BENTHIC HABITAT[1]

Draft – April 2017

1. OVERVIEW

The seafloor is a mosaic of various sediment types and other characteristics. These characteristics create habitats that support different groups of shellfish, fish, and other species. The term benthic habitat refers to any habitat on the seafloor. In Narragansett Bay, most benthic habitats are muddy or sandy. The species living in benthic habitats cycle nutrients, regulate water quality, and add to the overall productivity of the ecosystem. These habitats show degradation when nutrient pollution causes high levels of organic matter on the Bay's bottom, leading to low levels of dissolved oxygen (hypoxia). The group of species inhabiting a benthic habitat changes in response to water quality and dissolved oxygen levels, making them an indicator of benthic habitat quality and overall ecosystem condition.

Little was known about the Bay's benthic habitats before the first published study of them in the 1950s. However, researchers suspect that historically benthic habitats may have been more diverse when nutrient and other pollution was low, water temperatures were lower, patterns of shellfish harvesting were different, and eelgrass was abundant. Studies of benthic habitats throughout the Bay over the last several decades have shown that habitat quality is poorer in the upper Bay, where pollution is higher, than in the lower Bay. Benthic habitat quality improved between 1988 and 2008, as indicated by an increase in pollution-sensitive species. The presence of these species suggests that benthic habitats are recovering from high organic loading and pollution, but are not fully recovered.

The benthic habitat quality indicator for Narragansett Bay is still under development as research is ongoing to study the responses of benthic habitats to multiple stressors. The most recent data available are from 2008. There have been large reductions in nutrient inputs to the Bay since 2008, but the response of benthic communities is unknown. If a benthic habitat assessment were conducted today, it could show more aerated sediments and a different suite of benthic species than was observed in 2008.

2. INTRODUCTION

Benthic habitats, or biotopes, are descriptors of the abiotic environment (e.g., sediment type) and the associated assemblage of species living there (Connor et al. 2004, Costello 2009, Davies et al. 2004). Many benthic organisms such as burrowing worms and small crustaceans live within the mud or sand, are attached to the bottom, and/or do not move large distances in their adult phase, making them particularly good indicators of water quality and sediment quality in different locations.

In particular, monitoring benthic habitats is a useful way to identify excessive nutrient inputs from wastewater treatment discharge, improperly functioning septic systems, runoff of fertilizers, and other sources. The seafloor receives a near-constant supply of organic matter that rains down from the water column or is produced from other bottom-dwelling organisms. This organic matter is usually derived from sources such as naturally decaying phytoplankton, zooplankton, macroalgae, and fish and shellfish excrement, together called "organic loading". However, excessive nutrients entering the water as pollution from human sources can amplify the amount of organic matter reaching the bottom.

[1] This chapter, written by Emily Shumchenia, contains material from the following publication: Shumchenia, E.J., M.L. Guarinello, and J.W. King. 2016. A Re-assessment of Narragansett Bay Benthic Habitat Quality Between 1988 and 2008. Estuaries and Coasts 39:1463-1477.

Nutrient pollution is problematic because high levels of organic matter can lead to low levels of dissolved oxygen, when decomposition occurs. Areas with high organic loading tend to favor pollution-tolerant species such as small polychaetes, while pollution-sensitive species such as deep-burrowing worms and shrimp tend to thrive in areas with lower organic loading. As a result, the types of benthic species found in an area can indicate whether the area has good or poor water quality.

Benthic biotopes are effective integrators of cumulative stressors such as eutrophication and hypoxia (Pearson and Rosenberg 1978, Valente et al. 1992, Germano et al. 2011). The structure of surface sediments and the composition, or successional stage, of benthic communities are linked to the degree of organic loading to a water body (Rosenberg 2001) and readily indicate recent (weeks to months) and longer-term water quality changes in Narragansett Bay (Cicchetti et al. 2006, Shumchenia and King 2010a). Coastal marine biotopes comprise mosaics at the landscape scale (Bostrom et al. 2011) and are ecologically meaningful units for conservation and management purposes (Salomidi et al. 2012). Biotope mosaics are interrelated and functionally connected such that a change to one biotope may affect others, as well as the entire ecosystem (Bostrom et al. 2011). The composition of a biotope mosaic and how it changes over time may indicate degradation or recovery of an ecosystem (Dunning et al. 1992, Wiens et al. 1993, Pittman et al. 2007). Thus, historical and recent data that describe biotope mosaics can help assess the effects of human alterations and multiple stressors on Narragansett Bay (i.e., Cicchetti and Greening 2011).

The abiotic element of benthic biotopes (i.e., surficial geology, sediment organic content, contaminants) in Narragansett Bay has been described Bay-wide by a few different efforts since the 1950s. McMaster (1960) measured sediment grain size throughout the Bay in a systematic survey that resulted in the first comprehensive surficial sediment maps of the Bay. (McMaster [1984] also mapped subsurface geology of the Bay in subsequent work.) In the 2000s, investigators measured sediment grain size, organic content, and the concentration of metals throughout the Bay, with the highest density of samples occurring in the Upper Bay (Murray et al. 2007). Also in the 2000s, two projects partnered to map the Bay bottom using new technologies in addition to traditional grab samples and sediment cores. Both projects collected acoustic bathymetry and backscatter information, as well as sediment profile imagery, along with the traditional bottom samples. The BayMap project concentrated on habitats deeper than 15 feet, while the MapCoast project focused on waters shallower than 15 feet (King et al. 2007). These data were used to map the shape of the Bay bottom (Figure 1a) as well as the texture of the surface sediment (Figure 1b). These maps provide the context for understanding how benthic communities and other estuarine fauna (e.g., eelgrass, fish, and shellfish) relate to benthic habitats.

