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NOTE

Intertidal oyster reefs can persist and function in a temperate North American Atlantic estuary

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ABSTRACT: Intertidal oyster reefs in lower Delaware Bay are ephemeral and it is generally assumed that oyster mortality due to predation, disease and winter ice scouring inhibits their persistence. In June 2006, shell-bag oyster reefs of varying height were constructed on the intertidal sand flats in lower Delaware Bay, USA, to determine the potential for oyster reef restoration in this temperate estuary. Oyster settlement, mortality and recruitment were compared among reefs, as was habitat value for motile fauna. Oysters recruited shortly after reefs were constructed. Motile macrofauna immediately began using the reefs, increasing species richness and abundance relative to the adjacent sand flat. Little post-settlement mortality was observed in oysters by October 2006 and most survived exposure to snow and ice during winter. Shifting sediments nearly buried the shortest reef by April 2007, a process that may be more important in limiting the development of oyster reefs in this system than predation, disease or ice shear. Results indicate that there is good potential for the development of intertidal oyster reefs in this region.

KEY WORDS: *Crassostrea virginica* · Habitat · Recruitment · Mortality · Sedimentation · Delaware Bay

INTRODUCTION

As in many North American Atlantic Coast estuaries, the Eastern oyster *Crassostrea virginica* Gmelin is strongly linked to the history and socio-economic structure of communities surrounding Delaware Bay, USA. Post-World War II technological improvements facilitated a rapid expansion of the oyster fishery until overfishing and 2 virulent oyster diseases (Dermo and MSX) decimated the industry (Farley 1988, Ford 1996). A sustainable subtidal population remains and supports a small but viable fishery (Canzonier et al. 1998); however, recent recruitment failures nearly forced its closure (Powell et al. 2006, 2007). As a result, a major subtidal shell-planting program is in progress to increase oyster recruitment and production for the fishery (US ACE 2006).

In addition to the socio-economic structure it supports, *Crassostrea virginica* is also ecologically valuable. Dame (1996) summarizes a variety of ecosystem processes influenced by marine bivalve molluscs, one of which is creation of habitat. Gregariously settling oysters form beds and reefs that create spatial heterogeneity, giving the beds an intrinsic habitat value (Breitburg 1992, Harding & Mann 2000). This habitat provides nursery grounds and refuge from predation, as well as reproduction and foraging sites for a variety of estuarine species (Coen & Luckenbach 2000, Harding & Mann 2001, Luckenbach et al. 2005, Rodney & Paynter 2006). Studies in Virginia, Maryland, Louisiana and the Carolinas have quantified (1) increases in species diversity and abundance (Coen et al. 1999, Coen & Luckenbach 2000, Breitburg et al. 2000, Luckenbach et al. 2005), (2) effects of intertidal reefs on reducing shoreline erosion (Meyer et al. 1997, Piazza et al. 2005) and (3) effects of reef height on recruitment and persistence (Lenihan 1999, Nestlerode et al. 2007), via the creation and restoration of

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oyster beds and reefs. In Delaware Bay, Maurer & Watling (1973) surveyed the fauna associated with subtidal oyster beds. Intertidal oyster reefs occasionally form along the Cape Shore in lower Delaware Bay (Fig. 1), but few studies have examined their ecology. The Cape Shore consistently receives high oyster recruitment (Powell et al. 2007), but substrate is limiting and mortality is high, resulting in the formation of ephemeral oyster reef habitat. This study investigated the use of shell-bags to construct intertidal oyster reefs. Our objective was to gather information about the effects of reef height on (1) oyster recruitment and mortality, (2) habitat utilization by motile fauna and (3) reef persistence within the intertidal zone.

MATERIALS AND METHODS

In June 2006, 3 oyster shell-bag reefs were constructed on the sand flats of the Cape Shore region of lower Delaware Bay, USA (Fig. 1A). Mesh bags (14.3 mm opening) were filled with 19 l of oyster shell and arranged side-by-side in a 1.5 m × 3 m rectangular footprint to form the base of each reef. The shell-bag reefs mimic the small oyster reefs that form periodically on the sand flats (Fig. 1B–E). Reefs were separated by 10 m, aligned parallel to the beach and contained 1 (Reef 1), 2 (Reef 2) and 3 (Reef 3) layers of shell-bags; each layer was ca. 16 cm high. Maximum tidal amplitude at the Cape Shore is ~2.75 m. During

