; lace bryozoan (*Membranipora membranacea*); the green alga dead-man's fingers (*Codium fragile* var. *tomentosoides*); six tunicates including *Styela clava, S. canopus, Diplosoma listerianum, Asciliella aspersa, Botryllus schlosseri,* and *Botrylloides violaceous*; and numerous shellfish pathogens including MSX (*Haplosporidian nelsoni*), SSO (*H. costalis*), Dermocystidium (*Perkinsus marinus*), and QPX, an unidentified quahog parasite. Threatening species, those that are not yet present but pose considerable threats to native ecosystems, include the veined rapa whelk (*Rapana vanosa*) from Japan; Nori (*Porphyra yezoensis*), an edible Asian red alga commercially cultivated in the Gulf of Maine; the Chinese mitten crab (*Eriocheir sinensis*); the intentionally cultivated Pacific oyster (*Crassostrea gigas*); and the "killer algae" *Caulerpa taxifolia*, which is an escaped ornamental alga associated with marine aquaria (MAISWG, 2002).

Aquatic invasive species have had long-term, wide-ranging effects on Narragansett Bay ecosystems and on fisheries. Significant impacts are community changes due to competitive dominance and predation and transmission of disease. For example, the ubiquitous green crab is known to compete with native crabs for food resources, and prey upon the commercially important clam species *Mya arenaria* and *Mytilus edulis* (Flimlin and Beal, 1993). Since its introduction, the green crab has become one of the most dominant omnivorous shoreline consumers in the Northeast. The common periwinkle is the most abundant grazer in the Bay's intertidal habitats and has effectively driven the ecology of all Bay cobble and rock beach ecosystems via top-down control of algae and seaweeds and displacement of expected species (Bertness, 1999; Fig. 12.6). The alga dead man's fingers has also been found to affect cobble beach communities by contributing to the dislodgement of cobbles due to increased drag, and introduced tunicates are responsible for the displacement of native fouling organisms (Bertness, 1999). The invasive shellfish parasites MSX and *Dermocystidium* have been implicated in the continued scarcity of the once abundant and economically important native, the American oyster (*Crassostrea virginica*), in Narragansett Bay (RIDEM, 2004b).

Extraction of Biotic Resources

Since the 1800s finfish and shellfish in Narragansett Bay have been greatly affected, both in community composition and abundance, by fishing. Commercial fishing practices have evolved from early gears, such as the small trap, hand-line, hand dredge and tong, and small surface net, to massive, modern, efficient, and potentially destructive gears, such as the otter trawl, hydraulic dredge, long-line, and gillnet. Recreational fishing has also persisted throughout the period. A drop in finfish stock has driven most commercial finfishing out of the Bay and into coastal waters, while Bay shellfishing and recreational fishing remain important. Commercial fisheries data have been used to indicate fish abundance and community composition, and, coupled with trawl data captured by the RIDEM from 1960 to 2000, have shed light on fish populations and the effects of fisheries on the Bay.

Oviatt et al. (2003) analyzed historic and current fisheries and trawl data to explore trends and formulate hypotheses in finfish abundance and community structure in Narragansett Bay over time. Rhode Island fishery survey data compiled from the 1860s and the mid-1900s revealed a shift in target species from primarily in-Bay species to a mix of in-Bay and offshore species. More recently, RIDEM trawl surveys conducted within Narragansett Bay revealed that overall biomass of demersal species has decreased by a factor of four in recent times. Biomass of pelagic species changed little, but species composition has shifted, with a decrease in scup biomass and an increase in bluefish, butterfish, and bay anchovy biomass. Historically important codfish, tautog, and alewife populations no longer support distinct commercial fisheries due to drastically reduced numbers (Oviatt et al., 2003).

The Narragansett Bay shellfish fishery has persisted since early times, but also with shifts in targeted species from the American oyster, the soft-shelled clam (*Mya arenaria*), and the bay scallop (*Argopecten irradians*) to the American lobster and the quahog more recently (Fig. 12.7). Oviatt et al. (2003) theorize that this shift may be associated with competitive release resulting from changes in demersal finfish assemblages, with the shift in harvest being a direct reaction to population shifts in respective species. Currently, approximately 8 million pounds of quahogs are extracted from Bay waters annually (see *NBEP.org*). Overall, it is estimated that shellfish biomass has dropped 17 percent since 1960 and 88 percent since 1898 (Oviatt et al., 2003).

Both direct and indirect harvesting pressures have been implicated as instrumental factors driving finfish and shellfish population shifts in Narragansett Bay. Oviatt et al. (2003) estimated that between the mid-1800s and mid-1900s, finfish catches within Narragansett Bay actually exceeded the Bay's capacity for production, and fish populations were apparently repopulating the Bay from nearby offshore waters. Currently, due to recent heavy fishing pressure in these nearby offshore waters, those populations no longer exist. Fish trapping, which was the most highly utilized and effective harvesting method employed in early times, is thought to have affected target populations while otherwise minimally impacting the environ-

Figure 12.7. A quahog fisherman digging from a small, modern, commercial skiff in upper Narragansett Bay. Inconsistent with trends in sophisticated modern gear, quahogs are harvested manually with a long hand rake known as a bullrake or by diving. *Photo from NBNERR photo library.*

ment (Oviatt et al., 2003). However, efficient but destructive commercial fishing practices of the last century, especially scallop dredging and trawling, have greatly impacted benthic habitat, which in turn may have effected the recruitment of various commercial species, including the once commercially important bay scallop. Relative abundance of total fish yield has declined an estimated 81 percent since 1891, attributed mostly to impacts of trawl fishing in the past 40 years (Oviatt et al. 2003). The dynamics between fishing pressure and populations of target species are tightly intertwined in such a small ecosystem as Narragansett Bay, yet direct relationships are often confounded by many other natural and anthropogenic factors, such as extreme weather events, siltation, warming, impasse, toxins, hypoxia, and disease, many of which may act synergistically (DeAlteris et al., 2000). Thus, harvest restrictions imposed within the last century have had limited success in restoring target populations.

Summary

A long history of human exploitation has affected virtually every ecological function in Narragansett Bay and its watershed. Sources of degradation and pollution are centered in and around industrial and residential growth centers, mostly in the upper Bay near the Providence and Fall River metropolitan areas, although effects are often widespread. There is a distinct gradient in nearly all contaminants, ranging from high levels of contamination in the upper Bay to relatively low levels in the lower Bay. For persistent contaminants buried within Bay sediments, this gradient is slowly moving down-Bay as sediments are resuspended by activities such as dredging, trawling, and bioturbidation, and resettle in lower reaches. Modifications to natural hydrologic systems have directly affected or facilitated environmental degradation throughout the Narragansett Bay watershed. Widespread damming, watershed urbanization, and diversion, canalization, and dredging of waterways have directly contributed to fish impasse, urban runoff, and habitat loss, while indirectly contributing to water and sediment pollution.

Nutrient loading perhaps has the greatest immediate impact on Narragansett Bay ecology, having ascending trophic effects on all biota and direct effects on certain benthic species through oxygen depletion associated with eutrophication. Nutrients enter the Bay primarily through WWTF effluent, both directly and via riverine transport. Steps are currently being taken to reduce nutrient loading to the Bay by 50 percent by 2009, but under changing climate conditions, these reductions could have as-yet-unknown consequences on Bay productivity. Persistent pollutants, such as metals, synthetic organic compounds, and PHCs also enter the Bay through direct WWTF discharge and riverine sources, but are also attributed to urban runoff. Sediments in the upper reaches of Narragansett Bay and its main-stem rivers contain some of the highest concentrations of persistent contaminants on record, yet due to current limited bioavailability, have limited immediate impacts on Bay life. They do, however, limit hydrologic restoration efforts, especially riparian restoration, due to the probability of resuspension.

The Narragansett Bay ecosystem has also responded to direct anthropogenic inputs and withdrawals of biota. Aquatic nuisance species, introduced primarily through fouling and bilge exhaust associated with the shipping trades, have been affecting trophic dynamics since the 1800s. Currently, exotic shellfish diseases are impacting economically important species, such as the American oyster. A long history of persistent fishing has also affected Bay ecology through direct extraction and ascending and cascading trophic consequences. Efficient, but sometimes destructive, modern fishing practices are thought to also directly degrade benthic systems.

Literature Cited

Bertness, M. 1999. *The Ecology of Atlantic Shorelines*. Sinauer Associates, Inc., Sunderland, Mass.

Burroughs, R. 2000. Narragansett Bay ecosystem management: Goals, trends, and issues. White paper prepared for the Narragansett Bay Summit 2000, Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 23pp.

Carey, D., A. Desbonnet, A.B. Colt, and B.A. Costa-Pierce. 2005. State of science on nutrients in Narragansett Bay: Findings and recommendations from the Rhode Island Sea Grant 2004 Science Symposium. Report prepared for Rhode Island Sea Grant. 43pp.

