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A review of shellfish restoration as a tool for coastal water quality management.

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Abstract

Filter feeding by populations of bivalve mollusks is reviewed with respect to their ability to act as an estuarine filter, increase clarity of coastal waters and facilitate the removal of nitrogen and other nutrients from eutrophic coastal waters. Most bivalve mollusks clear particles from waters at rates of 1 to 4 L/h, and populations of shellfish in healthy assemblages can filter a substantial fraction of the water in coastal estuaries on a daily basis. Actively growing shellfish incorporate nitrogen and other nutrients into their tissues as they grow. On average, 16.8 g of nitrogen is removed from estuaries for every kilogram of shellfish meats harvested. In addition to removal of nutrients through shellfisheries and molluscan aquaculture, shellfish beds may act to promote removal of nitrogen from estuaries by increasing organic nitrogen deposition to the sediments that stimulates denitrification processes. It is suggested that shellfish restoration projects and establishment of small-scale molluscan shellfish aquaculture operations may mitigate the effects of coastal housing development in Southern New England and serve as an important adjunct to efforts to restore submerged aquatic vegetation and to reduce nutrient loading in estuaries through source reduction and innovative sewage treatment strategies.

Introduction

The input of inorganic nutrients such as nitrogen and phosphorus into coastal embayments and estuaries and resultant eutrophication is seen as a significant environmental problem that is expected to intensify as coastal development continues (Nixon, 1995). There is good evidence that terrestrial inputs of nitrogen and other nutrients into estuaries either by surface runoff or groundwater discharge were considerably less in pre-colonial times. In fact, evidence suggests that most of the nutrients entering coastal embayments and estuaries such as Buzzards Bay or Narragansett Bay may have been from offshore upwelling (Nixon, 1997). Terrestrial anthropogenic sources of nutrients in southern New England have been demonstrated to include point sources such as community sewage treatment facilities (Nixon et al., 1995), individual sewage disposal systems (Postma *et al.*, 1992), as well as non-point sources, including fertilization and other agricultural practices (Gold et al., 1989), management practices for home lawns (Morton et al., 1988), and other runoff and non-point sources (Nixon et al., 1995).

There is a growing body of evidence that coastal eutrophication is resulting in changes in estuarine and coastal benthic communities (Pearson and Rosenberg, 1978; Valente et al., 1992; McClelland and Valiela, 1998; Newell and Ott, 1999). Coastal eutrophication is implicated in increases in the duration and intensity of phytoplankton blooms that increase benthic shading, leading to loss of seagrasses and other submerged aquatic vegetation (Kemp et al., 1983; Twilley et al., 1985; Short and Burdick, 1996). Additionally, there is growing evidence that increased nutrient inputs can result in increases in the length and duration of hypoxic (low oxygen) events in estuarine waters (e.g. Officer et al., 1990), that may have very deleterious effects on estuarine community structure.

In order to effectively manage the inputs of nutrients into coastal water and control eutrophication, a number of management strategies have been proposed or are in the process of implementation. Typically these management strategies involve source reduction of nutrients, for example tertiary treatment or denitrification systems have been proposed for community sewage treatment facilities (e.g. Arundel, 2000), or the use of constructed wetlands as a strategy for nutrient removal (e.g. Frostman, 1996). Innovative individual sewage disposal systems have been designed to remove nitrogen from domestic wastewater through denitrification processes (Gold et al., 1992), and such systems are gaining greater acceptance by communities throughout the southern New England Region (*e.g.* Lucht et al., 1998; Douglas et al., 2000). In addition to strategies to reduce the amount of nutrients at the source, these community wastewater management plans have included analyses of soil types and assessment of environmentally critical areas in the process. Recently, projects to restore submerged aquatic vegetation in coastal areas have begun as a means to mitigate or counteract the effects of coastal eutrophication (*e.g.* Davis and Short, 1997).

It has long been known that beds of bivalve mollusks have the ability to clean the water through their filter feeding, and it is well known that many once thriving coastal shellfish beds have been depleted through overfishing or other means. The purpose of this paper is to review the existing literature on the filter feeding by bivalve mollusks to develop a case for the restoration of estuarine and coastal shellfish beds as a complementary part of integrated community coastal water management strategies.

