Economic Valuation of Ecosystem Services Provided by Oyster Reefs

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Valuation of ecosystem services can provide evidence of the importance of sustaining and enhancing those resources and the ecosystems that provide them. Long appreciated only as a commercial source of oysters, oyster reefs are now acknowledged for the other services they provide, such as enhancing water quality and stabilizing shorelines. We develop a framework to assess the value of these services. We conservatively estimate that the economic value of oyster reef services, excluding oyster harvesting, is between $5500 and $99,000 per hectare per year and that reefs recover their median restoration costs in 2–14 years. In contrast, when oyster reefs are subjected to destructive oyster harvesting, they do not recover the costs of restoration. Shoreline stabilization is the most valuable potential service, although this value varies greatly by reef location. Quantifying the economic values of ecosystem services provides guidance about when oyster reef restoration is a good use of funds.

Keywords: ecosystem services, ecosystem management, oyster reef habitat, valuation

The concept of valuing ecosystem services in economic terms is not new (e.g., Freeman 1993), and efforts to apply this approach to a wide range of habitats and ecosystems have proliferated dramatically following the release of the Millennium Ecosystem Assessment (MA 2005). However, the incomplete state of scientific understanding of ecosystem function in many systems limits our ability to quantify all of their associated ecosystem services, which consequently impedes decisions about how best to manage for the long-term return and sustainability of these services (Nelson et al. 2009). Because the value of most ecosystem services is not captured in the marketplace framework (Ruffo and Kareiva 2009), nonmarket methods and modeling are usually necessary to estimate the economic value of these services. In practical terms, values of ecosystem services are likely to be highly context specific, which raises questions about the transferability of and the ability to compare service valuation efforts across different environmental conditions. Quantifying the value associated with ecosystem services will enhance our ability to allocate limited resources in order to manage ecosystems effectively. Economic valuation of services specific to habitats that have been degraded by anthropogenic activities will be particularly useful for planning, implementing, justifying, and managing mitigation and restoration efforts.

Oysters, which create reefs and are therefore an ecosystem engineer, or *foundation species* (Jones et al. 1994), form one of the most degraded estuarine habitats in the world; roughly 85% of oyster reef habitat has been lost globally over the past 130 years (Lotze et al. 2006, Beck et al. 2011). Furthermore, oyster reef restoration efforts historically lagged far behind progress in other estuarine habitats, such as salt marshes, seagrass beds, and mangroves, even though the cost of restoring and value of ecosystem services derived from oyster reefs is roughly comparable to that of these other estuarine habitats (table 1). Conversely, vegetated estuarine habitats have long been recognized for their important ecosystem services (Thayer et al. 1978). In a recent review of estuarine ecosystem services, the need for a comprehensive framework to evaluate habitat-specific services was illustrated by the lack of information on the value of associated services for many habitats (Barbier et al. 2011). Despite oyster reef habitat's acknowledged importance to estuarine ecosystem function, the value of ecosystem services provided by oyster reefs has yet to be quantified exhaustively. The paucity of information for this critical habitat underscores the acute need for a comprehensive and quantitative framework for the valuation of oyster reef ecosystem services.

Contrary to the traditional view, in which oysters are valued solely as a fishery commodity, the scientific literature clearly shows that oysters provide a host of nonmarket ecosystem services. Oysters grow vertically and in dense assemblages that create biogenic habitat rich in mollusks besides oysters and that harbors polychaetes, crustaceans,

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Table 1. Comparison of restoration effort for five coastal habitats in the United States.

Habitat type	Area restored[a]	Restoration cost[b]	Percentage global loss[c]
Salt marsh	36,625	3–242	50–80
Seagrass	3946	14–1035	29–65
Mangrove	1399	5–771	50
Coral reef	150	15–9267	20
Oyster reef	69	52–260	80–85

[a] Estimates (in hectares) of area restored in the United States as of 19 March 2009 using the National Estuaries Restoration database at *https://neri.noaa.gov/neri.*

[b] Restoration costs (in $1000 per hectare) were obtained from the following sources: Spurgeon (1998) for salt marshes, seagrass beds, mangroves, and coral reefs; Fonseca and colleagues (1982) for seagrass beds; Lewis and Streever (2000) for mangroves; Spurgeon and Lindhal (2000) for coral reefs; and Henderson and O'Neil (2003) for oyster reefs. All cost estimates were then transformed to 2011 dollars.