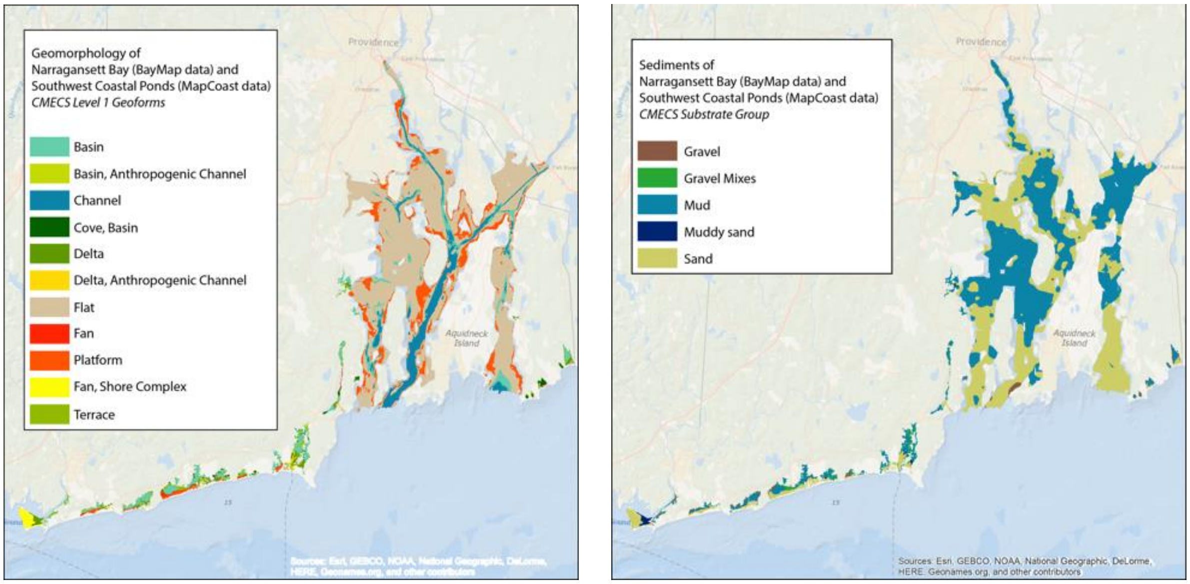

Figure 1. Maps of abiotic (nonliving) benthic habitats in Narragansett Bay and Southwest Coastal Ponds. Left: Geomorphology, or the shape of the Bay bottom, as derived from bathymetry surveys and supporting. Right: Sediment type, derived from benthic samples and grain size analyses.

Benthic biotopes (i.e., including benthic fauna and abiotic elements) in Narragansett Bay were first qualitatively described in the context of commercially important species such as shellfish and demersal fish. The first quantitative studies of benthic biotopes did not occur until the 1950s. Phelps (1958) found that sediment grain size and percent sediment organic matter were the most important factors influencing benthic species distribution in the Bay. Since the 1950s, there have been numerous directed studies of benthic biotopes (i.e., to determine the effects of human actions such as dredging, wastewater discharges, and other development) but no consistent and Bay-wide monitoring effort (see Frithsen 1990 for a detailed accounting of Narragansett Bay benthic studies). Analyses of benthic sampling efforts between the 1950s and around 1980 show a gradient of increasing benthic species abundance and diversity from the Providence River estuary to Conimicut Point, likely due to the decreasing gradient of organic loadings, sewage effluent, incidences of hypoxia and anoxia, and phytoplankton blooms (Frithsen 1990). South of Conimicut Point, there was little spatial variation in benthic species abundance and diversity within this same time period; this pattern was attributed to lower exposure to stressors (Frithsen 1990). More recent efforts to monitor benthic biotopes are summarized in Table 1. Each survey has spatial and/or temporal limitations, and only a few can provide a consistent trend assessment over more than 10 years.

Table 1. Recent efforts to monitor benthic habitat and/or community composition in Narragansett Bay.

Benthic monitoring strategy	Organizing group	Spatial extent	Temporal extent	Future sampling
Benthic macrofauna community composition and abundance	Marine Ecosystems Research Laboratory, URI-GSO	4 stations in Upper Bay	4 stations 2000, 2001, 2002, 2004; 1 station 2005-2010	None planned
Trends report	EPA	Upper Bay	Trends analysis of data 1950s-2015	None planned
National Coastal Condition Report	EPA	Bay wide (some stations permanent, others changing)	Summer 2005/6, 2010, 2015	2020
Benthic video sled	Narragansett Bay Commission	3 transects in Providence River estuary	Monthly, 2014-present	Monthly
Sediment profile imagery	URI	Bay wide	1988, 2008	None planned

The benthic macrofauna monitoring efforts by the Marine Ecosystems Research Laboratory at the University of Rhode Island (Table 1) described a recent spatial trend in benthic habitat quality that corresponded to the down-Bay gradient in nutrients and contaminants (Calabretta and Oviatt 2008). The United States Environmental Protection Agency (EPA) Trends report described changes in the benthic community in the Upper Bay (i.e., Providence River, Greenwich Bay, Mount Hope Bay) from the 1950s to 2015 from a variety of studies, including those listed in Table 1, except for the benthic video sled (Chintala et al. 2015). The trends report found that overall benthic diversity has declined since the 1950s and that there has been a shift from pollution-sensitive to pollution-tolerant species at many of the locations sampled (Chintala et al. 2015). The EPA Trends report linked those patterns with stressors including nutrients, legacy contaminants, and changing phytoplankton communities (Chintala et al. 2015). Pelletier et al. (2017) discussed a subset of the findings from the EPA Trends report for data collected in Greenwich Bay in 2004. These authors found that Greenwich Bay was primarily impacted by eutrophication-related stressors, that the sediments were enriched with organic carbon, and that the resulting benthic community was depauperate (Pelletier et al. 2017). The National Coastal Condition Assessment 2010 does not report estuary-specific trends, but the national benthic index showed a statistically significant increase of 67 percent of the total coastal area rated "good" in 2010 from 50 percent rated "good" in 2005-2006 (US EPA 2015). The benthic video sled deployed by the Narragansett Bay Commission is unique when compared to the other surveys in Table 1 as it primarily sampled epifauna (i.e., organisms living on the sediment surface). The benthic video survey is conducted only in portions of the Providence River estuary, but at monthly intervals—a high sampling frequency.

