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Quantification and Valuation of Nitrogen Removal Services Provided by Commercial Shellfish Aquaculture at the Subwatershed Scale

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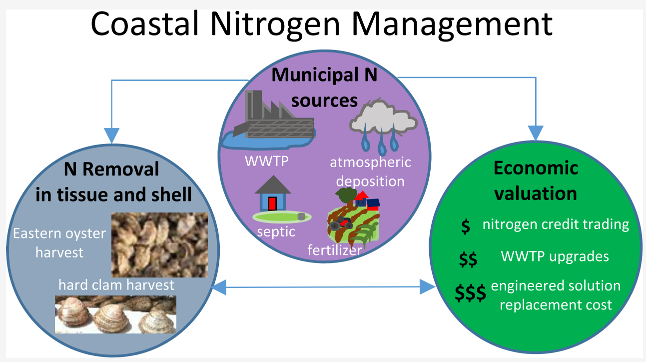
ABSTRACT: Eutrophication is a global environmental challenge, and diverse watershed nitrogen sources require multifaceted management approaches. Shellfish aquaculture removes nitrogen, but the extent and value of this ecosystem service have not been well-characterized at the local scale. A novel approach was employed to quantify and value nitrogen reduction services provided by the shellfish aquaculture industry to a municipality. Cultivated hard clam and eastern oyster nitrogen removal in Greenwich Bay, Connecticut, was valued using the replacement cost methodology and allocated by municipal nitrogen source. Using the preferred analysis allocating replacement costs by nitrogen source, aquaculture-based removal of 14 006 kg nitrogen was valued at \$2.3−5.8 (2.3−6.4€) million year^{-1}. This nitrogen removal represents 9% of the total annual Greenwich-specific nitrogen load, 16% of the combined nonpoint sources, 38% of the fertilizer sources, 51% of the septic sources, 98% of the atmospheric deposition to the watershed, or 184% of the atmospheric deposition to the embayments that discharge to Greenwich Bay. Our approach is transferable to other coastal watersheds pursuing nitrogen reduction goals, both with and without established shellfish aquaculture. It provides context for decisions related to watershed nitrogen management expenditures and suggests a strategy to comprehensively evaluate mechanisms to achieve nitrogen reduction targets.



■ INTRODUCTION

Excess nutrients in the coastal environment, or eutrophication, is a serious problem confronting resource managers worldwide.[1−3] Overabundance of nutrients has been linked to a variety of environmental problems, including overgrowth of micro- and macroalgae, hypoxia, and loss of important seagrass habitat.[4] Recognition of the ecological, economic, and social losses resulting from poor water quality has led to national and multinational efforts to combat eutrophication in coastal waters, e.g., the U.S. Clean Water Act (33 U.S.C. §§1251−1387) and the EU Water Framework Directive.[5]

The primary target of most coastal nutrient reduction programs has been nitrogen, which frequently limits primary production[6,7] (but also see ref 8). Nitrogen management programs to date largely have focused on restricting land-based sources.[9−11] Point sources of nitrogen, which have a well-defined waste stream, are well-characterized in many locations and have been a priority for nitrogen reduction. These include wastewater treatment plants (WWTPs) and large animal feeding operations. In contrast, nonpoint sources of nutrients, such as stormwater, car emissions, and fertilizer, are much more challenging to quantify and require multifaceted management approaches.[12]

There has been growing interest in the potential contributions of shellfish aquaculture to nitrogen management in the United States and Europe.[13−15] Two programs in the United States have incorporated shellfish aquaculture formally within overall nitrogen reduction planning at scales both local[16] and regional.[17] Shellfish naturally remove plankton and detritus from the water through suspension-feeding activities and incorporate nutrients from ingested food into tissues, shell proteins, and other organic constituents during growth. When shellfish are harvested, nitrogen contained within the tissue and shell is removed from the local environment. There is some evidence that additional nitrogen reduction may be realized through enhancement of

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sediment denitrification by shellfish aquaculture activities,[18] but to date, this pathway has not been incorporated into nitrogen management programs.

The nitrogen reduction services provided by shellfish aquaculture can be considered within a broader ecosystem service framework. Ecosystem services have been defined as the benefits that people receive from ecosystems.[19] These benefits may be quantified according to indicators of physical flows, such as tons of carbon sequestered or tons of fish provided, or using estimation of monetary flows with the assignment of dollar values.[20] Efforts are underway to develop accounting systems that rigorously catalog ecosystem services and associated ecosystem assets to better support the incorporation of ecosystem services into governmental planning decisions.[21] A key function performed by ecosystems is nitrogen cycling.[22] We use the term "function" here though some ecosystem service categorization approaches would refer to nitrogen cycling as an ecosystem "service". When the balance of that cycle is disrupted through excess nitrogen inputs, a range of ecosystem services that directly benefit the public, such as clear water for boating, swimming, and water views and fish and shellfish for consumption, may be disrupted.[23] Multiple field and laboratory studies have investigated various aspects of the nitrogen cycle in coastal and marine ecosystems, including the uptake of nitrogen by bivalves and seaweeds.[24−29] A more limited number of studies has sought to assign a monetary value to the physical flows of nitrogen within the system (see Table S1).[30−35]

Research conducted in New York and North Carolina evaluated the benefit of nitrogen reductions from seaweed and oyster growth, respectively, using a nutrient credit-based valuation.[32−34] This valuation approach multiplies expected nitrogen removal or sequestration by the value of a nitrogen nutrient credit within existing, relevant trading programs. By comparing the removal rates of nitrogen by an oyster reef versus soft bottom habitat and then multiplying by the trading price per kilogram in North Carolina in 2011 ($28.23; 31.33€), Grabowski et al.[32] estimated the benefits of nitrogen removal by an oyster reef to be in the range of $1385−6716 (1537−7454€) hectare^{-1} year^{-1}. Two studies (Kim et al.,[33,34]) used experimental data to estimate nitrogen removal by kelp farm systems, then multiplied this by the value of a nutrient credit in Connecticut (CT) to arrive at annual values of between $147 and 1226 (163−1360€) hectare^{-1}, depending on the species and location of the farm.