Colt, A.B., T. Tyrrell, and V. Lee. 2000. Marine recreation and tourism in Narragansett Bay: Critical values and concerns. White paper prepared for the Narragansett Bay Summit 2000, Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 38pp.

Crawley, K., M. Pryor, R. Ribb, S. Kaplan, A. Langhauser, and M. Peck. 2000. Land use and transportation in the Narragansett Bay watershed: Issues and challenges. White paper prepared for the Narragansett Bay Summit 2000, Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 47pp.

Deacutis, C. 1998. Nutrient impacts and signs of problems in Narragansett Bay. Report prepared for Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 16pp.

DeAlteris, J.T., M. Gibson, and L.G. Skrobe. 2000. Fisheries of Rhode Island. White paper prepared for the Narragansett Bay Summit 2000, Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 48pp.

Ely, E. and D. Trew Crist. 2001. *Narragansett Bay Window: The Cooperative Bay Program—Phase 1*. Rhode Island Sea Grant, Narragansett, R.I. 16pp.

Erkan, D.E. 2002. Strategic Plan for the Restoration of Anadramous Fishes to Rhode Island Streams. Completion of report in fulfillment of Federal Aid in Sportfish Restoration Project. R.I. Department of Environmental Management Division of Fish and Wildlife, Providence, R.I. 82pp.

Flimlin, G. and B.F. Beal. 1993. Major predators of cultured shellfish. Northeastern Regional Aquaculture Center Bulletin No. 180-1993. University of Massachusetts, Dartmouth, Mass. 6pp.

Gibson, M.R. 1996. Comparison of trends in the finfish assemblage of Mt. Hope Bay and Narragansett Bay in relation to operations at the New England Power Brayton Point Station. R.I. Department of Environmental Management Division of Fish and Wildlife Research Reference Document 95/1. Revised August 1996.

Greene, R. and C. Deacutis. 2000. Narragansett Bay Water Quality: Status and Trends 2000. A summary of water quality information. Report prepared for the Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 33pp.

Hale, S.O. 1988. *Narragansett Bay: A Friend's Perspective*. Rhode Island Sea Grant, Narragansett, R.I. 130pp.

Harrington, M.P. 2000. The impact of Narragansett Bay on Rhode Island's industrial development. White paper prepared for the Narragansett Bay Summit 2000, Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. 43pp.

Hartmann, P.C., J.G. Quinn, R.W. Cairns, and J.W. King. 2004. The distribution of polycyclic aromatic hydrocarbons in Narragansett Bay surface sediments. *Marine Pollution Bulletin* **48:** 351–358.

Keller, A., M. Pilson, and R. Johnston. 1996. Estuarine Profile of Narragansett Bay, Rhode Island. Draft Final Report. University of Rhode Island Graduate School of Oceanography. 244pp.

King, J., J. Corbin, R. McMaster, J. Quinn, P. Gangemi, D. Cullen, J. Latimer, J. Peck, C. Gibson, J. Boucher, S. Pratt, L. LeBlanc, J. Ellis, and M. Pilson. 1995. A Study of Sediments of Narragansett Bay, Volume I: The Surface Sediments of Narragansett Bay. Final Report Submitted to the Narragansett Bay Project. Providence, R.I. 201pp.

King, J., C. Gibson, E. Lacey, and J. Peck. 1998. Trace metal contaminants in the sediments of Narragansett Bay. Final Report, Grant No. NA77FE0493, URI/NOAA Cooperative Marine Education and Research Program.

King, J., J.G. Quinn, and R.M. Wright. 2003. Inorganic and organic characterization of dredged sediments from the proposed Quonset Point Channel in Narragansett Bay. URITC Project No. 536143. University of Rhode Island, Narragansett, R.I.

Latimer, J.S. and J.G. Quinn. 1998. Aliphatic and biogenic hydrocarbons entering Narragansett Bay from tributaries under dry weather conditions. *Estuaries* **21(1):**91–107.

Mallin, M.A., M.R. McIver, H.A. Wells, D.C. Parsons, and V.L. Johnson. 2005. Reversal of eutrophication following sewage treatment in the New River Estuary, North Carolina. *Estuaries* **28(5):**750–760.

Massachusetts Aquatic Invasive Species Working Group. 2002. Massachusetts Aquatic Invasive Species Management Plan. Massachusetts Aquatic Invasive Species Working Group, Massachusetts Office of Coastal Zone Management, Boston, Mass. 60pp.

Narragansett Bay Estuary Program. 2005. Ballast Water and Introduced Species: Management Options for Narragansett Bay. Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, R.I. Available on-line at: *www.nbep.org/pubs/index.html*. 25pp.

Narragansett Bay Estuary Program. 2006. Rhode Island's Coastal Habitats: Anadramous Fish Habitats. Narragansett Bay Estuary Program, R.I. Department of Environmental Management, Providence, RI. Available on-line at: *www.nbep.org*.

Nixon, S.W. 1995. *Metal Inputs to Narragansett Bay: A History and Assessment of Recent Conditions*. Rhode Island Sea Grant, Narragansett, R.I. Available on-line at: *seagrant.gso.uri.edu/bookstore/metals.pdf*.

Nixon, S.W., B. Buckley, S. Granger, L. Harris, A. Oczkowski, L. Cole, and R. Fulweiler. 2005. Anthropogenic Nutrient Inputs to Narragansett Bay: A Twenty-Five Year Perspective. A report to the Narragansett Bay Commission and Rhode Island Sea Grant. 29pp.

Oviatt, C., S. Olsen, M. Andrews, J. Collie, T. Lynch, and K. Raposa. 2003. A century of fishing and fish fluctuations in Narragansett Bay. *Reviews in Fisheries Science* **11:**221–242.

Pruell, R.J., E.J. Hoffman, and J.G. Quinn. 1984. Total hydrocarbons, polycyclic aromatic hydrocarbons and synthetic organic compounds in the hard shell clam, Mercenaria mercenaria, purchased at commercial seafood stores. *Marine Environmental Research* **11:**163–181.

Raposa, K.B. and C.T. Roman. 2003. Using gradients in tidal restriction to evaluate nekton community responses to salt marsh restoration. *Estuaries* **26:**98–105.

R.I. Department of Environmental Management. 2003. The Greenwich Bay Fish Kill—August 2003: Causes, Impacts and Responses. R.I. Department of Environmental Management, Providence, R.I. 32pp.

R.I. Department of Environmental Management. 2004a. Estuary and Coastal Assessment, Chapter IIIF. State of Rhode Island and Providence Plantations 2004 Section 305(b): State of the State's Waters Report. R.I. Department of Environmental Management Office of Water Resources, Providence, R.I.

R.I. Department of Environmental Management. 2004b. Rhode Island Fisheries Stock Status: An Overview. A Report to the General Assembly by Division of Fish and Wildlife. R.I. Department of Environmental Management Division of Fish and Wildlife, Jamestown, R.I. 21pp.

R.I. Department of Environmental Management. 2005. Plan for Managing Nutrient Loading to Rhode Island Waters. Report prepared for the R.I. Department of Environmental Management, Providence, R.I.16pp.

Tiner, R.W., I.J. Huber, T. Nuerminger, and A.L. Mandeville. 2004. Coastal Wetland Trends in the Narragansett Bay Estuary During the 20th Century. U.S. Fish and Wildlife Service, Northeast Region, Hadley, Mass., in cooperation with the University of Massachussetts and the University of Rhode Island. National Wetland Inventory Cooperative Interagency Report. 37pp.

U.S. Army Corps of Engineers. 2005. Waterborne Commerce in the United States, Part 1—Waterways and Harbors, Atlantic Coast. U.S. Army Corps of Engineers, Institute for Water Resources. IWR-WCUS-05-1. Available at: *www.iwr.usace.army.mil/ndc/wcsc/pdf/wcusat105.pdf*.

U.S. Environmental Protection Agency. 2005. Superfund in New England. U.S. Environmental Protection Agency. Available on-line: *www.epa.gov/region01/superfund/index2.htm*.

U.S. Navy. 2005. History: Narragansett Bay. Naval Station Newport/United States Navy. Available on-line: *www.nsnpt.navy.mil/history.htm*.

CHAPTER 13.