Sediment profile imaging (Table 1) is a rapid reconnaissance technique that delivers clear images of benthic biotopes regardless of water column turbidity (Germano et al. 2011). In 1988, sediment profile imaging was used in the first comprehensive survey of benthic habitat quality in Narragansett Bay (Figure 2) in the context of organic enrichment from wastewater treatment facility discharges (Valente et al. 1992). The 1988 imaging study provided the first in-situ snapshot of benthic processes in

Narragansett Bay soft sediments. Many researchers were surprised by the finding that a substantial proportion of the bottom had been exposed to high levels of organic deposition and low concentrations of dissolved oxygen (Granger et al. 2000). Many of the sites identified as having excessive organic enrichment and degraded benthic habitat were located in the Providence River estuary or shallow embayment sub-regions of the Bay, near wastewater treatment facility outfalls, or in coves and other spatially constricted areas that received effluent (refer to Figure 2; Valente et al. 1992). These sites were sampled again in 2008 using the sediment profile imaging technique, providing the main data source supporting a status and trends assessment for Bay-wide benthic habitat quality (to be discussed in detail in the Methods; Shumchenia et al. 2016).

Like most estuaries and coasts globally, there has been a great deal of human intervention and human-mediated change in Narragansett Bay and its watershed since the 1980s. Human population in the watershed has increased by about 200,000 to a total of about 2 million people (Nixon et al. 2009), increasing both impervious surfaces and wastewater treatment facility loads. Between 1980 and 1995, the Field's Point wastewater treatment facility in Providence (responsible for approximately 55 percent of total effluent discharged directly to the Bay) transitioned from being considered by EPA as one of the worst such facilities in the country to one of the best (Nixon and Fulweiler 2012). The Field's Point plant initiated secondary treatment of its sewage in June 1988, just months before the Sediment Profile Imaging benthic habitat assessment took place. Although chemical contaminants were one of the dominant ecological stressors in the Narragansett Bay watershed, they have declined in concentration since the 1950s (Nixon and Fulweiler 2012) and decreased in prominence relative to other stressors in the Bay (e.g., Shumchenia et al. 2015). In the 1990s, seasonal nutrient- and stratification-driven hypoxia was discovered in the Providence River estuary and Upper Narragansett Bay, prompting state and academic programs to monitor this indicator (Deacutis 2008, Codiga et al. 2009). In 2003, severe hypoxia and anoxia caused a large fish kill and nuisance macroalgal concentrations in Greenwich Bay (RI DEM 2003). The fish kill resulted in media and political attention, and in 2004 the Rhode Island Department of Environmental Management (RI DEM) began implementing a statutory mandate to 11 wastewater treatment facilities within the upper Narragansett Bay watershed to reduce summer season nitrogen discharges to the Bay between 48-65 percent with respect to 1995-1996 levels (RI DEM 2005). Most monitoring efforts since the 2003 fish kill and 2004 nutrient reduction mandate have focused on dissolved oxygen data to evaluate compliance with water quality standards (RI DEM 2005) and highlight the summer recurrence of bottom water hypoxia in Upper Narragansett Bay (i.e., Providence River estuary, Upper Narragansett Bay, Upper and Middle West Passage, and Upper East Passage (Bergondo et al. 2005, Deacutis et al. 2006, Melrose et al. 2007, Codiga et al. 2009). Climate change has caused warmer water temperatures linked to decreased rates of primary productivity in mid-Narragansett Bay with potential implications for the estuarine food web, and further Bay-wide changes are expected due to mandated nutrient reductions (Fulweiler and Nixon 2009).

Given these trends over the past several decades in land use, improvements in wastewater treatment facilities, hypoxic events, and responses to climate drivers, it is important to evaluate and monitor the response of benthic communities, which can serve as excellent indicators of Narragansett Bay ecosystem quality.