[c] The global loss estimates were obtained from the following sources: Lotze and colleagues (2006) and Airoldi and Beck (2007) for salt marshes and mangroves; Lotze and colleagues (2006) and Waycott and colleagues (2009) for seagrass beds; Wilkinson (2008) for coral reefs; and Lotze and colleagues (2006) and Beck and colleagues (2011) for oyster reefs.

and other resident invertebrates (Wells 1961, Bahr and Lanier 1981, Rothschild et al. 1994). These resident invertebrates are consumed by juvenile fish and mobile crustaceans that use oyster reefs for foraging and refuge from predators, which leads directly and indirectly through the provision of forage species to an enhanced production of economically important fishery stocks (Coen et al. 1999, Breitburg et al. 2000, Harding and Mann 2001, Peterson et al. 2003, Tolley and Volety 2005).

The authors of several studies have concluded that dramatic reductions in the abundance of filter-feeding oysters from estuaries throughout the southeastern United States have probably contributed in shallow waters to ecosystem regime shifts from communities dominated by benthic flora and fauna to those primarily consisting of planktonic and microbial organisms (Dame et al. 1984, Newell 1988, Ulanowicz and Tuttle 1992, Paerl et al. 1998, Jackson et al. 2001, Baird et al. 2004, Lotze et al. 2006). By intercepting suspended particles and nutrients before they enter microbial loops, oysters promote an increased transfer of energy among trophic levels that results in primary production moving up the food chain to bottom-feeding fishes; crabs; and higher-order predators such as red drum, tarpon, and bottle-nosed dolphins (Coen et al. 1999, Baird et al. 2004). Oyster reefs help counteract increases in anthropogenic nitrogen loading in estuaries by promoting bacterially mediated denitrification induced by concentrated bottom deposits of feces and pseudofeces (Newell et al. 2002, Piehler and Smyth 2011). Filtration by oysters also benefits submerged aquatic vegetation (SAV), a habitat long recognized as critical for many fish species (Thayer et al. 1978), by filtering sediments and phytoplankton from the water column—thereby increasing light penetration—and by continuous fertilization of the benthic plants through deposition of biodeposits (Newell 1988, Everett et al. 1995, Newell and Koch 2004, Carroll et al. 2008, Wall et al. 2008). Seston removal by dense aggregations of bivalves, including oysters, has been inferred from fluorometric field measurements (Grizzle et al. 2006), although this effect is probably strong only in shallow estuarine tributaries with abundant oysters (Pomeroy et al. 2006). Oyster reefs reduce erosion of other estuarine habitats such as salt marshes and SAV by serving as a living breakwater that attenuates wave energy and stabilizes sediments (Meyer et al. 1997). In many of its functions, the landscape setting of an oyster reef can greatly influence the provision of its ecosystem services. For instance, Grabowski and colleagues (2005) found that oyster reefs located on mud flats augmented juvenile fish abundances, whereas oyster reefs at the edges of salt marsh and seagrass habitat had no effect on juvenile fish. The large number of ecologically focused oyster reef restoration efforts since the mid-1990s offers the opportunity to review reef restoration effects on service provision and value (Rothschild et al. 1994, Lenihan and Peterson 1998, Peterson et al. 2003, Grabowski and Peterson 2007).

Destructive harvesting of oysters began over a century ago, shortly after the advent of the mechanical dredge, which allowed fishers to decimate oyster reefs and, as a result, remove the structural foundation onto which successive generations of oysters must settle and grow (Hargis and Haven 1988, Rothschild et al. 1994, Lenihan and Peterson 1998, 2004). Early attempts to rebuild reefs over the past several decades to bolster sagging oyster-fishing harvests have been further compromised by oyster disease; sedimentation impacts on relic reef footprints; the accelerating degradation of water quality; and in some locations, depressed spawning stock biomass (Rothschild et al. 1994, Lenihan and Peterson 1998, Peterson et al. 2003). All of these factors have contributed further to the decline in the quantity and quality of oyster reef habitat in the southeastern United States. Efforts to rebuild eastern oyster (*Crassostrea virginica*; Gmelin 1791) populations in this region, where harvests are less than 1% of the historic maxima circa 1900 (Wilberg et al. 2011), were typically focused on rebuilding the oyster fishery rather than on recovering the reef habitat to support its ecosystem goods and services (Newell 1988, Rothschild et al. 1994).

A century after the onset of steep declines in oyster landings around the United States (Kirby 2004), scientists and managers have finally begun focusing on managing oyster reefs as a habitat for other species and for a broader array of services instead of just for oyster harvest. This is part of a larger trend toward a more holistic and ecosystem-based approach to fisheries and ocean management (Christensen et al. 1996, Jackson et al. 2001). Although the transition from single-species to ecosystem-based management has been hindered by insufficient modeling capacity and a paucity of necessary data on ecosystem function, both of these impediments are being increasingly addressed within the science and management communities. Efforts to quantify ecosystem functions and to value ecosystem services can provide the necessary information to convince fisheries managers, policymakers, and the public that ecosystem-based management initiatives in estuaries are worthy of continued support. For oyster reefs, significant strides have been made in measuring some ecosystem services directly or through modeling efforts. These advances provide an opportunity to estimate economic values for services that are relevant to coastal managers and thus to improve their ability to assess and implement various habitat restoration options and to manage reefs more effectively. Here, we describe approaches for quantifying some of the most valuable and important ecosystem services from oyster reefs by estimating their economic values in the southeastern United States. We then compare these service flows to the economic value derived from destructively harvesting reefs for oysters.

