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RESTORING OYSTER REEFS TO RECOVER ECOSYSTEM SERVICES

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15.1 - INTRODUCTION

Overharvesting of wild oysters and environmental mismanagement in estuaries around the world have resulted in the loss of fisheries income and collapse of an ecologically important ecosystem engineer and its associated ecosystem goods and services. The decline of the eastern oyster, *Crassostrea virginica* (Gmelin 1791), throughout the mid-Atlantic and southeastern U.S., has reduced landings to 1–2% of the historic peaks approximately a century ago in many estuaries such as the Chesapeake Bay and eastern North Carolina (Frankenberg 1995, Heral et al. 1990, Newell 1988, Rothschild et al. 1994). Declines in the abundance of oysters are a consequence of degradation of oyster reefs via destructive harvesting practices as well as overfishing, oyster disease, sedimentation, and water quality degradation, which collectively have greatly reduced the quantity and quality of intact reef habitat (Frankenberg 1995, Rothschild et al. 1994). Although restoration efforts have proceeded for several decades in estuaries throughout the eastern U.S., these efforts have traditionally focused on reversing the trend of declining landings rather than rebuilding sustainable oyster reefs that create habitat and other ecosystem services (Peterson et al. 2003).

Ecosystem Engineers

TABLE 15.1 Ecosystem services that are provided by oyster reef habitat.

Ecosystem Service	Benefit/Value
1. Production of oysters	(↑ market & recreational value)
2. Water filtration & concentration of pseudofeces	(↓ suspended solids, turbidity, phytoplankton biomass, & microbial production; & ↑ denitrification, submerged aquatic vegetation [SAV], & recreational use)
3. Provision of habitat for epibenthic inverts	(↑ biodiversity & productivity)
4. Carbon sequestration	(↓ greenhouse gas concentrations)
5. Augmented fish production	(↑ market & recreational value)
6. Stabilization of adjacent habitats and shoreline	(↑ SAV & salt marsh habitat; ↓ effects of sea-level rise [SLR])
7. Diversification of the landscape & ecosystem	(↑ synergies among habitats)

Oyster reefs are valued for the wide diversity of ecosystem goods and services that they provide (Table 15.1). Oyster reefs are the only hard substrate in a predominately soft-sediment environment (Lenihan 1999, Lenihan and Peterson 1998). The biogenic structure formed by vertically upright oyster aggregations creates habitat for dense assemblages of mollusks other than oysters, polychaetes, crustaceans, and other resident invertebrates (Bahr and Lanier 1981, Lenihan et al. 2001, Rothschild et al. 1994, Wells 1961). Juvenile fish and mobile crustaceans also recruit to and utilize oyster reefs as refuge and foraging grounds, so that oyster reefs augment the tertiary productivity of estuaries (Breitburg et al. 2000; Coen and Luckenbach 2000; Coen et al. 1999; Grabowski et al. 2005; Harding and Mann 2001, 2003; Luckenbach et al. 2005; Peterson et al. 2003; Rodney and Paynter 2006; Soniat et al. 2004; Tolley and Volety 2005). Removal of filter-feeding oysters from estuaries such as in the Chesapeake Bay and the Pamlico Sound has resulted in trophic restructuring that promotes planktonic and microbial organisms over demersal and benthic flora and fauna (Baird et al. 2004, Dame et al. 1984, Jackson et al. 2001, Newell 1988, Paerl et al. 1998, Ulanowicz and Tuttle 1992). Oysters also promote pelagic fauna by preventing primary production from entering microbial loops and thus allowing it to pass up the food chain to bottom-feeding fishes, crabs, and higher-order predators like red drum, tarpon, and dolphins (Coen et al. 1999, Peterson and Lipcius 2003). By filtering nutrients, sediments, and phytoplankton from the water column, oyster reefs also structured estuarine communities

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In addition to filtering water and providing critical habitat for transient and resident fish and invertebrates, oyster reefs perform several other important ecosystem services. Oyster reefs attenuate wave energy and reduce erosion of other valuable habitats such as salt marshes and SAV (Henderson and O'Neil 2003, Meyer et al. 1997). Oysters sequester carbon from the water column as they form calcium carbonate shells. As a carbon sink, oyster reefs potentially reduce concentrations of greenhouse gases (Peterson and Lipcius 2003). Oyster reefs also promote denitrification by concentrating deposition of feces and pseudofeces, which potentially enhances watershed management activities aimed at reducing anthropogenic N and promotes greater benthic plant production (Newell 2004, Newell et al. 2002). Finally, oyster reefs are an important component of the estuarine landscape. The location of an oyster reef could influence landscape-scale processes, such as providing a corridor between shelter and foraging grounds (Micheli and Peterson 1999, Peterson et al. 2003).