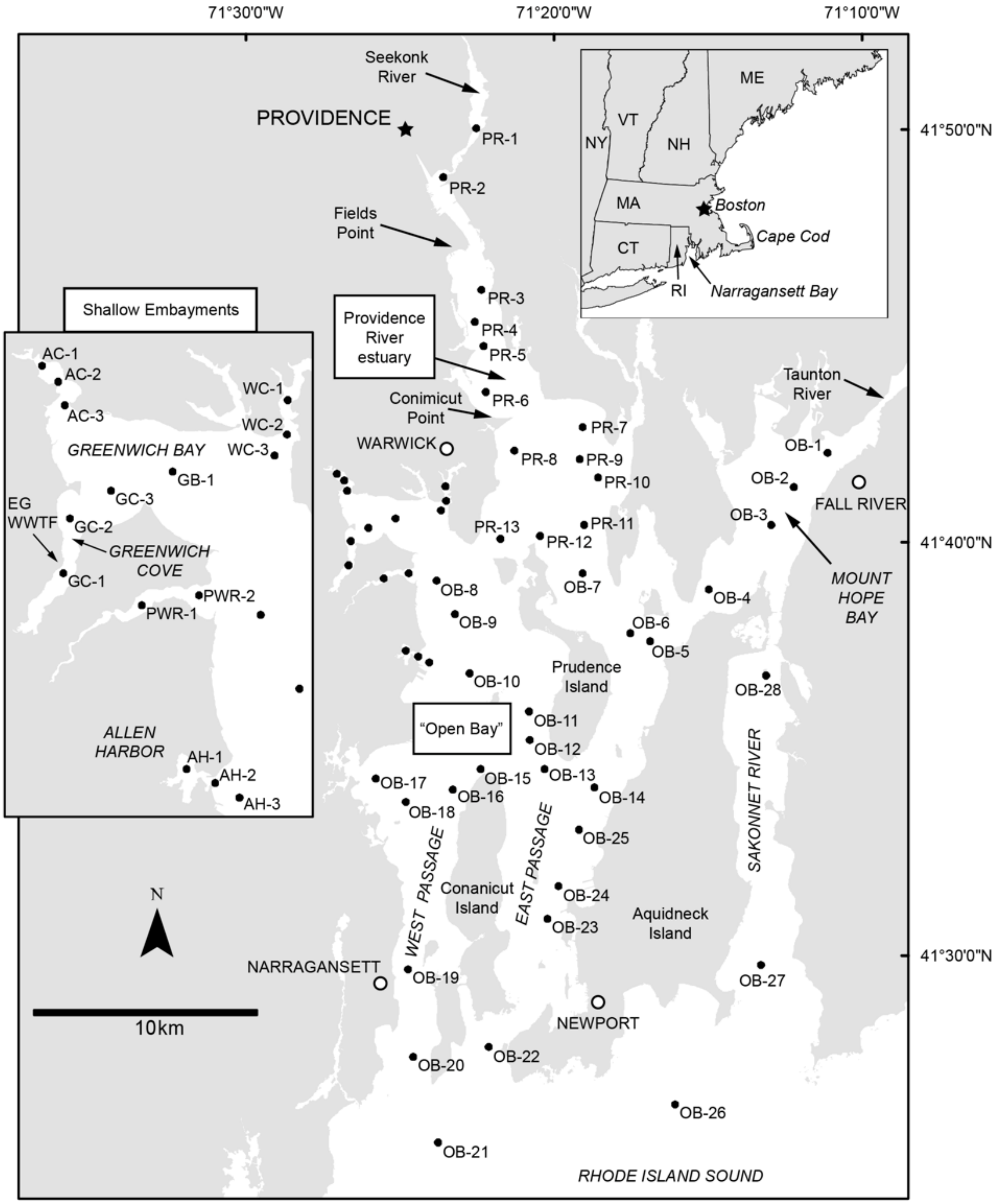

Figure 2. Locations within Narragansett Bay where sediment profile images were taken in 1988 and 2008. Three sub-regions used in the 1988 analyses are highlighted for comparison: Providence River estuary stations (PR-); Open Bay (OB-); Shallow Embayments (inset). Note locations of Fields Point and East Greenwich (EG) Waste Water Treatment Facilities (WWTF).

3. METHODS

Using sediment profile imagery, researchers assessed Bay-wide benthic biotope diversity at 52 sites throughout the Bay in 1988 and 2008 (Figure 2; Shumchenia et al. 2016). This study aimed to characterize how increased temperatures and changes in anthropogenic nutrient inputs may have influenced benthic organic enrichment and habitat quality between 1988 and 2008. To understand these stressor-response relationships, the researchers defined eight general biotopes from sediment and biota descriptors that were present in both 1988 and 2008 (Table 2).

Table 2. Descriptions of the eight biotopes based on observed sediment type and biota.

Sediment category	Dominant biota	Other biota	Biotope
Organic-rich mud; mud; sandy mud; sand	*Ampelisca* spp.	Small tube-building fauna; shallow-burrowing fauna; *Beggiatoa* spp.; *Mulinia lateralis*	*Ampelisca* beds occasionally with other small tube-building and shallow-burrowing fauna on substrates ranging from organic-rich muds to sand. *Beggiatoa* spp. or *Mulinia lateralis* may be present.
Organic-rich mud	None dominant	*Beggiatoa* spp.; tube-building polychaetes; shallow-burrowing fauna	Organic-rich mud with tolerant species such as *Beggiatoa* spp., tube-building polychaetes, and shallow-burrowing fauna.
Mud with shell hash	Burrowing fauna	Tube-building polychaetes; deep-burrowing fauna	Burrowing fauna on mud with shell hash. Tube-building polychaetes or deep-burrowing fauna may be present.
Mud	Burrowing fauna	Tube-building polychaetes; *Chaetopterus*; deep-burrowing fauna	Burrowing fauna on mud. Tube-building polychaetes, larger tube-builders such as *Chaetopterus*, or deep-burrowing fauna may be present.
Sandy mud	None dominant	Burrowing fauna; tube-building fauna	Burrowing and tube-building fauna on sandy mud.
Mud	*Crepidula fornicata*	Mobile crustaceans; mobile gastropods; *Beggiatoa* spp.	*Crepidula* bed on mud. Mobile crustaceans, gastropods or *Beggiatoa* spp. may be present.
Very coarse sand with shell hash	None dominant	Rafting macroalgae; *Crepidula fornicata*	Very coarse sands with shell hash. Rafting macroalgae or *Crepidula* beds may be present.
Hard sand	None dominant	Epibenthic sponges; rafting macroalgae; attached macroalgae; mobile gastropods	Hard sands with epibenthic sponges, rafting or attached macroalgae, and/or mobile gastropods.

Using only the subset of stations that could be directly compared between years, the proportion of images for which the biotope changed between 1988 and 2008 was calculated for the entire Bay and for each Bay region (Providence River estuary, Shallow Embayments, Open Bay; see Figure 2). For biotopes that changed, the resulting 2008 biotope was noted. The biotope mosaic, or the spatial arrangement of different biotopes, was described for each survey year Bay-wide and within Bay regions.

