Assessing the long-term economic value and costs of the Crab Hole and Clam Shoal oyster reef sanctuaries in North Carolina.

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Background

Oyster reefs are an important example of a broader class of natural resources (e.g., forests, water, etc.) where direct economic returns are primarily associated with extraction. As a consequence, shellfish habitats comprise one of the most universally degraded estuarine habitats in the world (Lotze et al. 2006, Beck, 2011). This impact has resulted in the loss of not only the revenues associated with fishing for shellfish but also the other ecosystem services that shellfish habitats provide. When oyster reefs, for example, are managed as a habitat and protected from unsustainable fishing practices, they provide a host of ecosystem services whose values are realized both within and outside of the marketplace (Grabowski and Peterson 2007). Intact oyster reef habitats are ecosystem engineers that create nursery habitat rich in prey for juvenile fish and mobile crustaceans (Lenihan et al. 2001, Peterson et al. 2003, Grabowski et al. 2005). Because of this high habitat value, oyster reefs can qualify as essential fish habitat (Coen et al. 1999, Coen and Grizzle 2007). Oyster reefs filter the water and reduce inorganic N nutrients in estuaries by promoting denitrification associated with concentrated deposits of feces and pseudofeces (Newell et al. 2002, Newell 2004). Oyster reefs may also benefit submerged aquatic vegetation (SAV), a habitat that has been historically recognized as critical for many fish species (Thayer et al. 1978), by filtering particulates (sediments and phytoplankton) from the water column, which consequently increases light penetration (Everett et al. 1995, Newell 1988, Newell and Koch 2004, Wall et al. 2008) and provides fertilization to the seagrasses by biodeposition (as shown for hard clams and oysters by Everett et al. 1995, Carroll et al. 2008, Wall et al. 2008). Oyster reefs can reduce erosion of other estuarine habitats such as salt marshes and SAV by providing a buffer that attenuates wave energy (Meyer et al. 1997). They also remove oceanic carbon to create calcium carbonate shells, potentially reducing concentrations of greenhouse gases (Peterson and Lipcius 2003), and providing a localized chemical buffer to globally increasing acidity of ocean waters (National Resource Council 2010).

Sharp declines in oyster populations in the eastern U.S. (Beck et al 2011) have coincided with increased external nutrient loading in many coastal systems (Paerl et al. 1998).

Consequently, bottom-water hypoxia has increased and present-day food webs are dominated by phytoplankton, microbes, and pelagic consumers that include many nuisance species rather than benthic communities supporting higher-level consumer species of commercial and recreational value (Breitburg 1992, Ulanowicz and Tuttle 1992, Lenihan and Peterson 1998, Paerl et al. 1998, Jackson et al. 2001). Newell (1988) raised awareness about the potential consequences of oyster reef loss by pointing out that oyster populations in the Chesapeake Bay in the late 1800's were large enough to filter a volume of water equal to that of the entire Bay every 3.3 days, whereas reduced populations currently in the Bay would take 325 days. Healthy oyster reefs enhance pelagic-benthic coupling and can affect water quality by feeding upon suspended particles and influencing nutrient flux (Newell 1988, Baird and Ulanowicz 1989, Grizzle et al. 2006).

Manipulative experiments have been used to demonstrate that oysters affect water quality by reducing phytoplankton biomass, microbial biomass, nutrient loading, and suspended solids in the water column (Prins et al. 1995, Prins et al. 1997, Cressman et al. 2003, Nelson et al. 2004, Porter et al. 2004, Grizzle et al. 2006). Oyster reefs also concentrate these materials as feces and pseudofeces in the sediments, which stimulates sediment denitrification (DNF) (Dame et al. 1989, Piehler and Smyth 2011) and fertilizes benthic plants (Carroll et al. 2008). In general, bivalve control of phytoplankton biomass is thought to be most effective when bivalve biomass is high and water depth is shallow (Officer et al. 1982, Pomeroy et al. 2006, North et al. 2010). Large-scale restoration efforts especially targeted to shallower tributaries will likely be necessary before water quality improvements are substantial in estuaries where nutrient and suspended solid loading rates currently far surpass the filtration capacity of local populations of oysters and other suspension-feeding bivalves.

Oyster filtration affects sediment properties. Organic matter levels are enhanced relative to sediments without oysters, as are nutrient pools (Dame 1987). Sediment oxygen levels can be indirectly affected by deposition from oyster filtration as microbial degradation utilizes available oxygen. These changes alter the cycling of materials. Piehler and Smyth (2011) found sediments associated with oyster reefs to have higher rates of denitrification than reference sediments without oysters. Oyster reefs also capture sediments independent of filtration because of their emergent structure and its effect on water velocities. As water is slowed by oyster reefs, the suspended materials settle out of the water column and are deposited on the reef or adjacent sediments. The structure of reefs also increases the likelihood that deposited sediments will remain there rather than be eroded and transported away. This potential for disproportionately high deposition of particles around oyster reefs suggests that oyster reefs may promote high rates of sedimentation and burial of all of the materials associated with sediments (Newell and Koch 2004).