Previous attempts to assess the monetary value of ecosystem services provided by oyster reefs are limited, which inhibits the ability of managers to evaluate alternative habitat restoration options and make informed choices about how to manage restored oyster reefs. A more holistic understanding of the value of these services will also guide future restoration efforts. Here we discuss how to quantify the economic value of each of the ecosystem services provided by oyster reefs. We also provide quantitative estimates of the value of some specific functions (i.e., oyster harvests, water quality improvements, and recreational and commercial fishery benefits) where data are available in order to compare the value of harvesting oysters in a traditional fishery to the monetary value of providing other oyster reef services.

15.2 ◆ EVALUATING ECOSYSTEM SERVICES PROVIDED BY OYSTER REEFS

OYSTER REEFS AS A FISHED COMMODITY

Consumer demand for oysters continues to promote wild oyster fisheries in the U.S. where populations are still viable. Increased oyster landings in the Gulf of Mexico have partly compensated for lost productivity throughout many historically productive regions such as Delaware Bay, the Chesapeake Bay, Pamlico Sound, and the south-Atlantic coast of the

U.S. Even though the precipitous decline in landings in the Chesapeake during the 1980s was partly buffered by increased oyster prices, the loss in dockside value after adjusting for inflation from 1980 to 2001 is estimated at 93% (National Research Council 2004). Given that catch per unit effort (CPUE) also decreased by 39% during this time period (National Research Council 2004) and fuel costs have increased, the erosion of profits experienced by the industry during the past couple of decades is even greater than 93%. This decline in CPUE largely reflects increased regulations restricting harvesting practices and decreased oyster biomass in the oyster habitat. For instance, Rothschild et al. (1994) divided the total harvest value by the estimated amount of total oyster bottom, which they estimated declined by 50% between 1890 and 1991, and determined that a century of overharvesting reduced the annual oyster yield in Maryland per unit oyster bottom from 550 g/m^2 in 1890 to 22 g/m^2 in 1991.

We calculated the commercial value of oysters per unit of reef area in two ways. First, we multiplied the oyster yields reported in Rothschild et al. (1994) by the dockside market price ($3.01/lb of oysters in 1991) in coastal Maryland. Overharvesting reduced the value of oyster yields from $36.45 per 10 m^2 of oyster bottom in 1890 to $1.46 per 10 m^2 in 1991 (both values are in 1991 dollars). This reduction in value may be slightly underestimated if it is partly a consequence of decreased harvesting effort rather than a decrease in the density of harvestable oysters per unit of reef. However, it is unlikely that this pattern is largely due to reduced effort given that increases in oyster prices over the past two decades would likely motivate greater harvesting effort, and fishery-independent sampling efforts have determined that the density of living oysters in the Chesapeake Bay is two to three orders of magnitude below historic levels (Rothschild et al. 1994).

Second, we calculated the harvest potential using data from oyster reef projects in which oyster reefs were restored in coastal North Carolina. Using data on oyster densities of legally harvestable sizes in the Neuse River Estuary (Lenihan and Grabowski 1998, Lenihan and Peterson 2004), we estimated that subtidal reefs in this region contain 0.6–1.6 bushels of oysters per 10 m^2 worth $12.80–$32.00. The value of oysters on these reefs is roughly comparable to historic yields in Maryland a century ago and approximately an order of magnitude greater than the present oyster fishery production from reefs in Maryland. This difference is largely a consequence of experimental reefs in North Carolina having not been subjected to continual harvest because they were designated as reef sanctuaries. Furthermore, these results suggest that harvesting by traditional methods such as dredging and hand-tonging would likely result in rapidly decreasing oyster yields in subsequent years if harvesting were initiated on these reefs in North Carolina (Lenihan and Peterson 2004).