Bivalves as Filter Feeders

All of the economically important bivalve mollusks derive most of their nutritional needs from filtering particles from the water (Jorgensen, 1966). These filtered particles include suspended silt and clay particles, phytoplankton and detritus particles. The bivalves can actively sort particles according to their nutritional value, and they ingest food particles and release the rejected particles as mucous-coated masses called pseudofeces that are deposited to the seabed (Reid, 1981). There is also some evidence that bivalves can remove dissolved organic nitrogen (DON) in the form of free amino acids directly from seawater (Manahan et al., 1982). The rates of particle filtration are species specific and size specific, but typical filtration rates fall in the range of 1 to 4 L/h for individual animals (Haven and Morales-Alamo, 1970; Mohlenberg and Riisgard, 1979; Doering and Oviatt, 1986), and many species of bivalves are capable of removing particles in the 1 µm size range, or particles in the size range of most bacteria (Palmer and Williams, 1980; Wright et al., 1982).

Bivalves and Sanitary Water Quality

Since bivalves are filter feeders, one of the greatest shellfishery concerns is that they can potentially concentrate water-borne pathogenic bacteria and viruses or other pollutants in their tissues, thereby posing a public health threat. Because of this potential threat to human health, the cleanliness of shellfish growing waters and the methods of harvesting and marketing of bivalve mollusks has been closely regulated by the National Shellfish Sanitation Program (NSSP) since 1925. At present, the NSSP is administered jointly by the U.S. Food and Drug Administration (FDA) and the Interstate Shellfish Sanitation Conference (ISSC), an interstate body of shellfish producing states that establish the nationwide NSSP criteria (ISSC, 1999). For states to conduct interstate commerce in shellfish harvested in their state waters, they must comply with current NSSP-ISSC protocols. These shellfish sanitation protocols require the states to close waters to shellfishing if specific coliform bacterial standards (*i.e.* 70 MPN total coliform or 15 MPN fecal coliform) are exceeded on a regular basis (Migliore, 1991). In many parts of southern New England, very productive shellfishing grounds are closed due to inadequate sanitary water quality. Because of the very strict regulatory standards for shellfish growing waters, the shellfishing industry and shellfish aquaculturists are typically among the most passionate defenders of estuarine and coastal water quality.

As a result of the potential for the economic benefit of shellfisheries, a number of municipalities and non-profit organizations have seized upon the idea of shellfishery restoration in concert with pollution reduction to restore lucrative recreational and commercial shellfisheries. For example, Macfarlane (1997) outlined the effort by the Town of Orleans to install properly sited storm drains to direct runoff away from key shellfish beds in municipal waters. This action opened shellfishing beds that were closed in excess of 12 years. Similarly, Tammi and Turner (1998) reported that the Water Works Group, a non-profit community organization in Westport, Massachusetts focused on restoring scallop fisheries and water quality in the Westport River. Their efforts led to the reopening of oyster fishing grounds that had been closed for several years due to agricultural runoff. They worked with local farmers to fence in cattle well away from the estuary. On Martha's Vineyard, several grass roots citizen's organizations have rallied to restore and protect 176,261 acres of shellfish growing waters around the island (Karney, 2000). Among the accomplishments of the Martha's Vineyard citizens groups include the pressuring local boards of health to inspect and replace failed septic systems, the encouragement of the removal of underground oil storage tanks, promotion of no-discharge zones for boaters and helping to establish pump-out facilities for marine heads, mapping road drainages and working with road engineers to direct road runoff away from critical shellfish beds, and working with farmers to fence livestock in areas away from critical water bodies and to improve manure handling practices.

The commonality of all of these local efforts to improve coastal water quality is the recognition that recreational and commercial shellfisheries have economic and social importance in coastal communities. Furthermore, coastal land values are often tied to good water quality so there is often a strong vested interest that urges involvement. Beyond the direct economic benefits of shellfisheries however, healthy shellfish beds may have an economic value by virtue of their ability to filter the water and remove excess nutrients from the water column.

Bivalve Assemblages Act to Modify their Own Environment

Since Karl Moebius' (1880) pioneering work in oyster reef ecology, it has been known that, "Any change in the relative factors of the bioconose [community] produces changes in other factors of the same. If, at any time, one of the external conditions of life should deviate for a long time from its ordinary mean, the entire bioconose or community would be transformed. It would also be transformed if the number of individuals of a particular species increased or diminished through the instrumentality of man, or if one species disappeared from, or a new species entered into the community."

Since individual bivalves have the capability of filtering anywhere from 1 to 4 liters per individual on an hourly basis, communities of bivalves have the capability of filtering considerable volumes of water. In a classic theoretical exercise, Newell (1988) estimated that in 1870 when massive oyster reefs were intact in the Chesapeake Bay it took a mere 3.3 days for the oysters to filter the entire volume of the bay. By 1988 after decades of overfishing, oyster diseases and pollution had reduced oyster populations to only a small fraction of their original numbers and the time for the oysters to filter the bay had increased to 325 days.