Oyster reef restoration provides the opportunity to recover these valuable associated ecosystem services. Here we use cost-benefit analysis to assess the long-term value that would be derived from restored oyster reef projects in coastal North Carolina. We couple market and non-market approaches to determine the long-term value of each ecosystem service provided by the oyster reef sanctuaries that were created at Crab Hole and Clam Shoal in Pamlico Sound. We utilize published work that synthesizes existing ecological information on services provided by shellfish habitats to assess the value of each ecosystem service (e.g., Prins et al. 1995, Prins et al. 1997, Cressman et al. 2003, Peterson et al. 2003, Nelson et al. 2004, Porter et al. 2004, Grizzle et al. 2006, Piehler and Smyth 2011) coupled with information on the landscape setting and environmental characteristics of each site to produce quantitative estimates of the value of each ecosystem service provided by restored oyster reef habitat.

Because oyster reefs provide a variety of services that are not directly valued by markets, we used the productivity and replacement cost approaches to assess the value of filtration and shoreline buffering provided by the two oyster reef sanctuaries. Specifically, we measured the cost of removing nitrogen via a local waste water treatment facility, restoring sea grass habitat, and providing a shoreline buffer equivalent to the scale and landscape context of each sanctuary. Shellfish habitats are analogous to wastewater treatment facilities because they act as a natural biofilter by removing nutrients and suspended solids, which lowers turbidity. In many locations, nutrients are among the primary impairments of water quality, and many municipal waste water treatment plants are facing expensive mandates to upgrade their facilities to dramatically increase nutrient removal. Thus the filtration rate of an individual unit of shellfish habitat can be quantified and compared to the cost of processing a similar amount of suspended solids and nutrients with a waste treatment facility. Finally, the value of services was compared to the costs of constructing each reef sanctuary to determine the breakeven point for each reef sanctuary. These two sanctuaries serve as informative case studies regarding the economic benefits derived from restoring oyster reef habitat relative to the costs associated with reef construction, and thus will hopefully serve to guide policy on future oyster reef restoration.

Approach

I. Quantification of Service Values

a. Fish Utilization

i. Commercial Fish Value

Oyster reefs provide important habitat for recreationally and commercially valuable fish species (Zimmerman et al. 1989, Meyer et al. 1997, Coen et al. 1999, Harding and Mann 1999, Lenihan et al. 2001, Peterson et al. 2003, Grabowski et al. 2005). Peterson et al. (2003) quantified the value of augmented fish production from a unit of oyster reef after reviewing existing data to compare densities of fish on oyster reefs vs. mud bottom. They found that a 10-m^2 plot of restored oyster reef habitat creates an additional annual production of 2.6 kg of fish and large mobile crustaceans because oyster reef habitat either augments recruitment of nektonic species or enhances their growth and survival during critical life-history stages. Although the augmented fish production values in Peterson et al. (2003) were estimated for the Tampa Bay estuary, the approach involved synthesis of all available data from the Chesapeake Bay through Texas and the nektonic species assemblage on reefs is very similar across this geographic range. Furthermore, ecological equivalents exist in different biogeographic zones; for instance, the oyster toadfish in North Carolina is functionally equivalent to the Gulf toadfish in the Gulf of Mexico.

Grabowski and Peterson (2007) utilized these data in order to convert augmented fish production estimates into landings values for each of the 13 species groups that were augmented by oyster reef habitat. Future landings values were discounted at a rate of 3% to adjust for the opportunity cost of capital adjusted for inflation. Scaling the estimate of finfish value up to a 1-acre reef sanctuary that lasts fifty years would result in ~$40,000 in additional value from commercial finfish and crustacean fisheries.

We used the annual estimates of augmented commercial fish value per unit oyster reef derived in Grabowski and Peterson (2007) to calculate the value of augmented fish production from the oyster restoration activities funded by the North Carolina Coastal Federation at the Crab Hole and Clam Shoal restored oyster reef sanctuaries. 144 mounds were built at Crab Hole covering 18.60 acres of oyster reef habitat, with the footprint of each mound covering approximately 0.129 acres. 209 mounds were built at Clam Shoal covering 26.96 acres. Thus the two reefs resulted in a total of 45.56 acres of newly restored reef habitat. Although the surface area of reef is larger than 45.56 acres of bottom covered because these high-relief reefs extend 2-3 m into the water column, it is unclear whether high-relief reefs augment fish production above and beyond the same surface area of cover by flatter reefs. Thus our estimate here is likely conservative if this added surface area results in additional reef habitat for fish. When scaling the value of augmented fish production in Grabowski and Peterson (2007) to the size of the Crab Hole and Clam Shoal oyster sanctuaries, we estimate that the annual commercial fish values of these two sanctuaries are $32,448 and $44,134 in present value, respectively (Table 1). We assume here that oyster reefs constructed in the fall experience full fish productivity by the following warm season (Peterson et al. 2003, Grabowski et al. 2005, Grabowski and Peterson 2007). See the *Discussion* section for estimates of the value of commercial fish and other ecosystem services accrued over the projected lifetime of the reef.