Research and Monitoring at the NBNERR

Kenneth B. Raposa

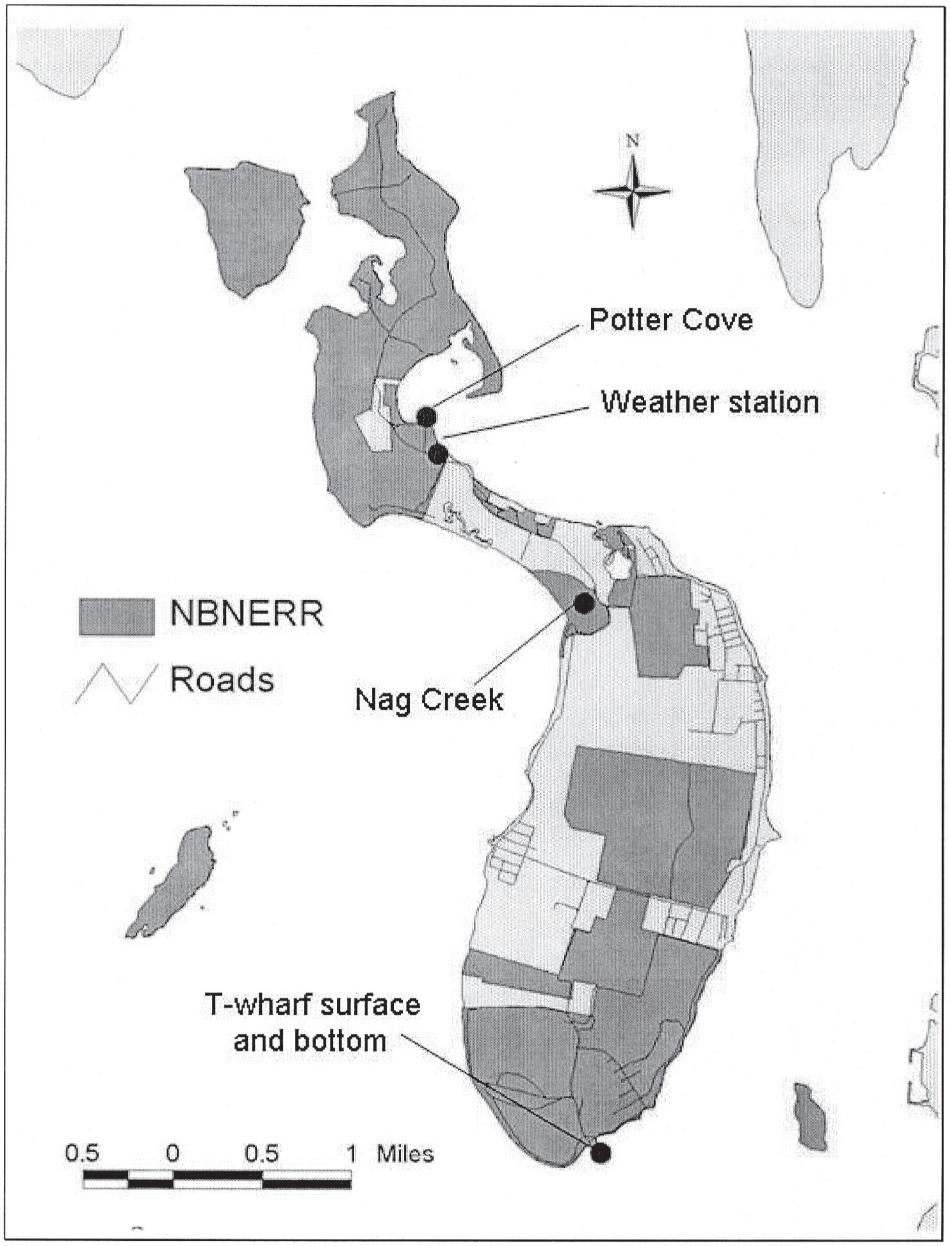


Figure 13.1. Locations of the NBNERR SWMP water quality and meteorological monitoring stations.

Figure 13.2. The System-Wide Monitoring Program at T-wharf on Prudence Island. Two water quality sondes are continuously deployed in PVC tubes extending into the Bay and data are transmitted near real time via telemetry. Nutrient and chlorophyll samples are also collected using the ISCO sampler shown here on the pier. *Photo from NBNERR photo library.*

Research and Monitoring at the NBNERR

One of the primary goals of the NERR System is to protect natural habitats that are representative of the biogeographic regions in which they are located in order to provide platforms for conducting estuarine research and monitoring. This vision is realized at the NBNERR, where research and monitoring is conducted by scientists from a variety of academic, government, nonprofit, and private institutions and by an active internal NBNERR research program. The Reserve provides financial support to two graduate students per year through the NERR Graduate Research Fellowship (GRF) program to conduct high-quality research in the Narragansett Bay watershed. Aside from this, the NBNERR does not provide financial assistance or funding to outside researchers to conduct research and monitoring. Instead, it provides information, collaboration, and logistical help to researchers working in the NBNERR and throughout Narragansett Bay (the NBNERR has a jurisdictional boundary out to the 5.4 m (18-foot) depth contour around its properties, but focuses its research and monitoring program throughout all of Narragansett Bay to address questions relevant to the current needs and issues facing the Bay and watershed). The work of visiting students and scientists is augmented by research and monitoring conducted by Reserve staff. Research at the NBNERR is directed by the Reserve's research coordinator, but is also conducted by other staff members that include water quality, natural resources, and GIS specialists, volunteers, and student interns.

The goal of this section is to provide an overview of all the research and monitoring activities that have taken place in, or have been associated with, the NBNERR since its inception. This includes national NERR programs (e.g., the SWMP), research and monitoring that is conducted by NBNERR staff scientists, and work done by visiting researchers who either conduct research directly in the NBNERR or are assisted in some way by the Reserve in their efforts elsewhere in Narragansett Bay and its watershed.

NERR Programs

System-Wide Monitoring Program

The primary long-term monitoring program at the Reserve is the SWMP. Nationally, the goal of SWMP is to track short-term variability and long-term change in estuarine water quality parameters. The first phase of this program is accomplished by continuously deploying automated dataloggers at stations located strategically around each Reserve in the NERR System. As the NERR program has grown so has the SWMP, which has undergone systematic expansion and enhancement since 1992 (Ross, 2003). At the NBNERR, the SWMP began in 1995 with the deployment of Yellow Springs Instruments' (YSI) water quality sondes at Potter Cove and T-wharf, both located on Prudence Island (Fig. 13.1). These two sites were selected in accordance with NERR guidance that recommended the selection of one site in an impacted area (i.e., Potter Cove) and one in a relatively pristine area (i.e., T-wharf). In 2001, the SWMP was expanded by adding two more water quality monitoring sites to each Reserve. At the NBNERR, one additional site was added in a salt marsh creek in Nag West Marsh, and the fourth site was established at T-wharf (Fig. 13.1). It was determined that the original T-wharf station was situated in the immediate region of the pycnocline that seasonally occurred at this site. This led to a confounding situation where data were sometimes collected from distinct layers either above or below the pycnocline depending on season and tide stage. In order to collect discrete datasets from both the surface and bottom water layers at T-wharf to examine stratification patterns, the original site was abandoned and moved further out on T-wharf where the water is deeper. At this new site, two sondes are maintained, one each in the surface and bottom layers (Fig. 13.2). The original T-wharf station was maintained for approximately two weeks after establishing the new surface and bottom stations in order to collect overlapping data for comparing new and old stations.

The rationale for the current distribution of SWMP stations at NBNERR is to collect data along a gradient in habitat types, from salt marsh (Nag Creek) to shallow cove (Potter Cove) to open Bay water (T-wharf surface and bottom). Each sonde collects data every 15 minutes on water temperature, salinity, depth, dissolved oxygen, turbidity, and pH. In addition, a chlorophyll sensor (which is not required for the national SWMP program) was added to the T-wharf surface sonde in January 2003 and to the remaining three stations in June 2003.

In 2002, the national SWMP program was expanded again when dissolved nutrient and chlorophyll monitoring was initiated at each NERR site (Ross, 2003). Each site began collecting nutrient and chlorophyll data using replicated water grabs once per month from each of the four water quality monitoring stations. In addition, one site was selected

where the same data would be collected approximately every two hours over a 24-hour period using an automated ISCO (Teledyne ISCO, Inc.) sampler. Thus, this program was designed to capture data that reflect spatial, seasonal (using the monthly grabs at four stations), and diel (using the ISCO sampler) patterns. The NBNERR began collecting monthly nutrient and chlorophyll samples in March 2003 from each of the four water quality stations, and ISCO samples from T-wharf bottom in August 2003.

A complement to the SWMP water quality monitoring effort is the concurrent collection of meteorological data from at least one weather station at each NERR site. The rationale for this is that some patterns and trends observed in water quality parameters could potentially be explained or related to meteorological patterns. At the NBNERR, equipment was purchased to establish a Campbell weather station near Potter Cove in 1996 (Fig. 13.1). However, the regular collection of all meteorological data did not occur until February 2002. Since then, air temperature, relative humidity, barometric pressure, wind speed and direction, ambient solar radiation (PAR), and precipitation have been collected nearly continuously.

