Managing Oysters in South Carolina: A Five Year Program to Enhance/Restore Shellfish Stocks and Reef Habitats Through Shell Planting and Technology Improvements

Loren D. Coen[1] , Nancy Hadley[2] , Virginia Shervette[3] , and Bill Anderson[4]

A SC SALTWATER RECREATIONAL FISHERIES LICENSE PROGRAM FINAL REPORT

Marine Resources Center

SCDNR

217 Fort Johnson Rd

Charleston, SC 29412

www.dnr.sc.gov

2011

[1] current address: Coastal Watershed Institute, Florida Gulf Coast University, 10501 FGCU Blvd., Ft. Myers, FL 33965

[2] SCDNR, Marine Resources Division, PO Box 12559, Charleston, SC 29422-2559

[3] current address: Belle W. Baruch Institute for Marine & Coastal Sciences, 607 EWS Building University of South Carolina, Columbia, SC 29208

[4] SCDNR retired

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The Eastern oyster, *Crassostrea virginica*, forms intertidal reefs that are a dominant feature of many Atlantic and Gulf Coast estuaries (Bahr and Lanier 1981; Burrell 1986, 1997, 2003; Dame 1996; DeBlieu et al. 2005; ASMFC 2007; Beck et al. in review), and provides viable recreational and commercial fisheries in many coastal areas (MacKenzie et al. 1997; ASMFC 2007). Though diseases are often cited as the primary reason for oyster declines, overharvesting, habitat destruction, water quality declines, and little or no shell replacement have been major causes for the dramatic declines throughout the Atlantic and Gulf Coasts. Recent research by South Carolina Department of Natural Resources (SCDNR) and other groups across the U.S. has shown that oysters and the habitat they generate are far more valuable for their 'ecosystem services' than previously envisioned (Coen et al. 1999b, French McCay et al. 2003, Newell 2004, Newell et al. 2007, ASMFC 2007, Coen et al. 2007b, Grabowski and Peterson 2007). Scientists have suggested that this broader view for shellfish communities is so compelling that it is time to move the issue of oyster reef restoration and protection into the management arena (Kaufman and Dayton 1997, Jackson et al. 2001, Jordan and Coakley 2004, Lotze et al. 2006, ASMFC 2007, Grabowski and Peterson 2007, Powers et al. 2009, C. Peterson, UNC, pers. comm.).

SCDNR enhances oyster resources and fish habitat by deploying shell to serve as hard substrate for oyster recruitment. In recent years, the effectiveness of this enhancement in creating self-sustaining oyster habitat has been inconsistent. As oyster shell becomes scarcer and more expensive, the state needs to optimize the effectiveness of shell planting activities (cf. Powers et al. 2009). The primary goal of this five-year project was to evaluate the effectiveness of SCDNR shell-planting activities and make recommendations for improvement. As part of this project, we also evaluated the current status of Public Shellfish Grounds for the first time in order to establish a baseline for future comparisons and prioritize restoration needs. We quantitatively evaluated success of shell planting each year using a suite of conventional and innovative tools. For most annual efforts, selected planting sites were chosen based on their status as Public Shellfish Grounds. This constraint, except when federal funding was available, limited the location and site characteristics that could be used to evaluate planting variables. Finally, we conducted experiments to evaluate different management techniques. There are currently efforts underway at SCDNR using Saltwater Recreational Fishing License revenues to evaluate a suite of alternative materials. A report will be forthcoming in the near future on that effort.

Overview of Findings

Recreational shellfish grounds throughout the state were surveyed/assessed for the first time (Table 1), which provides a basis for prioritizing restoration activities. A total of 81 large-scale reefs covering 9 acres was constructed at 34 sites from 2002 through 2006, using a total of more than 150,000 bushels of shells (Table 2). Fifteen of 20 PSGs and 8 recreational-only SSGs received plantings during this time period. In addition, shell was planted on four additional SSGs and two undesignated areas with other funding. Sites were selected for planting based on the status of existing oyster populations, logistical considerations such as accessibility, the potential for successful restoration, and other factors such as harvest pressure.

Restored sites were studied over time to evaluate the success of the planting for developing sustainable oyster habitat. These studies included:

1. Measuring the area of coverage (footprint) immediately after planting and after one or more years of exposure;
2. Evaluating potential and actual oyster recruitment;
3. Evaluating oyster populations after one or more years of growth;
4. Evaluating shell depth over time at some sites; and
5. Evaluating shell movement and the effectiveness of retarding shell movement with a mesh covering.

Some of these studies yielded information which can be used to gauge the success of the restoration effort, while others yielded information which we can use to modify/improve our restoration strategies. We additionally collected baseline information on each site, which allows us to evaluate success in terms of site attributes and improve site selection in the future.

For this study, we evaluated restoration success based on the following criteria: (a) shell 'retention', as measured by initial and final footprints; and (b) oyster population parameters on the constructed reefs, which were compared to data collected from natural oyster populations over the last decade. We were not able to obtain both pieces of the success measure (footprint and population) at all sites, but we do have both footprint and population data for 43 of the 61 reefs constructed from 2002 to 2005. 2006 reefs were not evaluated as part of this study. We rated these 43 restored reefs, based on footprint retention and oyster populations, on a scale of 1 to 5, with 1 being the lowest and 5 the highest (Table 14, Figure 9). Seventy-seven percent of the reefs were average or better than average (Scores of 3, 4, or 5), while 23% were below average (Scores of 1 or 2).

Composite success scores were evaluated on the basis of site attributes and time of planting (Tables 15 and 16). Time of planting (early, middle, or late in the planting season) did not have a significant effect on success. Neither creek width nor shoreline slope had a significant effect on reef success, nor did bottom firmness. There were significant effects related to substrate type, boat wakes, and wave energy. Sites with muddy substrates were more likely to be successful than those with sand/shell substrates. Sites with estimated (limited direct observations) high boat traffic were less likely to be successful than sites with lesser levels of boat traffic. Similarly, sites with high energy (wind, current) were less likely to be successful than sites with less energy. Sites with high energy (boat or wind/current) are often characterized by firm, sandy bottom as the finer sediments are washed away. Thus all the attributes that appeared to affect success were related (directly or indirectly) to energy levels at the site. This should be interpreted cautiously because none of these parameters were actually measured; the sites were simply characterized based on anecdotal observations.

Oyster recruitment (larval supply, survival, and growth potential) was assessed at restoration sites annually by placing shell trays adjacent to planted areas. Recruitment varied significantly among years, with the 2004 mean recruitment almost three times that in 2003 (Table 17, Figure 10). For all trays deployed statewide during the same period (2002-2005), 2005 recruitment was highest overall, with both 2004 and 2005 having significantly greater recruitment than 2002 and 2003. Recruitment varied significantly among SRFAC sites in all years, with the exception of 2004. Oyster recruitment based on deployed trays at a given site was always higher than the oyster recruitment documented on the adjacent constructed reefs (Figure 18). This may be due to differences in timing (trays are deployed in spring but the reefs are sometimes not constructed until late in the summer) or to factors related to the tray itself, such as greater shell stability or increased interstitial space.

For stabilizing shell in areas exposed to heavy waves, strong currents, or boat wakes, we evaluated the utility of covering planted shell with a lightweight plastic polypropylene diamond mesh. We found that adjacent unmeshed areas of reefs often had significantly higher oyster densities than meshed areas after one or more years of recruitment. These results led us to conclude that meshing was not an effective restoration tool as deployed. However, in contrast, MRD's Office of Fisheries Management, Shellfish Management Section, found excellent mesh results in a study conducted in Two Sisters Creek in the ACE Basin NERR in 2000 (Anderson and Yianopoulos 2003). Unfortunately, that study had no unmeshed treatments for comparison.

Field trials building upon prior and current work with scientists from University of Central Florida (L. Walters and P. Sacks) tested the stability of meshed and unmeshed shell when exposed to boat wakes of varying magnitudes. In our South Carolina trials, shell under mesh, regardless of distance or wave energy, moved significantly less than unmeshed shell. We hypothesize that mesh-covered shell is more stable on the shoreline than unmeshed shell, but that a related negative effect is greater sedimentation. Shell movement may shed sediment and/or keep sediment stirred up and in suspension. Thus, covering planted shell with mesh may actually retard recruitment if time lapse between planting and oyster recruit arrival is great enough to allow sediment to cover the shell surfaces.

As an adjunct to the mesh overlay experiments, we evaluated several commercially available meshes for longevity in field applications, with a view to finding an environmentally-friendly mesh which would serve the purpose of retaining the shell but would eventually degrade benignly. Meshes deployed at three field sites for up to 12 months showed very little, if any, ultraviolet (UV)-associated damage, but were damaged at high energy sites, apparently as a result of wave/current action. Jute mesh disassociated rapidly at all field sites. Water and mud appear to be acting as a significant filter to UV since mesh exposed on an experimental platform degraded much more rapidly. We will continue to evaluate new meshes as they become available, but none of those tested to date meets the goal of stabilizing the shell for a sufficiently long period of time and then degrading harmlessly.

In 2004, we conducted a small-scale experiment to evaluate recruitment on different shell types: local SC oyster shell, Gulf oyster shell, and whelk shell. Mean total oyster recruitment on the three different shell types was not significantly different. This supports previous results observed at small-scale (SCORE) restoration sites indicating that these three shell types are equally attractive to oyster larvae as cultch.

We conducted a pilot experiment to evaluate shell quarantine times with regards to oyster disease transmission (Bushek et al. 2004). This is an issue because much of the oyster shell recycled in SC is originally derived from other states, mostly Gulf Coast states, which may have different or more virulent oyster pathogens. This is not a human health issue, but it is an important oyster resource issue. We found that both the amount of oyster tissue present and parasite abundance declined precipitously after one month and was virtually eliminated by three months. The results support the recommendation that the quarantine of shell for one month or more can dramatically reduce the potential risk of spreading *P. marinus* (Dermo, the pathogen used as a test case in this study) when planting oyster shell from other geographic areas. This recommendation is applicable to virtually any region, but several parameters such as effects of climatic conditions and shell pile configuration should be taken into consideration. There is also the possibility that other pathogens not studied here may persist after 30 days. With that in mind, SCDNR errs on the side of caution and quarantines recycled shells for at least 90 days prior to planting.

Recommendations

Our overall recommendations to enhance the effectiveness of SCDNR's shell planting program are as follows:

(1) Restoration sites should be revisited after one year to determine if maintenance planting or other adaptive management is needed.

(2) Public grounds should be reassessed regularly to adjust restoration priorities. (e.g., if a public ground is in good condition it can be given reduced priority, whereas if one has declined in status it should be given priority for restoration.)

(3) New technology should be exploited to develop rapid and consistent monitoring methods that can expedite future efforts and allow a smooth transition to the "next generation" of managers.

(4) The shell recycling program should be expanded to reduce reliance on out-of-state shell sources.

(5) The evaluation of alternative cultch materials that are more readily available than shell should be a priority. We should investigate using non-shell foundations with shell veneers to reduce overall shell requirements.

(6) Boat wakes are a threat to natural and restored reefs. SCDNR should explore the feasibility of establishing no-wake zones or restricting large vessel traffic in shellfish growing areas, particularly in the smaller creeks.

(7) Public outreach and education activities should be continued and expanded to increase public awareness of ecological value of oyster reefs, negative effects of boat wakes, and the need to recycle shell.