We begin by presenting estimates of the commercial oyster harvest value derived from a unit of oyster reef habitat and then turn to the value of services per unit area provided by unharvested reefs (table 2).

Oyster harvest value

Dramatic declines in the density of legally harvestable oysters in historically productive regions such as the Delaware Bay, the Chesapeake Bay, Pamlico Sound, and the south Atlantic Coast of United States (Kirby 2004), coupled with regulations intended to allow natural rebuilding of oyster populations, have greatly reduced commercial oyster landings from wild-stock fisheries. Grabowski and Peterson (2007) estimated that overharvesting in Virginia reduced the value of oyster yields from a net present value (in 2011 dollars) of $65,876 per hectare of pristine oyster bottom in 1890 to $2640 per hectare of degraded bottom in 1991 (oyster yields were derived from Rothschild and colleagues [1994]). They also used sampling data on oyster densities of legally fishable size from unharvested sanctuaries in the Neuse River Estuary (Lenihan and Peterson 1998, 2004) to determine that these sanctuary reefs contain oysters worth $20,890–$52,224 per hectare in 2011 dollars. Reef sanctuaries in North Carolina contain densities of legally harvestable oysters similar to what the oyster yields were per unit area in Maryland a century ago and about one order of magnitude greater than the present landings in Maryland, as was described by Rothschild and colleagues (1994). Collectively, these studies suggest that the average oyster harvest value of a pristine reef in North Carolina and Virginia is $51,217 per hectare (in 2011 dollars). These results also suggest that traditional harvesting methods that degrade reef habitats (i.e., mechanical dredging, tonging) would probably decrease the density of legally harvestable oysters and, consequently, the value of oyster landings on restored oyster reefs in the sanctuaries of North Carolina shortly after the inception of harvesting (Lenihan and Peterson 2004).

To estimate the economic value derived from oyster harvests, the costs of harvesting must be subtracted from the value of the catch. We used estimates from the Chesapeake Bay oyster fishery from the 2006 season for the ratio of harvest value to costs associated with harvesting reported

Table 2. Ecosystem services provided by oyster reef habitat.

Ecosystem service	Ecosystem process	References	Bioeconomic model valuation method
Water quality improvement	Chlorophyll *a* removal	Newell et al. 2002, Grizzle et al. 2006	Replacement cost of using sewage treatment plant to remove nitrogen, nitrogen credit market
	Reduce turbidity	Newell and Koch 2004	
	Denitrification	Piehler and Smyth 2011	
	Increase benthic algal or pseudofecal production	Newell et al. 2002	Not applicable
	Bacterial biomass removal	Cressman et al. 2003	Not applicable
Seashore stabilization	Shoreline stabilization	Meyer et al. 1997	Cost of a sill to stabilize salt marsh and seagrass habitat, value of protected habitats
Carbon burial	Bury carbon dioxide	Not applicable	Traded carbon pollution credits
Habitat provisioning for mobile fish and invertebrates	Increased fish production	Peterson et al. 2003	Commercial dockside landings value, recreational fisher willingness to pay for improved fishing
Habitat for epibenthic fauna	Increased epibenthic faunal production and biodiversity	Wells 1961, Bahr and Lanier 1981, Lenihan et al. 2001	Already captured in fish values
Diversification of the landscape	Synergies among habitats	Micheli and Peterson 1999, Grabowski et al. 2005	Not applicable
Oyster production	Increased oyster production	Heral et al. 1990, Rothschild et al. 1994, Lenihan and Peterson 1998, 2004, Grabowski and Peterson 2007	Commercial oyster dockside value, recreational value-license program

by Wieland (2008). If we apply the maximum ratio of revenue to cost from the 18-year period for dredging (i.e., 1.5 in 2006) observed in Wieland's study, our average gross estimate of oyster value of $51,217 derived from pristine reefs results in a net value of $17,072. We estimate that the net annual value of oysters taken from degraded reefs worth $2639 would be $880. This estimate is probably optimistic, given that it is unlikely that harvesters would be able to sustain this profit rate at low oyster densities. We reasonably assume that if they are opened to destructive harvesting, oyster sanctuaries and pristine reefs would quickly switch from producing harvests at the upper end of this range in year 1 to levels near the annual value for degraded reefs in subsequent years.