All water quality and meteorological data are passed through rigorous standardized quality control measures, first at the NBNERR and later through the Centralized Data Management Office (CDMO), a group located at the North Inlet-Winyah Bay NERR in South Carolina that oversees and manages all SWMP data collected by NERR sites. Once data have passed quality control, they are posted on the Internet at *www.nerrs.noaa.gov/Monitoring/Water.html* and are available for user download. More recent data that have not been posted on the web can be requested directly from the NBNERR research coordinator. In addition, data from the T-wharf bottom water quality station and the weather station are now equipped with near real-time telemetry capabilities, and these data can be viewed on the Internet at *www.weather.gov/oh/hads*.

NBNERR SWMP data are actively downloaded from the Internet and requested from the Reserve for a variety of purposes. For example, a graduate student from Brown University has used NBNERR SWMP data in his efforts to examine the relationship between dissolved oxygen levels in Narragansett Bay and blue mussel mortality, a relationship that ultimately affects multiple estuarine trophic linkages. A professor from Roger Williams University in Bristol, R.I., has requested salt marsh SWMP data for use in a marine ecology undergraduate course. In addition, the RIDEM recently used SWMP data from both Potter Cove and T-wharf to help determine the extent of a recent anoxic event in nearby Greenwich Bay that killed over one million estuarine fish, mostly Atlantic menhaden.

Graduate Research Fellowship Program

As of 2008, the NBNERR has supported the research of seven graduate students with funding through the GRF Program. Four of these fellows have come from Brown University and the other three from the University of Rhode Island (Fig. 13.3). These students have conducted research on a wide range of topics, including the ecology of cobble beach plant communities, the ecology of migratory sharp-tailed sparrows, salt marsh trophic dynamics, and the effects of winter water temperatures on the ecology of ctenophores in Narragansett Bay.

The first NBNERR GRF fellows were John Bruno from Brown University and Deborah DiQuinzio from the University of Rhode Island, both of whom received their initial funding in 1997. Bruno's research investigated various aspects of the ecology of cobble beach plant communities in Narragansett Bay. The first part of his research found that fringing *Spartina alterniflora* beds along cobble beach shorelines facilitate the formation of diverse plant assemblages behind them (Bruno, 2000). These communities formed because the *S. alterniflora* beds reduced water flow velocity and stabilized the substrate, enabling other plant seedlings to survive. Further research showed that the relationship between the foundation *S. alterniflora* beds and the cobble beach plant communities behind them depended on the size of the *S. alterniflora* bed. Most beds were less than 30 m in length and did not support any cobble beach plant species (Bruno and Kennedy, 2000). There was a strong, positive correlation between *S. alterniflora* bed size and cobble beach plant species richness, due to the fact that longer beds reduced wave-related disturbance more than shorter beds.

DiQuinzio's research as an NBNERR GRF focused on the ecology of the salt marsh sharp-tailed sparrow in Rhode Island salt marshes. More specifically, her research examined sharp-tailed sparrow site fidelity patterns, return rates, survival rates, and movement patterns among salt marshes in Rhode Island. This work showed that sharp-tailed sparrows exhibited moderate breeding site fidelity and strong natal philopatry in Rhode Island (i.e., these birds showed a strong tendency to return to breed within their natal home range) (DiQuinzio et al., 2001). Further research examined the nesting ecology of sharp-tailed sparrows in a tide-restricted salt marsh in southern Rhode Island compared to unrestricted marshes elsewhere, including in the NBNERR. From this work it was shown that salt marsh sharp-tailed sparrows tended to nest in short grasses, including salt marsh hay (*Spartina patens*), short cordgrass (*S. alterniflora*), and short common reed (*Phragmites australis*). After restoration of the tide-restricted site, 91 percent of nests failed due to increased tidal flooding, indicating that restoration efforts may have short-term negative impacts on sharp-tailed sparrow populations (DiQuinzio et al., 2002).

The next two fellows, Brian Silliman and Andrew Altieri, were both from Brown University. Silliman was funded from 2000 to 2002 and Altieri from 2001 to 2003. Silliman's research focused on investigating the degree to which top-down and bottom-up forces control the structure of salt marsh plant communities at different latitudes. This included conducting similar studies in both the NBNERR in Narragansett Bay and at the Sapelo Island NERR in Georgia. A major finding from this work was that top-down forces have a significant effect on salt marsh plant assemblages and on primary production of salt marshes at lower latitudes; in other words, a trophic cascade in these southern marshes was revealed (Silliman and Bertness, 2002). More specifically, Silliman discovered that when top predators in Georgia salt marshes (e.g., the blue crab, *Callinectes sapidus*) were excluded from the marsh, predation pressure on a primary grazer (the snail, *Littorina littorea*) was relieved, resulting in significant effects on the biomass and production of *S. alterniflora*. The same result was not observed further north in the NBNERR where an abundant predator (the mummichog, *Fundulus heteroclitus)* was excluded from Rhode Island salt marsh habitats. Here, top down forces were less important and instead coastal eutrophication is driving shifts in salt marsh plant assemblages. This work illustrates the power of using multiple NERR sites at different locations and latitudes to investigate the applicability of research results to different areas.

Altieri's research focused primarily on investigating the effects of hypoxia on the blue mussel in Narragansett Bay. One impetus for this research was a large die-off of the mussel in Narragansett Bay that coincided with hypoxic events during the warm summer months of 2001. Events such as this have the potential to severely alter the community structure and function of the benthic communities in estuaries such as Narragansett Bay. Part of Altieri's research examined this in more detail and used laboratory experiments to quantify the tolerance of three important bivalve species to low dissolved oxygen levels. This work found that mortality of blue mussel, quahog, and soft-shelled clam differed in response to varying levels of hypoxia. For example, 50 percent mortality was observed at three, seven, and 19 days for blue mussel, soft-shell clam, and quahog, respectively. This clearly shows that blue mussel is the most susceptible of the three species to hypoxic events in Narragansett Bay, which typically last up to five days. Using field experiments, Altieri further illustrated that hypoxia resulted in reduced blue mussel growth rates, higher mortality among larger individuals, and reduced mussel density and cover (Altieri and Witman, 2006). This in turn resulted in a greater than 75 percent reduction of the planktonic filtration capacity of mussels in Narragansett Bay. Thus, Altieri found that hypoxia greatly impacts the blue mussel and its ability to filter the Bay and ultimately results in a reduced capacity to control future eutrophication and hypoxia.

The next student, Hao-Hsien (Howard) Chang from URI received three years of funding beginning in 2005. Chang's research focused on exploring the effects of winter temperatures in Nar-

Figure 13.3. The NBNERR supports and funds graduate student research through the NERR GRF program. Two of the fellows include (*left photo*) John Bruno from Brown University, who studied the ecology of cobble beach plant communities; and (*right photo*) Deborah DiQuinzio from URI, who studied sharp-tailed sparrows (shown here with other URI researchers). *Photos from NBNERR photo library.*

ragansett Bay on the timing and size of ctenophore *(Mnemiopsis leidyi)* blooms. Ctenophores exhibit top-down control over estuarine processes in Narragansett Bay through direct predation on zooplankton. In recent years, the onset of ctenophore blooms has been occurring earlier, and the bloom size greater, in response to warming water temperatures. It is therefore critical to understand how minimum winter water temperatures affect the timing and size of the blooms of this important estuarine trophic component. Chang explored these relationships through a suite of laboratory and field methods.

The two current fellows are Keryn Bromberg from Brown University and Elizabeth DeCelles from URI. Bromberg's research focuses on determining the effects of anthropogenic stressors on salt marsh plant biodiversity. Forbe habitats—a diverse group of plants in the high salt marsh zone—have largely disappeared from southern New England, and Bromberg is examining the individual and combined effects of climate change and mosquito ditching on this habitat. DeCelles is currently conducting research into the function of tide-restricted and restored salt marshes as foraging habitats for wading birds in Narragansett Bay. DeCelles will also examine regurgitation samples from egrets and cormorants from islands in Narragansett Bay to determine, for the first time, the birds' specific foraging habits in the Bay.

CICEET

The Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) was established jointly between NOAA and the University of New Hampshire for the purpose of funding research at the 27 NERR sites to develop and apply new technologies in estuarine environments. The link between CICEET and the NERR System is logical in that CICEET aims to fund projects that develop technologies essential for managing estuarine environments while the NERR System aims to promote research and monitoring activities that lead to better estuarine resource management. In order to be considered for CICEET funding, all principal investigators must first contact the individual NERR site(s) where they propose to conduct research in order to discuss the project and find ways that the NERR site can assist in study design and implementation. From 1998 through the spring of 2006, 19 research projects at the NBNERR have been funded through the CICEET program at a total funding level of almost $4.2 million (Table 13.1). Thirteen different principal investigators have been or are currently conducting the 19 projects, 12 of which are completed, with the remaining seven still ongoing. These projects are predictably diverse and include efforts to develop in situ methods for treating PCBs in marine and freshwater sediments, determine relative eutrophication of coastal embayments using aerial video imagery, and develop a mechanical seeding apparatus for seeding large areas with eelgrass. Details of each research project are not provided here, but Table 13.1 provides current citations and further information on each project can be found at *ciceet.unh.edu*.