(8) Studies evaluating methods of stabilizing shell against waves, currents and boat wakes should be continued.

(9) Shell planting activities should be expanded to restore oyster habitat in additional areas such as those closed to harvesting.

INTRODUCTION

Estuaries and their component habitats are recognized as some of the most productive and important ecosystems, providing critical feeding, spawning, and nursery areas for species that include economically-important fish, shellfish, and waterfowl. South Carolina's coastal zone contains approximately 578,000 acres of wetlands and estuarine area, inclusive of marshlands, tidal creeks, rivers, and sounds (SCDHEC 2010). Recently, the South Carolina Department of Natural Resources (SCDNR) has been generating updated and detailed maps of intertidal oysters and adjacent marsh habitats across the state through its current large-scale statewide remote sensing program using ¼ m resolution imagery. This information will aid in identifying areas that are in need of protection, enhancement, or restoration.

The Eastern oyster, *Crassostrea virginica*, forms living subtidal and intertidal reefs that are a dominant feature of many Atlantic and Gulf Coast estuaries (Kennedy et al. 1996, ASMFC 2007, Anonymous 2007, Beck et al. in review). Eastern oysters and shell habitats they generate are unique in their ecological role because they form living reef structure (Zimmerman et al. 1989; Kaufman and Dayton 1997; Coen et al. 1999b; 2007b; Coen and Luckenbach 2000; Lenihan and Micheli 2000; Jackson et al. 2001; Lenihan et al. 2001; Lehnert and Allen 2002; Grabowski and Peterson 2007; ASMFC 2007; Beck et al. in review) in estuaries throughout their distribution. They support a host of other associated organisms (over 300 species in North Carolina) generally not found in surrounding sand or mud habitats (Wells 1961; Stanley and Sellers 1986a,b; Coen et al 1999b; Coen et al. 2006, 2007b; ASMFC 2007). Recent research has attempted to quantify the contribution of oyster habitat to ecosystem functioning (Peterson et al. 2003; Grabowski and Peterson 2007, Brumbaugh and Toropova 2008) in economic terms. Oysters create complex three-dimensional habitats utilized by numerous fishes, crustaceans, other invertebrates, birds, and mammals (reviewed in Coen et al. 1999b, 2007b, ASMFC 2007) and they appear to rival salt marshes in terms of harboring organisms (Glancy et al. 2003, Coen et al. 2006, 2007b, Tolley and Volety 2005, Rodney and Paynter 2006, ASMFC 2007). Shell alone, once planted, attracts a diverse community of organisms prior to oysters and other sessile organisms recruiting (Dumbauld et al. 1993, Lehnert and Allen 2002, Coen et al. 2006, 2007b, ASMFC 2007). With time, oysters and mussels accumulate and cumulatively these bivalve molluscs can filter significant quantities of water, potentially improving water clarity/quality (Cressman et al. 2003, French McCay et al. 2003, Nelson et al. 2004, Newell 2004, Grizzle et al. 2006, 2008, ASFMC 2007, Fulford et al. 2007, Newell et al. 2007). They also form a unique association with fringing saltmarsh habitats where the two habitats often abut (DeBlieu et al. 2005, Piazza et al. 2005, Coen et al. 2006).

Oyster populations have declined significantly along the Atlantic Coast in many areas where commercial oyster harvesting was traditionally important (Rothschild et al. 1994, MacKenzie 1996, MacKenzie et al. 1997, Kirby 2004, NRC 2004, Street et al. 2005, Thayer et al. 2005, Lotze et al. 2006, ASMFC 2007). The causes of the decline are diverse, and include over-harvesting, pollution and its related impacts, habitat destruction, and oyster diseases. Diseases such as Dermo (*Perkinsus marinus*) and MSX (*Haplosporidium nelsoni*, probably introduced to the East Coast) impact oyster populations, but not human health throughout most of the East Coast of the U.S. (Ewart and Ford 1993, Ford and Tripp 1996, Bobo et al. 1997, Burreson et al. 2000). These diseases often cause significant mortalities in oysters before they are able to reach a harvestable size.

Hydrodynamic forces associated with natural (Goodwin 2007) or anthropogenic causes such as boating (Zabawa and Ostrom 1980, Nanson et al. 1994, Crawford et al. 1998, Grizzle et al. 2002, Coen unpublished data) can result in the atypical erosion/disturbance of marsh-edge habitats (e.g., oyster reefs, *Spartina, Juncus*) and negatively affect associated communities (Piazza et al. 2005, ASMFC 2007). The loss and/or disturbance of marsh edge habitat, if significant, may reduce estuarine productivity and negatively impact commercial and recreational fisheries (Micheli and Peterson 1999, National Research Council 2007). Possible effects on marshes and oyster reefs include both reduced oyster productivity and destabilization of the marsh edge resulting in a greater likelihood of marsh habitat loss.

Shoreline erosion associated with tidal channels is a major problem in South Carolina, as it is elsewhere (Gabet 1998, NRC 2007). Undercutting by wind waves, tides, and boat impacts can cause slumping (calving) of large masses of sediment embedded with *Spartina* (Gabet 1998, Chose 1999, L. Goodwin 2007, Coen et al. in prep., N. Vinson pers. comm.). Spartina has been documented to be an important habitat for estuarine productivity (e.g., as a feeding ground for juvenile fishes and their prey) and is known to perform many other ecological functions such as buffering run-off (Weinstein and Kreeger 2000).

Many potentially harvestable shellfish beds in the U.S. have been closed to reduce health risks from consumption of contaminated shellfish (see National Shellfish Sanitation Program's Website, *http://www.issc.org/*). Currently, approximately 33% of South Carolina's state waters are closed to harvesting by 2010 South Carolina Department of Health and Environmental Control (*http://www.scdhec.net/environment/water/docs/sftrend.pdf*).

South Carolina oysters typically establish intertidal beds in locations where salinity is moderately high, food supply is sufficient, and siltation is not excessive, although oysters can live in highly turbid waters (reviewed in Coen 1995). In southern North Carolina, Georgia, and South Carolina, oysters grow along fringing marsh, bordering creeks and rivers ("fringing reefs") or isolated from shorelines on "oyster flats" (Galstoff 1964; Bahr and Lanier 1981; Burrell 1986, 2003; Street et al. 2005; Coen et al. 1999a; Powers et al. 2008). A SCDNR survey in the 1980s estimated that SC's coast has more than 2,000 acres of intertidal oyster beds (Anderson, unpublished data). In contrast, oysters in the Chesapeake Bay (Maryland and Virginia), and Gulf of Mexico (e.g., Apalachicola Bay, Florida) have primarily subtidal beds (Galstoff 1964, Stanley and Sellers 1986b, ASMFC 2007).

Intertidal oyster reefs generally consist of densely-growing, vertical clusters of oysters built upon a fragile (Lenihan and Micheli 2000, Lenihan and Peterson 2004) matrix of both live oysters and dead shell surrounded by fine sediments (Bahr and Lanier 1981; Dame et al. 1984a,b; Burrell 1986, 2003; Anderson et al. 1979; Coen et al. 1999a; Giotta 1999; Coen and Walker 2005; Coen et al. 2006; 2007a,b, in review;). Hence they can be impacted significantly by harvesting activities, which may disrupt the fragile underlying matrix (Lenihan and Micheli 2000, Beck et al. 2001, Lenihan and Peterson 2004, Coen and Bolton-Warberg 2005, Powell et al. 2006, Beck et al. in review). Oysters are generally harvested in our state by handpicking oyster clusters at low tide in authorized areas (Burrell 2003). On the other hand, when done with care, harvesting can be highly beneficial to oyster populations, decreasing densities and reducing tidal elevation to allow for faster growth.

With the realization that oysters are ecologically significant as well as a harvestable resource, most Atlantic and Gulf Coast states have established oyster restoration and enhancement programs. Most restoration programs rely heavily on substrate replenishment. Oysters must attach to a hard substrate, other oyster shell being preferred. The demand for oyster shell (coupled with the decreased harvests) has created a widespread shortage of shell. In SC, the shell shortage was exacerbated by the transformation of the oyster industry in the late 1980s from a cannery-based industry to a shell-stock/oyster roast industry. When the industry was based on cannery production, shell was stockpiled at the canneries where it was easily accessible for replanting. With the current industry focused on oyster roasts, shell is widely scattered and more difficult to locate.

To the best of our knowledge, oyster populations in South Carolina are relatively stable (Burrell 2003; Coen et al. 2005, 2006, 2007b), although assessing this widespread resource is difficult and data are therefore scarce. It is clear from the example of the Chesapeake Bay that managing and enhancing our existing oysters is a cheaper and more achievable alternative than restoring them should they fall below sustainable levels. Enhancing and restoring oysters in South Carolina, even in closed areas, will have greater impacts than just oyster resource augmentation: it can provide manifold effects on marshes and other habitat services mentioned already above (Meyer et al. 1997, Glancy et al. 2003, ASMFC 2007, French McCay 2007, Brumbaugh and Toropova 2008, Beck et al. In review). It also may provide a more natural, less costly and intrusive approach for shoreline protection than hard bulkheading (Riggs 2001, Rogers and Skrabel 2001, Piazza et al. 2005, NRC 2007).

SCDHEC and SCDNR share responsibility for the management and enforcement of harvesting related to most shellfish resources (Coen and Bolton-Warberg 2005, Coen et al. 2005, 2006), except whelk (SCDNR alone). A statewide resource survey of South Carolina's washed oyster shell deposits was completed in 1978 (Anderson et al. 1979). In the early 1980s SCDNR began mapping the state's intertidal oyster resources by classifying beds into one of nine "strata" (see Appendix 3). From this, GIS shellfish maps were produced through the tedious process of ground surveys and manual aerial photograph interpretation (summarized in Jefferson et al. 1991).

In 2004, SCDNR received funding for a state-wide program to collect and analyze high resolution (¼ m multi-spectral) imagery of the entire state's coastline (over 300 km of shoreline), in order to assess all intertidal oyster resources, including oyster flats, 'undesignated,' and 'closed' areas (Smith et al. 2005). This statewide program will be completed in 2008 with the imagery and associated products made available through SCDNR's image clearinghouse. This project, when completed, should enable us to: (1) complete future evaluations of oyster resources using high-resolution imagery as a part of a longer-term monitoring plan to periodically assess broad scale changes in the condition of the state's shellfish beds; (2) provide government agencies and other interested users with high-resolution imagery and maps (see link at *http://www.dnr.sc.gov/GIS/descoysterbed.html*) of oyster resources, marsh, and other features within the coastal zone; and (3) allow us to focus our oyster restoration efforts using current state management plans and status and trends analyses from other South Carolina programs/projects.

For resource management purposes, shellfish areas in South Carolina are classified into four categories by SCDNR. 'State Shellfish Grounds' (SSGs) are the areas where recreational and commercial harvesting occurs. Note that some SSGs have been designated as "Recreational-Only". 'Public Shellfish Grounds' (PSGs) are the areas where recreational harvesting only occurs. 'Culture Permits' are the areas under private management for commercial harvesting; permit holders pay an annual fee to SCDNR and incur planting requirements based on the extent of the resource. 'Grant Areas' are the grounds that are privately held based on declarations by the 'British Crown and Lords Proprietors' land conveyances (so called 'Kings Grants') dating back to pre-colonial and colonial days and more recent South Carolina legislative grants.