In a similar exercise, Rice et al. (2000) estimated that northern quahogs in the Providence River section of Narragansett Bay are able filter a considerable amount of water. The standing crop of quahogs in the Providence River averages 9.1 clams/m^2 or about 26,400 metric tons (Figure 1). The population of quahogs, however, is composed of mostly older adults with valve lengths in excess of 60 mm. The quahogs collectively filter about 1.0 x 10^7 m^3 of water daily (Table 1). The mean tidal excursion of the Providence River is 1.22 m, and the area of

Figure 1. Length-Frequency diagram showing quahog population characteristics in the Providence River, Rhode Island. Overall density of quahogs in the Providence River averages 9.1 clams/m^2 or about 26,400 metric tons shell-on weight overall.

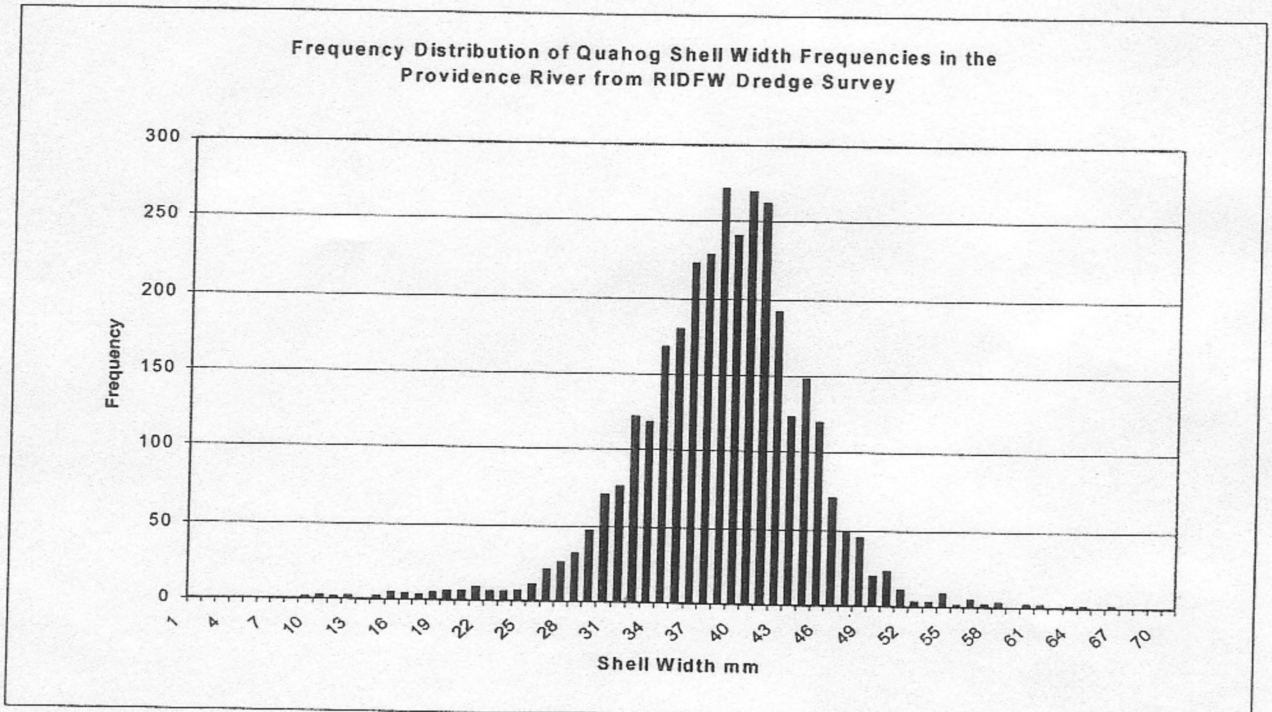

Table 1. Spreadsheet table showing quahog biomass per size class of quahogs *Mercenaria mercenaria*, in the Providence River section of Narragansett Bay. The table also presents quahog filtration rates per size class, and amount of organic nitrogen locked up in quahogs of each size class. Filtration Rate calculated from data in Doering and Oviatt, 1986.