Table 1. The annual present value of commercial fish derived from the Crab Hole and Clam Shoal oyster reef sanctuaries.

Crab Hole Sanctuary		
Reef area	Augmented fish value	Value of fish per sanctuary
# acres	$ $acre^{-1}$ yr^{-1}	$ yr^{-1}
18.60	$1,736	$32,286

Clam Shoal Sanctuary		
Reef area	Augmented fish value	Fish value of sanctuary
# acres	$ $acre^{-1}$ yr^{-1}	$ yr^{-1}
26.96	$1,736	$46,798

ii. Recreational Fish Value

A separate fishery value that is not adequately captured above involves whether recreational fishers derive additional or substitutional value from reef restoration activities. The value derived from recreational fishing can be quantified because recreational fishers are willing to purchase bait, fishing rods, tackle, fuel, boats, trucks, lodging, etc. and use their time when they go fishing (Smith 1989, Easley and Smith 1992). A fisher's willingness to incur these expenses and use time fishing is influenced by factors such as the cost of the trip, the net value that would be derived from other recreational activities, and the quality of the fishing experience, which is largely influenced by their expected catch. Demand for recreational fishing is also influenced by local variation in economic and demographic factors such as income and preferences (Easley and Smith 1992). Easley and Smith (1992) surveyed fishermen in 1988 and used a policy model that determined that a 5% increase in the average catch would be worth $10 (in 1988 dollars) more per fishing trip in coastal North Carolina for fishermen. Thus, the above value can be thought of as the average amount that a fisher would be willing to pay for slightly enhanced catch rates while recreational fishing.

Oyster reefs augment the production of commercially and recreationally valuable finfish in estuaries (Peterson et al. 2003). Recreational captains have been known to target restored oyster reefs in North Carolina in the Neuse River Estuary to capture red drum and other reef associated species (D. Gaskill, pers. comm.). Additionally, scientific surveys of fishers at and around restored reefs in Middle Marsh, NC in 1997-2001 found that oyster reefs augment catch rates by 39.1% over unstructured mud bottom (Grabowski et al. 2001).

These comparisons between habitats were conducted by recreational anglers that were willing to use identical methods and quantify fishing time on vs. off of oyster reef habitat. Clearly, the presence of an oyster reef augmented recreational angler catch rates far beyond the 5% used in the survey conducted by Easley and Smith (1992) to determine the added value of increased catch rates per fishing trip. Therefore, local oyster restoration efforts are likely worth greater than $10 in 1988 dollars or $19.73 in 2011 dollars per fishing trip (i.e., the net present value of increased catch). Thus multiplying this dollar estimate by the number of boats visiting the two oyster reef sanctuaries should provide a highly conservative estimate of the value of these restoration efforts to the recreational fishing industry.

Unfortunately the degree to which the Crab Hole and Clam Shoal oyster reef sanctuaries are currently being targeted by recreational fishermen is unknown. The North Carolina Division of Marine Fisheries (DMF) estimated that in 2008 there were 803,308 Carolina Recreational Fishing Licenses (CRFL) issued to potential fishers in coastal waters (NC-DMF 2009). Crosson (2010) conducted a survey of a subset of these license holders and estimated that recreational fishers annually conduct a total of 6,047,089 trips throughout coastal North Carolina. The average cost per trip was $139, so that expenditures for inshore trips totaled $840,545,308. This estimate expanded to close to $1.5 billion when indirect and induced economic effects were calculated and added to it (Crosson 2010).

We quantified the value of recreational fishing on these reefs by multiplying the estimated number of trips that occur on these reef sanctuaries annually by the value that fishermen derive from increased catch derived by Easley and Smith (1992). Currently the number of recreational fisher trips that occur annually to these reef sanctuaries is unavailable, so we multiplied the estimate by Crosson (2010) of total annual trips in NC by a wide range (0.1% and 1.0%) of possible values to estimate the total number of trips to the oyster sanctuaries. While both of the oyster sanctuaries are most proximal to Dare County, which includes major tourist destinations such as Nags Head, Cape Hatteras, and Manteo, these sanctuaries are accessible by boat from several other coastal NC counties located along Pamlico and Albemarle Sounds. We then apportioned these visits to the sanctuaries based on the size of each sanctuary. We then multiplied the estimated number of annual trips occurring in each sanctuary by the value of increased catch per trip ($18.61; Easley and Smith 1992) to the recreational fishing industry in NC. Using this method, we estimated that the value of recreational fishing at Crab Hole and Clam Shoal sanctuaries ranged from an additional $48,708-$497,083 and $70,601-$706,008 in present dollars annually to recreational fishermen in NC, respectively (Table 2).