At the beginning of the SRFAC-supported program, OFM estimated that 44.8% of South Carolina's oysters were located in Beaufort County, 46.8% were located in Charleston County, and 5.3% were located in Georgetown County. Together, these three counties account for 97% of the SC oysters. State Shellfish Grounds (SSGs) range in size from 0.03-18.5 acres, with an average acreage of 4.80 (+0.74). At the time of this study, there were 72 designated SSGs, of which 8 were designated 'Recreational-Only.' The 64 remaining may be permitted for commercial harvesting or relaying (oysters or clams, intertidal or subtidal). Of these 64 SSGs, 21 are essentially 'clam only,' with few or no harvestable oysters, or are subtidal and can only be harvested mechanically. During this time period, fourteen of the 64 SSGs were 'closed' to some extent by DHEC for harvesting oysters or clams. Ten areas have "oyster flats," but only two of those 10 had been mapped prior to the current ongoing statewide remote sensing program (Sewee Bay, S272, 50.4 acres; Clark Sound, S205, 31.4 acres). Five additional SSGs that may have some intertidal oyster acreage had not been surveyed as of 2002.

SSGs and PSGs vary both in aerial extent and in quantity of resource. Of the 24 most important SSGs, 23 have harvestable oysters that are in DHEC 'Approved' or 'Conditionally Approved' waters. Based on data from the MRD statistics section, 15 SSGs have reported harvests of less than 100 bushels cumulatively for a 10-year period. From 1994-2003, approximately 83% of the commercial SSG landings came from just 6 SSGs; the next 10 SSGs accounted for another 15%, yielding approximately 98% of the state's commercial harvests from SSGs. Thus, we recommended that by assessing these 16 SSGs, OFM could assess a majority of the commercially-productive grounds with reduced manpower.

Annual commercial harvests on SSGs typically range from 20,000 to 30,000 bushels. Recreational harvesting levels are unknown but OFM-SMS assumes, based on a study conducted in 1996, that annual recreational harvesting pressure is approximately 43% of the commercial harvests from SSGs. Recently a change in commercial harvest reporting requirements made it possible to collect information on catch per unit effort (CPUE). From 2004-2006, the average CPUE on SSGs was 4.5-4.6 Bu/hr with CPUEs on individual grounds ranging from 1 Bu/hr to 11.3 Bu/hr.

At the time of this study, there were 20 designated Public Shellfish Grounds (PSGs), and an additional 8 State Shellfish Grounds (SSGs) that were 'Recreational-Only' areas. Although all 28 are for recreational harvesting of either oysters or clams, six are essentially 'clam only' with few or no harvestable oysters. Although the harvest status of grounds varies annually, during this study four of the 22 recreational oyster grounds were partially restricted or conditionally approved by SCDHEC. The remaining 18 recreational areas with oysters were 'Approved' for harvesting during this time period. The 20 PSGs are estimated to total approximately 100 acres. PSGs range from 0.1-9.9 acres, with an average (+1SE) acreage of 2.95 (+0.59). Eleven of these grounds have oyster flats (as opposed to fringing banks), six of which had been surveyed as of 2001. The eight recreational SSGs total an additional 50 acres. Recreational harvesting is not limited on SSGs or PSGs, with the exception of management closures (R. Haggerty and B. Anderson, pers. comm.). Management closures are most often implemented after a restoration activity but may also be used in cases of severe over-harvesting.

When we began our program in 2002, there were nine Grant Areas along the South Carolina coast, including a large portion of North Inlet National Estuarine Research Reserve (North Inlet-Winyah Bay NERR). As of 2007, there are 13 Grant areas, but most of these have not been thoroughly surveyed to determine acreage of actual oyster grounds, nor have all of the state's 'undesignated' or polluted areas been surveyed. Current SCDNR shellfish management area maps can be found at *http://www.dnr.sc.gov/marine/shellfish/pubshell.html* and *http://www.dnr.sc.gov/marine/shellfish/stateshell.html* and current resource status reports can be found at *http://www.dnr.sc.gov/marine/publications.html*).

The Shellfish Research Section has been quantitatively assessing the status of South Carolina oyster resources by direct sampling with random and replicated quadrats for almost a decade (Coen et al. 2005, 2006). Population information collected includes the number and size of live oysters, the ratio of live:dead shell, the disease status of a population, and associated fauna. Recruitment and early growth of oysters were assessed statewide on an annual basis at selected SSGs and PSGs and other relevant sites, including restoration sites (Coen et al. 2005a,b). This long-term monitoring provides essential information on natural populations that can be used to establish targets for restoration.

Overview of the 2001-2006 SRFAC Program

The primary goal of this five-year project was to evaluate the effectiveness of SCDNR shell-planting activities and make recommendations for improvement. The specific objectives were to: (1) survey existing recreational oyster grounds to evaluate the state of the resource and make planting recommendations; (2) study large-scale restoration efforts on selected PSGs and SSGs in order to evaluate effectiveness; (3) evaluate restoration success in terms of site characteristics in order to improve site selection; (4) evaluate restoration alternatives (e.g., different substrates, substrate stabilization methods) to determine whether they are effective both in terms of cost and results. Ultimately, the findings were to be applied to future SCDNR planting operations, yielding 'more bang for the buck.'

MATERIALS AND METHODS

Assessment of Resource Status

One of the first tasks under this project was to assess the status and extent of these recreational shellfish grounds, which had not been surveyed since they were designated by the county legislative delegations in 1986. OFM typically assesses the fringing reefs in State Shellfish Grounds (SSGs) annually using a “rapid assessment” method conducted according to a written protocol. Three criteria are typically employed: (1) ‘Quantity’ which is based on the overall density of oysters on reefs, including new recruits (values range from 1–5; typically 1–4 are most common); (2) ’Quality’ which is based on overall shell appearance, such as evidence of recent growth, shade or color and relative shell thickness, as an indication of ‘health’ (as with quantity, values can range from 1–5, but 1–4 are most common); and (3) oyster ‘Size’ which is a numerical rating corresponding to a visually estimated overall length of individuals (range is from 1-5, 3=approx. a 3” oyster). The size criterion is intended to reflect the relative portion of ‘harvestable’ oysters but this measure is potentially less relevant as we have shown that 3” oysters rarely make up more than 10% of an oyster population and SC has no minimum harvest size. The three scores are averaged to yield an overall mean of the three qualitative ‘measures’ and OFM uses this and other information including landings and effort (or CPUE) annually to open and close SSGs to commercial harvesting (R. Haggerty, pers. comm.). Grounds were classified according to geographic location (North, Central, and South) and suitability for restoration in order to generate planting recommendations (Table 1).

Figure 1. Large-scale restoration activities: a - planting shell with barge and water cannon; b - shoreline prior to planting; c - shoreline immediately after planting; d - shoreline with newly planted area

Table 1. Public Shellfish Grounds and Recreational-only State Shellfish Grounds by geographical location, resource status score (0-4), and harvest status. Highlighted sites were recommended for planting based on factors such as accessibility, proximity to other monitoring areas, likelihood of success, and experimental value (blue sites are in the northern sector, yellow in the central sector, and green in the southern sector).

Site	PSG#	County	Composite Score	Harvest Status
Clam Bank Flats (MI)	R351	Georgetown	2.3	Restricted/Conditional
Jones Creek	S342	Georgetown	2.2	Approved
Brookgreen (MI)	S354	Georgetown	2.0	Approved
Lachicotte Oyster Factory (MI)	R355	Georgetown	1.3	Approved
Kiawah River	R186	Charleston	4.0	Approved
Gray Bay	R234	Charleston	3.9	Approved
Capers Creek	S262	Charleston	3.5	Approved
Long Creek	R292	Charleston	3.2	Approved
Hickory Bay	R274	Charleston	3.0	Approved
Clark Sound	S203	Charleston	3.0	Conditional/Prohibited
Leadenwah	R175	Charleston	2.8	Approved
Ashe Island	R132	Colleton	2.6	Approved
Hamlin Creek	R252	Charleston	2.5	Conditional
Leadenwah	R174	Charleston	2.5	Approved
Leadenwah	R173	Charleston	2.4	Approved
Leadenwah	R181	Charleston	2.0	Approved
Cole Creek	S196	Charleston	1.9	Approved
Folly River	R201	Charleston	1.8	Approved
Green Creek	R193	Charleston	1.1	Approved
Capers Creek	R121	Beaufort	4.0	Conditional
Station Creek	R089	Beaufort	3.3	Approved
Chechessee Point	R061	Beaufort	3.3	Approved
May River/Bull Creek	R008	Beaufort	3.1	Approved
Hunting Island/Johnson Creek	S108	Beaufort	2.9	Approved
Pinckney Island	R037	Beaufort	1.3	Approved
Pinckney Island	R036	Beaufort	1.0	Approved

Shell Planting

During our cooperative SRFAC-funded program, OFM and a staff member from the SRS section evaluated PSGs annually to recommend potential sites for planting. Planting decisions were based on resource status, accessibility, regional needs, and various other criteria such as: (1) making sure that some SSGs or PSGs were included in each of the coastal regions (South: Beaufort/Colleton, Central: Charleston, North: Georgetown); (2) logistics of shell deployment; and (3) availability of shell resources. SCDNR usually plants 4-8 areas each year (Table 2), either through contracts or using SCDNR equipment and manpower. The most common planting method is to float shell off a barge using a water cannon (Figure 1). The target area is marked in advance with PVC poles to assure that the correct area of the shoreline (which is not visible at high tide) is planted. Although planting depth is sometimes varied depending on the existing substrate at a site, typical planting depth is 3 inches. At this depth, OFM estimates that 3.8 bushels will plant a square meter. To cover an acre requires 15,500-16,000 bushels of shells.

Planting operations generally begin in late spring, but can be delayed by weather, difficulty in letting contracts, and logistical problems (e.g. shell delivery, equipment problems). SCDNR typically aims to conclude planting by the end of August, but this is not always possible. From 2002 to 2006, more than 150,000 bushels of shells were planted at 34 sites covering an estimated nine acres (Table 2). Within these 34 sites, 81 separate 'footprints' or reefs were created.

Table 2. Total number of sites, footprints, bushels, and area covered (acres and m^2) by plantings each year.

Year	No. of Sites	No. of Footprints	Est. Bushels	Area (m^2)	Area (acres)	Comments
2002	7	23	10,629	2,153	0.5	
2003	7	18	25,685	6,732	1.7	
2004	8	11	20,036	3,237	0.8	Additional funding from Murrells Inlet SAMP
2005	4	9	46,619	12,113	3.0	Additional funding from NMFS
2006	8	20	49,708	13,002	3.2	Additional funding from NMFS
Total	34	81	152,677	37,237	9	

Research Questions Incorporated in Shell Plantings

In order to maximize success of DNR planting efforts, we attempted to address the following questions at large-scale restoration sites.

- Do we need to select sites with low wake or wave energies or stabilize these footprints with mesh, given results from prior work supported by the Fishing Stamp Program (Coen and Bolton-Warberg 2005) and OFM NERR-supported efforts in the ACE Basin (Anderson and Yianopoulos 2003)?
- Is the timing of planting critical?
- What site conditions (such as bank slope, prior shell, sediment type, creek width/depth, boat traffic) maximize the success of our investment?
- What is the best material (=cultch) given that oyster and other shell (e.g. whelk shell) is getting harder and harder to obtain? Does shell type matter (SC or Gulf oyster shell, whelk)?
- Does shell need to be planted at a particular thickness (estimated to be either shallow 3" or deeper 6" layers) as a function of site characteristics (e.g. sediment composition, slope)?