Monitoring

Additional long-term monitoring, both biotic and abiotic, is carried out throughout Narragansett Bay by a variety of agencies and investigators. A summary of monitoring activities in Rhode Island and Narragansett Bay was recently compiled into a database following a Rhode Island monitoring workshop and is listed at *www.ci.uri.edu/Projects/mon_ind/RPT_Brief/Brief.html*. Table 13.2 shows an abridged list of programs listed in this database that are relevant to the NBNERR, including all programs in Narragansett Bay and upland and freshwater programs that address issues faced by the NBNERR.

Some of these long-term monitoring programs, particularly the ones operated by RIDEM, have stations located within the estuarine boundaries of the NBNERR (Table 13.3). For example, the RIDEM fish trawl survey has 12 stations (out of a total of approximately 265 in Narragansett Bay) located within the Reserve's estuarine boundary. Similarly, the RIDEM juvenile finfish seine survey has two stations located in the NBNERR (out of 20 located around the Bay). Every year since 1964, RIDEM monitors the number of coastal bird nests throughout Rhode Island, and two of these sites are located within the NBNERR. Other notable monitoring programs that have stations within the Reserve are the annual seal counts conducted by Save The Bay, annual waterfowl surveys conducted by EPA, Prudence Island white-tailed deer surveys conducted by RIDEM, and ichthyoplankton surveys conducted by URI and RIDEM.

Additional monitoring programs are now being conducted by the NBNERR (Table 13.3). Notable among these efforts is the ecological monitoring of a recent restoration at Potter Pond salt marsh, along with simultaneous monitoring at Coggeshall salt marsh in the North Prudence Unit that serves as an experimental control. This monitoring began in 2000 before restoration in early 2003, and will continue at varying frequencies, indefinitely. Data

Table 13.1. CICEET research projects in the NBNERR.

Principal Investigator	Research Project	Years	Funding
Richard Crawford, WHOI	Assessing relative eutrophication of coastal embayments with calibrated aerial video imagery	1998–ongoing	$199,722
Taylor Eighmy, UNH	Phosphate-based heavy metal stabilization technologies for contaminated sediments and dredge material	1998–2001	$251,796
Robert Costanza, University of Maryland	Sediment dynamics in tidal marshes: Functional assessment of accretionary biofilters	1998–2001	$199,432
Scott Nixon, URI	Density-dependent effect on grazing and success of seed-generated seagrass plants	1998–2001	$211,462
John King, URI	Developing and applying a new *in situ* technology for the investigation of episodic contaminant transport events within estuaries	1999–2002	$260,762
Kevin Gardner, UNH	Development of reuse alternatives for the management of dredged, contaminated sediments	2000–2002	$220,321
John King, URI	Developing and applying a new *in situ* technology for the investigation of episodic contaminant transport events within estuaries (II)	2001–2002	$103,443
Scott Nixon, URI	The mechanical seeding of marine sediments for the restoration of *Zostera marina* L. habitat	2001–2004	$204,631
Taylor Eighmy, UNH	Pilot-scale reactive barrier technologies for containment of contaminated sediments and dredged materials	2001–2004	$378,899
Kevin Gardner, UNH	*In situ* treatment of PCBs in marine and freshwater sediments using colloidal zero-valent iron	2001–2003	$219, 014
Frederick Short, UNH	Interactive GIS-based site selection model for eelgrass restoration on CD-ROM	2002–2004	$223,468
David Smith, URI	Microbial source tracking using F-specific coliphages and quantitative PCR	2003–2006	$173,441
Kevin Gardner, UNH	Polychlorinated biphenyl remediation in sediments: Pilot-scale demonstration	2003–ongoing	$373,610
Scott Nixon, URI	Field plot demonstration project for large-scale restoration of eelgrass (*Zostera marina* L.) Using mechanical seeding apparatus	2003–2006	$115,108
Jose Amador, URI	Evaluation of leachfield aeration technology for improvement of water quality and hydraulic functions in on-site wastewater	2004–ongoing	$232,294
Thomas Mulcahy, NEIWPC	Presentation of nutrient pollutant load and source estimation model results for enhanced nutrient loading analyses of New England	2004–ongoing	$159,348
Andrew Hong, University of Utah	*In situ* sediment ozonator (ISO) for remediation of PCB, PAH, and other recalcitrant chemicals	2004–ongoing	$229,997
Alfred Hanson, URI	A new autonomous technology for monitoring microbial indicators of fecal contamination in coastal waters	2004–ongoing	$199,460
Thomas Boving, URI	Field demonstration of wood filter technology for stormwater treatment	2005–ongoing	$198,178
TOTAL			**$4,154,386**

collected include water quality (using the same methods as described for the SWMP), vegetation (emergent and macroalgae), nekton, and birds. From 2003 to 2005, the NBNERR also conducted weekly driving surveys for target wildlife species, including large mammals, reptiles, raptors, and winter waterfowl, with the goal of quantifying the species composition, relative and seasonal abundances, and distribution of these species to promote more informed stewardship and management decisions (Raposa and Rehor, 2004). Other recent NBNERR efforts on Prudence Island include monitoring of breeding songbirds, spotted salamander egg masses, the distribution and area of fringing salt marshes, osprey and barn swallow nesting success, and upland vegetation communities in multiple habitats in the South Prudence pine barrens.

Research

As described above, the NBNERR was established to provide an ideal setting for conducting coastal and estuarine research, and it provides support in a variety of ways to fulfill this function. Until recently, the Reserve only supported research efforts that were conducted within the 5.4 m depth boundary of the Reserve around Prudence, Patience, Hope, and Dyer islands. A broader, more holistic approach that focuses on all of Narragansett Bay and its watershed was adopted to expand the amount of research conducted and supported by the NBNERR in Narragansett Bay. It is hoped that the new approach will better incorporate the NBNERR into the local and regional scientific community and more effectively promote quality research in Narragansett Bay and its watershed.

As with monitoring, research in the NBNERR is conducted by both visiting researchers and by the NBNERR itself, and it addresses a wide variety of topics (Fig. 13.4). Much of the work by visiting researchers has been funded and promoted by the NERR GRF program and CICEET. However, the NBNERR has also attracted visiting researchers that have not received funding from these programs. This includes researchers from Brown University, URI, EPA, the Smithsonian Institution, the Lloyd Center, Roger Williams University, the University of Houston, and Save The Bay, among many others. As is the case with research funded through CICEET, there are too many projects conducted by visiting researchers to describe each one here. However, Appendix 13.1 provides basic information on these research efforts, many of which are detailed in the appropriate sections elsewhere in this document.

In the future, the NBNERR research and monitoring program will continue to include projects conducted by staff as well as visiting researchers. On the terrestrial side, there will be an enhanced

Table 13.2. Monitoring programs conducted in and around Narragansett Bay, including upland programs relevant to the resources of the NBNERR. Most data are from a Rhode Island monitoring database located at *www.ci.uri.edu/Projects/mon_ind/RPT_Brief/Brief.html*.

Agency	Monitoring Program
Barrington Land Conservation Trust	Diamondback terrapin population study
Brown University	Barrington River and Palmer River monitoring
EPA	Coastal 2000/EMAP
	Winter waterfowl monitoring
EPA Atlantic Ecology Division (AED)	Aircraft remote sensing for chlorophyll *a*
	Amphipod population studies
Jamestown Land Trust	Breeding and migratory bird monitoring
Narragansett Bay Commission	Providence, Seekonk, and Ten Mile rivers water quality monitoring
	Regional river fecal monitoring
NBEP (multiagency)	Volunteer dissolved oxygen night survey
NBNERR	SWMP water quality monitoring
	SWMP nutrient monitoring
	SWMP meteorological monitoring
NOAA	National Status and Trends Program
	PORTS
NOAA Fisheries	NOAA Restoration Center programs
NOAA Fisheries; NOAA Cooperative Marine Education and Research Program (CMER); Rhode Island Sea Grant	Lobster tagging program
NOAA; NBNERR; EPA; RIDEM; URI	Narragansett Bay Window monitoring
Pokanoket Watershed Alliance	Runnins River monitoring
RIDEM	Rhode Island shellfish disease survey
	American shad and river herring monitoring
	Air quality monitoring
	Aquatic furbearer surveys
	Artificial substrate monitoring
	Biotoxin shellfish poisoning sampling
	Maritime bird nest count monitoring
	Baseline water quality monitoring in Rhode Island
	Coastal pond finfish monitoring
	Freshwater fish surveys
	Gill net pelagic fish monitoring
	Sport fish trawl monitoring
	Juvenile finfish seine monitoring
	Lobster fishery monitoring
	Rapid bioassessment protocol monitoring
	Shellfish growing area monitoring
	Shellfish shoreline monitoring
	Summer Canada geese monitoring
	Upland game monitoring
	Waterfowl surveys
RIDEM; URI GSO	Ichthyoplankton monitoring
R.I. Department of Health	Beach water quality monitoring
	Drinking water monitoring
	Coastal lagoon water quality monitoring
Rhode Island Sea Grant	Impacts of ctenophores on ichthyoplankton
Rhode Island Sea Grant; Brown University	Salt marsh plant community status and monitoring
Rhode Island Sea Grant; RIDEM	Larval lobster settlement index
Rhode Island Sea Grant; CMER	Lobster shell disease program
Rhode Island Sea Grant (multiagency lead)	Rapid assessment survey for marine bioinvasives
Rhode Island Surfrider Foundation	Rhode Island coastal beach water quality monitoring
Save The Bay	Salt marsh, eelgrass, herring run, horseshoe crab, seal, and other monitoring
The Nature Conservancy—Rhode Island	Rhode Island odonata atlas
URI; RIDEM	Galilee salt marsh restoration and bird monitoring
	Pond breeding amphibian monitoring
URI; ASRI	Fall migratory bird monitoring in Kingston
URI Cooperative Extension	URI Watershed Watch (surface water quality)
URI Geosciences (multiagency lead)	Long-term beach profile monitoring
URI Natural Resources Science	Water table levels in southern Rhode Island forested wetlands
URI GSO	Narragansett Bay benthic infauna monitoring
	Pollution, circulation, and habitat monitoring in coastal ponds
	Water column nutrients
	Narragansett Bay phytoplankton monitoring
U.S. Fish & Wildlife Service; URI	Avian productivity and survivorship monitoring
U.S. Army Corps of Engineers	Disposal area monitoring system
U.S. Department of Agriculture APHIS	CAPS survey to detect invasive species
U.S. Geological Survey	National water quality assessment program
WHOI Sea Grant	Rocky shore intertidal crab monitoring

