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A Role for Shellfish Aquaculture in Coastal Nitrogen Management

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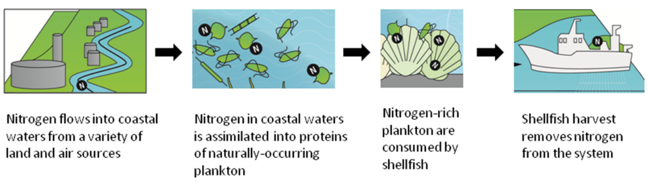

Excess nutrients in the coastal environment have been linked to a host of environmental problems, and nitrogen reduction efforts have been a top priority of resource managers for decades. The use of shellfish for coastal nitrogen remediation has been proposed, but formal incorporation into nitrogen management programs is lagging. Including shellfish aquaculture in existing nitrogen management programs makes sense from environmental, economic, and social perspectives, but challenges must be overcome for large-scale implementation to be possible.

INTRODUCTION

Eutrophication of aquatic environments is a worldwide concern. Excess nutrients can lead to a variety of problems in the estuarine environment, including hypoxia, fish kills, loss of habitats such as submerged aquatic vegetation, and nuisance and/or toxic blooms of algae.[1,2] Management programs to lessen eutrophication in estuaries and coastal ecosystems typically have focused on nitrogen as this nutrient has been described most often as the primary limiting factor for phytoplankton growth in the coastal environment.[3−5] Recent discussions also have recommended consideration of phosphorus for coastal and estuarine management,[6−8] but nitrogen remains a major component of any comprehensive, coastal nutrient-reduction program.[9−11]

Shellfish have been recognized for their role as "keystone species" and "ecosystem engineers" in the coastal environment.[12−14] The restoration of shellfish (particularly oyster) populations has been recommended to mitigate undesirable environmental changes associated with eutrophication in the Chesapeake Bay.[15] The mechanism of action proposed is that the filtration and deposition of suspended particulate matter on oyster reefs reduce water turbidity and enhance denitrification processes by bacteria in the sediments below, resulting in nitrogen removal from the estuary in the form of nitrogen gas. There is debate about the scale of shellfish restoration that would be needed to restore a eutrophic ecosystem as a whole.[16−18] Some of this debate is attributable to conflicting results from measurements of denitrification in sediments under and around oysters.[19,20] Natural denitrification processes are known to vary considerably in both space and time.[21] Quantifying the enhancement of denitrification processes in restored oyster habitats has proven to be extremely challenging, but recent work suggests that quantification methods may be improving.[20]

The use of shellfish aquaculture for coastal nutrient remediation has been proposed.[22,23] A variety of local, state, and federal agencies in the region around Long Island Sound, U.S., recently have been exploring the application of these concepts in the Northeastern United States.[24,25] This concept is being called "nutrient bioextraction" by scientists and resource managers involved in the Long Island Sound effort (Figure 1). Nitrogen in the coastal environment comes from a variety of sources, but inorganic (and some organic) forms can be assimilated by phytoplankton. The phytoplankton then are filtered and consumed by shellfish, and nitrogen from the phytoplankton is incorporated into shellfish tissues and shell. When the shellfish are harvested from natural beds or from a farm setting, the nitrogen contained in their bodies is removed from the local environment. Although the focus of this paper is shellfish aquaculture, it is also worth noting that seaweed aquaculture provides many of the benefits and opportunities for nitrogen reduction, through direct assimilation of dissolved inorganic forms of nitrogen in coastal and estuarine waters (Figure 1). Macroalgal nutrient bioextraction can be a complement to shellfish bioextraction at times and places; for example, winter in temperate regions, when phytoplankton do not compete well for nutrients. Shellfish nutrient bioextraction addresses one specific symptom of eutrophication—accumulation of phytoplankton biomass that reduces water clarity and contributes to benthic, microbial oxygen demand on a system-wide scale when this biomass is not assimilated by higher trophic levels.

WHY DO WE NEED SHELLFISH AQUACULTURE? CURRENT CHALLENGES FACING COASTAL AND ESTUARINE NITROGEN MANAGEMENT PROGRAMS

The Clean Water Act defines point source pollution as "any discernible, confined and discrete conveyance...from which pollutants are or may be discharged".[26] Major point sources of nitrogen include wastewater treatment plants, other industrial plants and large animal farms. As the name implies, point sources release nitrogen in concentrated waste streams that are relatively straightforward to sample and monitor. Having a concentrated and identifiable source of nitrogen can make management more cost-effective and efficient.