Additional research in Long Island Sound, the Mission-Aransas Estuary in Texas, and the Chesapeake Bay in Maryland estimated the replacement cost for services associated with nitrogen sequestration by oysters. Replacement cost is an economic valuation approach for ecosystem services that uses the costs of the required substitute capital investments (e.g., wastewater treatment plant (WWTP) upgrades) that provide equivalent services to the ecosystem. In the Mission-Aransas Estuary, Beseres Pollack et al.[30] used field-based estimates of nitrogen removal rates by the existing oyster population to determine the necessary specifications (and cost) for equivalent implementation of biological nitrogen removal at a WWTP. This analysis resulted in an estimated value for the nitrogen removal services of oysters in the Estuary of $113 471 (125 953€) year^{-1}. Bricker et al.[31] evaluated oyster aquaculture in Long Island Sound as a nitrogen removal service by applying costs that would be associated with WWTP and agricultural or urban best management practices (BMPs). That study arrived at a value of between $8.5 and 230 (9.4−255€) million year^{-1}, depending upon the replacement technology and acreage covered. Using the average cost of alternative abatement technologies in the Chesapeake Bay at the time, Newell et al.[35] estimated the value of nitrogen removal by oysters in the upper Choptank to be approximately $315 000 (349 650€) year^{-1}.

Researchers have also explored the economics of shellfish as a nutrient reduction strategy using optimization models that project the best mix of nutrient management approaches for meeting a specified target and the cost savings generated by including shellfish farming as part of that mix. For example, Gren et al.[36] provided an optimized cost-effectiveness model that includes mussel farming as an abatement measure for meeting Baltic Sea nutrient targets, finding cost reductions of up to approximately 0.37 billion euros with the inclusion of mussel farming. A recent advancement of the approach included uncertainty in the optimization model, leading to cost savings as high as 1.2 billion euros, depending on model assumptions.[37] While optimizing by cost effectiveness is one approach to valuing the economic gains from the presence of clams and oysters, our objective is instead to present the likely range of costs for replacing the nitrogen sequestration currently provided by clams and oysters given available highly localized data on nitrogen sources and shellfish farming practices in Greenwich Bay. Recognizing that this may not be a least-cost solution, we believe such an approach more accurately reflects real-world considerations in Greenwich Bay.

This paper describes a novel and transferable approach to quantifying and valuing the nitrogen reduction services provided by the shellfish aquaculture industry at a local scale. The novelty of the approach is its use of local-scale data on nitrogen sources as a means of allocating replacement abatement technologies (and their associated costs) based on locally calibrated values for nitrogen sequestration by clams and oysters in Greenwich Bay, CT. Recent literature reviews have highlighted the stability of percent nitrogen content within tissues and shells of bivalve shellfish across time and space, but also identified tissue dry weight per individual as much more variable,[17] highlighting the need for local shellfish dry weight data. We demonstrate the application to a well-established industry, as well as the use of an aquaculture model to predict industry potential where limited or no industry currently exists. Leveraging the local-scale data on nitrogen sources within our target watershed from nitrogen load modeling performed by Vaudrey et al.,[38] our valuation methodology better assigns potential replacement costs for lost clam and oyster nitrogen sequestration and removal services by constraining the analysis to the real-world options available to watershed resource managers. These improvements to the replacement cost methodology should provide a more detailed understanding of the potential tradeoffs associated with gains or losses of shellfish populations for consideration by natural resource managers and the public.

■ MATERIALS AND METHODS

Study Location. Greenwich Bay is located on the north-western shore of Long Island Sound on the Northeastern coast of the United States (Figure S1). The Town of Greenwich has devoted 6945 total seafloor acres (28 km^2) to three categories of shellfish use, including commercial shellfish aquaculture of hard clams (*Mercenaria mercenaria*; 4173 acres (16.9 km^2)) and eastern oysters (*Crassostrea virginica*; 6.3 acres (0.03 km^2)), recreational shellfishing (primarily hard clams; 920 acres (3.7 km^2)), and seed oystering (1835 acres (7.4 km^2)) on areas designated by the State of Connecticut as "natural beds" (K.

DeRosia-Banick, State of Connecticut Department of Agriculture, Bureau of Aquaculture (CT DA/BA), personal communication). Commercial shellfish aquaculture leases are managed jointly by the CT DA/BA and the Greenwich Shellfish Commission, although leases are officially classified as "town" or "state" based upon distance from shore. For the purposes of this study, we considered all leases classified by CT DA/BA as "Greenwich," which included both town and state waters up to the Greenwich/Stamford town line, designating this area "Greenwich Bay."