Overall, the sediment profile imagery technique showed great promise for its ability to provide information that indicates benthic habitat quality. For example, the researchers noticed examples of both apparent biotope fidelity (Figure 3 a, b) and marked change (Figure 3 c, d). For sites showing a stark change in sediment type between years, apparent biotope change could actually reflect high degrees of small-scale benthic heterogeneity or a shift in sediment transport dynamics in the intervening 20 years. Of the 38 stations that could be reliably compared between years, biotope change was observed at 24 stations (63 percent). The Providence River Estuary saw the highest degree of benthic biotope change (8/10; 80 percent), followed by Shallow Embayments (6/10; 60 percent) and Open Bay (10/18; 55 percent).

While the sediment profile imaging data reported here provided a whole-estuary characterization of benthic habitat quality change over time, there are some important caveats. First, benthic habitat quality was measured at just two points in time over a 20-year span. Because benthic habitat quality was not continuously measured between 1988 and 2008, we cannot determine if and what changes occurred in each year between 1988 and 2008, nor can we project with certainty what future assessments will find. Other limitations related to the technology and approach are discussed in Data Gaps.

This approach provided a Bay-wide quantitative analysis of the status and trends in benthic habitat quality over several decades. However, there is currently no established restoration target for benthic habitat quality in Narragansett Bay. In the Discussion, we describe what we expect the benthic biotope mosaic to look like under improving water quality conditions. With future work, these descriptions could form the basis of a restoration target.

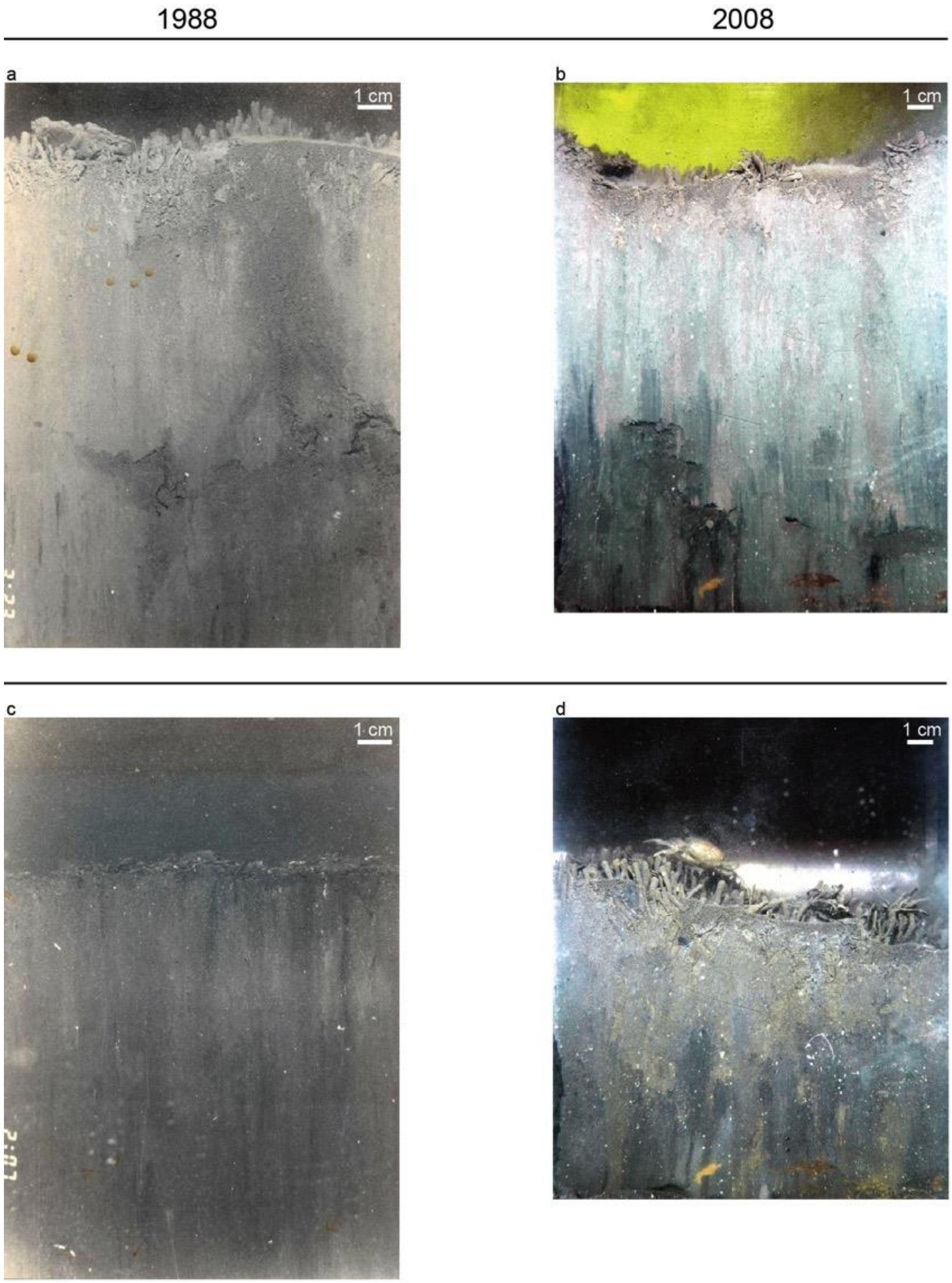

Figure 3. Example images of a site within Narragansett Bay (OB-2) where benthic biotope appeared to remain the same (*Ampelisca* beds) between 1988 (a) and 2008 (b) surveys; example images of a site (PR-3) where benthic biotope appeared to change from organic-rich muds with tolerant species to *Ampelisca* beds between 1988 (c) and 2008 (d) surveys.