Many areas with documented water quality impairments linked to nitrogen have already invested heavily in reducing

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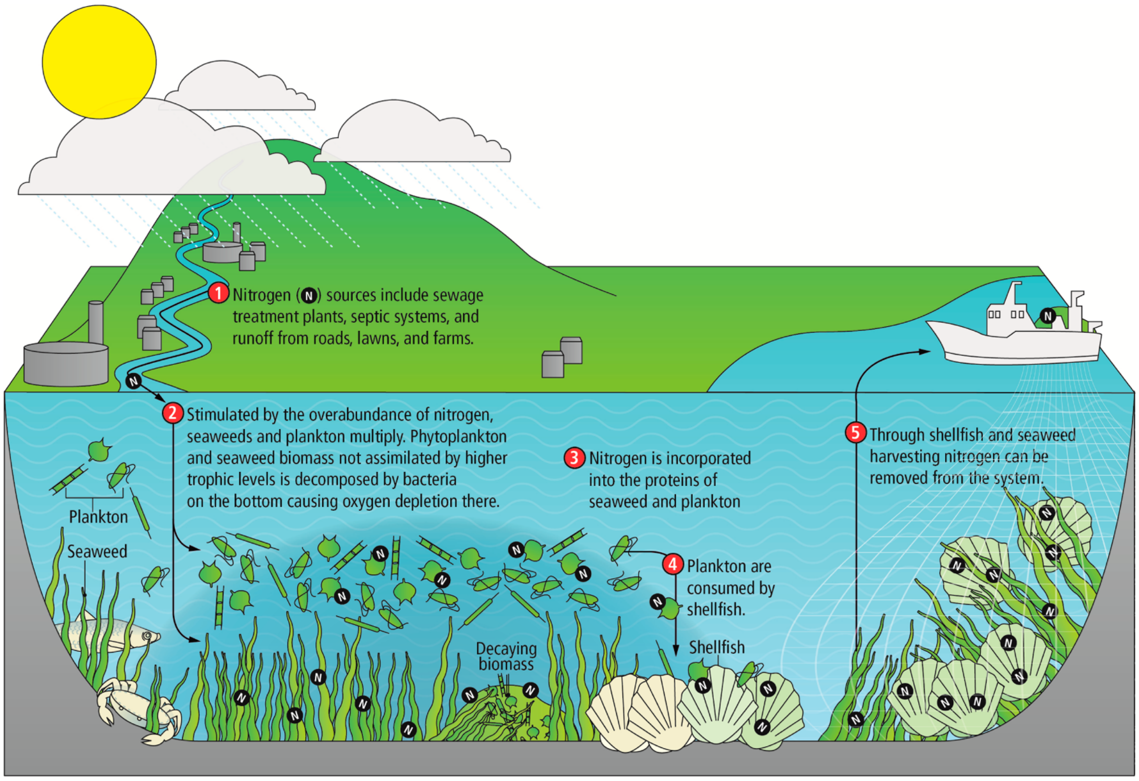

Figure 1. Illustration of the nutrient bioextraction process. Note that the schematic includes nutrient removal by both shellfish and seaweed aquaculture, but this paper focuses solely on shellfish. Figure courtesy of Lucy Reading Ikkanda/Long Island Sound Study.

point sources of nitrogen to our coastal waters. In a region that is more urban and suburban than agricultural, such as the Long Island Sound watershed, the major focus of point source nitrogen reduction has been improvements to wastewater treatment.[27] The Clean Water State Revolving Fund (CWSRF) has been an effective tool for states and municipalities to upgrade wastewater treatment plants (WWTPs) in the Long Island Sound region and elsewhere in the United States.[28] The total amount of money devoted to wastewater treatment from 1988 to 2011 (including federal and state grants and money from bonding initiatives) was reported to be $1.7 billion for 324 projects in Connecticut[29] and $9.8 billion for 2,442 projects in New York.[30] A portion of these funds have targeted nitrogen removal upgrades to wastewater treatment plants in the Long Island Sound watershed. These considerable efforts have met with success, as point source nitrogen loads from both states declined from 1995 to 2010: from 21 000 kg/day to 11 300 kg/day in Connecticut and from 64 000 kg/day to 50 000 kg/day in New York.[31] Four large New York City WWTPs are in the process of being upgraded for nitrogen removal, so as these upgrades continue to come online over the next four years, the loads should be reduced even further.