BEYOND OYSTERS: VALUING ADDITIONAL ECOSYSTEM GOODS AND SERVICES PROVIDED BY OYSTER REEFS

Although the value of oyster landings throughout the eastern U.S. has been recorded since the nineteenth century, economic evaluations of the additional ecosystem services provided by oyster reefs are limited. This paucity of economic data is partly a reflection of viewing oysters narrowly as a fishery resource to exploit rather than holistically as an ecosystem engineer that should be managed as a provider of a multitude of goods and services. Of further concern, a century of overharvesting has left most if not all ecosystems across the coastal U.S. with two to three orders of magnitude fewer oysters (Frankenberg 1995, Heral et al. 1990, Rothschild et al. 1994), and existing oyster reefs may be so degraded that they do not perform the same services as intact historic reefs (Dame et al. 2002, Jackson et al. 2001, Lenihan and Peterson 1998, Newell 1988). However, scientists have utilized oyster reef restoration over the past two to three decades to investigate how oyster reefs function (Coen et al. 1999, Dame et al. 1984, Grabowski et al. 2005, Harding and Mann 1999, Lenihan et al. 2001, Meyer et al. 1996, Newell et al. 2002, Peterson et al. 2003, Zimmerman et al. 1989). This information has assisted managers not only in shifting from an exploitable-resource to a valued-habitat view of oyster reefs but also in enhancing the ability to recover goods and services through oyster reef restoration. Incorporation of ecological data into economic models that integrate the value of each of these services will further managers' capacity to decide among management options and alternative restoration designs in order to maximize the value created by restored reefs.

Oysters as a biofilter

Oysters are filter feeders that feed upon suspended particles in the water column, pumping such a high rate of water flow that they are considered an important biofilter that helps maintain system functioning (Baird and Ulanowicz 1989, Grizzle et al. 2006, Newell 1988). The decline of oyster populations in estuaries along the eastern U.S. has coincided with increased external nutrient loading into these coastal systems (Paerl et al. 1998). Collectively these ecosystem perturbations have increased bottom-water hypoxia and resulted in restructured food webs 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, Jackson et al. 2001, Lenihan and Peterson 1998, Paerl et al. 1998, Ulanowicz and Tuttle 1992).

Perhaps one of the most compelling examples of the consequences of loss of filtration capacity is Newell's (1988) estimate that oyster populations in the Chesapeake Bay in the late 1800s 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. Two other examples of the filtration capacity of bivalves include the introductions of the clam (*Potamocorbula amurensis*) in San Francisco Bay and zebra mussels (*Dreissena polymorpha*) in the Great Lakes, which have demonstrated how dramatically suspension feeding by bivalves can remove suspended solids and nutrients from the water column (Alpine and Cloern 1992, Carlton 1999, Klerks et al. 1996, MacIsaac 1996). Although the decline in oyster populations undoubtedly contributed to the decline in water quality in the Chesapeake over the past century, the application of quantified changes in water quality as a consequence of small-scale restoration studies to larger-scale, estuarine-wide management of water quality presents some significant challenges.

Experimental manipulation of oyster populations has demonstrated that oysters can influence water quality by reducing phytoplankton biomass, microbial biomass, nutrient loading, and suspended solids in the water column. Other potential water quality benefits could result by concentrating these materials as pseudofeces in the sediments, stimulating sediment denitrification, and producing microphytobenthos (Dame et al. 1989). For example, Porter et al. (2004) manipulated the presence of oysters in 1000-l tanks and found that oysters increased light penetration through the water column by shifting algal production from phytoplankton to microphytobenthos-dominated communities. Microphytobenthos biomass subsequently reduced nutrient regeneration from the sediments to the water column. Cressman et al. (2003) determined that oysters in North Carolina decreased chlorophyll a levels in the water column by 10–25% and fecal coliform levels by as much as 45% during the summer. Grizzle et al. (2006) developed a method to measure seston *in situ* and subsequently demonstrated that this method more precisely identifies differences in seston than traditional techniques conducted in a laboratory, suggesting that studies relying upon laboratory analyses may underestimate the effects of oysters on seston. Nelson et al. (2004) transplanted oyster beds in small tributaries in coastal North Carolina and noted that some small reefs reduced total suspended solids and chlorophyll a levels. Laboratory studies also have found that bivalves influence local plankton dynamics and reduce turbidity levels (Prins et al. 1995, 1998). On the other hand, Dame et al. (2002) removed oysters from four of eight creeks in South Carolina and noted that the presence of oyster reefs explained little of the variability in chlorophyll a, nitrate, nitrite, ammonium, and phosphorous. 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), so that small-scale restoration efforts or restorations in deeper water may not necessarily achieve detectable gains in water quality.