Table 13.3. Monitoring programs conducted by the NBNERR or within the NBNERR by other agencies.

Agency	Monitoring Program
EPA AED	Aircraft remote sensing for chlorophyll *a*
	Winter waterfowl monitoring
	Coastal 2000/EMAP
NOAA	PORTS
NOAA Fisheries	NOAA Restoration Center programs—oyster restoration
NBNERR	SWMP water quality monitoring
	SWMP nutrient monitoring
	SWMP meteorological monitoring
	Salt marsh monitoring
	Wildlife driving surveys
	Salamander monitoring
	Spotted salamander egg mass monitoring
	Upland vegetation monitoring
	Osprey and barn swallow monitoring
	Land cover mapping
RIDEM	Maritime bird nest count monitoring
	Freshwater fish surveys
	Sport fish trawl monitoring
	Juvenile finfish seine monitoring
	Upland game monitoring (deer)
	Breeding bird and owl surveys
RIDEM; URI GSO	Ichthyoplankton monitoring
Rhode Island Sea Grant; Brown University	Salt marsh plant community status and monitoring
Save The Bay	Salt marsh, eelgrass, herring run, horseshoe crab, seal, and other monitoring
The Nature Conservancy—Rhode Island	Rhode Island Odonata atlas

focus on examining the ecology of the Reserve's islands from an ecosystem perspective—important in light of ongoing and future land management practices as well as the emergence of a new top predator (coyote; Chapter 6) on Prudence Island. Some specific terrestrial needs at the Reserve include more frequent monitoring of white-tailed deer populations, upland vegetation, and tick populations, and research into the ecology and effects of coyote immigration. There is also a need to monitor hydrologic parameters on Prudence Island, including wetland water levels, groundwater, and stream flows, and to understand the effects of increasing residential development and subsequent water demand on these parameters (although the NBNERR stewardship program has begun to address these needs).

In estuarine habitats of the Reserve, a continued focus on understanding how salt marsh systems and processes are responding to local and large-scale human-related changes is essential. In addition, the NBNERR must begin a comprehensive baseline monitoring program in its salt marshes, which are in a relatively natural state in comparison to many marshes in Narragansett Bay. There is a continuing need for baseline ecological data (e.g., vegetation, nekton, water quality, birds) from unrestricted (i.e., no barriers to tidal flow) salt marshes in New England, and the NBNERR is in prime position to address this need. Two additional estuarine research needs of particular importance to the Reserve are the mapping of subtidal soils and habitat types and the monitoring and quantification of ephemeral drift macroalgal populations in Narragansett Bay.

More specific research and monitoring needs in both terrestrial and estuarine habitats at the NBNERR include:

Terrestrial

- Detailed maps of ponds, streams, and vernal pools in NBNERR and on Prudence Island
- Effects of invasive species on forested wetland habitats in NBNERR
- Ecological effects of restoration of pine barren habitats
- Additional surveys of Lepidoptera on Prudence, Patience, Hope, and Dyer islands
- Inventory of invertebrate faunal groups on Prudence, Patience, Hope, and Dyer islands
- Institutionalization of NBNERR long-term tick monitoring, and reestablishment of human serological testing for tick-borne diseases
- Herpetofaunal use of Patience, Hope, and Dyer islands
- Breeding bird surveys on Patience, Hope, and Dyer islands
- Syntheses of existing data from NBNERR breeding bird monitoring program, including comparisons with other nearby stopover sites (e.g., Block Island, R.I.)
- Ecology of white-tailed deer *(Odocoileus virginianus)* and the ecological effects of recent reductions in deer abundance on Prudence Island
- Top-down ecological effects of the emergence of coyotes *(Canis latrans)* as a top predator on Prudence Island

- Ecological effects of NBNERR land management practices, such as controlled burns, woodcutting, and invasive species control, on invertebrate species of concern (e.g., tiger beetles), herpetofauna, mammals, and other flora and fauna
- Mapping and monitoring of rare plant and invasive species distributions
- Complete species inventories of individual Reserve parcels

Estuarine

- Ecosystem responses to nutrient reduction efforts in Narragansett Bay, including effects on phytoplankton dynamics
- Enhanced spatial resolution of ongoing water quality monitoring programs in the Bay
- Additional mapping and monitoring of eelgrass cover, distribution, and health over time in Narragansett Bay
- Ecological effects of efforts to transplant and restore eelgrass to the Bay
- Ecological effects of efforts to restore tidal flow to salt marshes
- Restoration of shallow pool habitats to ditched salt marshes in Rhode Island, and effects of pool restoration on fishes and estuarine birds
- Fisheries use of eutrophic areas of upper Narragansett Bay, and effects of recurring hypoxia on fish populations in Greenwich Bay and other impacted areas
- Ecology of abundant estuarine birds, such as cormorants, gulls, terns, and shorebirds in Narragansett Bay
- Factors affecting recent declines in nesting wading birds at heronries in the Bay

a.

b.

c.

Figure 13.4. The NBNERR attracts and supports researchers from throughout the Rhode Island scientific community and beyond. Some examples include (a) Brown University (Mark Bertness); (b) URI (Grace Klein-MacPhee (center)); (c) EPA (James Latimer); and NBNERR staff (Matthew Rehor) (bottom photo, page 163). *Photos from NBNERR photo library.*

- Syntheses of NBNERR SWMP data, including water quality, meteorological, and nutrient data
- Ecological impacts of estuarine invasive species in Narragansett Bay
- Ecological responses to large-scale changes in climate, such as warming water temperature and sea-level rise
- Identification and modeling of primary factors that affect fisheries, productivity, and water quality

Literature Cited

Altieri, A.H. and J.D. Witman. 2006. Local extinction of a foundation species in a hypoxic estuary: Integrating individuals to ecosystem. *Ecology* **87:**717–730.

Anderson, J.F., R.C. Johnson, L.A. Magnarelli, F.W. Hyde, and J.E. Myers. 1987. Prevalence of *Borrelia burgdorferi* and *Babesia microti* in mice on islands inhabited by white-tailed deer. *Applied and Environmental Microbiology* **53:**892–894.

Bertness, M.D., P.J. Ewanchuk, and B. Silliman. 2002. Anthropogenic modification of New England salt marsh landscapes. *Proceedings of the National Academy of Science* **99:**1395–1398.

Bertness, M.D., B.R. Silliman, and R. Jefferies. 2004. Salt marshes under siege. *American Scientist* **92:**54–61.

Bricker-Urso, S., S.W. Nixon, J.K. Cochran, D.J. Hirschberg, and C. Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries* **12:**300–317.

Bruno, J.F. 2000. Facilitation of cobble beach plant communities through habitat modification by *Spartina alterniflora*. *Ecology* **81:**1179–1192.

Bruno, J.F. and C.W. Kennedy. 2000. Patch-size dependent habitat modification and facilitation on New England cobble beaches by *Spartina alterniflora*. *Oecologia* **122:**98–108.

Carroll, M.C., H.S. Ginsberg, K.E. Hyland, and R. Hu. 1992. Distribution of *Ixodes dammini* (Acari: Ixodidae) in residential lawns on Prudence Island, Rhode Island. *Journal of Medical Entomology* **29:**1052–1055.