As limits of technology are approached, nitrogen reductions at point sources become increasingly more expensive. Costs of nitrogen removal at WWTPs in the Connecticut River Basin have been estimated to increase from $12 per pound at 8 mg/L total nitrogen discharged to $14 per pound at 5 mg/L total nitrogen discharged to $37 per pound at 3 mg/L total nitrogen discharged.[32,33] It is not unusual for costs to upgrade individual plants to a higher level of nitrogen reduction to run into the tens and hundreds of millions of dollars.[34]

Currently, advances in wastewater treatment processes for nitrogen removal result in effluent total nitrogen concentrations of 8 mg/L after biological nitrogen removal, and 3 mg/L after enhanced nitrogen removal.[35] It is worth noting that 3 mg/L of nitrogen in effluent still constitutes a substantial input of nitrogen in terms of potential phytoplankton and/or bacterial growth, equivalent to 200 μM total nitrogen. Oceanographic literature suggests that 1 μg/L chlorophyll can be produced from the addition of 1 μM inorganic nitrogen, if nitrogen is the major limiting nutrient in an ecosystem.[36] For perspective, chlorophyll concentrations in excess of 20 μg/L in surface waters are considered high for estuarine environments.[37] This chlorophyll:nitrogen estimation is based on inorganic nitrogen, and substantial fractions of the total nitrogen in wastewater effluent are organic, but a significant fraction of this organic nitrogen has been demonstrated to be biologically available, both within the effluent itself and also after transformations that occur when the effluent comes into contact with sunlight and salt water.[38,39] Although effluent is diluted considerably upon mixing with receiving waters, it still contains sufficient biologically available nitrogen to support considerable phytoplankton production.

As efforts to upgrade wastewater treatment plants and reduce other point sources of nitrogen succeed, an increasing portion of the total nitrogen load to coastal and estuarine waters comes from nonpoint sources. Nonpoint sources of nitrogen are diffuse, including sources such as fertilizer runoff from agricultural fields and suburban lawns, stormwater inputs from urban and suburban areas, and atmospheric deposition directly onto an estuary and onto land within the watershed. In the Long Island Sound watershed, point source nitrogen loads from the northern states (CT, MA, NH, VT) were estimated to range from 27 to 50% between 1999 and 2009, with a general decline in point source contribution occurring over the time period, likely attributable to successful point source nitrogen management (John Mullaney, USGS Connecticut Water Science Center, personal communication). Nonpoint sources are thought currently to constitute the majority of nitrogen loads to the Sound from the New England states (i.e., Connecticut, Massachusetts, New Hampshire, and Vermont).

The diffuse nature of nonpoint source nitrogen makes it challenging to address within the context of an ecosystem-scale nitrogen management program. A wide variety of best management practices (BMPs) have been developed to deal with agricultural and stormwater runoff, two major categories of nonpoint source nitrogen. These BMPs can be expensive, may incur regular maintenance effort and cost, and typically need to be implemented throughout the watershed.[40−42] Information about the effectiveness of nitrogen removal by different types of BMPs is growing, and it is clear that there can be large variation in BMP performance, but many types of BMPs have been demonstrated to be effective at removing nitrogen from runoff.[43−46] Some nonpoint sources of nitrogen, such as atmospheric deposition, currently have limited options for management reductions, which underscores the need for new management tools. Finally, the emphasis on land- and air-based sources of nitrogen fails to recognize the potential for large amounts of organic material to be contained within estuarine sediments. These sediments can be a source of nitrogen to the water column and increase the lag time of ecosystem response to nitrogen management.[41] Indeed, estuaries were classically characterized as nutrient-trapping systems,[47] although natural export processes can be substantial.[48] Certainly, a process, such as shellfish nutrient bioextraction, that contributes to nutrient export from an estuary will hasten the whole-system response to reductions in nutrient loading.

This lag in ecosystem response to nitrogen management is a final challenge to resource managers today. Coastal nitrogen management programs have been established for decades in many locations worldwide, and successful reductions of point source loads have been documented in a variety of estuaries. Two recent reports, however, have highlighted the occurrence of hysteresis and the existence of complex trajectories that estuaries may take as nitrogen loads are progressively reduced.[49,50] Duarte and colleagues developed four scenarios that incorporate the concepts of regime shifts and shifting baselines into ecosystem response to management efforts. Kemp and colleagues concluded that large estuaries with relatively high nonpoint source nutrient loads, long-term changes to biological communities, habitats, and/or biogeochemical cycles, and other shifts in "baseline conditions" tended to exhibit time lags and hysteresis in the response of hypoxia occurrence to nutrient reduction.[50] The reality facing many resource managers today is that even more nitrogen reductions may be necessary than are planned to effect change on an ecosystem scale.