Attributing a single value per unit of oyster reef restored may be inappropriate if the relationship between the spatial extent of oyster reef habitat and water quality is nonlinear (Dame et al. 2002). For instance, in some estuaries large-scale restoration efforts may be necessary before water quality is measurably improved because nutrient and suspended solid loading rates currently far surpass the filtration capacity of the oyster populations present in these bays. Future research efforts that provide empirical data on this functional relationship will greatly benefit attempts to model the economic services provided by oyster reefs. Because these inherent difficulties exist in generalizing the economic benefits associated with oyster filtration, one alternative approach would be to quantify the cost of providing a substitute for this service. As a natural biofilter that removes suspended solids and lowers turbidity, oyster reefs are analogous to wastewater treatment facilities. Thus the filtration rate of an individual unit of oyster reef can be quantified and compared to the cost of processing a similar amount of suspended solids and nutrients with a waste treatment facility.

Larger-scale restoration efforts within shallow coastal embayments designed to achieve improvements in water quality could have substantial indirect benefits of great economic value. First, by decreasing water turbidity (i.e., by filtering suspended solids) and suppressing nutrient runoff, oyster reefs can promote the recovery of SAV in polluted estuaries (Peterson and Lipcius 2003). Newell and Koch (2004) modeled the effects of oyster populations on turbidity levels and found that oysters, even at relatively low biomass levels (i.e., 25 g dry tissue weight m^{-2}), were capable of reducing suspended sediment concentrations locally by nearly an order of magnitude. This reduction would result in increased water clarity that would potentially have profound effects on the extent of SAV in estuaries such as the Chesapeake Bay.

Recognized as extremely important nursery grounds for many coastal fish species (Thayer et al. 1978), vegetated habitats such as SAV have been reduced in estuaries such as the Chesapeake Bay by agricultural runoff, soil erosion, metropolitan sewage effluent, and resultant N loading from all of these sources as well as atmospheric deposition. Nitrogen loading at levels of 30 kg N ha^{-1} yr^{-1} within Waquoit Bay, Massachusetts, resulted in the loss of 80 to 96% of the total extent of seagrass beds, and seagrass beds were completely absent in embayments with loading rates that doubled this amount (Hauxwell et al. 2003). They also found that nitrogen loading increased growth rates and standing stocks of phytoplankton, which likely caused severe light limitation to SAV by reducing light penetration through the water. Kahn and Kemp (1985) created a bioeconomic model to estimate damage functions for commercial and recreational fisheries associated with the loss of SAV in the Chesapeake Bay and determined that a 20% reduction in total SAV in the Bay results in a loss of 1–4 million dollars annually in fishery value. If improvements in water quality from oyster reef habitat increase the amount of SAV in the estuary, then the value of augmented fishery resources created by this additional SAV should be attributed to oyster reefs.

Second, improvements in water quality in general are valued by the general public who use estuarine habitats for activities such as swimming, boating, and sportsfishing. For instance, Bockstael et al. (1988, 1989) surveyed residents in the Baltimore–Washington area in 1984 and determined that their annual aggregate willingness to pay in increased taxes for moderate (i.e., ~20%) improvements in water quality (i.e., decreased nitrogen and phosphorous loading and increased sportsfishing catches) was over $100 million. The National Research Council (2004) used the consumer price index to adjust estimates reported in the preceding studies to 2002 price levels and reported 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, $26 million for recreational boaters, and $8 million for striped bass sportsfishermen. Although there are several potential sources of error in these estimates, they may be underestimated given that improvements in the Chesapeake Bay water quality will likely result in increased recreation in the Bay and these analyses did not include the value that U.S. residents outside of the Baltimore–Washington area place on Bay resources despite the nation-wide recognition and utilization of the Chesapeake Bay (Bockstael et al. 1988). Evaluation of ecosystem services provided by oyster reefs should include assessment of this suite of benefits if larger-scale oyster restoration efforts achieve measurable improvements in water quality in estuaries along the Atlantic and Gulf coasts of the U.S.