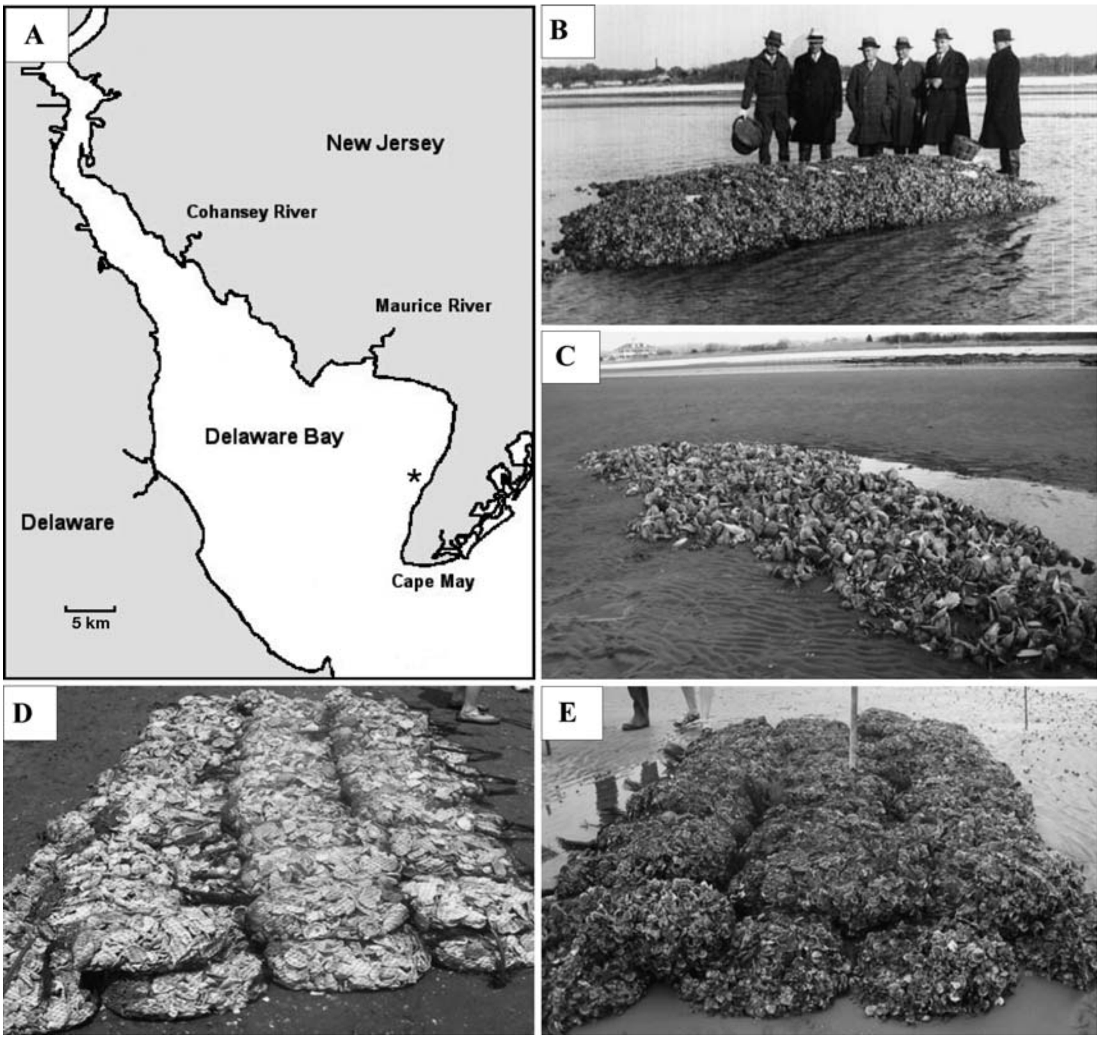

Fig. 1. (A) Lower Delaware Bay showing location of study site (*: 39° 04′ 25′ N, 74° 54′ 46′ W) at Rutgers' Cape Shore Hatchery Facility near Green Creek, New Jersey. (B) Historical (ca. 1940) intertidal oyster reef at study site. (C) Recent (ca. 2004) intertidal oyster reef at study site. (D) Two-layer shell-bag reef constructed on intertidal sand flats, 26 June 2006, before recruitment. (E) Two-layer shell-bag reef on 5 October 2006, after natural oyster recruitment