Biomass Calculations by Size Class with 5 mm group centered on mid-point							
Shell Width (mm)	Biomass (metric tons)	Length (cm)	Individual FR (L/hr)	Proportion of total biomass	Quahog numbers	Population FR (cu m/hr)	Organic-N content (tonnes)
3	0	0.57	0.178	0	0	0	0
8	0.578561	1.52	0.460	2.19E-05	4375	2.013981	0.00167
13	5.12419	2.47	0.735	0.000194	38764	28.53042	0.014793
18	25.93476	3.42	1.008	0.000982	196219	197.8259	0.074868
23	78.96895	4.37	1.277	0.00299	597449	763.4581	0.227968
28	703.7288	5.32	1.545	0.026646	5324295	8229.19	2.031524
33	3580.788	6.27	1.811	0.135583	27091644	49083.04	10.33702
38	9462.755	7.22	2.076	0.358298	71593650	148668.3	27.31708
43	8756.715	8.17	2.340	0.331565	66251971	155044.3	25.27889
48	2878.576	9.12	2.602	0.108994	21778738	56687.34	8.309872
53	491.3499	10.07	2.864	0.018604	3717376	10648.89	1.418429
58	276.9662	11.02	3.125	0.010487	2095470	6549.518	0.799546
63	115.1425	11.97	3.385	0.00436	871197	2949.66	0.332393
68	33.65765	12.92	3.645	0.001274	254565	927.959	0.097163
Totals	26410.29				1.998×10^8	439780.1	76.24121

the Providence River is 2119.8 ha (URI Environmental Data Center), so the mean tidal prism of the Providence River is 2.58×10^7 m^3. The semidiurnal tide cycle is about 12.5 hours, so on a single tide cycle the population filtration by quahogs represents a water volume equal to 21.3% of the tidal prism.

A number of studies suggest that filtration by populations of bivalves can in fact control the biomass of phytoplankton in the water column. For example, Cloern (1982) and Officer et al. (1982) argue that populations of infaunal clams in South San Francisco Bay are responsible for controlling phytoplankton populations in the overlying water column. Several studies have shown that filter-feeding bivalves can increase water clarity, thereby increasing light penetration (Cohen et al., 1984; Peterson and Black, 1991). However, this process of filter feedings acting to simply clear the water and depositing the filtrate on the bottom is not a completely simple process. A number of studies suggest that in many instances once filtered material eventually decomposes to regenerate new nutrients, which in turn stimulates new production of phytoplankton (Doering et al., 1986, 1987). Thus aquatic ecosystems with bivalves have a more active exchange process between the water column and the sediments and are able to process a greater amount of nutrients.

Nitrogen Removal through Aquaculture and Shellfisheries

Once bivalves have filtered and ingested phytoplankton or detrital particulates there are four possible pathways in which pathways for nutrients in the food to be processed by the bivalves: a) incorporated into soft body tissue or shell, b) expelled as pseudofeces before ingestion, c) expelled as feces after ingestion and digestion, and d) excreted as ammonia into the water (Newell, 1981). Tissue growth of bivalves in actively growing shellfish beds or in actively managed shellfish aquaculture operations is an effective means of removing nitrogen, phosphorus and other organic nutrients from the water (Rice, 1999a). This is not true for bivalves that are mature and not actively growing. In a mature state the bivalves are generally in a state of nitrogen balance in which the organic nitrogen ingested in the food is equal to the nitrogen defecated or excreted as ammonia. According to U.S. Department of Agriculture Food Tables, shucked oyster or clam meats on a dry weight basis are typically 30 percent protein. Shell material is less that 1 percent protein by weight. Assuming that bivalve soft tissues are 80 percent water and that nitrogen is 14 percent of the weight of typical proteins, it can be concluded that for each kg of shellfish meats harvested from an actively growing shellfish bed or aquaculture farm, 16.8 g of nitrogen would be harvested from the growing waters.

In the case of quahogs in the Providence River of Rhode Island (Figure 1), it is recommended that only ten percent of the standing stock of 26,400 metric tons be removed annually by relay or fishing to maintain maximum sustainable yield (Rice et al., 2000). At this rate of exploitation, 8 metric tons of nitrogen would be harvested annually. However, this rate of nitrogen removal is quite miniscule in comparison to the estimated 4580 metric tons of nitrogen discharged into the Providence River annually from sewage treatment plants and surface runoff (Nixon *et al.*, 1995).