Given the large amount of annual recreational fishing effort that occurs in NC, the value of recreational fishing in the sanctuaries could be much higher if they become a popular destination for recreational fishermen. However, if recreational and commercial fishermen are competing for the same fish, generating both recreational and commercial fishing value from the reefs may not be possible at the levels that we compute assuming independence of these two activities. Yet several aspects of our calculations for both recreational and commercial fish values are conservative (e.g., estimated recreational catch rate on reefs is likely far greater than 5% as compared to adjacent mud bottom), thus we include both in our summary estimates of the value of services provided by oyster reefs (see *Discussion* section below).

Table 2: The annual present value of the Crab Hole and Clam Shoal oyster reef sanctuaries to recreational fishermen.

Crab Hole Sanctuary			
% of NC Trips to reef sanctuaries	Fishing effort # trips yr^{-1}	Added value per trip $ $trip^{-1}$	Fish value of sanctuary $ yr^{-1}
0.1%	2,469	$19.73	$48,708
1.0%	24,687	$19.73	$487,083

Clam Shoal Sanctuary			
% of NC Trips to reef sanctuaries	Fishing effort # trips yr^{-1}	Added value per trip $ $trip^{-1}$	Fish value of sanctuary $ yr^{-1}
0.1%	3,578	$19.73	$70,601
1.0%	35,783	$19.73	$706,008

b. Denitrification

We utilized nitrogen flux data from oyster reefs and sub-tidal flats to determine the amount of additional nitrogen removed from the system when an oyster reef is added to the system. Piehler and Smyth (2011) quantified nitrogen flux in both habitats. Intact cores were incubated in a flow-through system. Inlet and outlet samples were analyzed using a membrane inlet mass spectrometer to quantify dissolved N_2 concentrations and calculate N_2 flux (Kana et al. 1994). Dissolved inorganic nutrient fluxes were also calculated during these experiments. Data used here were collected quarterly for one year during each season. The primary mechanism by which oyster reefs remove nitrogen from the system is by increasing local denitrification rates. We then subtracted the amount of nitrogen removed in subtidal mud-bottom habitats from the amount removed by oyster reefs to obtain the amount of augmented nitrogen removed by 1 m^2 of oyster reef habitat. This value was then multiplied by 14 to convert μmol N to μg N. This value was also multiplied 12 to approximate the number of (dark) hours in the day in which DNF occurs (Piehler and Smyth 2011) and 365 to scale this rate from an hourly to an annual estimate. Next we divided this value by 1,000,000,000 to covert μg N to kg N and then divided the product by 0.000247 to determine the annual removal rate of an acre of oyster reef habitat.

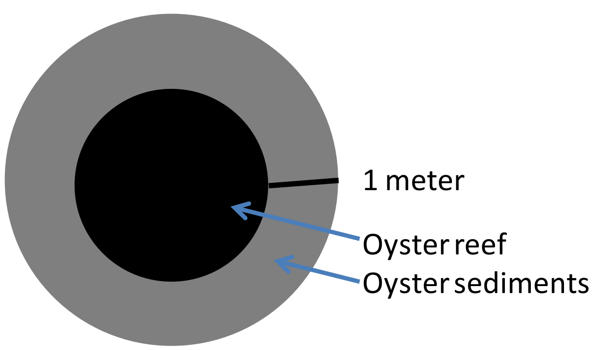

Figure 1: Schematic showing a representative oyster reef and the 1m halo around the reef that was designated as oyster affected sediments affected by oyster biodeposition.

The dollar value of N removal via DNF was estimated using the published rates from the North Carolina nutrient offset program. The North Carolina nutrient offset payment value is a regionally derived value based specifically on factors in NC. The current trading price of the North Carolina Nutrient Offset Credit Program is $28.53 per kilogram of nitrogen removed (15A NCAC 02B .0240). This value is reviewed annually and will likely rise as more expensive urban best management plans for nitrogen offsets are needed. To best estimate the annual value of habitat specific N removal, mean annual rates of DNF per acre were multiplied by this $ value. Thus, the annual value of an acre of oyster reef and surrounding sediments was then determined by multiplying kilograms of nitrogen removed by an acre of reef via DNF per year by $28.53. Using the above value and empirical results from Piehler and Smyth (2011) described above, the additional value (the value above subtidal muddy flats without oysters) of nitrogen removal from 1 acre of oyster reef habitat was determined to be $2,555 per year (Table 3).