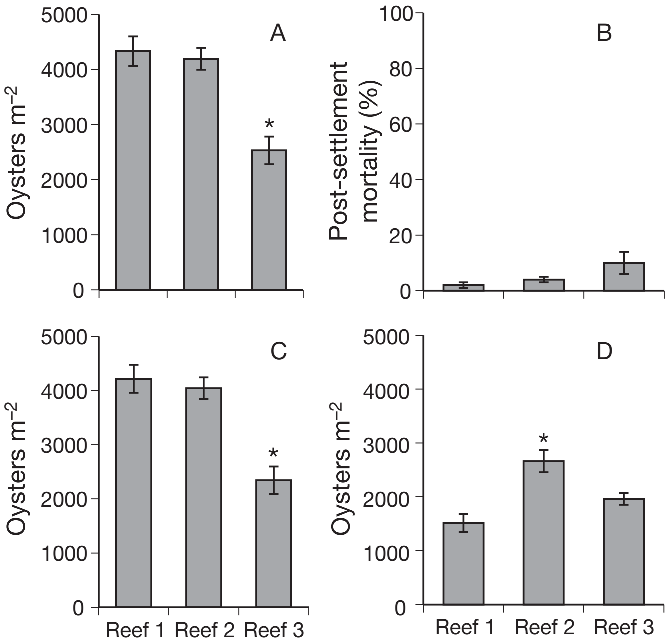

Fig. 2. *Crassostrea virginica.* (A) Estimated settlement, (B) post-settlement mortality through October 2006, (C) recruitment through October 2006 and (D) abundance in April 2007. Data are means ± SE calculated from 10 cm^2 quadrats (n = 16 per reef). *p < 0.001 for Tukey's post hoc comparisons

high tide, the mean water depth was ~2 m where the constructed reefs were located. Reefs were exposed for ~4 h during low tide.

On 5 October 2006 and 10 April 2007, live and dead oysters were counted on all 3 shell-bag reefs without disturbing reef structure by using a 10 cm^2 quadrat haphazardly placed along 4 transects (n = 16 per reef). Transects were perpendicular to the beach and approximately evenly spaced across each reef. Settlement was estimated as the sum of live and dead oysters m^{-2} in October 2006. Dead oysters included boxes (empty valves), gapers (boxes containing oyster tissue) and scars (marks left from recently detached oysters). Post-settlement mortality was estimated as the number of dead oysters divided by the number of dead plus live oysters in October 2006. Recruitment was defined as the number of live oysters m^{-2} in October 2006. Overwinter survival was calculated as the number of live oysters m^{-2} in April 2007 divided by October oyster recruitment. One-way ANOVA and Tukey's post hoc comparisons ($\alpha = 0.05$) were used to test for differences among reefs in oyster settlement, recruitment, post-settlement mortality, and April 2007 oyster abundance. Reef persistence over time was documented photographically.

Motile fauna were sampled every 2 wk with unbaited, galvanized steel 6.35 mm mesh traps (length = 45 cm, diameter = 23 cm, 25.4 mm funnel entrances at each end) secured to the reef base or in a control sand area (10 m from the nearest reef) during low tide. At the next low tide, all individuals captured were identified to species and enumerated. Sixteen collections were conducted from 27 July to 16 October 2006 using 1 trap per treatment, while 4 collections were completed from 17 to 26 October 2006 using 5 traps per treatment.

RESULTS

Natural oyster settlement occurred shortly after reefs were constructed and extensive recruitment was evident in October (Fig. 1E). Estimated settlement and recruitment through October 2006 for Reefs 1 and 2 were significantly greater and nearly double that of Reef 3 (Fig. 2A,C). Post-settlement mortality through October 2006 increased from Reef 1 to Reef 3, reinforcing the pattern of differential settlement. At this time, mortality was 10% or less for all reefs and differences among reefs were not statistically significant (Fig. 2B, p = 0.08). In contrast, over-winter mortality was greatest on Reef 1 (64% vs. 34 and 16% on Reefs 2 and 3, respectively); this altered live oyster abundances among reefs by April 2007 (Fig. 2D). Highest oyster abundance in April 2007 occurred on Reef 2 and was significantly greater than abundances on Reef 1 and Reef 3.

The primary cause of over-winter mortality on Reef 1 was sedimentation (Fig. 3). Shortly after reef construction, sediments accumulated in front of each reef. Small, shallow (<10 cm deep) tidal pools often formed behind each reef, increasing in area with the height of the reef. By April 2007, sediments covered most of Reef 1, eliminating any remnants of a tidal pool. The heights of Reef 2 and Reef 3 protected them from the effects of sedimentation. Sediments accumulated in the first layer of each reef, but the accumulation decreased with reef height (Fig. 3).