Our objectives were to carefully document the site prior to planting, assess post-planting characteristics, and then follow oyster recruitment and other criteria (e.g. footprint changes) over time. In 2002 and 2003, a multi-factorial design was used to evaluate different shell types with and without overlaying mesh (Figure 2 and 3). In subsequent years, we simplified our designs and objectives, given the difficulties of planting shell following a rigorous experimental design. At some sites we investigated the planting depth of the shell. In 2003, we investigated the utility of placing a geotextile material below shell to retard sinking. In 2004, 2005, and 2006, we focused more on evaluating success and footprint changes. Details of planting designs are shown in Appendices 1 and 2.

In addition to the planned treatments, site performance was evaluated relative to site characteristics (often chosen after the fact) such as shoreline slope, firmness, and creek width. Evaluations included change in footprint over time (is the shell staying on the bank?); change in shell depth over time (is the shell moving around, piling up?); recruitment of oysters to the planted shell; size of recruited oysters; and abundance of oysters after multiple years of recruitment and growth. Methods for each of these evaluations are described below. Additionally, we monitored oyster recruitment at reef construction sites with shell trays deployed in the early spring to compare recruitment potential with adjacent reef recruitment.

Footprint Monitoring

The ‘footprint’ of a planting is the actual area (in m^2) of bottom the shell initially covers. In 2002 and 2003, reef footprints were estimated by measuring the length and width of each reef either with a tape measure or a laser rangefinder shortly after construction and calculating area. In 2004, using funds from SCDNR and NMFS, we purchased several submeter, mapping-grade surveying GPS units (Trimble ProXRs, Appendix 5) which allowed us, for the first time, to more accurately measure reef areas by walking the planted edge of shell and then placing that footprint on a GIS map or aerial image (see Appendix 5). Reef footprints were re-measured at annual intervals for some sites and at the end of the study for others, thus allowing us to calculate the change in reef size (area). Elevation can also be assessed now using RTK GPS instruments (see Gambordella et al. 2007).

Figure 2. Three shell types used in SRFAC and SAMP reef plantings: whelk shell (top), South Carolina oyster shell (left), and Gulf oyster shell (right).

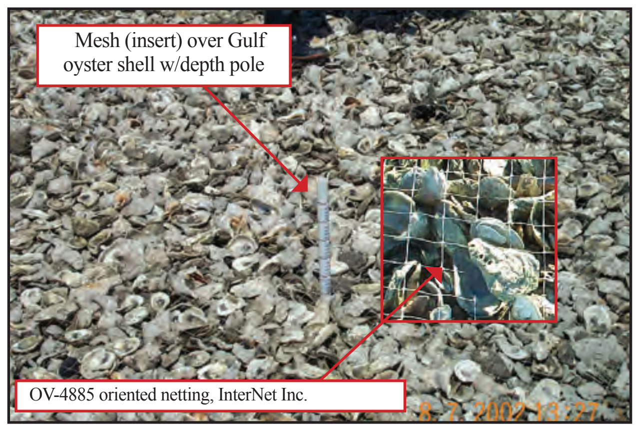


Figure 3. Photograph of a meshed oyster reef and a depth pole used in monitoring change in shell depth.

Oyster Population and Associated Community Development

We monitored post-settlement recruitment and growth of oysters on a subset of the constructed SRFAC reefs, as well as development of associated key ‘resident’ communities (mussels, crabs, ectoparasitic snails=*Boonea*). Direct assessment of successful oyster recruitment at constructed reefs was generally evaluated at one-year post-construction to assess how reefs were developing. These early assessments allowed us to modify methods and recommend specific changes or additional plantings in the following year. Reef progress over time was followed on an annual basis at some sites, while at other sites, reefs were allowed to develop for several years before a final assessment was made in fall 2006. At this time, the oldest reefs were 4 years old and the youngest assessed reefs were 1 year old.

We employed stratified random quadrat sampling on the reefs to assess reef development. Quadrats (Figure 4) were placed along a transect line established parallel to the shoreline at mid-reef tidal height. Once a quadrat was placed, a digital photograph was taken prior to excavating the quadrat to a depth of 11 cm (see Van Dolah et al. 2000, Coen et al. 2004, Coen and Bolton-Warberg 2005, Coen et al 2006 for more details). The number of replicate quadrat samples collected varied as a function of reef size (allowable area) as we wanted to minimize disturbance through repeated sampling on many of the smaller constructed reefs. Usually, 4-8 quadrat samples were collected for individual footprints or reefs. Samples were stored in a walk-in refrigerator until they could be washed and processed.

Samples were washed on a 0.5 or 1.0 mm sieve to remove mud and sand, while retaining small animals, such as crabs and mussels. Crab and mussel abundances were recorded for each sample on a numerical scale: 0 (none detected), 1 (<10 individuals), 2 (10-50 individuals), and 3 (>50 individuals). After sieving, all live oysters were retained and shells were sorted according to shell type (SC, Gulf or whelk). Shell height (SH) of live oysters was measured to the nearest 0.01 mm with digital calipers and data were stored in an Access® database for later Quality Assessment/Quality Control (QA/QC).

a. b.

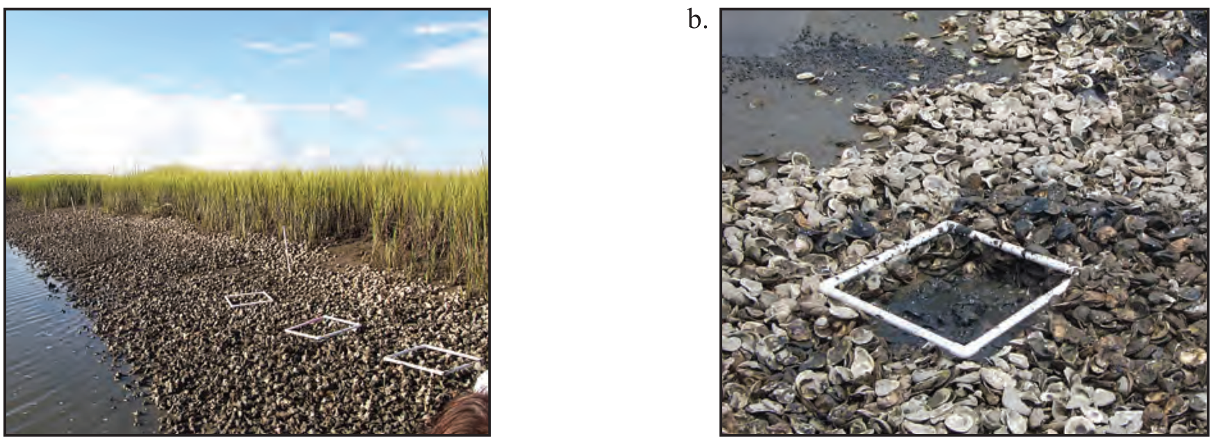


Figure 4. Photographs of reef sampling. (a) Quadrats placed along a transect located at mid-reef shoreline height. (b) An excavated quadrat after sampling.

Figure 5. A typical shell tray collected from the field after deployment of 9-12 months. Trays are filled with 11.5 gallons of South Carolina oyster shell and then covered with plastic mesh to prevent shell loss.

Oyster Recruitment Potential

Since the late 1990s (Giotta 1999, Coen et al. 2007a), SCDNR's Shellfish Research Section has used plastic trays filled with shell (Figure 5) to assess annual recruitment and early growth of oysters at multiple sites statewide annually (Van Dolah et al. 2000, Coen et al. 2004, Coen and Bolton-Warberg 2005). Plastic trays (with a total bottom area of 0.38 m^2) were filled with local oyster shell (~11.5 gallons per tray) and deployed, generally in triplicate, at SRFAC restoration sites each spring (Figure 5). Each year additional trays were placed at other sites (e.g. a changing subset of SSGs) in conjunction with various studies. Trays were retrieved the following spring (9-12 months after deployment) and processed similarly to the quadrat samples. This method allowed us to estimate annual recruitment potential of oysters and compare recruitment potential among sites and years. A one-way ANOVA was used to evaluate if recruitment potential varied significantly among SRFAC sites and years.

Mesh Stabilization Treatments

At some restoration sites it was apparent that boat wakes, wind waves, and tidal currents were strong enough to move recently planted shell and impact sediments and fringing marshes (Anderson 2002; Bishop 2004, 2007; Bishop and Chapman 2004; Coen and Bolton-Warberg 2005; Goodwin et al. 2006; Goodwin 2007; Coen et al. in prep.). This is problematic because shell can be washed away entirely into the subtidal or relocated to an area less conducive to spatfall. Constant movement of shell also deters settlement of oyster larvae and can damage or kill young recruits Walters et al. 2002, 2004, Wall et al. 2005, L. Walters et al., unpublished data) by scraping them off or burying them in the sediment. Previous small-scale and large-scale experiments have demonstrated that shells can be stabilized by covering them with mesh (Anderson and Yianopoulos 2003, Coen and Bolton-Warberg 2005). In conjunction with shell plantings in 2002 and 2003 we designed planting experiments to determine whether stabilizing mesh (from InterNet, UV-stabilized, # OV-4885, 1.25" × 1.5") was an effective tool for large-scale plantings and whether effectiveness varied for different shell types (see Figure 3). The original design called for adjacent meshed and unmeshed plots planted with the different shell types. Unfortunately, because of planting constraints and shortage of some shell types we were unable to complete the shell type/mesh experiment (see Appendix 2 for detailed description of mesh experimental designs and an explanation of results).

We tested for significant differences in oyster density between meshed and unmeshed reefs with two separate statistical analyses. First, we used a randomized block ANOVA to test for differences in oyster density between meshed and unmeshed reefs and among sites at two years post-construction (2004 data were used for reefs constructed in 2002, and 2005 data were used for reefs constructed in 2003). Second, we used randomized block ANOVA to test for significant differences in oyster density between meshed and unmeshed reefs and among sites at year three (2005 data for reefs constructed in 2002 and 2006 data for reefs constructed in 2003).

Shell Depth Planting and Monitoring

In 2002, we planned treatments to examine the effect of planting depth on shell retention and recruitment over time for different shell types with and without mesh overlay. Hamlin Creek had the most complete set of these experiments. Three plots were planted with whelk shell, two at a depth of 6 inches and one at a depth of 3 inches; four plots were planted with Gulf shell, three at 6 inches depth and one at 3 inches; and one plot had South Carolina shell planted at 6 inches depth. Half of each plot was covered with mesh. We also had depth treatments but not shell treatments at Pinckney Island where South Carolina shell was planted at either 3 inches or 6 inches depth. Shell retention was evaluated over time by measuring changes in the footprint and changes in the shell depth.

In order to evaluate changes in shell depths on constructed reefs and to compare shell movement between meshed and unmeshed areas, a subset of reefs planted in 2002 and 2003 was selected for reef depth monitoring (see Appendix 2). Numbered, graduated (drilled and marked, 1 and 5 cm), and replicate PVC poles (Figure 3) were installed within the reef footprint just after planting and monitored quarterly for approximately one year. The poles were originally positioned at a known height above the base substrate and the shell height could be measured directly by reference to the numbered gradations. At other sites, shell depth was monitored by probing the shell layer with a calibrated depth rod used by OFM-SMS since the 1980s to measure "shell strata depth." Both of these methods reveal whether the shell has moved, but do not account for shell 'sinkage' or coverage by silt.