4. STATUS AND TRENDS

Based on the sediment profile imagery study, benthic habitat quality improved between 1988 and 2008 (Shumchenia et al. 2016). Biotopes dominated by pollution-sensitive *Ampelisca spp.* tubiculous amphipods increased >5-fold between 1988 and 2008 and expanded into the more urban, anthropogenically stressed Providence River estuary (Figure 4). In 1988, conditions did not favor widespread *Ampelisca* beds; stations with high organic loading and surface sediments indicated poor water quality conditions (Valente et al. 1992). Between 1988 and 2008, conditions theoretically became increasingly favorable for *Ampelisca* beds, as management strategies to reduce organic loadings and improve water quality were initiated, and changes in climate were noted (e.g., increase in temperature). In 2008, there was an increase in the proportion of *Ampelisca* beds Bay-wide, and especially in areas where organic loading was known to be previously high. Water quality monitoring programs continue to record hypoxic events (see http://www.dem.ri.gov/bart), but it is possible that hypoxia occurs now over a smaller area, with less frequency and/or intensity than previous events (the first Bay-wide dissolved oxygen monitoring program did not begin until 1999; Prell et al. 2004).

The benthic biotope mosaic of 2008 may represent improved conditions for the protection and growth of other organisms. When the critical boundaries of organic enrichment were in the more-shallow, protected (constricted) regions of the Bay, as in 2008, robust *Ampelisca* beds may have served as structural habitat and provided food for other organisms like crustaceans and juvenile fish. When the critical boundaries of organic enrichment existed in deeper, less protected waters, as in 1988, we observed fewer *Ampelisca* beds. With future warming and decreasing anthropogenic nutrient inputs, *Ampelisca* beds should be monitored more frequently as potential indicators of patterns in organic enrichment and important habitats.

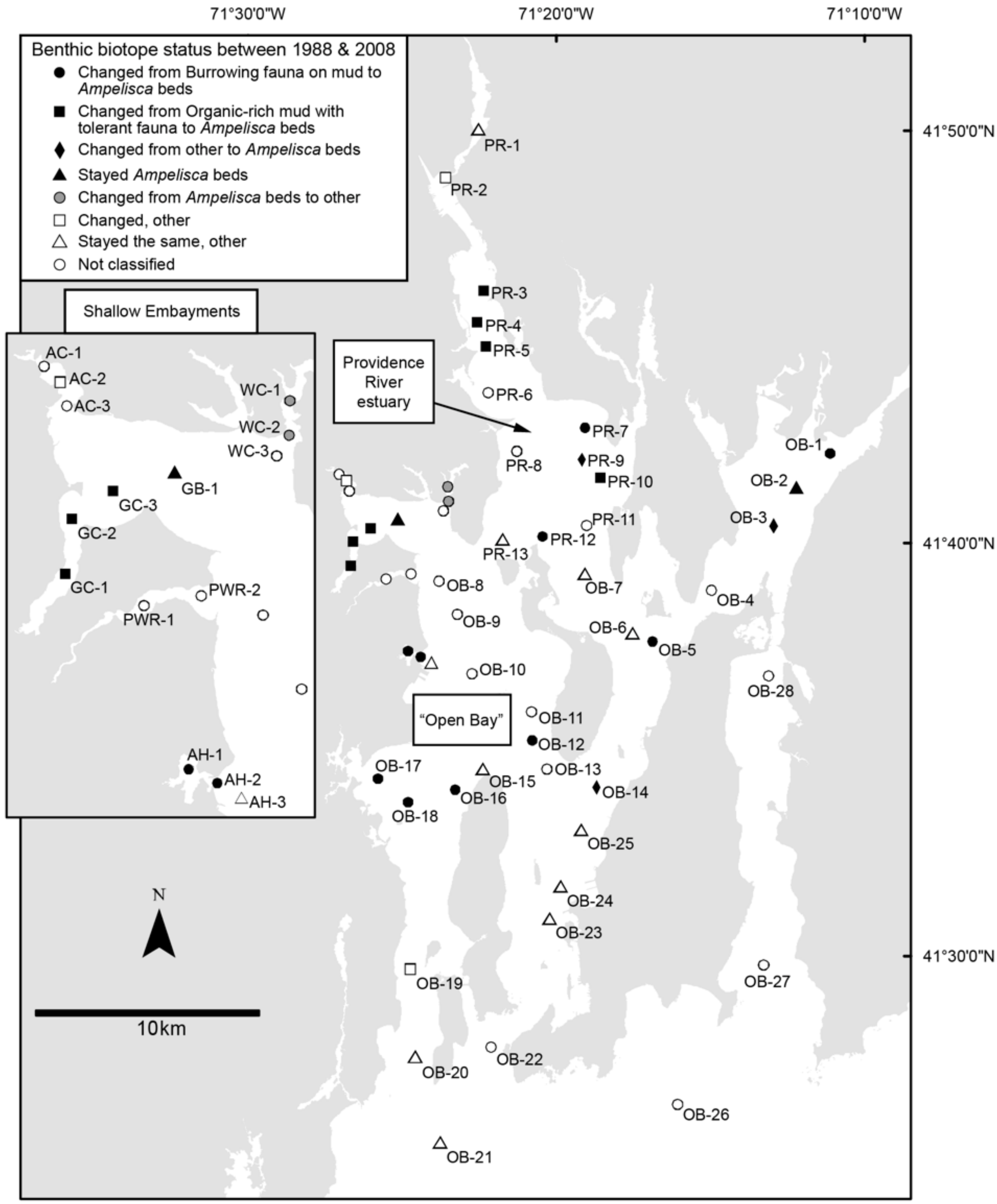

Figure 4. Benthic biotope change between the 1988 and 2008 surveys in Narragansett Bay was primarily from burrowing fauna on mud or organic-rich muds with tolerant species to *Ampelisca* beds.