■ SHELLFISH AQUACULTURE IS A GOOD FIT FOR COASTAL AND ESTUARINE NITROGEN MANAGEMENT PROGRAMS

Concomitant with increases in nutrient loadings to estuaries and coasts have been declines in the natural capacity of these ecosystems to assimilate nutrients. Shellfish populations, seagrass beds, and salt marshes historically have been important components of estuarine nutrient assimilation mechanisms, and significant declines of all three have been well-documented worldwide.[51−53] The expansion of shellfish aquaculture in the nearshore environment would have the effect of increasing the assimilative capacity of the ecosystem for nutrients, including nitrogen, without deleterious effects on water quality. The nitrogen assimilated by shellfish through their feeding activities could come from any source in the environment, including sources such as benthic sediments and the atmosphere, both of which have proved difficult to address by traditional nitrogen management programs.

Shellfish aquaculture also is appealing from a regulatory standpoint because the nitrogen removal can be measured directly within organism tissue and shell, then also estimated based upon simple measurements of shell length. Higgins and colleagues[54] recently demonstrated the feasibility of this approach using oysters from two floating-raft aquaculture installations in Chesapeake Bay. The total nitrogen content of the oysters was highly correlated with the total shell length ($r^2 = 0.76$). This type of relationship allows for a relatively precise, accurate and straightforward estimation of nitrogen removal from shellfish harvest numbers. These predictive equations need to be generated in other locations, and with other shellfish species, because they are specific to a waterbody and industry, but they represent a promising tool for resource managers.

Harvest-based estimates of nitrogen removal are useful, but are calculated only after removal has occurred. Another tool for resource managers is predictive estimates of nitrogen removal at the estuary scale that can be made based on existing shellfish resources. Carmichael et al (2012)[55] measured soft tissue nitrogen assimilation in oysters from four estuaries in Massachusetts, and used these numbers to predict offsets of 1−15% of the total nitrogen loads, based on typical planting densities and 0.5−1% of estuarine bottom under cultivation. Beseres Pollack et al (2013)[56] measured environmental variables, oyster shell height and biomass in the Mission-Aransas estuary, Texas, and used this information to calculate nitrogen removal through wild harvest (21 665 kg y^{-1}), as well as nitrogen removal from denitrification and burial by existing oyster reefs (13 650 kg y^{-1}). These authors also estimated the value of nitrogen removal services provided by these oysters to be $293,993 per year.

For planning purposes, more detailed predictive models are also needed. Nitrogen removal at the shellfish farm scale has been modeled in a number of places around the world using the Farm Aquaculture Resource Management model.[57,58] A recent review of model outputs of the quantity of nitrogen removed per unit area for a variety of cultivated shellfish species indicates that shellfish aquaculture compares favorably to existing, approved agricultural and stormwater best management practices.[59] Predicted nitrogen removal in this review was reasonably constrained, which was somewhat surprising given large differences in culture practices, species cultivated, and locations modeled. The potential for a large amount of nitrogen removal at the farm setting, however, also was identified, on the order of several hundred pounds per acre per year (tens of grams per square meter), for shellfish farms in China, Europe, South America, and the United States. The use of existing models at a variety of environmental scales, from the farm up to the ecosystem, could help provide guidance to regulators when making predictions about impacts of the expansion (or in some locations, the establishment) of the shellfish aquaculture industry at the level of an estuary.

The cost per unit of nitrogen removed from shellfish aquaculture also is thought to compare favorably to existing best management practices for agricultural and stormwater runoff.[42,60] Comparisons performed for the Virginia portion of

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Chesapeake Bay indicated a wide range of estimated costs possible for agricultural and urban nonpoint sources of nitrogen, although in general agricultural best management practices appear to be more cost-effective than urban offsets.[42] Shellfish aquaculture was the only option reviewed that has the potential to be without cost, which was under the assumption that in some circumstances oyster growers would be willing to expand operations without payment for nitrogen reduction services provided. The upper range of estimated costs for shellfish aquaculture ($150 per pound of N removed) was comparable to those upper estimates for agricultural BMPs ($23 to $2800 for three types of BMPs in four locations) and consistently less than upper estimates for urban BMPs ($366 to $2215 for five types of BMPs).[42]