Mesh Underlayment Treatments

In 2003 and 2005, we evaluated the use of various geotextile materials to prevent shells from sinking into softer substrates. In 2003, two meshes, a woven jute material and a biodegradable plastic mesh called ‘Radix’ (from Tenax, # OG4511, 0.9” ×1.25”) were placed under portions of the shell planted at Leadenwah Creek (at R174). Another portion of this subplot had no underlayment. In 2005, an underlayment of cocoa/hay mat (Landlok®, CS2) was used at two subplots in Wallace and Capers Creeks.

Oyster Recruitment on Different Shell Types

In 2004, we evaluated recruitment differences among shell types (Figure 2) by deploying recruitment trays filled with different shell types (local oyster shell, Gulf oyster shell, or whelk shell; n=3 trays per shell type) in Folly River. When the trays were retrieved 12 months later, we counted the shells in each tray and determined the number of oyster spat per shell, the total spat per tray, and the size of each spat. One-way ANOVA was used to determine whether recruitment varied among the three shell types.

Shell Quarantine Protocols

With the creation of a shell recycling program it was necessary to develop protocols for handling and storing shell. Much of the shell acquired through the recycling program is Gulf oyster shell. Oysters from other areas may have associated fauna (pathogens or larger “hitch-hikers”) which might not be native to South Carolina and which might present a danger to native stocks. One particular pathogen of concern is *Perkinsus marinus,* the causative agent of ‘Dermo.’ While Dermo is found in all South Carolina oyster populations, there is concern that strains from other areas may be more virulent or may differ to a large enough extent that South Carolina oysters would have reduced immunity to them. Since recycled oyster shells may not have been thoroughly cooked, replanting shells could introduce unwanted strains of *Perkinsus marinus* or other pathogens into South Carolina waters.

To prevent this, it is necessary to treat the shells in some manner to kill residual pathogens. We conducted a pilot study using SRFAC funding to determine whether storing shells on high land was adequate to remove most tissue from large live Texas-derived Gulf oysters as a worst case scenario. Heavily infected Gulf oysters were placed in small (approximately 100 bushel) shell piles for periods of 1-3.5 months and then assayed for the presence of *P. marinus*, along with assessing pathogen status (live or dead). These results have been published and are being used as guidelines in several other eastern U.S. states (Bushek et al. 2004).

Evaluation of Current and Potential Shell Stabilization Materials

Small- and large-scale oyster restoration projects across the U.S. have been increasing exponentially, with some programs beginning to use stabilizing mesh (e.g., bags, flat roll material) to: (1) simplify setting and later shell deployment (e.g., Chesapeake Bay); (2) minimize community restoration program logistics (Hadley and Coen, 2002, Hadley et al. In press, Brumbaugh and Coen 2009); or (3) stabilize shell in areas with high disturbance (Chose 1999; Coen and Fischer 2002; Coen and Bolton-Warberg 2003, 2005; Coen et al. 2008; Coen unpublished data). As part of our expanded SCORE Program (mesh bags) and work supported here using rolls of mesh, we have been investigating the suitability of “eco-friendly” ‘biodegradable’ and ‘non-photostabilized’ mesh, as alternatives to UV-stabilized meshes for intertidal oyster restoration.

The purpose of this experiment was to investigate the suitability of currently available off-the-shelf biodegradable and non-photo-stabilized mesh types for estuarine restoration, especially as it applies to oyster restoration. ‘Photodegradable’ is a term given to products that degrade when exposed to sunlight. ‘Photo-degradability’ typically means that the product will break down into small pieces if left uncovered in sunlight (UVA and B primarily). However, these smaller pieces of plastic often make these products not truly ‘biodegradable’ for marine and estuarine use. Degradation rates were quantified for samples deployed both in the field and at our lab (=control) site by directly measuring changes in tensile strength (lbs/ft) and ‘survivability’ over time.

Three field sites were used for this experiment: (1) Charleston Harbor; (2) Palmetto Islands County Park (where we are also doing extensive oyster reef restoration); and (3) the Cape Romain Wildlife Management Area. The latter two are also smaller-scale SCORE restoration sites. These three sites were chosen for their proximity to our lab and their site characteristics. Both the Cape Romain and the Palmetto County Park sites were relatively similar with regard to current/wave energy, boat traffic, and bank characteristics. The Charleston Harbor site differs significantly as it encounters high wave energy and has a large fetch versus the two other creek sites. Two land-based platforms were constructed on the grounds of our facility (FJ Marine Science Center) at Fort Johnson. The platforms were placed such that they would be exposed to the sun at all hours of the day.

Recently, some companies have begun producing “eco-friendly” meshes that are popular in agriculture, road construction, landscaping, and land rehabilitation. Four of these mesh types were used in our experiments: (1) a loosely woven organic jute fiber mesh; (2) a non-UV-stabilized green mesh by Tanex called “Radix”; (3) a biodegradable oriented tubular mesh (DelStar, Inc.) cut flat; and (4) a non-biodegradable UV-stabilized black mesh currently being used by us for our large-scale restoration. The mesh was cut into 4’ x 5’ rectangular sections that were laid side by side, alternating mesh types, with replicates assigned randomly at each plot. At the Palmetto County Park and Cape Romain sites, eight mesh plots (n = 2 for each mesh type) were laid over loose shell on the shoreline & eight plots (n = 2 for each mesh type) over live oyster clusters. Plots at the Charleston Harbor site were all placed over a sandy-shell matrix bank. Plots were anchored using 5’ lengths of 3/8” rebar on all four sides, with two 2.5’ lengths of “J” shaped rebar on each end to hold down the horizontal rebar. Plots were spaced approximately 2’ apart.

Two control platforms were constructed on April 23, 2003, at Fort Johnson to evaluate mesh degradation under natural exposure conditions. Platforms were elevated off the ground, with 4” x 4” vertical posts to prevent warping of the 4’ x 8’ x ¾” exterior grade plywood sheets. One platform was covered with a sheet of 1/8” (0.118”) thick UV-opaque plastic (OP-3 Acrylite® by Cyro Corp.). This material is purported to reduce UVA & UVB by 90-95%. The plastic sheet was suspended above the platform using PVC pipe ‘stands’ with a central supporting bolt with plastic nuts. The other platform was left uncovered, exposing the replicate mesh squares to natural environmental conditions (e.g., rain & UV). Eight pieces of each mesh type were stapled to each platform in a randomized block design. Meshes were first sampled on August 15, 2003, and sent to Tenax Corp. for tensile strength analysis. Monthly UV readings for both UVA and UVB intensities were taken at the two platforms using a MACAM Photometrics Model UV-203 IP-67 radiometer (Macam Photometrics Ltd., Livingston, Scotland) loaned by Dr. J. Weinstein, The Citadel). Radiation intensities were measured for UVA (332-406 nm) using a 33 mm^2 silicon photodiode, fitted with a glass absorption filter and a cosine-corrected input diffuser. The UVA sensor, in addition to UVB (292-330 nm) and visible light (400-700 nm) sensors, was mounted to a single, black anodized aluminum housing (70 mm diameter) and connected to the radiometer through a 10-m coaxial cable. Readings (in $Watts/m^2$) were made at predetermined points on each platform, along with time of day, weather conditions, and temperature.

Data on mesh condition were collected on a quarterly basis at all field sites. To facilitate mesh sampling in the field, a 0.09 m^2 quadrat was placed over each mesh plot as a template for collecting replicate samples. Only one sample (‘swatch’) was cut from each of the mesh plots at a given time. Each ‘swatch’ was rinsed with freshwater to remove silt and allowed to dry before being sent to Tenax Corp, our industry partner, for tensile strength analysis (ASTM 4595 “Standard Test Method for Tensile Properties of Geotextiles” by the Wide-Width Strip Method). Tensile strength is defined as “the maximum resistance to deformation developed for a specific material when subjected to tension by an external force.” Platform samples at Fort Johnson were also sampled on a quarterly basis. Two replicate swatches were randomly selected and removed for processing as above.

Effects of Boat Wakes on Shell Movement With and Without Mesh

Resource Managers are concerned that increased recreational boating activities are negatively impacting intertidal oyster reefs. We have observed that boat wakes have direct and indirect effects on planted shell and intact oysters (Grizzle et al. 2002, Coen and Bolton-Warberg 2005, Wall et al. 2005, Coen unpublished data). We have conducted experiments in Charleston and other coastal counties using direct measurements and experimental mesh and no-mesh plots of loose shell, simulating a large-scale planting. In July 2003 and June 2004 we directly measured impacts at multiple sites in South Carolina (Baruch Lab and North Inlet-Winyah Bay National Estuarine Research Reserve, NERR) using a variety of boats and treatments to evaluate the direct impact of boat wakes on: (1) shell dispersal; (2) near bank turbidity; (3) flow rates/wave surge; (4) wake height; and (5) time until wake impact.

We focused on trying to evaluate shell dispersal and to understand the 'shedding' or 'non-shedding' (build-up) of sediment on meshed versus unmeshed (loose shell) treatments. Recently planted shell moves around until recruiting oysters and associated mussels aggregate the shell. This normal shell movement is not deleterious. However, wind-driven waves, strong currents and boat-generated wakes can cause excessive shell movements, which can damage fragile new recruits or wash the shells beyond the normal tidal range for reef development (Chose 1999; Walters et al. 2002, 2004, unpublished data; Wall et al. 2005).

At one site near Bowens Island (N32.67577; W79.96852), we tested two treatments (meshed/unmeshed) using replicate 0.25 m^2 quadrats (n = 3). Quadrats were deployed just above the water line and filled with 60 spray painted oyster shells (one side fluorescent pink, other fluorescent green). After placement, the PVC quadrats were removed and corners marked with fishing weights. Half the quadrats were covered with mesh and half were uncovered (Figure 6). We did a series of replicated trials with a 20' Privateer (2 stroke 115 HP engine) passing the area at three speeds and three distances. After each replicated pass, the number of shells that flipped over and/or moved out of the quadrat area were recorded as one of four possible resulting states. Distance from shore, boat speed, turbidity, wake travel time differential, and wave heights were measured during each replicate run (n = 2-4). Distance from shore was measured using a laser rangefinder; boat speeds were measured using GPS speed over ground in mph; water depth was measured using a Hawkeye handheld digital depth sounder. Transit rods marked in cm were used to measure wave height. Stopwatches were used for wave timing, and transparency/turbidity tubes were used for water clarity before and after each run. Quadrats were relocated between trials so that they were always just above the water line.

RESULTS

Shell Planting

In 2002, seven areas were selected for shell planting, including two in Murrell's Inlet (Georgetown County, Clambank S354 and Oaks Creek R351), two in Charleston County (Hamlin Creek North & South, R252), and three in Beaufort County (Bull Creek North & South, R008); and Pinckney Island R036, R037). Approximately 11,000 U.S. bushels of various shell types (South Carolina and Gulf oysters, whelk) were planted on more than 2,100 m^2 of shoreline (see Table 2 and Appendix 1 for locations, additional baseline data, and detailed site descriptions).