5. DISCUSSION

It has been suggested that *Ampelisca* spp. are organic enrichment opportunists (McCall 1977). There is also debate as to whether ampeliscids serve as indicators of impending hypoxia (Levin et al. 2009) or of improving conditions (Diaz et al. 2008, Rhoads and Germano 1986). A recent study of hypoxia in Greenwich Bay demonstrated that ampeliscids colonized degraded habitats soon after the resumption of normal oxygen conditions and were reliable indicators of improving water quality (Shumchenia and King 2010). Dense *Ampelisca* spp. communities in areas with high organic input and good water quality have been previously observed within Narragansett Bay and in Boston Harbor (Stickney and Stringer 1957, Diaz et al. 2008). The cessation of primary sewage discharges to Boston Harbor in the early 1990s appears to have set the stage for the observed widespread increases in *Ampelisca* spp. throughout the harbor. Prior to 1992, organic loading was high but water quality may have been too poor to allow *Ampelisca* spp. to thrive (Diaz et al. 2008). A decade later, declines in *Ampelisca* spp. tubes were associated with the reductions in organic loadings to the harbor and the eventual depletion of sediment organic inventories (i.e., surface sediment total organic carbon) (Diaz et al. 2008). This pattern indicate that *Ampelisca* spp. are the hallmark of a recovering benthic ecosystem but not a fully recovered benthic ecosystem. *Ampelisca* are an intermediate step on the path to lower organic loadings and improved water quality. A benthic ecosystem with lower organic loading will likely have different dominant species and few or no *Ampelisca* spp. However, reductions in organic matter and lower numbers of *Ampelisca* spp. in Boston Harbor apparently have coincided with positive changes in fish populations, as the recreational fishing community has made note of significant recent increases in winter flounder populations there (Powers 2015). Narragansett Bay could be exhibiting a pattern similar to the Boston Harbor example. Unfortunately, benthic biotopes were not continuously monitored between 1988 and 2008, and it cannot be determined where Narragansett Bay is located along the Boston Harbor trajectory.

Assuming that organic loadings in Narragansett Bay continue to decline, future surveys could find any of the following responses in benthic habitat quality.

1. No change: similar extent of *Ampelisca* beds with good or improving water quality.
2. Improving: biotopes reflecting more "mature" benthic communities (such as filter feeding shellfish and deep-burrowing crustaceans) increase under good or improving water quality conditions.
3. Declining: novel but more depauperate biotopes emerge (such as with stress-tolerant species), paradoxically with good water quality.

As organic loading continues to decrease and sediment organic matter inventories are depleted, changes in benthic community composition and reductions in overall benthic biomass are expected (e.g., Riemann et al. 2016). The nature of these Bay-wide changes could have a profound effect on the ecosystem services delivered by the benthos.

6. DATA GAPS AND RESEARCH NEEDS

The survey methods used for this analysis describe only a very small area in space (i.e., images are about 15 cm across and 20 cm deep). Therefore, members of the benthic community that exist deeper in the sediment column or in patchy distributions may not be adequately characterized by this method. A notable example is shellfish such as quahogs and soft-shell clams and burrowing crustaceans such as mantis shrimp and lobster. The sediment profile imaging technique is able to detect blue mussel beds, which are known to occur in some years in large swaths of Narragansett Bay, but none were imaged in either 1988 or 2008. The key to addressing this type of data gap is to combine results from multiple techniques. For example, traditional grab samples better capture some deeper-dwelling organisms, and underwater video transect surveys are one of the only methods to observe large mobile benthic fauna.

Obvious spatial gaps in this analysis are data for the Southwest Coastal Ponds and Little Narragansett Bay. In the Southwest Coastal Ponds, sediment profile imaging has been used to map benthic habitats (Stolt et al. 2011) and to monitor short-term benthic habitat quality (Guarinello 2009). Benthic communities have been described using traditional methods in both the Southwest Coastal Ponds and Little Narragansett Bay, but these data have not been compiled for a comprehensive status and trends assessment.

Links between benthic habitat quality and water column conditions such as hypoxia and nutrient levels are not explicitly accounted for in the *Ampelisca* biotope indicator reported here. However, these links are critical in the context of providing useful information about ecosystem condition to water quality managers. Previous work (Cicchetti et al. 2006, Shumchenia and King 2010) established links between benthic habitat quality and water column conditions in Greenwich Bay using a measure of sediment oxygen penetration visible in sediment profile images. This same parameter was measured in the 1988 and 2008 images (Shumchenia et al. 2016) but could not be quantitatively compared between years due to differences in camera technology. Sediment oxygen penetration can be measured in any future sediment profile images and then be compared with the data from the 2008 images. These analyses could provide a more robust benthic habitat quality indicator and more quantitative links between stressors and responses.

A monitoring program to track changes in benthic habitat quality could be implemented by building on the 1998 and 2008 survey protocols. Based on those surveys, critical boundaries in organic enrichment have been identified (i.e., where the gradient between "poor" and "good" benthic habitat quality is highest), and several new stations, in addition to some of the original locations sampled in 1988 and 2008, are proposed to improve the detectability of future changes (Figure 5). In this updated monitoring strategy, 22 original stations would be revisited and 15 new locations would be added to detect any further movement of the habitat quality gradient up the Bay and shoreward. This new monitoring strategy focuses on the Providence River estuary, Greenwich Bay, and the upper portion of the West Passage. A focus on these areas of Narragansett Bay targets biotopes in close proximity to the major wastewater treatment facilities discharging directly to the Bay. Due to the rapid nature of sediment profile imaging data acquisition, this survey plan could likely be completed in 1-2 days. One monitoring plan option could be to visit these 37 stations annually in August during neap tide, and then visit the full suite of approximately 50 original stations every 5 years in order to provide a Bay-wide perspective at a longer interval. New images should be analyzed to measure sediment oxygen penetration, conspicuous species, and benthic biotope type so as to continue interpretation in the context of the shifting critical boundaries of organic enrichment in the Bay. Along with the imagery survey occurring Bay-wide every 5 years, a subset of stations should be sampled for traditional benthic community enumeration and analysis, so as to continue comparisons with historical studies in the Bay. This effort could be coordinated with the US EPA National Coastal Condition Assessment to maximize efficiency.