■ SHELLFISH AQUACULTURE ALONE IS NOT GOING TO SOLVE OUR COASTAL NUTRIENT PROBLEM

The scale of the coastal eutrophication problem worldwide is such that, while shellfish aquaculture holds promise as an additional tool for coastal and estuarine nutrient management, it functions most effectively as a complement, not a replacement, for existing nitrogen source control efforts. Shellfish assimilate nitrogen that has already entered an estuary and contributed to phytoplankton growth. This is very different from land-based BMPs that intercept nitrogen before it enters the estuary. The amount of nitrogen removed in an aquaculture setting will depend upon farm productivity, which depends upon temperature, food availability, disease occurrence, unpredictable weather events such as large storms and hurricanes, and other factors, making annual productivity highly variable and difficult to predict. The issue of scaling is also important; individual farms may have environmental impacts locally, but large-scale implementation is necessary to be effective at the ecosystem scale. For shellfish aquaculture to become a significant component of any comprehensive nitrogen management program, there are some barriers to large-scale implementation that must be overcome. The remainder of this article discusses these challenges in more detail and offers suggestions or examples of current programs working to find solutions.

The primary constraint on the expansion of the shellfish aquaculture industry in the United States is not physical space or naturally occurring food availability, but rather the social acceptance of shellfish aquaculture itself. This was illustrated recently in a series of contributions by Byron and colleagues that focused on coastal waters off of Rhode Island.[61−63] These investigators calculated the ecological carrying capacity of coastal lagoons and Narragansett Bay using Ecopath models, resulting in estimates that 46% of the surface area of the coastal lagoons and 9% of Narragansett Bay could be devoted to shellfish aquaculture. These numbers were well above the cap established by the Rhode Island Coastal Resources Management Council restricting shellfish aquaculture leases to 5% of the surface area of the bay and of individual lagoons.[61] Use conflicts from wild harvesters of clams, recreational users, coastal homeowners, commercial fishing and tourism all were cited as pressures limiting shellfish aquaculture expansion. This tension among the many users of coastal and estuarine ecosystems is common around the United States, and has resulted in a variety of high-profile legal battles with the shellfish aquaculture industry, including California,[64] Massachusetts,[65] and elsewhere.

Marine spatial planning has the potential to reduce use conflicts in the coastal and estuarine environment. As part of the National Ocean Policy that was established by Executive Order 13547, nine regional bodies have been tasked with developing spatial plans for different sections of the United States coastline. The Northeast Regional Planning Body is including aquaculture specifically as one of the marine industries for inclusion in the plan and has reached out to the shellfish industry through public meetings.[66] The growing availability of online mapping tools also has benefited the aquaculture industry and regulators who can use GIS to visualize use conflicts more efficiently to find areas that are appropriate for industry expansion. Examples of these mapping tools include the Connecticut Aquaculture Mapping Atlas,[67] the New York Shellfish iMap,[68] the Maine Aquaculture Site GIS,[69] the Massachusetts Online Data Viewer,[70] and the Maryland Shellfish Aquaculture Siting Tool.[71] Combining mapping tools such as these with farm-scale models of productivity may provide a more comprehensive tool. Models such as Farm Aquaculture Resource Management (FARM)[57] and ShellSIM[72] can project the productivity of new or expanded shellfish farms based upon local water quality information and knowledge of local farming practices. Combining these two techniques by using maps to identify prospective areas without major use conflicts, then using a model to make projections about which of the prospective areas would be best suited to shellfish aquaculture production is being tested at the pilot scale in Long Island Sound.[73] This type of approach can encourage smart growth of the industry, while simultaneously minimizing conflicts with other user groups.