Water quality services

Ideally, it would be possible to estimate the direct value of each water quality service (e.g., nitrogen removal through denitrification, phytoplankton removal, seagrass enhancement) by estimating people's willingness to pay for associated improvements, such as increased recreational opportunities, enhanced aesthetics, and greater biodiversity protection. Unfortunately, we cannot estimate the marginal effects of oyster reefs on these broad services. Here, we rely on proxy measures: the cost of providing the same ecosystem service through alternative means. This *avoided-cost* approach is appropriate when the cost estimates derived reflect the actual willingness of individuals to pay for a particular service (e.g., Tietenberg 2005).

This avoided-cost proxy is most plausible for nitrogen removal by oyster reefs, because there is evidence about the cost that the nation is willing to shoulder to reduce nutrient concentrations in American waterways as a consequence of regulatory policies stemming from the Clean Water Act of 1972. Nutrient-trading programs in particular provide an estimate of the marginal cost of nutrient removal and also provide at least rudimentary adjustments for the differences in spatial characteristics and uncertainty of those nutrient removals. Even though nitrogen permit prices are not direct measures of a willingness to pay for ecosystem services, they provide a reasonable estimate of that value.

We used data on the difference between nitrogen flux in oyster reefs and that in the alternative soft-sediment bottom to determine the amount of incremental nitrogen removed from the system by oyster reefs. Piehler and Smyth (2011) quantified nitrogen fluxes in both habitats (see Piehler and Smyth [2011] for detailed methodology). They found that the primary mechanism by which oyster reefs remove nitrogen from the system is by increasing local denitrification rates. We determined the net hourly rate of nitrogen removal by each habitat to be 246 and 12 micromoles of nitrogen per square meter (m^2) per hour during the day in oyster reefs and in mud habitat, respectively (see supplemental table 1, available online at *http://dx.doi.org/10.1525/bio.2012.62.10.10*). We then subtracted the amount of nitrogen removed in soft-sediment habitats from that removed by oyster reefs to obtain the augmented amount of nitrogen removed by creating 1 m^2 of oyster reef habitat and converted this estimate to annual kilograms of nitrogen removed per hectare of oyster reef habitat.

The annual value of a hectare of oyster reef was then determined by multiplying the annual rate of nitrogen removal by $28.23, which is the current average trading price per kilogram of nitrogen removed for estuarine sites in the North Carolina Nutrient Offset Credit Program (North Coast Atlantic Conference Rule no. 15A NCAC 02B .0240). This value is reviewed annually and is likely to rise as more expensive urban best-management plans for nitrogen offsets are needed and as the lowest-cost options are used up. The value of nitrogen removal from 1 hectare of oyster reef habitat was estimated at $1385–$6716 per year in 2011 dollars.

Next, nitrogen removal through the consumption of phytoplankton was calculated. We estimated the amount of phytoplankton removed from the system using the filtration rate per oyster from Grizzle and colleagues (2006). The estimate from Grizzle and colleagues (2006) stems largely from measurements collected in early summer and, therefore, may overestimate the phytoplankton removal potential of oyster reefs. Calculations of phytoplankton removal were based on low (4 and 10 micrograms per liter [μg/L] of chlorophyll *a*) and high (40 μg/L of chlorophyll *a*) phytoplankton biomass (see supplemental table 2). Chlorophyll *a* removal was converted to carbon removal using a carbon:chlorophyll-*a* ratio of 30 (Wienke and Cloern 1987). Carbon removal was converted to nitrogen removal using the Redfield ratio (Redfield 1958). The dollar value of nitrogen removal was estimated using the same shadow price for nitrogen as was used above. This value was not included in the overall reef value presented below to avoid double crediting reefs for nitrogen removal from filtration and denitrification services.

We have not included nitrogen incorporated into oyster shells and tissue because of the uncertainty of its fate. There is the potential for long-term storage in shells or tissue, but there is also a significant likelihood of relatively short-term release of nitrogen by senescence of oysters, processing of shell for fertilizer, consumption of oysters, and the release of nutrients back into estuaries through sewage treatment facilities. We have also not included the fate of remineralized nitrogen provided to the rest of the food web through oyster excretion and biodeposition, because these processes have not been quantified adequately, and it is not completely clear that they would be characterized as an ecosystem service.

On the basis of the evidence that oysters promote recovery, productivity, and maintenance of SAV in estuaries—a habitat valued for its role as nursery grounds for many coastal fish species (Thayer et al. 1978)—it seems appropriate to credit reefs for the ecosystem services provided by this additional SAV habitat. One of the present authors, JO, used willingness-to-pay valuation surveys to determine the value of eelgrass habitat in the Peconic River Estuary to local residents. The collective value of ecosystem services in 1995 provided per hectare of seagrass habitat totaled $22,894 per year ($33,730 in 2011 dollars after inflating in line with the annual average consumer price index). Assuming a 20-year life span of seagrass beds and a 3% discount rate for future benefit streams, the total value of a hectare of seagrass bed is $516,876 (in 2011 dollars).