In 2003, more than 25,000 U.S. bushels of shell were planted at 7 sites in five distinct areas along the coast, creating more than 6,700 m^2 of reef footprint (see Table 2 and Appendix 1). Two sites, each considered only one reef, were located in Murrell's Inlet (Georgetown County R355, R351). Six reefs (=footprints) were located in Folly Creek and Folly River (S206 and R201, Charleston County). Four reefs were located in Leadenwah Creek (Charleston County, R173-175, R181). Three footprints were planted in Johnson Creek (Beaufort County, S108), and three at Pinckney Island (Beaufort County, R036-037). See Appendix 1 for locations, additional baseline data, and site descriptions.

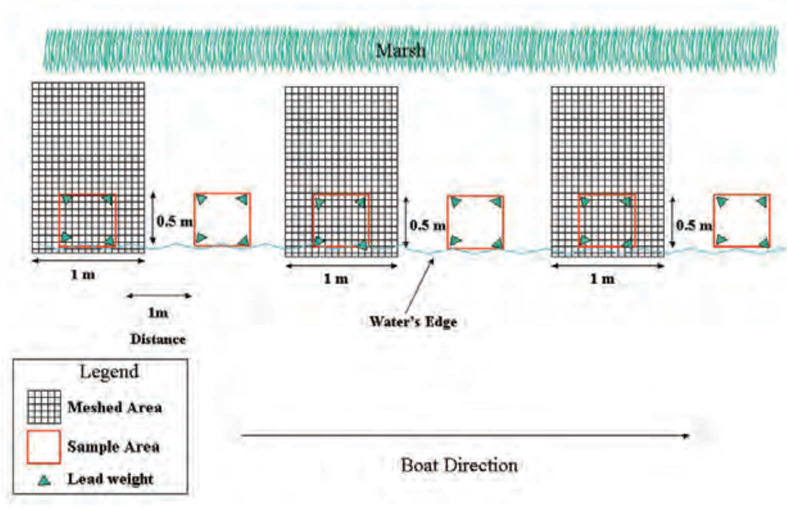


Figure 6. Experimental layout of the treatments for boat wake experiments (meshed and no mesh, n=3 each. Green lead weights mark the corners of each area during runs with quadrats removed.

In 2004, approximately 20,000 U.S. bushels of various shell types were planted on 3,904 m^2 of shoreline (Table 2) at eight sites creating 11 reefs or footprints: (1) four sites in Murrells Inlet (Georgetown County, S354, S358, and two 'Undesignated' areas), three in Charleston County (Hamlin Creek North & South, R252, and Cole Creek S196, recreational SSG) and one in Colleton County (Ashe Island, S132). See Appendix 1 for locations, additional baseline data, and site descriptions. Two undesignated areas in Murrells Inlet (Parsonage Creek and Allston Creek) were planted with funding received from the Murrell's Inlet Special Area Management Plan.

In 2005, more than 46,000 U.S. bushels of various shell types were planted on ~12,000 m^2 of shoreline at four distinct sites (Table 2). The amount of shell increased significantly as a result of enhanced NMFS funding to the Marine Resource's Division as part of the remote sensing program (CSC 2003, Smith et al. 2005). Nine footprints were created including six at Distant Island (S117) and Wallace-Capers Creek (S118 and R121) in Beaufort County. Additional sites in the northern portion of the state included Drunken Jack Island (S357) and Woodland Cut (S358) in Georgetown County. See Appendix 1 for locations, additional baseline data and site descriptions.

In 2006, approximately 44,000 bushels of shell and 5,000 bushels of seed oysters were planted on 13,000 m^2 in eight locations. Georgetown County sites included Drunken Jack Island (S357) and Woodland Cut (S358). Charleston County sites included Long Creek (R292), Governors Cut (S205/S206), First Sisters Creek (S206), and Cutoff Reach (S206). Beaufort County sites included Distant Island Creek (S117) and Wallace Creek (S118). The 2006 sites are not included further in this report as they were constructed at the end of this study and therefore were not sampled as part of this report, but planting details are included in Appendix 1.

Footprint Monitoring

Footprint retention was assessed for 53 reefs at 24 sites. Reefs were rated as 'Good' if they retained 70% or more of their original footprint, 'Fair' if they retained 30% - 69%, and 'Poor' if they retained less than 30%. Overall, seven reefs (13%) were 'Poor,' twenty reefs (38%) were 'Fair,' and twenty six reefs (49%) were 'Good' (Figure 7).

Twenty-two of the twenty-three footprints established in 2002 were reassessed in 2005 or 2006 (Table 3). Footprint retention ranged from 0 to 165%, with a mean retention of 77%. Twelve reefs (55%) had 'Good' retention. The three 'Poor' reefs were all at Bull Creek North.

Fifteen of eighteen reefs constructed in 2003 were reassessed for footprint retention in 2005 or 2006 (Table 4). Retention ranged from 0 to 118% with a mean of 72%. Eight footprints (53%) had greater than 70% remaining footprint ('Good'). The two 'Poor' reefs were one at Pinckney and one at Johnson Creek.

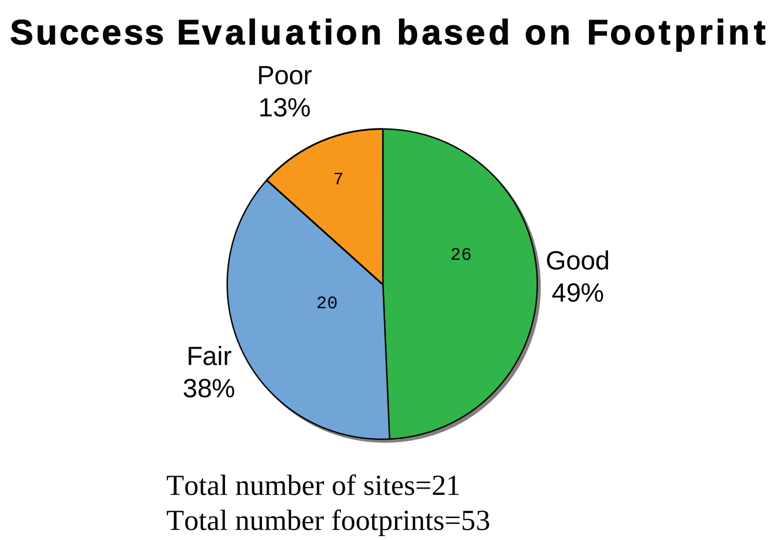


Figure 7. Success ratings of 53 reefs based on footprint retention. Reefs rated 'Good' have >70% of the original footprint remaining. Those rated 'Fair' have 30-70% of the original footprint. Those rated 'Poor' have less than 30% of the original area remaining.

Table 3. Change in footprint size and success rating based on footprint retention for reefs constructed in 2002. Reefs with >70% footprint remaining are scored 5 (Good), those with 30-70% remaining are scored 3 (Fair), and those with less than 30% remaining are scored 1 (Poor). An additional site (Murrells Inlet Clambank S354) was not measured due to inaccessibility.

Site	Footprints	Constructed	Last assessed	Initial area (m^2)	Final Area m^2)	% Remaining	Success Score
Oaks Creek S354	E	2002	2005	295	255.5	87%	5
	F			22	24.11	110%	5
	G			22	36.45	166%	5
	H			123	84.96	69%	3
Bull Creek North R008	A	2002	2006	129	13.627	11%	1
	B			68	0	0%	1
	C			107	0	0%	1
Bull Creek South R008	D	2002	2006	119	45.359	38%	3
	E			82	35.394	43%	3
	F			110	50.292	46%	3
Pinckney Island R037	A	2002	2006	32	14.282	45%	3
	B			32	26.13	82%	5
	C			110	76.31	69%	3
	D			71	76.31	107%	5
Hamlin South R252	A	2002	2006	65	75	115%	5
	B			57	59.189	104%	5
	C			24	23.669	99%	5
Hamlin North R252	D	2002	2006	23	29	126%	5
	E			42	50	119%	5
	F			36	37	103%	5
	G			46	47	103%	5
	H			44	26.867	61%	3

Table 4. Change in footprint size and success rating based on footprint retention for reefs constructed in 2003. Reefs with >70% footprint remaining are scored 5 (Good), those with 30-70% remaining are scored 3 (Fair), and those with less than 30% remaining are scored 1 (Poor). Three additional footprints (Murrells Inlet Clambank and two in Folly River) were not assessed.

Site	Footprints	Constructed	Last assessed	Initial area (m^2)	Final area (m^2)	Percent remaining	Success Score
Oaks Creek	R351	2003	2005	190	181	95%	5
Leadenwah Creek	R173	2003	2005	297	351	118%	5
	R174	2003	2005	133	131	99%	5
	R175	2003	2004	564	286	51%	3
	R181	2003	2005	492	268	55%	3
Folly S206	A	2003	2006	619	638	103%	5
	B	2003	2005	316	278	88%	5
	C	2003	2006	1,089	728	67%	3
	D	2003	2006	1,626	1,132	70%	3
Johnson S108	A	2003	2005	789	190	24%	1
	B	2003	2005	190	194	102%	5
	C	2003	2005	168	135	80%	5
Pinckney R37	A	2003	2005	517	257	50%	3
	B	2003	2005	27	0	0%	1
	C	2003	2005	368	304	83%	5

Eight of the eleven footprints constructed in 2004 were re-measured in 2006 and two were re-measured in 2005 (Table 5). Footprint retention ranged from 13% to 96% with mean retention of 48% ('Fair'). Seven reefs (70%) scored 'Fair,' two 'Poor,' and one 'Good.'

Initial and one-year footprints were measured at six out of nine 2005 reefs (Table 6). Five had 'Good' footprint retention and one had 'Fair' retention.

Table 5. Change in footprint size and success rating based on footprint retention for reefs constructed in 2004. Reefs with >70% footprint remaining are scored 5 (Good), those with 30-70% remaining are scored 3 (Fair), and those with less than 30% remaining are scored 1 (Poor). One additional footprint (Hamlin South) was not assessed.

Site	Footprint	Constructed	Sampled	Initial area (m^2)	Final area (m^2)	Percent remaining	Success Story
Murrells, Oaks Creek	S354	2004	2006	539	219	41%	3
Murrells Woodland Cut	A	2004	2006	340	185	54%	3
	B	2004	2006	327	173	53%	3
Parsonage	A	2004	2006	123	51.2	42%	3
	B	2004	2006	122	78.5	64%	3
Alston	D	2004	2005	267	34	13%	1
	C	2004	2005	190	102	54%	3
Hamlin	North	2004	2006	203	119	59%	3
Cole Creek	S134	2004	2006	440	0	0%	1
Ashe Island		2004	2006	370	356	96%	5

Table 6. Change in footprint size and success rating based on footprint retention for reefs constructed in 2005. Reefs with >70% footprint remaining are scored 5 (Good), those with 30-70% remaining are scored 3 (Fair), and those with less than 30% remaining are scored 1 (Poor). Three additional footprints (two at Drunken Jack Island and one at Wallace Creek) were not assessed.