Oysters as habitat for fish

Several studies have used restoration efforts to assess the role of oyster reefs as critical habitat for commercially and recreationally important fish species (Coen et al. 1999, Grabowski et al. 2005, Harding and Mann 1999, Lenihan et al. 2001, Meyer et al. 1996, Peterson et al. 2003, Zimmerman et al. 1989). Our ability to quantify the value of fish provided per unit area of oyster reef will be dependent upon several factors, such as (1) whether oysters successfully and regularly recruit to the reef and create vertical relief that provides habitat for important prey species; (2) the amount of existing oyster reef habitat already available locally; (3) whether other habitats are functionally redundant to oyster reef habitat and consequently compensate for oyster reef degradation; (4) an oyster reef's location (or landscape setting) within the network of oyster reefs and other important estuarine habitats that already exist; and (5) the biogeographic region (or ecosystem) where it is located.

Given the context dependency of oyster reef community processes, assessments of economic benefits for commercial and recreational fisheries must incorporate knowledge of the life history and ecology of local fish species. For instance, while water quality improvements in the Chesapeake Bay would generate value for striped bass fishermen if catches increased, improvements in water quality in the estuaries of the southeast would not provide this particular value because striped bass do not extend south of Cape Lookout, North Carolina. Peterson et al. (2003) reviewed existing data on oyster reef restoration efforts from the southeast U.S. and determined that each 10 m^2 plot of restored oyster reef habitat produces an additional 2.6 Kg yr^{-1} of production of fish and large mobile crustaceans for the functional lifetime of the reef. Because these efforts were focused on the southeast U.S., species that utilize oyster reef habitat located in other estuaries in the U.S. such as striped bass but are not indigenous to this region were excluded from the analyses. On the other hand, those species utilizing an oyster reef in the southeast U.S. clearly include ecological equivalents for species restricted to other biogeographic regions, so the degree of enhancement of fish production may be similar.

Using 2001–2004 dockside landing values from the southeastern U.S. and Gulf of Mexico (National Marine Fisheries Service 2006), we converted the amount of augmented production per each of the 13 species groups that were augmented by oyster reef habitat in Peterson et al. (2003) to a commercial fish landing value (Table 15.2). We then calculated the streamline of cumulative benefits provided by a 10 m^2 oyster reef for the functional lifetime of the reef (Figure 15.1). Future landings values were discounted at a rate of 3% to adjust for the opportunity cost of capital adjusted for inflation. Our estimates suggest that a 10 m^2 reef that lasts 50 years would produce finfish valued at $98.06 in 2004 dollars, whereas harvesting this same reef for oysters destructively after 5 years would reduce this finfish value to $17.45 in 2004 dollars. Although a future fishery resources. For instance, the provision of ecosystem goods and services by oyster reefs may be dependent upon the amount of oyster reef habitat already in the system, such that the marginal value of each unit of restored oyster reef may vary as more and more reefs are restored in the system. In particular, restoration of extensive amounts of reef habitat within some estuaries may result in reef-related species that are limited by factors other than habitat availability. However, this initial estimate may be conservative because the abundances of many fish and crustacean species that utilize oyster reef habitat also have been dramatically reduced from decades of overfishing, so that recent studies investigating fish use of restored reef habitat likely underestimated the potential abundance of these species. Enhancing our understanding of these processes to regional scales will be especially important if restoration efforts ever begin to approach historical levels of intact oyster bottom given that the amount of shell bottom in 1884 in just the Maryland portion of the Chesapeake Bay was estimated at 279,000 acres (Rothschild et al. 1994).

Other ecosystem services provided by oysters

Oysters create biogenic structure by growing in vertically upright clusters that provide habitat for a wide diversity of densely aggregated invertebrates (Bahr and Lanier 1981, Lenihan et al. 2001, Rothschild et al. 1994, Wells 1961). Although few of these species (i.e., mollusks other than oysters, polychaetes, crustaceans, and other resident invertebrates) are of commercial or recreational value to fishermen, they are consumed by many valuable finfish and crustacean species and thus indirectly benefit fisheries (Grabowski et al. 2005, Peterson et al. 2003). Given that we have already calculated the benefit of oyster reef habitat to fish in the previous section, we did not ascribe additional value to these benthic invertebrates that reside on oyster reefs. However, evaluations of estuarine biodiversity and its maintenance should include consideration of oyster reef habitats given that they can contain one to two orders of magnitude more macro-invertebrates than adjacent mud bottom (Grabowski et al. 2005).