Municipal Land Use and Nitrogen Loads. Greenwich is suburban, with a 2010 total population of 61 171 and population density of 1215 people km^{-2}.[39] Modeled nitrogen loads to the embayments that flow into Greenwich Bay were obtained from Vaudrey et al.,[38] whose methods are summarized in (Supporting Information, SI1). Loads were obtained for five categories of nitrogen sources: (1) atmospheric deposition to the embayment; (2) atmospheric deposition to the watershed; (3) fertilizer; (4) sewer; and (5) septic. Fertilizer sources in the Greenwich subwatersheds were exclusively suburban lawns and golf courses, with crop agriculture contributions functionally zero. These authors modeled six subwatersheds that discharge directly into Greenwich Bay (Figure S1; Captain Harbor, Greenwich Harbor, Smith Cove, Indian Harbor, Mianus River, and Greenwich Cove) and a seventh subwatershed whose discharge at times likely influences Greenwich Bay (Byram River; see Supporting Information, SI1 and Table S2 for more details). Nitrogen loads from the local Grass Island WWTP (47 million liters treated effluent day^{-1}) were obtained for 2015 from the CT Department of Energy and Environmental Protection (CTDEEP; K. Streich, personal communication). Maps of effluent pipes suggest that the discharge is directly to Greenwich Bay (J. Vaudrey, personal communication), and it was included here as a separate load located outside of the seven subwatersheds.

Calculation of Nitrogen Removal by the Greenwich Shellfish Aquaculture Industry. The ecological component of this study estimated nitrogen removed from Greenwich Bay by sequestration in the tissue and shell of clams and oysters and subsequent removal from Greenwich Bay by shellfish harvest. The same general approach was applied to both species, combining the number of animals harvested with the expected nitrogen content of those harvested animals, to yield nitrogen removal achieved by harvest. Two versions of this approach are presented in Figure 1, one that was applied to a large and established industry in Greenwich Bay (hard clam, *M. mercenaria*), and a second that was applied to a new and relatively small industry (eastern oyster, *C. virginica*). Methodological details of each step in Figure 1 are provided in Supporting Information, SI2.

Economic Analysis. Two approaches were used to value oyster and clam nitrogen removal services within Greenwich: (1) valuation based upon the cost of nutrient credits traded in Connecticut and (2) estimation of the cost of replacing clam and oyster nitrogen sequestration services with engineered approaches.

Nutrient Credit Valuation. Connecticut has had a nutrient trading program in place for WWTPs since 2002 (CT Public Act §§01−180). Credits are generated through infrastructure improvement investments. Nitrogen reductions are evaluated in conjunction with the cost to achieve the reduction to arrive at a dollar-per-pound value for nitrogen credits. The nutrient credit valuation approach used the following formula to calculate the

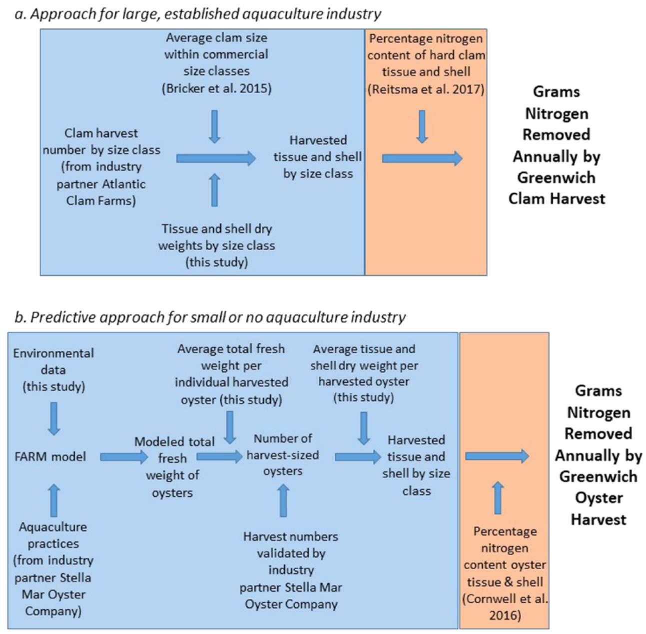

Figure 1. Approach for estimating nitrogen removal from cultivated shellfish in Greenwich Bay, Connecticut, based on the size of the local aquaculture industry. The blue box indicates steps to calculate animals harvested, the orange box indicates steps to calculate nitrogen removed by that harvest. (a) *M. mercenaria* harvest information, combined with direct measurements of local clams, and literature values for percent nitrogen content of the tissue and shell; (b) FARM model calibration and validation for *C. virginica*, combined with direct measurements of local oysters, and literature values for percent nitrogen content of the tissue and shell.

value of nitrogen assimilation and removal services $V = N \times T$, where N is the number of annual pounds of nitrogen removed by clams or oysters through bottom cultivation and T is the trading system credit value estimated annually by CTDEEP. For 2016, the value of a one-pound nitrogen credit was \$6.70 (7.44€).

Replacement Cost Estimation. The second approach calculated the value of nitrogen removal services using the estimated cost of replacing the clam and oyster nitrogen removal with a human-engineered approach (e.g., stormwater best management practices (BMPs), septic system upgrades). Similar approaches for cost estimation have been used previously.[30,40] In essence, this assumes that the town or state could invest in engineered treatment that would provide equivalent effectiveness to the annual nitrogen sequestration services provided by clams and oysters.