Site	Footprint	Constructed Year	Sampled Year	Initial area m^2	Final Area m^2	Percent remaining	Success Score
Distant Island	A	2005	2006	1,006	1,101	109%	5
	B	2005	2006	1,958	1,803	92%	5
	C	2005	2006	1,098	1,290	117%	5
Wallace Creek	B	2005	2006	4,242	2,834	67%	3
	R121	2005	2006	275	284	103%	5
Murrells Woodland Cut	S358	2005	2006	608	619	102%	5

Reef Development

Early recruitment and growth are shown in Tables 7-12. For reefs constructed in 2002, mean density at one year of age ranged from a low of 134 oysters/m^2 for meshed treatments (for example, Murrells Inlet Clambank) to a high of 776/m^2 for unmeshed treatments (Hamlin South, Table 7). Mean oyster sizes at one year of age ranged from a low of 22.7 mm on unmeshed reefs at Pinckney Island to a high of 40.8 mm for meshed treatments at Murrells Inlet's Clambank (Table 8). For reefs constructed in 2003, mean densities at one year of age ranged from a low of 798/m^2 for meshed treatments at Johnson Creek to a high of 2,746/m^2 for meshed treatments at Leadenwah Creek, R-181 (Table 9). Mean shell heights after one year ranged from a low of 27.0 mm on unmeshed treatments at Johnson Creek to a high of 36.5 mm on meshed treatments at Leadenwah Creek (Table 10).

Table 7. Mean oyster densities (#/m^2 ±1 SE) on reefs constructed in 2002 and sampled over time. NS indicates no sampling occurred in that year for a particular reef.

Site	Mean oyster density (#/m^2 ±1 SE) Year 1		Mean oyster density (#/m^2 ±1 SE) Year 2		Mean oyster density (#/m^2 ±1 SE) Year 3		Mean oyster density (#/m^2 ±1 SE) Year 4	
	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed
Murrells Clambank	134±30.3 (n = 15)	312±30.7 (n = 16)	NS	NS	NS	NS	NS	NS
Murrells Oaks Creek	369±84.8 (n = 8)	529±52 (n = 18)	564±92.5 (n = 7)	1,214±62 (n = 13)	NS	1,115±97.8 (n = 6)	NS	1,860±122 (n = 8)
Bull Creek North	260±57.8 (n = 24)	274±62.5 (n = 24)	213±97.2 (n = 12)	216±74.1 (n = 12)	NS	NS	NS	NS
Bull Creek South	514±43.0 (n = 24)	544±84.1 (n = 24)	590±169.3 (n = 12)	397±121.4 (n = 12)	1,026±208 (n = 8)	385±146 (n = 8)	NS	NS
Pinckney	384± 39.4 (n = 15)	669±101 (n = 14)	378±37 (n = 10)	545±86.8 (n = 10)	NS	NS	716±131 (n = 9)	647±167.2 (n = 7)
Hamlin Creek South	338±100.2 (n = 12)	776±137 (n = 12)	501±174.2 (n = 11)	1,124±200 (n = 11)	1,049±296 (n = 6)	1,761±301 (n = 6)	NS	NS
Hamlin Creek North	229± 35 (n = 18)	424±56.9 (n = 20)	353±66 (n = 16)	861±79 (n = 16)	619±123 (n = 6)	1,346±273 (n = 6)	3,023±814 (n = 8)	2,495±330 (n = 12)

For reefs constructed in 2004, mean densities at one year of age ranged from a low of 586/m^2 (Hamlin North) to a high of 1,417/m^2 (Murrells Inlet's Oaks Creek, Table 11). Mean shell heights at one year ranged from a low of 18 mm (Ashe Island site) to a high of 52.4 mm (Murrells Inlet's Woodland Cut, Table 11).

For reefs constructed in 2005, mean densities after one year ranged from a low of 1,212/m^2 to a high of 2,118/m^2 (Table 12). Mean shell heights at one year ranged from a low of 39.9 mm (Wallace Creek, R121) to a high of 54.0 mm (Distant Island A, Table 12).

Reef development was followed over time at a subset of sites (see Tables 7-12). Most reefs showed only modest gains in oyster density over time. Shell height increased very little and in some cases appeared to decrease over time (see Tables 8, 10, 11). This is probably the result of large numbers of small recruits with fewer larger individuals making up the overall oyster population.

In 2005 and 2006, a subset of reefs was sampled for a final determination of reef status (see Tables 7-12, 14). Mean densities ranged from a low of 385/m^2 for unmeshed 3-year old reefs (2002 Bull Creek sites, Table 7) to a high of 4,718 m^2 on meshed 3-year old reefs (2003 Johnson Creek sites, Table 9). Mean sizes ranged from a low of 21.9 mm on 3-year old reefs (2003 Folly Creek sites, see Table 8) to a high of 36.8 mm on 3-year old reefs (2003 Pinckney Island sites, Table 8).

Table 8. Mean oyster size (mm±1 SE) on reefs constructed in 2002 and sampled over time. NS indicates no sampling occurred in that year for a particular reef.

Planting year, area, and site	Mean oyster size (mm±1 SE) Year 1		Mean oyster size (mm±1 SE) Year 2		Mean oyster size (mm±1 SE) Year 3		Mean oyster size (mm±1 SE) Year 4	
	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed
2002 Clambank R351	40.8±2.28 (n = 15)	35.3±1.48 (n = 16)	NS	NS	NS	NS	NS	NS
2002 Oaks Creek R354	38.6±1.2 (n = 8)	38.7±0.72 (n = 18)	39.3±0.93 (n = 7)	43.7±1.79 (n = 13)	NS	NS	NS	26.4±0.90 (n = 8)
2002 Bull Creek R008	23.6±0.78 (n = 24)	24.1± 0.92 (n = 24)	24.8±1.28 (n = 24)	26.0±0.82 (n = 24)	23.0±2.07 (n = 8)	22.8±0.79 (n = 8)	NS	NS
2002 Pinckney R036, R037	25.9±1.01 (n = 15)	22.1± 1.03 (n = 14)	34.4±1.31 (n = 10)	31.8±1.40 (n = 10)	NS	NS	27.0±1.66 (n = 9)	24.9±3.19 (n = 7)
2002 Hamlin Creek South R252	31.5±1 (n = 12)	34.4±0.56 (n = 12)	33.1±1 (n = 11)	32.6±0.84 (n = 11)	29.2±0.84 (n = 6)	28.1±0.46 (n = 6)	NS	NS
2002 Hamlin Creek North R252	33.5±1.12 (n = 18)	35.5±1 (n = 20)	35.9±1.81 (n = 16)	35.6±0.59 (n = 16)	28.6±0.72 (n = 6)	29.4±1.34 (n = 6)	30.5 (1.31) (n = 8)	29.3±0.66 (n = 12)

Table 9. Mean oyster densities on reefs constructed in 2003 and sampled over time. NS indicates no sampling occurred in that year for a particular reef.

Site	Mean oyster density (#/m² ±1 SE) Year 1		Mean oyster density (#/m² ±1 SE) Year 2		Mean oyster density (#/m² ±1 SE) Year 3	
	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed
Leadenwah Creek R-173	NS	NS	523±113.5 (n = 4)	1,399±347 (n = 4)	NS	NS
Leadenwah Creek R-174	2,746±1,090 (n = 2)	2,100 (n = 1)	NS	NS	NS	1,115±98 (n = 6)
Leadenwah Creek R-181	NS	NS	2,143±239 (n = 4)	1,931±189 (n = 4)	NS	NS
Folly S-206A	No mesh treatment	NS	No mesh treatment	1,802±240 (n = 4)	No mesh treatment	1,650±302 (n = 8)
Folly S-206B	NS	NS	No mesh treatment	1,461±125 (n = 4)	No mesh treatment	1,955±184 (n = 8)
Johnson S-108B	1,385±239 (n = 6)	1,873±215 (n = 6)	2,728±309 (n = 4)	2,801±334 (n = 4)	4,718 (1,373) (n = 4)	3,344±619 (n = 4)
Johnson S-108C	798±186 (n = 6)	1,821±297 (n = 6)	1,907±153 (n = 4)	2,121±176 (n = 4)	1,738 (115) (n = 4)	2,832±371 (n = 4)
Pinckney Island R-037A	No mesh treatment	NS	No mesh treatment	NS	No mesh treatment	999+205.6 (n = 8)
Pinckney Island R-037C	No mesh treatment	NS	No mesh treatment	NS	No mesh treatment	1,317+167 (n = 8)

Table 10. Mean oyster sizes (mm+1 SE) for reefs constructed in 2003 and sampled over time. NS indicates no sampling occurred in that year for a particular reef.						
Site	**Mean oyster size** (mm+1 SE) **In Year 1**		**Mean oyster size** (mm+1 SE) **In Year 2**		**Mean oyster size** (mm+1 SE) **In Year 3**	
	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed
Leadenwah Creek R173	NS	NS	20.8+1.51 (n = 4)	15.4+(0.92 (n = 4)	NS	NS
Leadenwah Creek R174	36.5+2.18 (n = 2)	30.9 (n = 1)	NS	NS	NS	NS
Leadenwah Creek R181	NS	NS	23.5+0.73 (n = 4)	22.8+1.39 (n = 4)	NS	NS
Folly S206A	No mesh treatment	NS	No mesh treatment	24.7+1.39 (n = 4)	No mesh treatment	25.9+0.98 (n = 8)
Folly S206B	NS	NS	No mesh treatment	24.6+2.15 (n = 4)	No mesh treatment	21.9+0.67 (n = 8)
Johnson S108B	29.7+0.79 (n = 6)	27.8+0.8 (n = 6)	24.1+0.52 (n = 4)	22.6+1.07 (n = 4)	26.2+0.67 (n = 4)	26.3+1.44 (n = 4)
Johnson S108C	29.9+1.68 (n = 6)	27+0.93 (n = 6)	23.3+1.24 (n = 4)	25.2+1.02 (n = 4)	29.4+0.35 (n = 4)	25.1+1.37 (n = 4)
Pinckney Island R037A	No mesh treatment	NS	No mesh treatment	NS	No mesh treatment	36.8+1.41 (n = 8)
Pinckney Island R037C	No mesh treatment	NS	No mesh treatment	NS	No mesh treatment	31.7+2.05 (n = 8)

Table 11. Mean oyster densities (#/m^2 +1 SE) and sizes (mm+1 SE) on reefs constructed in 2004 and sampled in 2005 and/or 2006. NS indicates no sampling occurred in that year for a particular reef.				
Site	**Mean oyster density (#/m^2 +1 SE) Year 1**	**Mean oyster size (mm+1SE) Year 1**	**Mean oyster density (#/m^2+1SE) Year 2**	**Mean oyster size (mm+1SE) Year 2**
Oaks Creek	1,417+81 (n = 6)	38.1+2.78 (n = 6)	1,848+277 (n = 6)	39.7+3.29 (n = 6)
Woodland Cut (A-B)	1,349+108 (n = 8)	52.4+2.59 (n = 8)	2,035+216 (n = 8)	40.4+1.19 (n = 8)
Parsonage Creek (A-B)	871+116.1 (n = 8)	30.2+1.11 (n = 8)	NS	NS
Hamlin Creek North	586+81.4 (n = 4)	27.3+1.74 (n = 4)	NS	NS
Ashe Island	882+255.4 (n = 4)	18.1+1.15 (n = 4)	NS	NS

Table 12. Mean oyster densities (#/m²±1SE) and sizes (mm±1SE) on reefs constructed in 2005 and sampled at one year of age. Samples sizes are given in parentheses.