Oyster reefs attenuate wave energy and stabilize other estuarine habitats such as salt marshes (Meyer et al. 1997). Oyster reefs also promote sedimentation, which potentially benefits the establishment of SAV (Henderson and O'Neil 2003). Oyster reefs are a living breakwater that can and will rise at rates far in excess of any predicted sea-level rise rate and thus help stabilize shoreline erosion and habitat loss, which are otherwise predicted to be dramatic in many coastal estuaries if left

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unprotected by natural buffers (Reed 1995, 2002; Zedler 2004). Although there are currently insufficient data with which to quantify the generality of these processes and assess their economic value, these services are indicative of the integrated mosaic of estuarine habitats. Thus a more complete evaluation of the ecosystem services provided by oyster reef habitat will require not only a greater understanding of its role in influencing coastal geology within the estuarine landscape but also evaluations of the services provided by the habitats oyster reefs promote.

Investigation of how the landscape setting of restored oyster reefs influences these ecological processes will be pivotal to future assessments. For instance, an oyster reef located in between a salt marsh and SAV may be an important corridor for predators moving among habitats (Micheli and Peterson 1999, Peterson et al. 2003). Conversely, some ecosystem services provided by oyster reefs in these vegetated landscapes may be redundant. For instance, Grabowski et al. (2005) found that restored oyster reefs in vegetated landscapes do not affect juvenile fish abundances, whereas oyster reefs restored on mudflats isolated from SAV and salt marshes augment juvenile fish abundances and potentially increase fish productivity within estuaries. The landscape setting of an oyster reef will also influence other processes such as oyster recruitment and survivorship (Grabowski et al. 2005), which in turn could affect filtration rates and subsequent removal of seston from the water column. Ecological studies that quantify landscape and ecosystem-scale variation in these processes will enhance our ability to model spatial variability in the value of services provided by oyster reefs.

15.3 ⁂ CHALLENGES AND CONCLUSIONS

Evaluation of the ecosystem services provided by oyster reefs could assist coastal managers in readjusting management schemes to maximize the benefits of restoration efforts and consequently shift to an ecosystem approach to fisheries management. For instance, comparison of oyster harvest values with other services reveals the importance of evaluating ecosystem services rather than continuing to exploit oyster reefs for the oyster harvest value. Although the value of oyster harvests may initially measure up to other benefits such as the value of augmented fish production to the commercial fishery, the consequences of destructive oyster sampling either require continual restoration efforts or would result in oyster harvest levels similar to severely degraded estuaries along the eastern U.S. Whether oyster reefs can sustain less destructive oyster harvesting techniques (i.e., how quickly oysters grow to replace losses by harvest) such as diver collection of oysters by hand is unclear and merits further investigation.

Given that the value of augmented commercial fish landings surpasses oyster harvest values, the entire suite of ecosystem services that are sustained by intact reefs probably greatly exceeds the value currently derived from oyster harvests. Oyster restoration efforts at larger scales that enhance water quality potentially result in even larger benefits such as increased recreational use, heightened willingness to consume seafood, and reduced need for construction of wastewater purification systems. Water quality improvements from oyster restoration efforts and their economic values are more difficult to quantify; however, current estimates of the willingness of boaters, beach users, and recreational fishermen from the Chesapeake Bay to pay for local improvements in the Bay's water quality suggest that oyster restoration efforts capable of achieving significant gains in water quality will result in economic returns derived from these changes that far exceed the value of current oyster landings.

Lack of quantitative information on several of the other ecosystem services hinders a more complete evaluation of the suite of benefits provided by oyster reefs and, subsequently, hampers the ability of regulators to implement a more ecosystem-based approach to managing coastal resources. Insufficient data currently exist to fully evaluate local (landscape-scale) and regional variability in ecosystem services. This information would allow coastal managers to determine which reefs provide disproportionately valuable service and should be conserved as sanctuaries. It would also help managers identify those that are less valuable and could be harvested without as much concern for the ecosystem consequences. Placing oyster reefs in the greater context of the estuary requires landscape-scale data with simultaneous evaluation of each habitat across multiple trophic levels, which is difficult to obtain. However, larger-scale restoration efforts to assess the recovery of ecosystem services are currently being conducted in the Gulf of Mexico and in several estuaries along the East Coast of the United States. These studies will greatly enhance our ability to develop more holistic economic models that account for spatial variability in the provision of ecosystem goods and services by oyster reefs.

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