The basic formula is $C = N \times E_r$, where C is the estimated total replacement cost, N is the number of annual pounds of nitrogen removed by clams and oysters, and E is the cost per pound of nitrogen removal by engineered removal process r. The value for C was calculated in two ways: (1) under the assumption that wastewater treatment is the sole engineered removal approach used (therefore only one value of E_r) and (2) with nitrogen removal allocated across sources and, subsequently, engineered approaches.

The cost of wastewater treatment per pound of nitrogen assumed capital upgrades for nutrient removal equivalent to the services provided by clams and oysters. Importantly, these costs do not include costs for connecting new households that currently are on septic systems or cesspools. To estimate the cost per pound nitrogen removal for wastewater upgrades, the average cost of nutrient removal upgrade per million gallons per

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Table 1. Clam and Oyster Annual Nitrogen Removal by Commercial Size Class in Greenwich Bay, Connecticut[a]

species	limited industry: modeled oyster harvest based on FARM	established industry: reported harvest from industry partners	nitrogen removed annually by harvest (kg)	annual nitrogen removed per-acre (kg)
clams (littleneck: 61.7 mm, 42.6 g)	N/A	4.79×10^6	2368	0.567
clams (topneck: 74.3 mm, 76.0 g)	N/A	4.26×10^6	3837	0.920
clams (cherrystone: 85.9 mm, 119 g)	N/A	2.80×10^6	4025	0.964
clams (chowder: 100.8 mm, 197 g)	N/A	1.46×10^6	3536	0.847
oysters (mean 82.1 mm, 56.5 g)	8.96×10^5	8.56×10^5	240	38.1

[a]Morphometrics listed represent mean shell length and tissue + shell dry weight for clams and mean shell height and tissue + shell dry weight for oysters. Clam harvest was provided by Atlantic Clam Farms, oyster harvest model outputs were validated by Stella Mar Oyster Company (SMOC).

day (mgd) capacity (\$ mgd^{-1}) was first calculated using EPA data for upgrade costs at WWTPs in Connecticut (EPA 2006). Existing daily nitrogen removal at the Grass Island Treatment plant was estimated using its design capacity of 12.5 mgd in combination with its approximate removal efficiency of 75% (K. Streich, CTDEEP, personal communication). These values were compared with the nitrogen removal capabilities of current clam and oyster cultivation practices to estimate the total capital costs of equivalent engineered wastewater investments. Capital costs were annualized using straight-line depreciation, assuming a 15-year time period. Operating and maintenance (O&M) costs were assumed to be 5% of annualized capital costs, which is between conservative estimates for O&M used in previous work[30] and reports provided to municipal authorities in New England considering wastewater treatment.[41,42]

Averaged low- and high-cost estimates for stormwater BMPs, which could address atmospheric deposition to the watershed and fertilizer usage, were based upon previous cost estimate ranges for three types of BMPs—stormwater wet ponds, bioretention areas, and stormwater wetlands—reported in Stephenson et al.[40] These costs assumed a 20-year time period for each of the engineered solutions. Fertilizer sources within the Greenwich Bay watershed were exclusively suburban lawns and golf courses, so the application of cost estimates associated with agricultural BMPs to address fertilizer reductions was not possible.

Septic upgrade costs were estimated based upon a report from investigations into improved septic technologies in West Falmouth, MA.[43] The average, annual cost per pound of nitrogen removal (\$ lb^{-1}) was calculated based upon three test cases described (blackwater systems, eliminite systems, and hoot systems). Straight-line depreciation assuming a 30-year life span for the system was used to estimate annualized installation costs.

As cost data came from different time periods, all dollar values were inflated to 2016 using consumer price index data.[44] All USD to Euro conversions were calculated based on a 2016 conversion of 1.11€ = \$1.

RESULTS AND DISCUSSION

Calculation of Nitrogen Removal by the Greenwich Shellfish Aquaculture Industry. Shellfish aquaculture has been practiced in the United States for over a century, but in many locations, it remains a new and growing industry. We have demonstrated two versions of our approach for calculating nitrogen removal to broaden its potential for application beyond the relatively few municipalities that have a large and well-established industry. The first version, based on a well-established industry, enables calculation of nitrogen removal from annual harvest reports. The second version, for municipalities with limited or no shellfish aquaculture, enables predictions of harvest-based nitrogen removal for a new or growing industry. Quantile regression analysis yielded equations for the 50th quantile of tissue dry weight as a function of shell length ($y = 0.0000037 \times x^{3.27}$) and shell dry weight as a function of shell length ($y = 0.00011 \times x^{3.10}$) for Greenwich clams (Figure S4). Annual municipal-scale clam aquaculture nitrogen removal of 13 766 kg was converted to per-acre basis using information from CT DA/BA on leased acreage, which yielded an estimated 3.3 kg acre^{-1} (Table 1).

Monitored environmental data generated in this study were combined with cultivation practices from industry partner Stella Mar Oyster Company (SMOC) to run the FARM model. Environmental data are provided as Supporting Information (Figure S5). Modeled total production was 69 metric tons fresh weight, which was converted to 896 000 individuals based upon measurements of SMOC oysters (77 g fresh weight per oyster), a count very similar to the reported harvest of 856 000 oysters (Table 1). Per-acre annual nitrogen removal for oyster aquaculture was 38.1 kg, and total annual nitrogen removed by SMOC was 240 kg.