To determine the amount of acres surrounding the reef sanctuaries where denitrification in sediments is augmented by the proximity of oyster reef habitat, we estimated that at least a 1 meter "halo" surrounding each reef mound should exhibit elevated DNF rates (Fig. 1). This estimate is likely conservative given the empirical results in Piehler and Smyth (2011), which found elevated DNF rates in sediments up to 0.5-1 m away from the edge of <0.5 tall oyster reefs. In contrast, the reefs at the Crab Hole and Clam Shoal Sanctuaries are 2-3 m tall and likely could promote augmented DNF well beyond a meter from the edge of these reefs. With a 1 m halo around each reef, we estimated the total area of oyster reef sediments with augmented DNF to be 7.46 acres: 2.91 at Crab Hole and 4.55 at Clam Shoal.

We also credited the reef itself with promoting DNF using the published rates for augmented DNF in the surrounding sediments found by Piehler and Smyth (2011) (Table 2). This value is likely conservative given that Kellogg et al. (2011) recently quantified the rate of DNF on intact oyster reef mesocosms in a tributary of the highly eutrophied Chesapeake Bay and observed rates that were far greater (~7x higher) than those in Piehler and Smyth (2011). However, Kellogg et al. (2011) sampled reefs with large adult oysters and extremely high densities of living oysters (>100/m2), and conducted their work at a highly nitrogen-enriched tributary to the Chesapeake Bay. Thus their estimates of DNF augmentation by oyster reefs likely reflect the higher end of what reefs are capable of, and are not as representative of the Crab Hole and Clam Shoal Sanctuary sites. Together with Piehler and Smyth (2011), these two studies provide a range from which we have selected the conservative end of to avoid overestimating the value of augmented DNF from oyster reefs.

We have selected a conservative value for the cost of N removal in our replacement cost estimates of the non-market value of nitrogen removal. For instance, other potential values from the literature include $1,200 per kg, the high end cost for Chesapeake Bay (EPA Chesapeake Bay Program Use Attainability Analysis [http://www.chesapeakebay.net/uaasupport.htm]), and $787 per kg, an estimate derived from an Australian study of the cost per kg to remove N via stormwater management (Hatt et al. 2006). The cost of nitrogen removal through engineering solutions and nutrient management is typically towards the upper end of this range in coastal regions because of the high cost of land for siting the engineered removal facility (often wetlands), generally short distance to groundwater, and the proximity to receiving waters.

Table 3. The annual present value of augmented denitrification on oyster reefs and surrounding sediments at the Crab Hole and Clam Shoal oyster reef sanctuaries. DNF rates for sediments were derived empirically by Piehler and Smyth (2011).

Crab Hole Sanctuary					
Reef area	Halo area	DNF Value	Oyster reef DNF Value	Oyster sed. DNF Value	Value of DNF per sanctuary
# acres	# acres	$ acre^{-1} yr^{-1}	$ yr^{-1}	$ yr^{-1}	$ yr^{-1}
18.60	2.91	$5,621	$104,551	$16,378	$120,929

Clam Shoal Sanctuary					
Reef area	Halo area	DNF Value	Oyster reef DNF Value	Oyster sed. DNF Value	Value of DNF per sanctuary
# acres	# acres	$ acre^{-1} yr^{-1}	$ yr^{-1}	$ yr^{-1}	$ yr^{-1}
26.96	4.55	$5,621	$151,542	$25,582	$177,124

c. Filtration

Nitrogen removal through oyster filtration of phytoplankton was also calculated. This ecosystem service is highly redundant to the denitrification service described above because phytoplankton that are filtered are repacked as feces and psuedofeces before being deposited on the seafloor. Therefore, after calculating the value of nitrogen removal via filtration and denitrification, we only used the value of denitrification in our summary table calculations because this was the larger of the two values.

The amount of phytoplankton removed from the system was estimated using oyster filtration rates published in Grizzle et al. (2008). Calculations of phytoplankton removal were based on low (4ug/l chlorophyll a) and high (40ug/l chlorophyll a) phytoplankton biomass. Chlorophyll a removal was converted to carbon using a carbon: chlorophyll a ratio of 50 (Wienke and Cloern 1987). We used the Redfield Ratio to convert carbon removal to nitrogen removal (Redfield 1958). The amount of μmol N was then converted to kg N/acre/yr and $/acre/yr using the calculations described above for denitrification. The annual value of nitrogen removed from filtration ranged from $491 to $4,908 at the Crab Hole Sanctuary, and from $711 to $7,114 at the Clam Shoal Sanctuary (Table 4). These values were far less than those from augmented denitrification rates estimated on the reefs and in the sediments. Calculation of N removal both via filtration and enhanced N removal via DNF is double-counting because the enhanced DNF included (and was largely the result of) the N removed via filtration. Thus filtration values were excluded from our computation of total value of all ecosystem services provided by oyster reefs.

Table 4. The estimated annual present value of nitrogen removal from oyster filtration on oyster reefs and surrounding sediments at the Crab Hole and Clam Shoal oyster reef sanctuaries.