Empirical data quantifying the relationship between oyster restoration and SAV recovery are lacking; however, suspension-feeding bivalves potentially promote SAV by reducing turbidity and by depositing nutrients in biodeposits (Everett et al. 1995, Carroll et al. 2008, Wall et al. 2008). Newell and Koch (2004) modeled the effects of oyster filtration on light penetration through the water column and subsequent effects on SAV. Their results suggested that relatively modest densities of oysters would promote SAV growth in shallow estuarine waters, where oyster reefs are prevalent in the southeast Atlantic and Gulf of Mexico. Therefore, we estimate that one hectare of oyster reef would promote the creation of 0.005 hectares of additional SAV, worth $2584. We recognize that the effects of oyster reef habitat on SAV will probably be influenced by several factors (e.g., the existing amount of oyster reef habitat; water turbidity, velocity, and depth; and the availability of SAV seedlings); therefore, we recommend that further research be conducted to scale these effects under meaningful variation in order to understand better how they affect the degree to which oyster reefs promote SAV habitat. Large-scale restoration efforts will probably be necessary to quantify measurable effects on water quality improvements in many key estuaries because nutrient and suspended solid loading rates currently surpass the filtration capacity of many local oyster populations.

Developing direct measures of the value of each service has been challenging because of the lack of the relevant data needed to conduct these analyses. Although the cost of providing equivalent services may seem high, many services that we have left unquantified and do not add to our sum could amount to far greater values. For instance, the valuation of regional services, such as water quality improvements in the Chesapeake Bay, has been estimated to be worth over $200 million (Bockstael et al. 1989), and the loss of 20% of the SAV habitat in the Chesapeake Bay has resulted in an estimated loss in fisheries value of $1 million to $4 million annually. It is also likely that valuable public health benefits through pathogen removal would accrue from increased oyster reef habitat. However, some fraction of these values is included in our estimates of denitrification, and we lack the data to account for this properly or to estimate the marginal value of discrete additions of restored oyster habitat. To the extent that the estimates we presented above do not fully account for all the water quality benefits of value, the indirect measures of the values associated with oyster reef ecosystem services calculated in this study are probably conservative.

Oyster reefs as habitat for fish

Oyster reefs provide important habitat for recreationally and commercially valuable fish species (Coen et al. 1999, Lenihan et al. 2001, Peterson et al. 2003, Grabowski et al. 2005). Peterson and colleagues (2003) quantified the value of augmented fish production from a unit of oyster reef after reviewing existing data from the southeast Atlantic and Gulf of Mexico coasts on the densities of all species of fish and fished crustaceans on oyster reefs and mud bottom. They found that 10 m^2 of restored oyster reef habitat creates an additional 2.6 kilograms of fish and large mobile crustacean production annually, because oyster reef habitat either enhances the recruitment rate of early life stages or enhances growth and survival by the provision of habitat with food resources and shelter from predators during some life stages. Although the augmented fish production estimates from Peterson and colleagues (2003) were developed for the Tampa Bay estuary, the data were derived from a quantitative synthesis of multiple studies from Texas to Virginia and are therefore widely applicable.

Grabowski and Peterson (2007) used these data to convert augmented fish production estimates into the enhanced values of landings for each of the 13 species groups that were augmented by oyster reef habitat. Their annual estimate of fish value ($3.70 per 10 m^2) was adjusted to a net present value of $4.12 per 10 m^2 to determine the present value of commercial fish per unit oyster reef. Future landings values were then discounted at a rate of 3%. Using these estimates, we calculated the commercial fish value of a hectare of oyster reef to be $4123 per year in 2011 dollars. We did not adjust this value to account for any costs associated with fishing, because we assume that any augmented fish from oyster reef habitat would be caught with existing effort. This assumption deserves testing. Peterson and colleagues' (2003) estimate of the augmentation of fish production by a unit of oyster reef habitat that would be available to the fishery is low for older age classes, because their estimate is based on fish and crustacean populations continuously exposed to fishing pressure, which acts to cull production benefits that then go uncounted. Consequently, our estimates of the value of this service of augmenting commercial fishery production are conservative.

The value of fish produced by a unit of oyster reef will vary as a function of many ecological and economic factors as well as how these species are managed. Capturing how these dynamics interact across natural and social-science disciplines is emerging as a central challenge to the effective implementation of ecosystem-based management. For instance, the value of oysters and the price of boat fuel will undoubtedly influence harvesting pressure, which will affect the quality of oyster reef habitat and the ecosystem services that the oysters provide. Meanwhile, the implementation of fisheries regulations that modify how recreational and commercial fishermen use oyster reefs will potentially affect not only the species that use oyster reefs but also their value.