An informed siting and planning process will have the additional benefits of maximizing nitrogen reductions by new or expanded farms and ensuring that intensive aquaculture practices do not have unintended negative consequences. Models such as those described above can help to predict nitrogen dynamics at the farm setting, including assimilation, excretion and biodeposition. Physical factors influencing site selection can be taken into account; for example, current speed at a farm site must be strong enough to ensure sufficient delivery of planktonic food to the shellfish, as well as ensure that biodeposits are dispersed and do not accumulate in harmful quantities under gear that is suspended in the water above.[74] Adequate food must be available during the shellfish growing season to promote rapid growth and nutrient assimilation. Flushing times of a waterbody should be taken into account when planning the scale, intensity and/or types of aquaculture operations at a location. Another consideration is that bivalves assimilate only a portion (ca. 20−30%) of the seston biomass, and associated nutrients that are filtered.[75] In fact, suspension-feeding bivalves can be considered primarily to be nutrient recyclers.[76] Some have characterized nutrients recycled by bivalves as a cause of eutrophication,[77] and indeed these nutrients can be expected to stimulate primary production locally. We note, however, that recycling of nutrients to primary production during periods of active grazing by higher trophic levels (in warmer seasons) has the potential to contribute to wildlife and fishery productivity at the expense of the bacterial degradation of phytoplankton biomass that otherwise would cause benthic hypoxia. As benthic hypoxia is considered to be the most damaging consequence of eutrophication, processes that redirect primary production from destructive to productive pathways will benefit the ecosystem as a whole.

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Another major challenge to the implementation of shellfish aquaculture as part of a nitrogen management program is the frequent existence of additional water quality issues in the areas that are most in need of nutrient reductions. Areas where human activities contribute high loads of nutrients are likely also to have high abundances of pathogen indicator bacteria, such as fecal coliforms or *Enterococcus*. These areas are closed to shellfish harvest for human consumption to protect public health. The use of alternative species, without existing commercial markets, would alleviate this public health concern. It is, however, unlikely that payments for nitrogen reduction services provided would be substantial enough to encourage an industry based upon ecosystem services alone. Development of creative market solutions that do not involve human consumption, therefore, is a critical step in the implementation process. In Sweden, the use of mussel meat for chicken feed or compost is being explored.[22] In the United States, ribbed mussel meat has been proposed as a sustainable source of protein for finfish aquaculture.[78] Aquaculture-based nutrient remediation of human waste-derived sources of nitrogen might further challenge the social acceptance of farming and the marketability of its products. Certification and testing of products to ensure public trust in appropriate end uses would alleviate this concern.

It is worth emphasizing that when cost and efficiency (i.e., nitrogen removal per unit area) are taken into account, it is clear that shellfish compares more favorably to management practices for nonpoint sources of nitrogen than point sources such as wastewater treatment. This view is supported by previous work that has indicated shellfish aquaculture may have the largest impact, in terms of percentage of total nitrogen load offset, in surburban areas dominated by nonpoint source nitrogen, as opposed to heavily urbanized areas dominated by point sources.[55]

NEXT STEPS

We believe that shellfish aquaculture can be a cost-effective component of comprehensive strategies to address impairments in estuarine and coastal water quality caused by nitrogen enrichment. Doing so can help attain societal goals for water quality, local food production, and strengthened economies. The 2011 release of the U.S. Department of Commerce and NOAA Aquaculture Policies have underscored federal interest in promoting sustainable aquaculture in U.S. coastal waters. The NOAA National Shellfish Initiative, also released in 2011, is promoting an increase in bivalve shellfish in U.S. coastal waters through aquaculture and restoration activities. Increasing shellfish helps to restore the natural ability of a marine ecosystem to assimilate excess nutrients from all sources, including land, air, and even benthic sediments. Shellfish aquaculture compares favorably to existing best management practices for agriculture and stormwater nutrient controls, in terms of cost-effectiveness and quantity of nitrogen removed per unit area, which makes it a good candidate for inclusion in comprehensive strategies that address human-caused changes in both the assimilative capacity of aquatic systems and watershed loading. Additional research into species growth physiology and estuary-specific nitrogen removal potential will aid in development of local strategies to attain water quality standards. Large-scale implementation of shellfish aquaculture in the marine environment must overcome a variety of social constraints, and industry participation in ongoing marine spatial planning efforts is crucial. The use of noncommercial, suspension-feeding species for nitrogen reductions in waters closed to shellfish harvest for human consumption is promising, but markets for this product need development. Recycling "lost" nitrogen—a valuable resource, not a toxic pollutant—and the microalgal biomass containing it—also a valuable resource currently going to waste—using suspension-feeding shellfish to formulate fish aquaculture feeds also addresses the "feeding fish to fish" problem that is constraining sustainable fish aquaculture. Recognizing all dimensions of the benefits and providing economic incentives to shellfish farmers through payment for the nitrogen reduction services could help spur industry expansion. Inclusion in existing and planned nutrient trading programs would be a logical mechanism for funding these payments. Through a multipronged approach to implementation, shellfish aquaculture could become an important part of comprehensive, ecosystem-based nutrient management in estuaries worldwide.

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The authors declare no competing financial interest.

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