Per-acre nitrogen removal rates for oyster aquaculture (38.1 kg year^{-1}) were an order of magnitude higher than those observed for hard clam aquaculture (3.3 kg year^{-1}). This difference can be attributed primarily to differences in cultivation styles between the two industries. Hard clam aquaculture in Greenwich Bay, and Long Island Sound in general, is extensive in nature, relying on natural set within a large leased acreage, without external population enhancement through seeding activity, and without protection from predation through the use of clam nets or mesh bags.[45] Oyster aquaculture in Greenwich Bay is more intensive, and leased acres are stocked with spat on shell seed oysters in spring. Additionally, oyster growers reduce mortality losses by seeding with larger oysters from an upweller nursery system (SMOC, personal communication).

FARM model results for oysters' close alignment with actual harvest numbers reinforces the benefits and gives confidence in the use of this model to project potential harvest from a given farm area. Model outputs for the eight locations around Greenwich Bay were very similar and likely reflect thorough water mixing Bay-wide. We note that embayments with variable water conditions (e.g., salinity gradients, uneven distribution of chlorophyll, and/or organic matter) should exercise caution in applying model outputs beyond a single location. By sampling growing conditions at eight stations across Greenwich Bay, and

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Table 2. Proposed Linkages among Nitrogen Sources, Matched Engineered Approach, Cost Estimates for Engineered Approaches, and Allocation of Replacement Sequestration Services to these Engineered Approaches Based on Relative Proportion of Greenwich Bay Nitrogen Load

nitrogen source	engineered solution	nitrogen removal costs in 2016 USD per pound (euro)	proportion nitrogen removal (%)[a]	annual nitrogen removal replaced (lbs)—clams and oyster
sewer	WWTP capital upgrade	\$3.27 (3.63€)	47	14 339
septic	septic system upgrade	\$55.94 (62.09€)	17	5236
atmospheric deposition to watershed	bioretention areas, wet ponds, or constructed wetlands	\$202−557 (224−618€)	9	2702
fertilizer	bioretention areas, wet ponds, or constructed wetlands	\$202−557 (224−618€)	23	7089

[a]Proportion nitrogen removal does not sum to 100% as no engineered solution is proposed for an additional nitrogen source to the watershed—direct deposition to the embayment.

successfully applying the FARM model (calibrated to Long Island Sound[31]) to the cultivation practices employed by SMOC, we are confident that the per-acre oyster nitrogen removal that we report reflects average conditions in the Bay (Figure S5). Additionally, this was a unique opportunity to validate the FARM model with actual harvest numbers received directly from SMOC, which in other FARM model studies in the Northeastern United States[31,46] have not been available. Although the focus of this study was on actual bottom cultivation practices used in Greenwich, consideration of the sensitivity of the results to alternate cultivation approaches (e.g., cages for oysters) was warranted, as gear-based practices are common in other parts of the Northeast. We conducted a sensitivity analysis that suggested areal nitrogen removal rates were similar for the two cultivation practices; details are provided in Supporting Information, SI3. The success of the FARM model in estimating harvest under both cultivation practices gives us a high level of confidence that the model accurately represents harvest in this bay under these cultivation practices and can be confidently used to estimate oyster production in other waterbodies.

Nitrogen Removal Relative to Loads. The total annual nitrogen load from Greenwich sources, based upon the Vaudrey et al.[38] model output, was 162 237 kg (Supporting Information, SI1). Annual nitrogen removal by Greenwich clam and oyster aquaculture was 14 006 kg, which represents 9% of the total annual Greenwich-specific combined nitrogen load. Modeled nitrogen loads included five categories of nitrogen sources, including atmospheric deposition directly to an embayment, atmospheric deposition to the watershed, fertilizer, sewer, and septic. Nitrogen from two of those categories, atmospheric deposition to the watershed and fertilizer, is delivered to the embayments, and on to Greenwich Bay, via stormwater runoff. Nonpoint sources of nitrogen (i.e., nonsewer) were greater than point sources of nitrogen to Greenwich Bay, contributing 86 741 kg (53%) of the total load. Annual nitrogen removal by Greenwich clam and oyster aquaculture represented 16% of the combined annual nonpoint sources. Within the nonpoint source categories, fertilizer was the single largest contributor, with 37 327 kg (43%) of the nonpoint source load. Septic was the second largest contributor, with 27 571 kg (32%) of the nonpoint source load. Atmospheric deposition to the watershed contributed 14 228 kg (16%). Atmospheric deposition to the Greenwich embayments was 7615 kg (9%), although it is worth noting that this does not represent the total atmospheric deposition directly to Greenwich Bay. Vaudrey's study was focused on the embayments, which feed into Greenwich Bay (Figure S2), and did not measure the direct deposition to our entire study area. When compared sequentially to the load from each individual nitrogen source, annual nitrogen removal by Greenwich clam and oyster aquaculture represented 38% of the annual fertilizer sources, 51% of the septic sources, 98% of the atmospheric deposition to the watershed, or 184% of the atmospheric deposition to the embayments that discharge to Greenwich Bay (i.e., removal potential was greater than total atmospheric inputs).