The functional role of oyster reefs as habitat for fish is probably influenced by the amount of existing oyster reef habitat available for finfish and exploited crustaceans in a given estuary. Therefore, the marginal value of each unit of restored oyster reef may decrease as reefs are restored in the system, especially if large restoration projects or efforts in areas with large amounts of existing reef habitat result in fishery production for reef fish and crustaceans becoming limited by factors other than habitat availability. However, the abundances of many fish and crustaceans that use oyster reef habitat have been reduced by a long history of overfishing. Therefore, in studies conducted over the past two decades on fish use of restored reef habitat, the historical abundance of these species and, consequently, the functional significance of reefs as habitats for fishes within estuaries have probably been underestimated. Understanding how these processes scale across various gradients (e.g., salinity, latitude) will be especially important for taking restoration efforts to ecologically meaningful scales and especially to scales approaching historical levels of intact oyster bottom habitat.

Erosion protection

Oyster reefs can function as natural, living (as opposed to human-designed) breakwaters, bulkheads, or jetties, because they are structures that interact with tidal and wave energy just like engineered shoreline stabilization devices by baffling waves and increasing sedimentation rates (Meyer et al. 1997). The rate of vertical oyster reef growth on unharvested reefs is far greater than any predicted sea-level rise rate, and therefore, reefs could serve as natural protection against shoreline erosion, intertidal habitat loss, and property damage and loss along many estuarine shorelines. The current standard practice for inshore erosion protection is the use of engineered shoreline stabilization devices (Titus 1998). In locations where property owners would otherwise use these engineered devices, their cost can be used as a reasonable proxy for the economic value of oyster reef restoration. This assumes that reefs are perfect substitutes for human-made devices. Because oyster reefs can grow vertically faster than sea levels are expected to rise, an argument can be made that they are more resilient to sea-level rise than a fixed engineered device would be and, therefore, have a higher value as a shoreline stabilizer. But in addition, the relative risk of storm damage to engineered and oyster reef structures needs to be considered. Given that oyster reefs and unnatural engineered devices constitute similar physical structures, we assume an equivalence of value.

Estimates of the cost of these bulkheads and rock revetments ranged from $630 to $752 (in 2011 dollars) per linear meter (Allison 2001). Assuming that oyster reef has an average width of 5 meters, the value per hectare of oyster reef habitat would range from $1,074,475 to $1,504,265 (table 3a, 3b). These estimates represent the present value of stabilization services over the life of human-made structures and not an annual flow of benefits. We estimate the annual flow by assuming that these structures have a 20-year life span, and we assumed a constant annual value at a discount rate of 3%. We then used the average cost of our estimates of shore stabilization devices—$640 per linear meter—to estimate the value of oyster reef habitat shoreline stabilization relative to the percentage of reef habitat that provides this service.

Table 3a. The value of oyster reef habitat as a shoreline stabilizer.

Type	Cost (in dollars per linear meter [m])	Cost (adjusted)	Capital cost per hectare
Bulkhead	$630	$126	$1,260,359
Stone groin	$537	$107	$1,074,475
Stone sill	$752	$150	$1,504,265

Note: The adjusted cost assumes that 5 m^2 of oyster is required to protect 1 m of shoreline.

Table 3b. Approximated total value of shoreline stabilization for oyster reefs.

	Value (in dollars)	
Percentage of reefs that stabilize shorelines	Per 10 square meters	Per hectare
0.1	0.09	86
1.0	0.86	860
10.0	8.60	8600

Shoreline stabilization provides a stark illustration of the importance of location in determining the value of ecosystem services provided by oyster reef habitat. In locations where property owners demand such services and oyster reefs function as perfect substitutes for human-made structures, one hectare of oyster reef habitat is estimated to provide $85,998 of annual value. In locations where property owners would not otherwise build protective devices, any values created by shoreline stabilization and habitat protection will likely be far lower and could be zero. The significance of this result is that the economics of oyster restoration are likely to be strongly and positively affected by proximity to property that people wish to protect from erosion.

Conclusions

A fundamental goal of ecosystem-based management is to sustain the delivery of ecosystem goods and services that people rely on. With only 15% of the world's oyster reef habitat left (Lotze et al. 2006, Beck et al. 2011), substantial efforts are now under way to protect the remaining reef habitat, as well as to restore oyster reefs. The focus on oyster reefs has dramatically shifted from efforts to rebuild the oyster fishery to recovering and sustaining the ecosystem services associated with oyster reefs. Our estimates are aimed at helping refine future restoration efforts to quantify multiple disparate benefits of restoring oyster reef ecosystem services using a common unit of dollar valuation, a meaningful currency to people. Oyster reef restoration currently constitutes a small fraction of the overall estuarine habitat restoration efforts, even though this habitat is among the most degraded of all critical estuarine habitats. The cost of restoring oyster reef habitat is similar to those for

Table 4. Total annual value of ecosystem services provided by oyster reefs in 2011 dollars per hectare per year.