Crain, C.M. and M.D. Bertness. 2006. Ecosystem engineering across environmental gradients: Implications for conservation and management. *Bioscience* **56:**211–218.

Crain, C.M., B.R. Silliman, S.L. Bertness, and M.D. Bertness. 2004. Physical and biotic drivers of plant distribution across estuarine salinity gradients. *Ecology* **85:**2539–2549.

Davis, J.L., B. Nowicki, and C. Wigand. 2004. Denitrification in fringing salt marshes of Narragansett Bay, Rhode Island, USA. *Wetlands* **24:**870–878.

DiQuinzio, D., P.W.C. Paton, and W.R. Eddleman. 2001. Site fidelity, philopatry, and survival of promiscuous Saltmarsh Sharp-tailed Sparrows in Rhode Island. *Auk* **118:**888–899.

DiQuinzio, D., P.W.C. Paton, and W.R. Eddleman. 2002. Nesting ecology of salt marsh sharp-tailed sparrows in a tidally-restricted salt marsh. *Wetlands* **22:**179–185.

Donnelly, J. and M.D. Bertness. 2001. Rapid shoreward encroachment of salt marsh vegetation in response to sea-level rise. *Proceedings of the National Academy of Science* **98:**14218–14223.

Dorf, B.A. and J.C. Powell. 1997. Distribution, abundance, and habitat characteristics of juvenile tautog (*Tautoga onitis,* Family Labridae) in Narragansett Bay, Rhode Island, 1988–1992. *Estuaries* **20:**589–600.

Dyhrman, S.T. and B. Palenik. 1999. Phosphate stress in cultures and field populations of the dinoflagellate *Prorocentrum minimum* detected by a single-cell alkaline phosphatase assay. *Applied and Environmental Microbiology* **65:**3205–3212.

Ebel, G.D., E.N. Campbell, H.K. Goethert, A. Spielman, and S.R. Telford III. 2000. Enzootic transmission of deer tick virus in New England and Wisconsin sites. *American Journal of Tropical Medicine and Hygiene* **63:**36–42.

Emery, N.C., P.J. Ewanchuk, and M.D. Bertness. 2001. Competition and salt-marsh plant zonation: Stress tolerators may be dominant competitors. *Ecology* **82:**2471–2485.

Krause, P.J., K. McKay, J. Gadbaw, D. Christianson, L. Closter, T. Lepore, S.R. Telford III, V. Sikand, R. Ryan, D. Persing, J.D. Radolf, and A. Spielman. 2003. Increasing health burden of human babesiosis in endemic sites. *American Journal of Tropical Medicine and Hygiene* **68:**431–436.

Mather, T.N. and M.E. Mather. 1990. Intrinsic competence of three ixodid ticks (acari) as vectors of the Lyme disease spirochete. *Journal of Medical Entomology* **27:**646–650.

Meng, L. and J.C. Powell. 1999. Linking juvenile fish and their habitats: An example from Narragansett Bay, Rhode Island. *Estuaries* **22:**905–916.

Meng, L., J.C. Powell, and B. Taplin. 2001. Using winter flounder growth rates to assess habitat quality across an anthropogenic gradient in Narragansett Bay, Rhode Island. *Estuaries* **24:**576–584.

Meng, L., G. Cicchetti, and M. Chintala. 2004. Nekton habitat quality at shallow water sites in two Rhode Island coastal systems. *Estuaries* **27:**740–751.

Pennings, S.C., E.L. Siska, and M.D. Bertness. 2001. Latitudinal differences in plant palatability in Atlantic coast salt marshes. *Ecology* **82:**1344–1359.

Rand, T.A. 1999. Effects of environmental context on the susceptibility of *Atriplex patula* to attack by herbivorous beetles. *Oecologia* **121:**39–46.

Raposa, K. and M. Rehor. 2004. Monitoring wildlife in the Narragansett Bay National Estuarine Research Reserve using weekly driving surveys. Narragansett Bay National Estuarine Research Reserve Final Report. 18pp.

Ross, S.W. 2003. A history of the National Estuarine Research Reserve System-Wide Monitoring Program. Final Report to the National Estuarine Research Reserve System. 14pp.

Silliman, B.R. and M.D. Bertness. 2002. A trophic cascade regulates salt marsh primary production. *Proceedings of the National Academy of Science* **99:**10500–10505.

van de Koppel, J., A.H. Altieri, B.R. Silliman, J.F. Bruno, and M.D. Bertness. 2006. Scale-dependent interactions and community structure on cobble beaches. *Ecology Letters* **9:**45–50.

Wigand, C., R.A. McKinney, M.M. Chintala, M.A. Charpentier, and P.M. Groffman. 2004. Denitrification enzyme activity of fringe salt marshes in New England. *Journal of Environmental Quality* **33:**1144–1151.

Wigand, C., G.B. Thursby, R.A. McKinney, and A.F. Santos. 2004. Response of *Spartina patens* to dissolved inorganic nutrient additions in the field. *Journal of Coastal Research* **45:**134–149.

Appendix 13.1. NBNERR Research and Survey Projects

Research and survey projects conducted in or by the NBNERR, excluding GRF and CICEET research. This includes projects conducted entirely in the NBNERR and those that were larger in extent but included stations within the NBNERR. All known projects at the NBNERR are listed, but those resulting in a publication in a peer-reviewed scientific journal are italicized and cited.

Principal Investigator	Affiliation	Research Project/Publication	Project Years
Adamowicz, S.	URI	New England salt marsh pools: Analysis of geomorphic and geographic parameters, macrophyte distribution, and nekton use	1999–2000
Aliberti, M.	URI	Evaluation of community assemblages and habitat use by odonate nymphs in highly anthropogenic wetland systems on Prudence Island and Block Island, R.I.	2004–2005
Anderson, J. et al.	Connecticut Agricultural Experiment Station	*Prevalence of* Borrelia burgdorferi *and* Babesia microti *in mice on islands inhabited by white-tailed deer*	1984–1987
Armstrong, P.	Harvard School of Public Health	Pathogen diversity at the tick-human interface	1998
Auker, L.	URI	The effects of the invasive colonial tunicate *Didemnum* sp. on native species in Narragansett Bay	2005
Bertness, M. and Pennings	Brown University	Climate-driven processes and patterns in northern Atlantic salt marshes	1998–2003
Bertness, M. et al.	Brown University	*Anthropogenic modification of New England salt marsh landscapes*	2002
Bertness, M. et al.	Brown University	Will eutrophication help marshes keep up with sea level rise?	2003–ongoing
Bertness, M. et al.	Brown University	*Salt marshes under seige*	2004
Bertness, M. et al.	Brown University	The role of climate in regulating the primary productivity, abundance, and distribution of salt marsh plants	2005–ongoing
Bricker-Urso, S. et al.	URI	*Accretion rates and sediment accumulation in Rhode Island salt marshes*	1989
Bromberg, K. and M. Bertness	Brown University	Elucidating the history of human modification of New England salt marshes and the consequences of human disturbance on services provided by salt marshes	2005–ongoing
Bruno, J.	University of North Carolina-Chapel Hill	Metapopulation dynamics of the cobble beach plant community	1997–2005
Carroll, M.	URI	*Distribution of* Ixodes dammini *(Acari: Ixodidae) in residential lawns on Prudence Island, Rhode Island*	1991
Casagrande, R.	URI	Evaluation of native and exotic *Phragmites australis* and associated herbivores	2003–2006
Cicchetti, G.	EPA AED	Contributions of estuarine habitats to the ecological function and integrity of a small cove	1999–2001
Craig, N.	URI	Growth of the bivalve *Nucula annulata* in nutrient-enriched environments	1994
Crain, C.M. and M.D. Bertness	Brown University	*Ecosystem engineering across environmental gradients: Implications for conservation and management*	2006
Crain, C.M. et al.	Brown University	*Physical and biotic drivers of plant distribution across estuarine salinity gradients*	2004
Davis, J. et al.	EPA AED	*Denitrification in fringing salt marshes of Narragansett Bay, Rhode Island, USA*	2004
Donnelly, J. and M. Bertness	Brown University	*Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise*	2001
Dorf, B. and C. Powell	URI and RIDEM	*Distribution, abundance, and habitat characteristics of juvenile tautog (*Tautoga onitis, *family Labridae) in Narragansett Bay, Rhode Island, 1988–1992*	1988–1992
Dyhrman, S. and B. Palenik	Scripps Institution of Oceanography	*Phosphate stress in cultures and field populations of a dinoflagellate* Prorocentrum minimum *detected by a single-cell alkaline phosphate assay*	1999
Ebel, G. et al.	Harvard School of Public Health	*Enzootic transmission of deer tick virus in New England and Wisconsin sites*	2000
Emery, N. et al.	Brown University	*Competition and salt-marsh plant zonation: Stress tolerators may be dominant competitors*	2001
Enser, R.W.	R.I. Natural Heritage Program	The breeding birds of Prudence Island	1990
Fonseca, M.	NOAA-Beaufort, NC	***World Prodigy*** eelgrass planting project: Narragansett Bay, RI	1996–2000
Fraher, J.	URI	Atmospheric wet and dry deposition of fixed nitrogen to Narragansett Bay	1991
Halpin, P.	Brown University	Patterns and determinants of intertidal habitat use in the mummichog, *Fundulus heteroclitus*	1991-1994
Ho, C.	University of Houston	Using the NERR system to explore plant-herbivore interactions: Latitudinal variation and impacts of climate change	2004-2006
Hu, R.	URI	Identification of the wasp parasitoid of the deer tick, *Ixodes dammini*, in Rhode Island and its implication in the control of Lyme disease	1990
Hyland, K.	URI	Ticks and tick-borne diseases in Rhode Island: Assessment of risks and other epizootiologic considerations	19891990
Jivoff, P.	Smithsonian Institution	Factors regulating the local and regional distribution of green crabs along eastern North America	2001–002