Economic Analysis. Table 2 provides the proposed linkage between nitrogen sources and the matched engineered approach, along with associated cost estimates. Each engineered solution is matched to the nitrogen source that it is most likely to intercept. For example, septic system upgrade costs are most likely to reduce nitrogen derived from septic sources, whereas stormwater best management practices (BMPs) would be needed to address nitrogen derived from fertilizer or deposition to the watershed. The allocative approach required distribution of the current estimated N removal by clams and oysters (30 813 lbs year^{-1}) to each of these various engineered removal solutions, which was accomplished using the percentage allocation of nitrogen sources from Vaudrey et al.[38] within Greenwich. For example, as fertilizer and atmospheric deposition to the watershed contribute 32% of the total loadings, it is assumed that 32% of the oyster and clam sequestration services would be replaced with stormwater BMPs.

Table 3 summarizes the results from the economic analysis. The lowest value (\$100 871; 111 967€) obtained assumes that wastewater treatment upgrades alone could replace the nitrogen sequestration services provided by clams and oysters; the next lowest value (\$206 448; 229 157€) uses existing nitrogen credit costs as a proxy for the value of services, and the valuation assuming an allocated mix of engineered replacements to the sequestration services results in the highest value. The value under the allocated approach is driven by the high costs of BMPs needed to address nonpoint sources from fertilizer and direct

Table 3. Estimated Nitrogen Sequestration Annual Values by Alternative Valuation Approaches

valuation approach	estimate (2016 dollars) (euro)
nitrogen credit valuation	\$206 448 (229 157€)
WWTP upgrades alone	\$100 871 (111 967€)
allocated replacement solutions	
WWTP upgrades	\$46 940 (52 103€)
septic upgrades	\$292 949 (325 173€)
BMPs	\$1 975 941−5 455 561 (2 193 295−6 055 673€)
total of allocated solutions	\$2 315 829−5 795 449 (2 570 570−6 432 948€)

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deposition to the watershed. The BMP-engineered approaches have both the highest costs, and nonpoint sources represent the highest proportion of nitrogen sources within the Greenwich watershed. Table 3 compares the replacement costs for the allocated approach based upon modeled clam and oyster farming scenarios.

The results of this study highlight the substantial contribution of nitrogen sequestration services from oyster and clam aquaculture in Greenwich Bay, Connecticut. Although WWTP upgrades and nitrogen credit valuation approaches indicate an annual value of \$100 871 (111 967€) or \$206 448 (229 157€), respectively, the allocated solution approach suggests a substantially higher value of between \$2 315 829 and \$5 795 449 (2 570 570−6 432 948€; Table 3). These higher values, in our opinion, are likely more representative of the actual benefits as it is unlikely that WWTP upgrades alone (which already assume cost-free connection of properties currently using septic) would be able to address the substantial nonpoint sources of pollution within this watershed. And given that Long Island Sound continues to experience seasonal hypoxia after a 20+ year successful campaign to upgrade wastewater treatment plants, it is highly likely that further nutrient reductions will be mandated for coastal states and municipalities that may require addressing those nonpoint sources.[47] Furthermore, the credit values are essentially based upon the pricing of wastewater treatment upgrades; the determined credit price is based upon documented costs by WWTPs to perform upgrades.

Compared with annual, per-hectare oyster harvest nitrogen removal benefits from Beseres Pollack et al.[30] of approximately \$60 hectare^{-1} and previously published estimates of kelp farming nitrogen removal benefits of \$311−1600 (345−1776€) hectare^{-1} year^{-1},[33,34] the allocated approach indicates a higher range for the nitrogen removal benefits from clams and oysters (\$2419−6054 (2685−6720€) hectare^{-1} year^{-1}). Clearly, there are differences in species considered and economic approaches used across these studies. For example, costs associated with BMPs that were included in our estimates were not incorporated into either of the other noted studies. The high-cost estimates from Stephenson et al.[40] for wet ponds (\$383−653 (425−725€) lb N^{-1}) as a replacement, engineered approach also drive the results obtained here; the lower the proportion of wet ponds actually used in the watershed as a mitigation strategy, the lower the replacement costs for the clam and oyster services would be. Differences across biological populations considered in these studies (oysters alone versus oysters and clams versus kelp) will also change the estimated replacement value for the services; more productive species or populations (whether driven by species physiological characteristics or combinations of characteristics with ambient environmental conditions) will have a higher replacement cost.

Shellfish Aquaculture and Nitrogen Management. Nitrogen management is highly variable across watersheds because of inherent differences in source contributions to total nitrogen load from different land use profiles. Accordingly, there is no standardized approach to nitrogen management that can be applied universally across rural, urban, or suburban watersheds. Watersheds dominated by large point sources, such as sewage in urban areas or large animal feeding operations in rural areas, have well-defined effluent streams that can be targeted for nitrogen reduction through the National Pollution Discharge Elimination System.[48] This type of watershed is generally the exception, and resource managers will more commonly face a variety of point and nonpoint sources of nitrogen contributing to the total load. A portfolio approach can be effective in this situation, matching sources of nitrogen with relatively large contributions to the total load with technologies and/or policies to manage these sources (e.g., the Watershed Implementation Plan approach used by the Chesapeake Bay Program[49]). In practice, the wide range of price differences across technologies, willingness of communities to enact available nitrogen reduction policies (e.g., point-of-sale restrictions on fertilizer purchases), and availability of space to implement source reduction projects affect nitrogen management planning as much as the relative contribution of different nitrogen sources to total loads.