Ecosystem service values	Minimum	Maximum	Average
Oyster habitat state			
Pristine	12,186	21,959	17,072
Degraded	880	880	880
Finfish and mobile crustacean value			
Recreational	n/a	n/a	n/a
Commercial	4123	4123	4123
Water quality services			
Chlorophyll *a* removal[a]	0	0	0
Nitrogen removal[b]	1385	6716	4050
Recreational use	n/a	n/a	n/a
SAV enhancement[c]	0	2584	1292
Bacterial removal	n/a	n/a	n/a
Carbon burial	n/a	n/a	n/a
Shoreline protection[c]	0	85,998	860
Habitat for epibenthic infauna	0	0	0
Landscape processes	0	0	0
Nonoyster harvest service total	5508	99,421	10,325

Note: n/a represents insufficient data to assess the economic value of the service.

[a] The value of chlorophyll *a* removal was not included in the summary table because this service is considered potentially redundant if nitrogen removal through denitrification is also considered.

[b] The value of nitrogen removal was estimated by quantifying the value of enhanced denitrification rates on oyster reefs.

[c] The average submerged aquatic vegetation (SAV) enhancement and shoreline stabilization was valued assuming that 1% of the linear length of reefs perform this function.

seagrass, salt marsh, and mangrove restoration efforts and far less than the costs of restoring coral reefs (table 1). Therefore, one hopes that valuation efforts such as the present study, coupled with restoration cost and habitat loss information, will assist resource managers in deciding how best to use limited restoration funds and in prioritizing among the range of possible restoration projects.

In this article, we estimated an average annual value of services provided by restored and protected oyster reefs that ranges from $10,325 to $99,421 per hectare, depending on where the restored reef is located and the suite of ecosystem services that the restored reef provides. Both of these measures are at least an order of magnitude greater than the commercial value derived from harvesting the oysters produced by degraded reefs (table 4). This estimate of reef service value is probably conservative, because oyster reefs may provide additional services that are not valued here, such as recreational fishing, carbon burial, and augmented biodiversity. This value also does not include either the cost of restoring the reefs or the opportunity cost of choosing not to harvest the oysters. Using the median cost of restoration (table 1), our estimates suggest that a restored oyster reef would produce benefits equivalent to this cost (i.e., the break-even point) in 2–14 years, depending on where restoration is conducted and, consequently, on which services are achieved at what levels.

An alternative management scenario for oyster reefs is to open the restored reef to oyster harvesting as soon as it yields oysters of marketable size. Although the degree to which the ecosystem services discussed above are provided by highly degraded habitats is currently unknown, we assume that the provision of these services will be very low or nonexistent, because they scale with reef structure and oyster net metabolism, both of which are greatly degraded by harvesting (Lenihan and Micheli 2000). For the purposes of this study, we have assumed that highly degraded reefs provide little to no value other than remnant oyster harvests. Our estimates show that the value of oysters produced by such degraded reefs is insufficient to cover the cost associated with oyster reef construction (figure 1). Therefore, enhancing habitat purely to support a traditional oyster fishery with harvesting practices that result in degradation of the habitat is a poor use of public funds. A key question is whether there are socially acceptable, less destructive techniques, such as diver harvesting (Lenihan and Peterson 2004), in which oysters can be harvested without appreciable structural damage to the reefs so that a substantial fraction of the value of the other ecosystem services can still be sustained by these strategically fished oyster reefs. It is worth exploring whether such a hybrid approach is a viable management alternative.

Our estimates suggest that oyster reefs provide value not only as a commercial fishery resource for exploitation but also as a biogenic habitat providing diverse ecosystem services of substantial economic value. The total loss of goods and services from a century of overharvesting and the destruction of upward of 99% of reef habitat in some estuaries in the United States (Lotze et al. 2006, Beck et al. 2011, Wilberg et al. 2011) is staggering when one considers that our estimates imply an estimated present value ranging from $200,000 to $2,000,000 per hectare over 50 years. Because oyster reefs have been largely destroyed in areas such as the Chesapeake Bay and the southeastern United States (Kirby 2004), restoration efforts will be necessary in these regions in order to recover the goods and services potentially provided by reef habitat. Our analyses demonstrate that the total potential return on oyster reef restoration investments clearly justifies more restoration and protection of the existing oyster reefs and supports the assertion that these are economically efficient strategies. Oyster diseases have hampered many recent restoration efforts, so a 50-year life span for an oyster reef may seem unrealistic. However, historical reefs commonly existed for centuries prior to harvesting, and Lenihan and colleagues (1999) demonstrated that tall oyster reefs protected from damage by oyster-harvesting gear sustained oysters with low incidence and low intensity of the otherwise most serious oyster disease. In addition, the evaluation of reef sanctuaries in North Carolina determined that many reefs constructed two to three decades ago at natural reef elevations, undegraded by decades of dredge and tong damage, contain high densities of living oysters (Powers et al. 2009),