Appendix 13.1. Continued

Kerber, J. and B. Leudtke	Brown University and University of Massachusetts-Boston	Technical report on a prehistoric survey of Prudence Island, RI	1981
Klein-MacPhee, G. and E. Durbin	URI	An ichthyoplankton survey of Narragansett Bay with emphasis on the NERR	1990–91
Krause, P. et al.	University of Connecticut School of Medicine	*Increasing health burden of human babesiosis in endemic sites*	2003
Kutcher, T.	URI, NBNERR	Habitat classification and inventory for the Narragansett Bay National Estuarine Research Reserve	2003–2004
Kutcher, T. and K. Raposa	NBNERR	An analysis of the vegetative composition of an Atlantic coastal pitch pine barren	2005
Latimer, J. and J. Quinn	EPA, URI	Organic contaminant flux to Narragansett Bay from wet deposition samples collected at Prudence Island meteorological station	1991–92
Latimer, J.	URI	Wet deposition of organic contaminants to the coastal marine environment	1994
Mather, T. and M. Mather	Harvard School of Public Health	*Intrinsic competence of three ixodid ticks (Acari) as vectors of the Lyme disease spirochete*	1990
McKinney, R.	EPA, URI	Assessing the effects of habitat alteration on wildlife: Utilization of coastal habitats by wintering waterfowl in Narragansett Bay	2002–ongoing
McLaughlin, M.	URI	Using GIS and hedonic analysis to measure the social benefits of improving environmental quality along the Providence River corridor	1996
Mello, M.	The Lloyd Center	Survey of Lepidoptera on Prudence Island, Rhode Island	2002
Meng, L. and C. Powell	EPA AED, RIDEM	*Linking juvenile fish and their habitats: An example from Narragansett Bay, Rhode Island*	1988–1996
Meng, L. et al.	EPA AED, RIDEM	*Using winter flounder growth rates to assess habitat quality across an anthropogenic gradient in Narragansett Bay, Rhode Island*	1998
Meng, L. et al.	EPA AED	Aquatic stressors justification for winter flounder habitat alteration—population response demonstration project	2002
Meng, L. et al.	EPA AED	*Nekton habitat quality at shallow water sites in two Rhode Island coastal systems*	2004
Nomann, B.	Brown University	The importance of plant-bacterial interactions for New England salt marsh dynamics	2004
Norris, A.	Roger Williams University	Nocturnal behavior of the harbor seal (*Phoca vitulina*) from Prudence Island, Rhode Island	2003–2004
Osenkowski, J.	URI	Avian community dynamics on and adjacent to Prudence Island, RI	1999
Oviatt, C. and S. Whitehouse	URI	The role of *Crangon septemspinosa* in Narragansett Bay Estuarine Sanctuary and the impact of pollution from the upper Narragansett Bay on the structure and function on the benthic infauna-*Crangon* demersal fish food chain	1987–88
Paton, P. et al.	URI	Avian community dynamics in the salt marshes of the Narragansett Bay National Estuarine Research Reserve, with emphasis on the salt marsh sharp-tailed sparrow (*Ammodramus caudacutus*)	1997–1999
Pennings, S. et al.	University of Houston	*Latitudinal differences in plant palatability in Atlantic coast salt marshes*	2001
Pennings, S.	University of Houston	Latitudinal variation in plant-herbivore interactions in coastal salt marshes	2002–2005
Rand, T.	Brown University	Interactive effects of multiple ecological factors on the distribution of halophytic forbs in New England salt marshes	1996–2000
Rand, T.	Brown University	*Effects of environmental context on the susceptibility of* Atriplex patula *to attack by herbivorous beetles*	1999
Raposa, K. and M. Chintala	NBNERR, EPA AED	Comparing Breder traps and bottomless lift nets for sampling nekton on vegetated salt marsh surfaces	2001–02
Raposa, K. and R. Weber	NBNERR	Water quality patterns among different salt marshes in Narragansett Bay, R.I.	2003–04
Raposa, K. and T. Kutcher	NBNERR	Habitat and home range of eastern box turtles on Prudence Island, Rhode Island	2005–06
Raposa, K. et al.	NBNERR	Using a survey to gauge public opinion on the status of the Prudence Island, R.I., deer herd	2003–04
Raposa, K. et al.	NBNERR	Ecological responses to restoration of Potter Pond salt marsh	2000–ongoing
Raposa, K. et al.	NBNERR, EPA AED	Bird and nekton use of salt marshes along a human-disturbance gradient	2005–ongoing
Richardson, K. and N. West	URI	Land cover/use study using Landsat Multispectral Scanner and Thematic Mapper data unsupervised classification	1988
Satchwill, R. et al.	RIDEM	Preliminary assessment of biological and physical characteristics of the Narragansett Bay Estuarine Sanctuary	1982–83
Schroeder, C.	URI	Population status and distribution of the harbor seal in Rhode Island waters	1996–1999

Appendix 13.1. Continued

Sedor, K.	Rhode Island Sea Grant, RIDEM	An investigation of the hydrology and hydraulics of the Nag Creek salt marsh system Prudence Island, Rhode Island	1994–1995
Shaughnessy, G. and F. Golet	RIDEM, URI	Inventory of upland and wetland habitats of the Narragansett Bay Estuarine Sanctuary	1983
Short, F. et al.	UNH	Eelgrass in estuarine research reserves along the East Coast, USA Part 1: Declines from pollution and disease	1993
Short, F. et al.	UNH	Eelgrass in estuarine research reserves along the East Coast, USA Part 2: Management of eelgrass meadows	1993
Smayda, T.	URI	Characterization of plankton dynamics and environmental properties within the Narragansett Bay Estuarine Sanctuary	1986–87
Stachiw, M.	R.I. Historical Preservation Commission	Historic sites archaeological survey of Patience and Prudence islands, Rhode Island	1981
Stabach, J.	URI	Salt marsh pool restoration	2004
Tallman, J.	URI	Assessing the value of shellfish aquaculture gear as fish habitat	2005
Telford, S. and P. Krause	Harvard School of Public Health; University of Connecticut School of Medicine	Epidemiological study of Prudence Island residents for Lyme disease, babesiosis, and ehrlichiosis	1994–2005
Thursby, G.	EPA AED	Development of a coastal wetland plant condition index	1999–2001
Tyrrell, T. et al.	URI	The economic importance of Narragansett Bay	1994
Tyrrell, T. and M. McLaughlin	URI	The economic contribution of water quality in the Narragansett Bay: Phase II downtown Providence development	1995
Urish, D.	URI	Groundwater availability on Prudence Island, Town of Portsmouth, Rhode Island	1992
Urish, D. et al.	URI	The ecological impact of the Prudence Island landfill on the Nag Creek marsh system	1992–93
Urso, S. and S. Nixon	URI	The impact of human activities on the Prudence Island Estuarine Sanctuary as shown by historical changes in heavy metal inputs and vegetation	1984
van de Koppel et al.	Brown University	*Scale-dependent interactions and community structure on cobble beaches*	2006
Van Wesenbeeck	Brown University	Landscape patterns in species interactions among halophytic plants	2005
Vigness-Raposa, K.	URI	Landcover map of Prudence Island, Rhode Island, from Landsat imagery	2004
Vigness-Raposa, K.	URI	The relationship of landscape composition to the distribution of birds on Prudence Island	2004
Wigand, C. et al.	EPA AED	*Denitrification enzyme activity of fringe salt marshes in New England (USA)*	2004
Wigand, C. et al.	EPA AED	*Response of* Spartina patens *to nitrogen and phosphorous additions in a field manipulative experiment*	2004
Zhioua, E.	URI	Biological control of the lone star tick, *Amblyomma americanum*, using entomopathogenic fungi	1997–2001