Greenwich is an excellent example of a suburban watershed with a variety of nitrogen sources and challenges to implementing a portfolio approach to nitrogen management. Less than half of the total nitrogen load comes from point sources, of which nearly 100% is from local WWTP effluent. \$7.1 (7.9€) million was invested in 2014 in WWTP upgrades.[50] Some additional nitrogen reductions could be achieved through the implementation of biological nutrient removal technologies, but these gains would not be enough to balance inputs from nonpoint sources. Municipal nonpoint sources were dominated by stormwater, including both fertilizer and atmospheric deposition to the watershed, which together contributed 59% of the nonpoint source load (Figure S3). Siting for potential large-scale stormwater management projects, such as constructed wetlands or bioretention areas, would likely be challenging, with population density and impervious cover increasing in the lower parts of the watershed, virtually all of the waterfront property (riverine and coastal) privately owned, and extremely high-property values limiting opportunities for the town to purchase land to construct stormwater BMPs. Programs to connect septic systems to the municipal sewer system and/or upgrade septic systems with nitrogen reduction technology would be a logical approach. But again, the potential of these options to sequester the bulk of the nitrogen reaching Greenwich Bay is limited by the 32% total contribution of septic sources to the overall nonpoint source load (Figure S3).

Our results indicate that shellfish aquaculture makes an important annual contribution to nitrogen management in Greenwich, and we argue that these results are more broadly relevant to suburban coastal watersheds throughout the country. Municipalities increasingly face difficult and expensive paths to implement nitrogen reductions necessary to achieve water quality goals. One recent local economic assessment of the capital costs associated with a traditional sewering approach to nitrogen reduction in a small municipality in Massachusetts calculated that the projects necessary to meet nutrient reduction goals would be \$250 000 000 (278 000 000€) for a town with a year-round population of 14 842.[16] Municipalities with diverse and diffuse nitrogen sources could benefit from the inclusion of shellfish aquaculture as one part of a broader nutrient management plan.

The approach taken here is novel in its consideration of not just total nitrogen loads but the division of these loads into point versus nonpoint categories and the further division of nonpoint loads into five source categories. This allowed the assessment of nitrogen removal services provided by shellfish aquaculture within a more realistic management context at the municipal scale. It is clear that shellfish aquaculture alone is not going to enable a municipality to meet all nitrogen reduction goals. Moreover, no single management strategy will achieve this end, because most municipalities face a diverse range of sources that

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cannot be simply "turned off" (e.g., Figure S3). The categorization of nitrogen inputs from various sources raises important considerations for planning investments in nutrient removal for a watershed. Point sources represent a relatively small contribution of nitrogen loading to the watershed and also are the least expensive to mitigate from a treatment perspective. Further point source upgrades are not likely to have much of an effect on the nitrogen loading into this system. The expense of alternative terrestrial best management practices for nonpoint sources highlights the need to consider alternative approaches for more cost-effective options. Some nitrogen sources are more technologically difficult to address, such as atmospheric deposition to an embayment, which comprised approximately 50% of the total loads to two of the Greenwich Bay subwatersheds. Shellfish, and other in-water best management practices, offer additional value by addressing all sources of nitrogen to a waterbody, including those least tractable to intercept with other technologies.

Greenwich is typical of many suburban coastal watersheds in terms of nitrogen loads and sources, but it is remarkable in the large amount of seafloor acreage devoted to shellfish uses (Figure S1). Using the simple GIS tools available on the CT Aquaculture Mapping Atlas website,[51] we were able to estimate that shellfish uses (including commercial shellfish aquaculture, natural beds for seed oystering, and seasonal recreational harvest) comprise at least 50% of the total seafloor acreage of the town. In some U.S. coastal communities (and even within other parts of Connecticut), shellfish aquaculture leasing has become a controversial topic, with the siting of new or expanding operations getting pushback at the local level; e.g., Connecticut,[52] Maryland,[53] Mississippi,[54] Washington State.[55] Greenwich, and in particular its Town Shellfish Commission,[56] serves as an important example of how a robust shellfish aquaculture industry can thrive in a town with many other nearshore user groups and a highly developed suburban waterfront.

Study Considerations. It should be noted that the current study focused on an area with existing harvest and estimated the benefits of that harvest for nitrogen removal; it did not estimate the costs associated with either establishing a clam and oyster population or subsequently harvesting that population. In this way, these dollar value estimates should be viewed as gross benefits of the oyster and clam nitrogen removal rather than net benefits, which would account for the costs associated with the farming and harvesting process. At the same time, the economic analysis also did not include the value associated with the sale of the harvested product, which would offset these costs, assuming a profitable harvesting firm. From society's perspective, since it is only paying for the harvested product and not for the nitrogen sequestration and removal benefits, these benefits are "free" (a positive externality of the growing and harvesting activity).

Our study is limited in its focus on the harvest of clams and oysters and the sequestration of nitrogen in their tissues and shells; denitrification and deposition benefits are not included, and neither are the benefits from nonharvested clam and oyster populations. We determined that adequate data do not yet exist to assess whether burial in sediments was a major loss process for nitrogen in shellfish aquaculture and natural shellfish beds in Greenwich. This pathway was thus not included in removal estimates but does represent a possible additional avenue of nitrogen reduction. Denitrification losses associated with restored oyster reefs and oyster aquaculture operations have been measured and shown to represent appreciable losses in some places.[18,30,57] A recent literature review by an expert panel in the Chesapeake Bay region resulted in denitrification enhancement associated with restored oyster reefs being recommended to the Chesapeake Bay Program as a nutrient best management practice, with removal ranging from 26 to 73 kg acre^{-1} year^{-1}.[58] However, this expert panel review concluded that there is inadequate data to understand the environmental drivers of observed high variability in denitrification enhancement associated with oyster aquaculture practices.[59] For this reason, denitrification losses also were not considered here but may represent additional nitrogen reduction services being provided by the commercial shellfish aquaculture industry.