In smaller coastal water bodies, shellfish restoration or establishment of aquaculture projects may have a greater impact by removing a greater percentage of the nitrogen and phosphorus reaching the estuary. Because of this, it is often instructive to estimate the number of aquacultured shellfish it would take to mitigate the effects of nitrogen excreted by an average person living in the coastal zone. According to Valiela and Costa's (1988) estimates, an average person excretes and defecates 3.8 kg of nitrogen annually. This being the case, the weight of oyster meats harvested annually to compensate for the nitrogen excreted by the average person would be 3,800g ÷16.8g/kg meat ≅ 225kg of oyster meats. Assuming that oyster meats are harvested at an average 40g, this means that a modest oyster farm producing 5,600 oysters annually would mitigate the nitrogen produced by a single person. Again, this assumes that the shellfish are actively growing. Harvest of mature shellfish from established beds at rates greater than MSY will remove nitrogen on a short-term basis, but it would not be sustainable.

Nitrogen Removal by Deposition and Benthic Processes

Aside from harvest of bivalves as a means to remove nutrients from coastal water bodies, it is likely that the filter feeding and deposition of organic particulates to the benthic sediments is responsible for much greater removal of nutrients. A number of studies suggest that nitrogen can be removed through stimulation of sediment processes. For example, Kelly and Nixon (1984) and Doering et al. (1987) showed that increased organic sedimentation or presence of infaunal northern quahogs, *Mercenaria mercenaria,* increase the rates of inorganic nitrogen turnover in sediments suggesting that biogeochemical processes in the sediments are stimulated.

One biogeochemical process of extreme importance in coastal waters is denitrification. For example, about half of the nitrogen deposited into Narragansett Bay from rivers or in sewage discharges is removed via denitrification, and about 35% of the organic nitrogen mineralized in the sediments is removed from the ecosystem as elemental nitrogen (N_2) that eventually diffuses to the atmosphere (Seitzinger et al., 1984). Since 4,580 metric tons of nitrogen are discharged into the Providence River annually (Nixon et al., 1995), the estimated rate of denitrification would be 4,580 tons/yr. ÷ 2 = 2,290 tons/yr., which is considerably higher than the recommended 8 metric tons per year nitrogen removal in a well-managed natural harvest shellfishery (Rice *et al.* 2000).

There is some evidence that the rate of denitrification in marine sediments is a function of the amount of nitrogen supplied. In mesocosm experiments, Seitzinger and Nixon (1985) enriched sediments in experimental tanks with up to 65 times the inorganic nitrogen of control tanks and observed a 2.5 fold increase in the production of elemental nitrogen (N_2) and a hundred fold increase in the production of nitrous oxide (N_2O), an intermediary denitrification product. Several studies have shown that filter-feeding bivalves do increase the rate of nitrogen deposition to the benthos (e.g. Cloern, 1982; Officer et al., 1982; Rice, 1999b), so it is attractive to hypothesize that this organic nitrogen enrichment of the sediments will result in increased denitrification. However, direct confirmatory experiments have not been performed to date.

Conclusions and Recommendations

Typically, efforts to manage inputs of nitrogen and other nutrients into coastal waters have been strategies of source reduction and application of innovative wastewater technologies. Restoration of shellfish beds in coastal waters is often justified on the basis of the direct economics of commercial and recreational shellfisheries, but the ecological value of the shellfish beds as a way to mitigate the effects of eutrophication may be overlooked.

Shellfish restoration projects may be a cost effective complementary adjunct to coastal wastewater management strategies and other projects designed to mitigate the impacts of eutrophication. Shellfish beds act to filter particulates from the water column and increase water clarity, so projects to restore eelgrass or other submerged aquatic vegetation may be improved if there were parallel efforts to restore shellfish in adjacent areas. Shellfish beds act to deposit particulate organic nitrogen into the sediments, so there is good reason to suspect that restoring shellfish beds can mitigate eutrophication by promoting sediment denitrification. It may be an interesting exercise for the economics community to estimate the relative costs of a community shellfish restoration project in comparison to the cost of filters and engineered tertiary denitrification systems of a sewage treatment plant processing water at the same rates.

Finally, development of small scale aquaculture farms for bivalve mollusks in coastal water bodies most threatened by eutrophication may be a very economical means to mitigate the effects of excessive coastal housing development. While growing to marketable size, the bivalves like oysters, scallops and quahogs will filter the water and deposit organic material to the sediments. The bivalve culturist would be managing stocks for a stable year-to-year harvest, so it is in his best interest to manage his stocks well and add seedstock on a regular basis, thereby keeping the biomass of his shellfish and the rate of population filtration of his animals relatively constant. Additionally, the regular harvesting shellfish for market provides for regular removal nutrients from the estuary.

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