Thirteen different motile species were collected on the reefs while only 7 species were captured on the sand flat (Table 1). All species collected on the sand flat were present on the reefs and faunal abundances were higher on reefs than on the sand flat. Total abundance was inversely related to reef height (Table 1). The most commonly observed reef species were *Palaemonetes pugio*, *Nassarius obsoletus* and *Pagarus longicarpus*. *P. pugio* was the dominant species on all 4 sampling sites, while *N. obsoletus* was collected exclusively on the reefs. The yellow-phase American eel *Anguilla rostrata* was the most abundant of 5 fish species and was associated solely with the reefs.

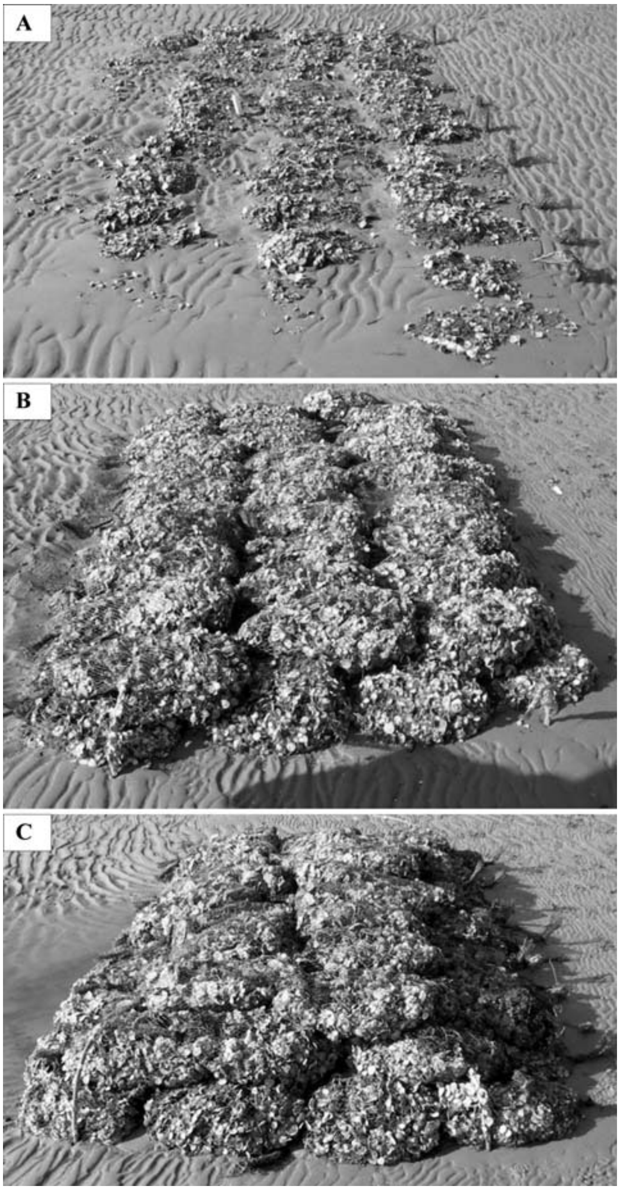

Fig. 3. Photographs comparing sedimentation around (A) Reef 1, (B) Reef 2 and (C) Reef 3 in April 2007

DISCUSSION

This study demonstrates the utility of shell-bag reefs for creating oyster reef habitat in temperate estuaries. The reefs consisted of wild oysters set on disarticulated shell, creating a habitat matrix similar to a natural oyster bed, which was quickly utilized by typical oyster reef fauna (Maurer & Watling 1973, Luckenbach et al. 2005). Oyster settlement, recruitment, survival and reef persistence varied according to reef height.

Although lower Delaware Bay is the highest oyster settlement zone in the bay (Powell et al. 2006, 2007), persistent intertidal reefs do not form. The absence of intertidal reefs in this region of the bay is often attributed to predation, disease, and freezing or ice shear. Our data demonstrate that shifting sediments contribute to the ephemeral nature of intertidal reefs. During winter 2007, several feet of ice accumulated on the Cape Shore flats (G. DeBrosse, Rutgers Cape Shore Shellfish Hatchery Manager, pers. comm.), yet oysters survived and Reefs 2 and 3 persisted. Therefore, it seems more likely that shifting sediments inhibit the formation of intertidal reefs rather than predation or harsh winter conditions. Both MSX and Dermo disease are highly prevalent at the Cape Shore (Haskin & Andrews 1988, Ford 1996), but generally cause mortality in older oysters and were not expected to significantly affect the oysters observed in this study.