Our replacement cost methodology has several important limitations. First, while replacement cost approaches ideally assume implementation of the least-cost approach (or combination of approaches) to replace the lost service, our intent in creating a replacement scenario based on the localized sources of nitrogen does not ensure the lowest cost mix of alternatives. Instead, we base our analysis on data on sources of nitrogen and ways that decision-makers may respond with appropriate abatement technologies. In effect, our model is forcing certain technologies to be used up to the percentage that matches the loading of nitrogen from an associated source. By including the range of costs from the literature, we intend to highlight the broad range of values that are possible given the uncertainty in cost estimates. Second, as with all replacement cost approaches, we assume that the affected municipality would take action to replace the lost nitrogen removal services should the clam and oyster harvest disappear. The actual decision to replace those services will be the result of a complex mix of social, economic, and political decisions. Finally, limited information is available on the septic upgrade and stormwater BMPs; more information in this regard could narrow the wide range of replacement costs associated with the terrestrial BMP approaches for mitigating nonpoint source pollution.

The focus here on nitrogen removal also does not account for other ecosystem services provided by clam and oyster assemblages (e.g., food production, habitat, shoreline protection) and the support of that habitat for the provision of additional ecosystem services and associated benefits (e.g., fish for recreation and food). For example, Grabowski et al.[32] found that nitrogen removal was, on average, only approximately 40% of the total nonharvest ecosystem service value generated by oyster reefs. Shellfish aquaculture also provides a sustainable source of local seafood, which is increasingly valued by consumers.[60]

Future Directions. Future work related to the incorporation of shellfish aquaculture into nutrient management should continue to investigate the tradeoffs between alternative nutrient management approaches as data continue to be compiled from the various geographies facing this issue and experimenting with solutions. A significant need remains to investigate how crediting systems, both in Long Island Sound and more broadly, can incorporate nitrogen management approaches that use in-water solutions. The Chesapeake Bay Program has recently made progress in advancing this issue.[17]

Future combined ecological-economic research is needed to evaluate the potential shifts in the value of the nitrogen sequestration provided by the wide range of shellfish aquaculture practices currently underway across the U.S. and Europe. As recognition is growing for the enhancement of the assimilative capacity of a waterbody provided by natural populations of shellfish, further ecological research into pathways such as denitrification enhancement is war-

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ranted.[58,59,61] Future economic research should also focus on evaluating specific benefit streams to recreational and commercial fishers, recreational boaters and beach users, waterfront property owners, and town residents more broadly, industries that may be valued at billions of dollars per year across the Long Island Sound region.[62] Such approaches, however, require significant funding for survey development and administration and in-depth data on the beneficiaries themselves. Johnston et al.,[63] for example, reported shellfish water quality benefits for recreationists (fishers, boaters, and swimmers) to the Peconic Estuary System (PES) of over \$55 (61€) million (2016 dollars) year^{-1} based upon approximately 3 million beach, boating, or fishing trips taken there per year. This dollar estimate is approximately 10 times what we observed in Greenwich coastal waters using the maximum for the allocated replacement costs (\$5.8 (6.4€) million). Although it is uncertain if Greenwich waters experience the same level of visitation (3 million beach, boating, or fishing trips) as the PES given the smaller geographic scale of Greenwich waters and more limited access points, estimated visitation to Greenwich Point Park (only one of several parks with beaches in Greenwich) totaled over 400 000 people in 2016 (M. Long, Town of Greenwich, personal communication).

The project process and results obtained demonstrate the benefits of interdisciplinary work across ecology and economics. Municipalities anticipating nutrient and other environmental management decisions benefit from quantitative monetary estimates and realistic performance expectations associated with implementation of best management practices. Moreover, the coupled ecological-economic approach provides a model for future interdisciplinary work that could be applied within any coastal watershed in the United States. The biological model is necessary to form a reasonable expectation of the harvest that could be obtained over a given acreage, and the economic model helps contextualize investments in terms of the typically "unpriced" economic benefits produced.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c03066.

Selected previous US studies on values of nutrient bioextraction services (Table S1); Map of Greenwich CT, USA, including location of subwatersheds, recreational harvest areas, commercial shellfish aquaculture leases, designated natural shellfish beds, Grass Island WWTP, and water sampling stations for FARM model calibration (Figure S1); details of modeled nitrogen loads from Vaudrey et al.;[38] approach to estimate the CT portion of the Byram River nitrogen load; and Greenwich Bay nitrogen load model outputs (Figures S2 and S3, Supporting Information SI1); details of the methodology used to estimate nitrogen removal by hard clam and eastern oyster sequestration and harvesting (Figure S4, Supporting Information SI2); environmental data from eight stations in Greenwich Bay, CT, sampled monthly (Figure S5); modeling nitrogen removal under an oyster cage cultivation scenario (Table S3, Supporting Information, SI3) (PDF)

Excel file detailing calculations of the Byram River nitrogen load (Table S2) (XLSX)

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Notes

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