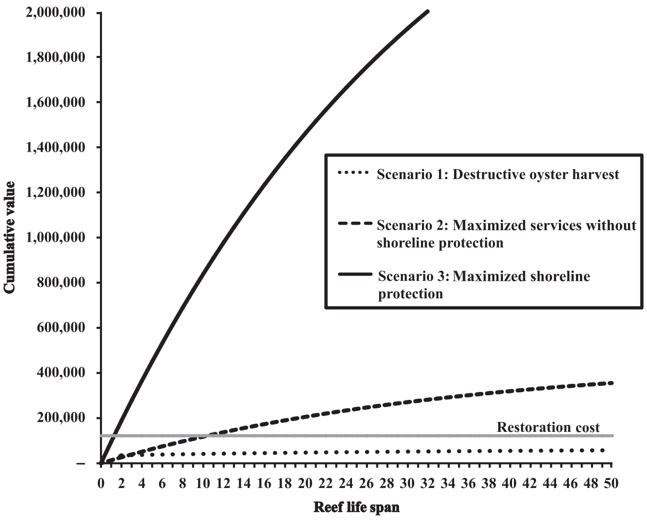

Figure 1. The cumulative value (in 2011 dollars per hectare) of reefs of varying life spans (in years) with destructive oyster harvesting (scenario 1), with no oyster harvesting or shoreline stabilization but positioned to maximize all other services (scenario 2), and with no oyster harvesting but positioned to maximize shoreline stabilization with the average value derived from other services (scenario 3). The values for future years were adjusted using a 3% annual discount rate. The gray line is the median cost per hectare of constructing oyster reef habitat.

which suggests that restored oyster reefs may be able to persist for several decades if they are left untouched.

In addition to making the case that resource managers should look closely at reef restoration as an efficient use of funds because of the high value of ecosystem services provided, our estimates also show the importance of location and other sources of heterogeneity in evaluating restoration projects. The clearest illustration of this is the value of shoreline stabilization services: Reefs that provide effective erosion protection potentially provide a value that dwarfs both restoration costs and the value of all other ecosystem services. A second illustration is the value of proximity to SAV habitat or potential SAV habitat: An oyster reef that is located near SAV or near an area where the presence of a high number of oysters could promote SAV development would have a higher potential to benefit this important habitat both by improving water quality and by baffling wave energy. Conversely, Grabowski and colleagues (2005) found that oyster reefs located next to a seagrass habitat did not augment juvenile fish abundance and, therefore, that this ecosystem service is not likely to be enhanced by oyster reef restoration in such landscape settings. Empirical and modeling studies that provide more detailed information will greatly enhance these assessments of how spatial location may be expected to influence of the values of diverse ecosystem services provided by oyster reefs.

Another important unknown factor is how reef characteristics, such as reef size and height, water depth, and salinity, affect ecosystem processes and the values derived from them. Establishing the relationship between oyster density and ecosystem services is particularly important, because allowing selective harvesting using nondestructive methods (*sensu* Lenihan and Peterson 2004) may ultimately maximize the total value of the goods and services provided by an oyster reef. Lenihan and Peterson (1998) also demonstrated that reef height and water depth are particularly important in areas where bottom water hypoxia and sedimentation issues are common. Developing decision-support tools that allow location-specific value estimates would be of great value in prioritizing restoration projects to enhance the value of the services that they provide.

Quantifying the value of ecosystem services should facilitate efforts to transition to ecosystem-based management by providing both an economic justification and a decision-making framework for prioritizing management actions. In this article, we developed estimates of the values of several important ecosystem services provided by oyster reef habitat. The estimates do not include the full range of services and involve some assumptions that deserve further consideration. In addition, our primary estimates are for a generic unit area of oyster reef habitat rather than for habitat with specific characteristics. We also used two restoration scenarios without oyster harvesting to demonstrate how much reef location can influence ecosystem service delivery and economic value. Nevertheless, many landscape-scale considerations will be necessary as managers attempt to maximize the utility of restoration efforts, because where an oyster reef is located will influence the degree to which it performs key functions. It is also unclear how the scale of restoration will affect processes such as water quality and SAV promotion. Our estimates of the total value of oyster reef services support the view that oyster reef restoration provides economic value through a range of diverse ecosystem services and that such restoration efforts should therefore receive serious consideration as a component of efficient estuary management.

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