Crab Hole Sanctuary			
Chl *a* conc.	Oyster density	Filtration value	Filtration value of sanctuary
g/l	#/m^2	\$ acre^{-1} yr^{-1}	\$ yr^{-1}
4	100	$26	$491
40	100	$264	$4,908

Clam Shoal Sanctuary			
Chl *a* conc.	Oyster density	Filtration value	Filtration value of sanctuary
g/l	#/m^2	\$ acre^{-1} yr^{-1}	\$ yr^{-1}
4	100	\$26	\$711
40	100	\$264	\$7,114

d. Submerged Aquatic Vegetation Enhancement

Ecologists value submerged aquatic vegetation (SAV) for the wide array of ecosystem services that it provides (Orth 1977; Thayer et al. 1978). For instance, SAV enhances production and exportation of organic carbon, nutrient cycling, and estuarine biodiversity; promotes stabilization of sediments; and provides nursery habitat for economically valuable finfish and shellfish species (Orth 1977; Thayer et al. 1978; Summerson and Peterson 1984; Spanier and Almog-Shtayer 1992; Rooker et al. 1998; Mosknes 2002; Orth 2006). It has been estimated that human activities have resulted in the loss of 29% of SAV worldwide since 1879 (Waycott et al. 2009). SAV has been reduced by a variety of environmental perturbations, including agricultural runoff, soil erosion, metropolitan sewage effluent, and resultant N loading from all of these sources as well as atmospheric deposition (Kahn and Kemp 1985, Hauxwell et al. 2003, Orth et al. 2006). In the North Atlantic, *Zostera marina* L. (eelgrass) has declined primarily as a consequence of estuarine eutrophication, physical disturbance, and wasting disease (Moore and Orth 1983; Giesen et al. 1990; Valiela et al. 1992; Short et al. 1995; Hughes et al. 2002). SAV restoration has been used in estuaries where SAV loss has occurred to recover ecosystem services associated with SAV habitat. However, SAV restoration is costly and ranges from \$45,000 per acre to collect, prepare, and plant the seagrass plugs, or \$245,000 per acre to also select and map sites, complete permitting requirements, and conduct monitoring efforts to establish that restoration was successful (Fonseca et al. 2001; price levels reflect 2001 dollars).

Oyster reefs provide an alternative to SAV restoration because they can assist SAV recovery in polluted estuaries by reducing water turbidity vial removal of suspended solids and attenuating nutrient runoff (Peterson and Lipcius 2003, Newell and Koch 2004, Carroll et al. 2008). Oysters are capable of reducing suspended sediment concentrations by nearly an order of magnitude even at relatively low biomass levels (i.e., 25 g dry tissue weight m-2; Newell and Koch 2004). This reduction would result in increased water clarity that would potentially have profound effects on the extent of SAV in estuaries.

If oyster reefs promote recovery of SAV, then these oysters should receive credit for the value of the services provided by this additional SAV habitat above and beyond that of the mud bottom that it replaced. Thus a holistic effort to value oyster reef habitat could entail quantifying associated benefits associated with SAV habitat. Because there is a market for SAV restoration, it is possible to use replacement cost valuation approaches to quantify the value of augmented SAV from oyster reef habitat. Here we used the complete cost estimate from Fonseca et al. (2001) of SAV habitat ($329,819/acre in present dollars) to quantify the value of this oyster reef service. Thus, natural SAV habitat recovery resulting from oyster restoration activities is highly valuable. Unfortunately empirical data that establish the relationship between oyster restoration and SAV recovery are extremely difficult to obtain, and will likely be influenced by a multitude of factors such as the existing sediment and nutrient load in the system, water velocity and depth, and the availability of SAV seedlings.

SAV currently exists within a km of the perimeter of the two oyster sanctuaries, so that a source of natural seeding is available. Moreover, the scale of restoration activities in these sanctuaries is large enough that it is plausible that these oyster sanctuaries could promote expansion of local SAV and associated ecosystem services. If we estimate that each acre of oyster reef habitat at the two sanctuaries will create between 0.001 and .01 acre of additional SAV habitat, the value of this oyster reef service ranges from $311 to $3,109 per acre of oyster reef habitat (Table 5). Note that we have selected the total cost of seagrass restoration efforts for these calculations, and have adjusted this cost to 2011 dollars by applying a 3% interest rate to arrive at the net present value.

Table 5. The estimated annual present value of SAV created by the Crab Hole and Clam Shoal oyster reef sanctuaries.