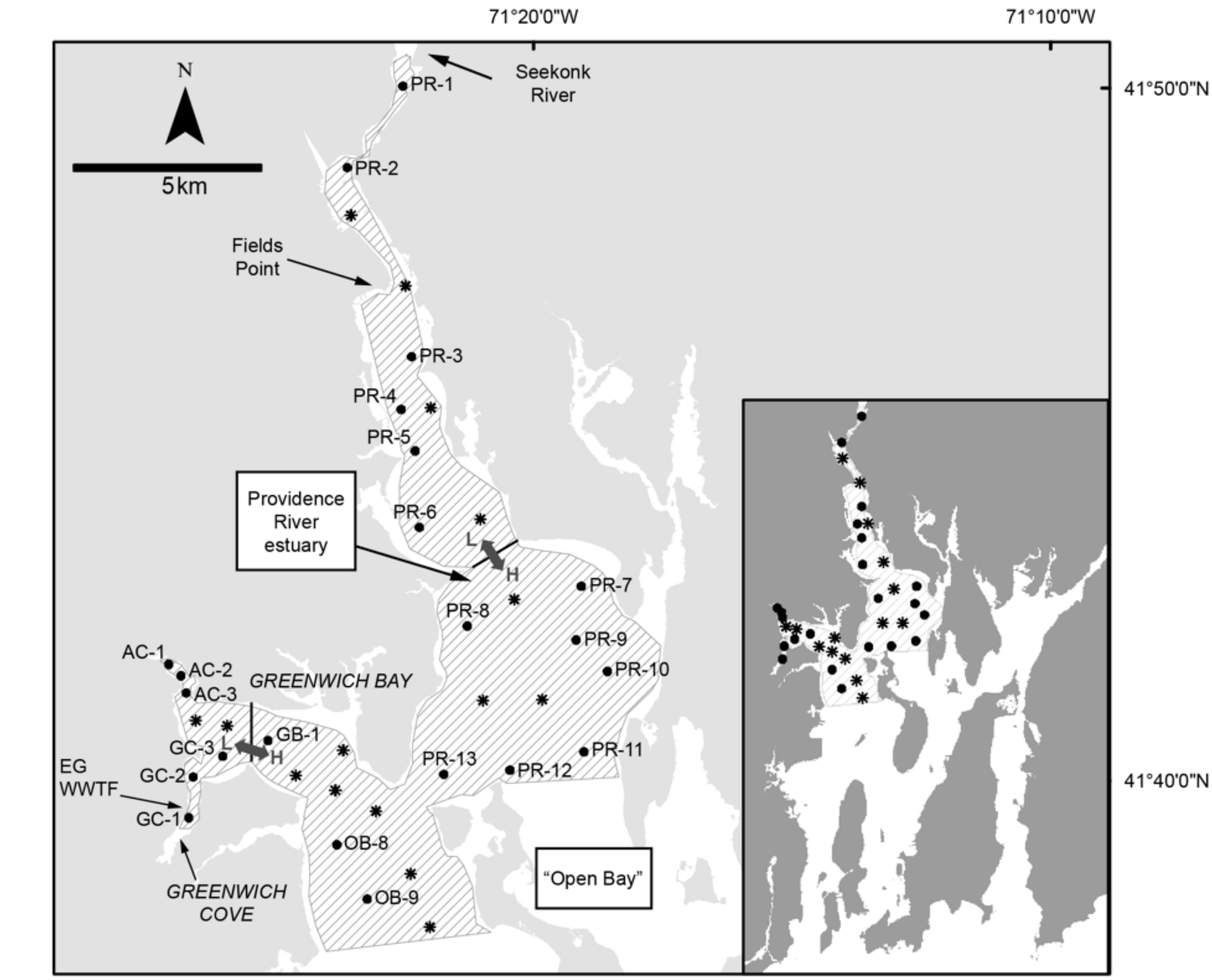

Figure 5. Proposed benthic biotope monitoring strategy for detecting changes in organic enrichment and habitat quality considering the results of Shumchenia et al. 2016. Closed circles = existing stations; star symbols = proposed new stations. Hatched area = monitoring focal area.

More work is needed to integrate the results of multiple ongoing efforts to monitor benthic habitats and/or communities (e.g., those described in Table 1). This work could take the form of using information from multiple surveys to fill gaps in time and space. For example, National Coastal Condition Assessment data for Narragansett Bay could be extracted and interpreted in the context of other benthic community analyses. Another example of using datasets to complement each other would be to use the benthic video data to provide a broader-scale characterization of the sites described using sediment profile imaging.

There is a particular need to coordinate benthic monitoring efforts planned for the upper Bay in the future. If the sediment profile imagery monitoring program proposed above is implemented, it could be coordinated with the Narragansett Bay Commission's benthic video work. Similarly, there are surveys of juvenile fish underway in the upper Bay through a collaborative project of the Rhode Island

Department of Environmental Management and the Nature Conservancy. Each monitoring effort would benefit greatly from increased coordination.

Additional types of data could also contribute to a more holistic assessment of benthic habitat quality in the future. For example, researchers are using benthic biogeochemistry to understand benthic nutrient fluxes and their relationships to climate change, eutrophication, and primary production in Narragansett Bay. Furthermore, changes to biogeochemical reactions (such as denitrification) can be measured on seasonal or annual time scales (Fulweiler and Heiss 2014), adding temporal resolution and improving our understanding of benthic ecosystem dynamics.

7. ACKNOWLEDGEMENTS

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