Results indicated that oyster habitat supports a greater abundance and perhaps a greater species richness of motile species than the adjacent sand flats. Decapod crustacean abundance on reefs was twice that on the sand flat, and 5 fish species utilized the reefs while only 3 species were captured on the sand flats. The highest species richness and abundance observed corresponded with the reef that supported greatest oyster recruitment (Reef 1), although this reef did not persist. Interestingly, 5 American eels *Anguilla rostrata* of increasingly larger size were captured over the course of the summer and fall on reefs, but not on the adjacent sand flat. The timing of these captures corresponds to eel migrations and may indicate that the oyster reef structure provides a useful refuge or foraging habitat for eels during their migrations.

Other studies have found similar responses. For example, in Chesapeake Bay, Rodney & Paynter (2006) observed a 4-fold increase in xanthid crabs and demersal fish on restored subtidal oyster reefs over non-restored controls and *Palaemonetes pugio* abundance was more than 10 times greater on restored reefs. On the Eastern Shore of Virginia, Arve (1960) found that 3 times as many fish were captured over subtidal shell plantings as on unplanted controls. Results from the present study show a 4-fold increase in xanthid crabs and almost twice the number of fish species on intertidal reefs as on sand flat. In South Carolina, Luckenbach et al. (2005) found that the decapod crabs *Eurypanopeus depressus* and *Panopeus herbstii*, which naturally inhabit intertidal reefs, were good indicators of community development on restored intertidal oyster reefs. Both crab species were captured in the present study, albeit at low frequencies with the gear used. These species are common on subtidal oyster beds elsewhere in Delaware Bay and, with a more appropriate sampling method, may likewise be good indicator species for intertidal oyster reefs in Delaware Bay. Sampling gear is known to influence size and

Table 1. Species sampled with wire mesh traps on the 3 intertidal shell-bag reefs and control sand plot. Values denote total number of individuals collected. Total abundance and species richness is shown for all 4 sampling sites. Reef 1: 1 shell-bag layer; Reef 2: 2 shell-bag layers; Reef 3: 3 shell-bag layers. Fish species and common names referenced from Nelson et al. (2004). Invertebrate species and common names referenced from Williams et al. (1989) and Turgeon et al. (1998)

Species name	Common name	Sand	Reef 1	Reef 2	Reef 3
Teleosts					
Anguilla rostrata	American eel	0	1	2	2
Bairdiella chrysoura	Silver perch	1	1	1	0
Lagodon rhomboides	Pinfish	1	1	0	1
Menidia menidia	Atlantic silverside	2	0	0	1
Opsanus tau	Oyster toadfish	0	0	1	0
Crustaceans					
Palaemonetes pugio	Daggerblade grass shrimp	15	40	35	29
Pagurus longicarpus	Longwrist hermit crab	10	19	11	20
Callinectes sapidus	Blue crab	4	2	5	2
Panopeus herbstii	Atlantic mud crab	1	3	0	0
Crangon septemspinosa	Seven spine sand shrimp	0	2	1	0
Eurypanopeus depressus	Flatback mud crab	0	1	0	1
Rhithropanopeus harrisii	Harris mud crab	0	1	0	0
Gastropods					
Nassarius obsoletus	Eastern mud snail	0	15	11	6
Total abundance		34	86	67	62
Species richness		7	11	8	8

composition of fauna collected. For example, Able et al. (2005) found that fish <20 mm total length were never captured in wire mesh traps. In the present study, small naked gobies *Gobiosoma bosc* were often observed in the reefs, but were never trapped. A more comprehensive sampling regime will likely reveal additional insights into the habitat value of intertidal oyster reefs in temperate estuaries like Delaware Bay.

Intertidal oyster reefs have been shown to reduce shoreline erosion along the southeastern Atlantic coast of the United States (Meyer et al. 1997) and in the northern Gulf of Mexico (Piazza et al. 2005). Rates of erosion are high in many areas of Delaware Bay, including the Cape Shore (Phillips 1986). In addition to property loss, erosion has eliminated valuable beach, dune, and marsh habitats, negatively affecting fisheries production, horseshoe crab spawning, and migratory shore bird foraging. The survival of the 2 taller intertidal reefs indicates that constructed intertidal oyster reefs represent a potentially viable strategy for reducing erosion in Delaware Bay and similar temperate estuaries, while also providing additional ecological services through the creation of a novel habitat and the ecological functions associated with oyster reefs.

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