Crab Hole Sanctuary			
% of SAV created relative to OR rest.	Augmented SAV value $ (acre oyster reef rest.)$^{-1}$ yr^{-1}	Reef area # acres	Value per sanctuary $ yr^{-1}
0.1%	$311	18.60	$5,785
1.0%	$3,109	18.60	$57,827

Clam Shoal Sanctuary			
% of SAV created relative to OR rest.	Augmented SAV value $ (acre oyster reef rest.)$^{-1}$ yr^{-1}	Reef area # acres	Value per sanctuary $ yr^{-1}
0.1%	$311	26.96	$8,385
1.0%	$3,109	26.96	$83,819

e. Shoreline Stabilization

The Crab Hole and Clam Shoal oyster reefs are subtidal and are located far enough from the shoreline that they are not expected to perform this function. The two sanctuaries are also not directly adjacent to other structured habitats such as seagrass beds or saltmarshes that typically benefit from the close proximity of oyster reef habitat that is capable of baffling wave energy and reducing erosive effects. Given that it is unlikely that the reefs at these two sanctuaries are stabilizing shoreline or other estuarine habitats, no value was attributed to these two sanctuaries for performing this service.

f. Additional Services

Oyster reefs provide other ecosystem services in addition to providing habitat for commercially and recreationally valuable fish, removing anthropogenic nitrogen, enhancing SAV proliferation, and stabilizing shoreline habitat. For instance, oyster reefs contain extremely high densities for epibenthic infauna. However, this value is likely captured in the commercial and recreational value of augmented fish estimates above because epibenthic fauna provide prey for higher trophic levels and thus are accounted for indirectly. It has been suggested that oysters are a carbon sink, and thus could aid in reducing anthropogenic sources of CO_2 emissions. Yet is currently unclear whether oysters are a source or a sink of CO_2. Oysters form calcium carbonate shells, thereby sequestering CO_2 from the water column. However, this removal of CO_2 is counterbalanced by both the eventual erosion of shell material that is not buried and the release of CO_2 when they respire, which may actually increase CO_2 emissions into estuarine water bodies. If oyster reefs are a net sink for CO_2, it would be possible to quantify the value or cost of CO_2 removal using carbon trading markets, which is similar to how we quantified the value of nitrogen removal.

If oyster reefs enhance water quality, they could increase coastal residents desire to live on the coast and other residents' willingness to visit the coast for recreational activities. For instance, oyster reefs that achieve improvements in water clarity should have tangible effects on the public's perception of these watersheds and their willingness to use them. Increased water clarity would also likely result in reduced jellyfish and their stings, which thrive in eutrophic ecosystems (Arai 2001, Jackson et al. 2001). It is currently unclear whether or oyster reefs are capable of increasing water quality because the vast majority of restoration efforts are too small to affect water quality through filtration processes. However, the Crab Hole and Clam Shoal oyster sanctuaries represent larger restoration efforts that may impact basin-scale processes. These recreational values are not insignificant, and may dwarf the estimates of each service detailed above. For instance, Bockstael et al. (1988; 1989) used a willingness-to-pay survey in 1984 in the greater Baltimore-Washington area in 1984 and found that residents were willing to pay ~$100 million in increased taxes to achieve a 20% improvement in water quality (i.e., decreased nitrogen and phosphorous loading). The National Research Council (2004) adjusted these estimates to 2002 price levels and found that a 20% improvement in water quality along the western shore of Maryland relative to conditions in 1980 is worth $188 million for shore beach users and $26 million for recreational boaters The Albemarle and Pamlico sounds are far less densely populated than the Chesapeake Bay, but represent the second largest estuarine ecosystem in the eastern U.S. and constitute a major U.S. tourist destination.

Finally, section 303(d) of the Clean Water Act requires that states monitor whether their waters meet minimum water quality standards. Failure to maintain these standards can result in water quality violations, inclusion on the EPA's 303(d) list of impaired waters, and development of an expensive total maximum daily load (TMDL) for basin-wide removal of N, P and sedimentation. The value of these water quality benefits are likely significantly higher if restored oyster reefs help maintain local water bodies maintain water quality standards and avoid being listed. Overall, our estimates here are likely conservative given the range of potential benefits that are not captured but may contribute extensively to the total ecosystem service value provided by oyster reefs.

II. Cost Analysis

The cost of constructing the oyster reefs at the Crab Hole and Clam Shoal oyster reef sanctuaries was estimated at $3,762,746 to deploy 54,500 tons of limestone marl and construct 45.56 acres of oyster reef sanctuaries. This estimate includes the cost of construction, including purchasing marl, transporting to the site, loading it onto the barge, and deploying at the sanctuaries. Thus, the reef restoration costs were estimated at $82,589 per acre. The costs for these reef sanctuaries trend toward the upper limit on typical oyster reef restoration costs, which is not surprising given the size and height of these reefs coupled with the building material, large marl, which is used to prevent harvesting of reefs and enhance spatial relief. However, the total cost would be even if higher if monitoring and adaptive management costs were also included. For instance, Fonseca et al. (2001) estimated that monitoring costs alone accounted for $145,000 out of the total cost of $245,000 per acre of restored SAV.

Discussion

We found that Crab Hole and Clam Shoal oyster reef sanctuaries collectively provide ecosystem services totaling over $11,000 per acre annually (Table 6). The annual value of ecosystem services provided by the 18.60 acres of oyster reef habitat at the Crab Hole Sanctuary was estimated at $206,218, whereas those of the 26.96 acres of reef at the Clam Shoal Sanctuary annually were worth $166,376. The cost of constructing these oyster reef sanctuaries ($3,762,746) was over an order of magnitude higher than the annual value derived from the ecosystem services. Using a 3% discount rate to account for the opportunity cost of capital, we estimated that these sanctuaries would break even in 9 years (Table 7). This break-even point is likely conservative given that in many instances above we selected the lowest of a range of possible values for the extent of individual services. For instance, if augmented denitrification, recreational fishing or SAV enhancement trend towards the upper end of the range of values proposed above, then the break-even point would be much shorter. The estimate of 9 years is younger than the age of several of the sanctuaries revisited in Powers et al. (2010), many of which were still supporting high densities of living oysters. Given that the large marl substrate used to build the two sanctuaries cannot be manipulated by traditional harvesting techniques such as tonging or dredging, it is possible that these sanctuaries could persist for two or more decades.

Quantifying the value of ecosystem services provided by the two sanctuaries revealed that a wide range of ecosystem services contribute to their overall value. The value of nitrogen removed via denitrification was the biggest contributor to this estimate with DNF performed by the reefs and surrounding sediments collectively accounting for 59% of the total value of ecosystem services provided by these sanctuaries. Recreational fish value was the next most valuable service, and accounted for 23% of the total value. Commercial fish value contributed 15% of the overall value of ecosystem services. SAV enhancement accounted for the remaining 9% of ecosystem service value. Filtration values were not attributed to the reefs because this nitrogen removal is accounted for in the DNF calculation above. Similar to filtration, providing habitat for epibenthic fauna is likely already captured in the estimates of recreational and commercial fishing value, and thus no additional value was attributed to this service. The reef sanctuaries also received no credit for shoreline stabilization because they are subtidal and consequently do not perform this service. We were unable to estimate to other potential services, recreational value other than angling and carbon sequestration, thus our overall estimate is likely conservative.

Table 6. Summary of the annual values and percent contributions of the ecosystem services provided by the Crab Hole and Clam Shoal oyster sanctuaries.

	Value			
	$ per acre	Crab Hole	Clam Shoal	% of service value
Augmented Fish Production				
recreational value	$ 2,619	$ 48,708	$ 70,601	23%
commercial value	$ 1,637	$ 30,446	$ 44,130	15%
Denitrification				
reef area	$ 5,621	$ 104,551	$ 151,542	50%
sediments	$ 881	$ 16,378	$ 25,582	9%
Filtration (chl a removal)	$ -	$ -	$ -	0%
SAV enhancement	$ 330	$ 6,135	$ 8,892	3%
Shoreline stabilization	$ -	$ -	$ -	0%
Habitat for epibenthic fauna	$ -	$ -	$ -	0%
Carbon sequestration	n/a	n/a	n/a	n/a
TOTAL:	$ 11,087	$ 206,218	$ 300,747	100%

The estimates in this study, which were made using the best data that are currently available, could be enhanced with the following information. Efforts to sample fish biomass on these reefs would be especially useful for ground-truthing the commercial fish value estimates presented in this study. The estimate of recreational fishing activity on these reefs would also benefit from field data capturing current effort on the reefs. Also, the value of these reefs to the recreational fishery could be estimated more directly using a survey of boats that conduct recreational fishing in the general vicinity of the two oyster reef sanctuaries to determine their willingness-to-pay for incrementally better fish catch rates associated with oyster reef habitat. The DNF estimate would also benefit from direct measurements in the field. Density estimates of the oyster reef community would benefit our estimates of filtration rates. Efforts to quantify the effect of these reef sanctuaries on neighboring SAV beds should be conducted to better understand the relationship between oyster reef habitat and SAV proliferation. Efforts to quantify the value of other recreational uses and carbon sequestration would permit a more holistic estimate of the value of services associated with the oyster reef sanctuaries. In several cases, we have chosen conservative estimates of rates or processes to avoid overestimation of the value of a particular service. Thus it is conceivable that the value of oyster reef ecosystem services associated with the two sanctuaries far exceeds our estimate of ~$11,000.

Table 7. Projection of the value of the ecosystem services over varying lengths in the reef existence.

Long-term projected values	Additional Benefits		
Reef life span	Crab Hole	Clam Shoal	**Total**
1 year	$206,218	$300,747	**$506,964**
5 years	$972,749	$1,418,652	**$2,391,401**
10 years	$1,811,851	$2,642,394	**$4,454,245**
25 years	$3,698,626	$5,394,056	**$9,092,682**
50 years	$5,465,110	$7,970,288	**$13,435,398**

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