Site	Mean oyster density (#/m² ±1SE) Year 1	Mean oyster size (mm±1SE) Year 1
2005 Distant Island A	1,767+60.6 (n = 8)	42.1+0.93 (n = 8)
2005 Distant Island B	1.351+101 (n = 8)	54.0+2.13 (n = 8)
2005 Distant Island C	1,384+195 (n = 4)	46.3+ 1.72 (n = 4)
2005 Wallace B	1,212+216 (n = 8)	45.8+2.36 (n = 8)
2005 Wallace R121	2,118+236 (n = 4))	39.9+2.33 (n = 4)

Success Determinations Based on Oyster Population Parameters

To establish targets for evaluating restoration success, we used our unique, long-term reef dataset on natural oyster densities and sizes across the state. These sites have been selected randomly, as part of other programs (e.g., May River Study, Van Dolah et al. 2004). Oyster densities across 79 natural reef sites sampled from 1997-2006 ranged from a low of 500 to over 7,597/m²; with overall mean density (±1SE) of 2,348/m² (±167). Oyster mean sizes from these same reef samples ranged from a low of 10 mm shell height (SH) to 56 mm SH, with overall mean size of 32 mm SH (±1.0). We evaluated this natural population data set to determine total oyster density, mean SH, density of large oysters, density of small oysters, and maximum SH for each site and calculated percentiles for each of those parameters. Large oysters were defined as those with a SH of 60 mm or greater. Small oysters were defined as those with SH of 20 mm or less. We used the 70th percentile as the lower limit for a 'Good' reef and the 30th percentile as the lower limit for a 'Fair' reef (Table 13).

Table 13. Oyster population parameters from long-term DNR database on natural oyster populations. Data cover 79 sites statewide sampled over ten years.

		Mean (±1SE)	Min	Max	30th percentile (Fair)	70th percentile (Good)
Oyster Density	#/m²	2,348±167	500	7,597	1,395	2,836
Density of small oysters	#/m²	1,118±110	50	4,146	453	1,417
Density of large oysters	#/m²	240±16	10	606	146	297
Maximum SH	mm	101±2	42	144	93	110
Mean SH	mm	32±1	10	56	28	35

We evaluated restored sites based on the latest population assessment available, usually taken in 2006 (Table 14). Because the reefs were constructed from 2002-2005, they were anywhere from 1 to 4 years old at the time of the last assessment. For this analysis we did not distinguish among treatments (e.g. mesh vs. no mesh). Population data were available for 45 reefs at 20 sites.

Total densities for the 45 reefs for which population data were available ranged from 59 to 4,031/m^2 with an overall mean of 1,215/m^2 (Table 14). Twenty-nine of the restored reefs (69%) ranked 'Poor' relative to natural oyster reefs for total density. Density of small oysters ranged from 27 to 1,180/m^2 with a mean of 502/m^2. Twenty-four of the reefs (57%) ranked 'Poor' for density of small oysters. Density of large oysters ranged from 0 to 736/m^2 with a mean of 181/m^2. Twenty-eight of the reefs (67%) ranked 'Poor' for large oyster density but ten (24%) ranked 'Good'. Maximum oyster size ranged from 48 to 128 mm with a mean of 94 mm. Twenty-three reefs (55%) ranked 'Poor' for maximum size and ten (24%) ranked 'Good'. Mean oyster size ranged from 18 to 54 mm SH with an overall mean of 32 mm. Fifteen reefs (36%) ranked 'Good' for average size and eighteen (43%) ranked 'Poor'. The overall population scores (average of the five subscores) ranged from 1 to 4.2 with a mean score of 2.2 ('Fair'). Ten reefs had an overall population score of 'Good', nineteen had 'Fair' scores and sixteen had 'Poor' scores (Figure 8).

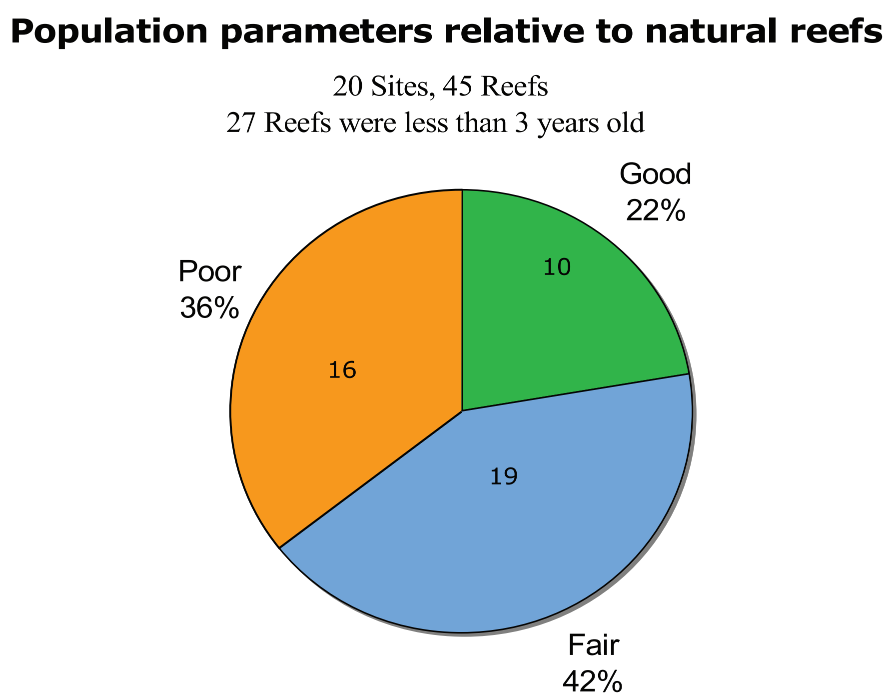


Figure 8. Success ratings of 45 reefs based on five oyster population parameters: total density, density of small oysters, density of large oysters, maximum height, and mean height. Parameters were compared to targets derived from natural populations. Sites rated 'Good' have average scores of 3.4 or better (scale of 1-5). Those rated 'Fair' have scores between 1.7 and 3.4, while those rated 'Poor' have scores below 1.7.

Table 14. Summary of oyster population data from restored reefs and resulting success score. Each reef was rated 1, 3, or 5 for each of the five parameters. Color coding indicates the score for each parameter as follows: Green=5, Blue=3, Orange=1. The five scores were averaged to give a mean success score. Mean scores less than 1.7 are considered 'Poor' and were 'recoded' to a score of 1. Scores between 1.7 and 3.4 were considered 'Fair' and were 'recoded' to a score of 3. Scores of 3.4 and up were considered 'Good' and were 'recoded' to a score of 5.

Site	Reef	Age at assessment	Total density	Density of small (<25 mm) oysters	Density of Large (>65 mm) oysters	Maximum shell height	Mean shell height	Mean Success Score	Recoded Score
		Years	(#/m^2)	(#/m^2)	(#/m^2)	(mm)	(mm)		
Ashe	S196	1	882	548	0	48	18	1.4	1
Bull North	A	2	373	136	4	71	31	1.4	1
Bull North	B	2	60	28	0	59	27	1	1
Bull North	C	2	211	91	1	83	24	1	1
Bull South	D	3	370	222	1	71	22	1	1
Bull South	E	2	171	85	1	61	23	1	1
Bull South	F	3	1,041	538	31	97	24	1.8	3
Distant Isl.	A	1	1,767	483	505	112	42	4.2	5
Distant Isl.	B	1	1,351	290	670	127	54	3.4	5
Distant Isl.	C	1	1,384	352	504	117	46	3.4	5
Folly	S-206 A	3	1,650	769	77	96	26	2.2	3
Folly	S-206 B	3	1,955	1,125	49	98	22	2.2	3
Hamlin N	D	1	267	62	21	86	38	1.8	3
Hamlin N	E	2	343	110	58	90	37	1.8	3
Hamlin N	F	3	793	259	46	91	31	1.4	1
Hamlin N	G	4	1,523	481	73	85	32	2.2	3
Hamlin N	H	4	2,024	628	56	83	30	2.2	3
Hamlin N	2004	1	586	286	30	78	27	1	1
Hamlin S	A	3	1,957	865	90	87	28	1.8	3
Hamlin S	B	3	853	321	26	91	29	1.4	1
Hamlin S	C	2	375	121	33	84	34	1.4	1
Johnson Cr.	B	3	4,031	1,880	194	94	26	3.4	5
Johnson Cr	C	3	2,285	1,027	105	83	27	1.8	3
Leadenwah	R-173	2	961	704	7	71	18	1.4	1
Leadenwah	R-174	1	2,531	1,111	520	91	35	3	3
Leadenwah	R-181	2	2,037	1,162	86	102	23	2.2	3
Clambank		1	226	65	32	102	38	2.2	3
Oaks 2002	E	3	1,115	542	191	123	31	3	3
Oaks 2002	F	2	683	217	231	103	42	2.6	3
Oaks 2002	G	2	896	310	225	108	38	2.6	3
Oaks 2002	H	4	1,860	972	152	105	26	2.6	3
Oaks 2004	S354	2	1,848	812	501	128	40	4.2	5
Woodland	A	2	1,790	756	612	124	42	4.2	5
Woodland	B	2	2,280	1,026	664	122	39	4.2	5
Parsonage	A	1	864	358	77	83	31	1.4	1
Parsonage	B	1	878	352	46	84	29	1.4	1

(continued next page)

Table 14. (continued) Summary of oyster population data from restored reefs and resulting success score. Each reef was rated 1, 3, or 5 for each of the five parameters. Color coding indicates the score for each parameter as follows: Green=5, Blue=3, Orange=1. The five scores were averaged to give a mean success score. Mean scores less than 1.7 are considered 'Poor' and were 'recoded' to a score of 1. Scores between 1.7 and 3.4 were considered 'Fair' and were 'recoded' to a score of 3. Scores of 3.4 and up were considered 'Good' and were 'recoded' to a score of 5.

Site	Reef	Age at assessment	Total density	Density of small (<25 mm) oysters	Density of Large (>65 mm) oysters	Maximum shell height	Mean shell height	Mean Success Score	Recoded Score
		Years	(#/m^2)	(#/m^2)	(#/m^2)	(mm)	(mm)		
Pinckney 02	A	4	363	191	20	82	21	1	1
Pinckney 02	B	4	536	264	56	95	25	1.4	1
Pinckney 02	C	4	966	412	95	100	30	1.8	3
Pinckney 02	D	1	435	197	13	94	28	1.4	1
Pinckney 03	R-37 A	3	999	330	189	123	37	3	3
Pinckney 03	R-37 C	3	1,317	553	173	110	32	2.6	3
Wallace	A	1	1,915	592	459	92	39	3.4	5
Wallace	B	1	1,212	362	505	124	46	3.4	5
Wallace	R121	1	2,728	576	736	87	43	3.4	5
Mean			1,215	502	181	94	32	2.2	3

Composite Success Evaluation

We combined the information from our footprint assessment and our population assessment to create a composite success score for those reefs for which both assessments were made. Composite success scores could be calculated for 43 reefs at 19 different sites (Figure 9). Each reef was given a separate footprint score and population score of 1, 3, or 5 (corresponding to 'Poor', 'Fair' and 'Good'). The two scores (footprint and population) were then averaged, giving a final score of 1 ('Poor'), 2 ('Below Average'), 3 ('Average'), 4 ('Good') or 5 ('Very Good'). Twenty-one reefs (47%) were 'Good' or 'Very Good', thirteen (29%) were 'Average,' and nine (24%) were 'Below Average' or 'Poor' (Figure 9).

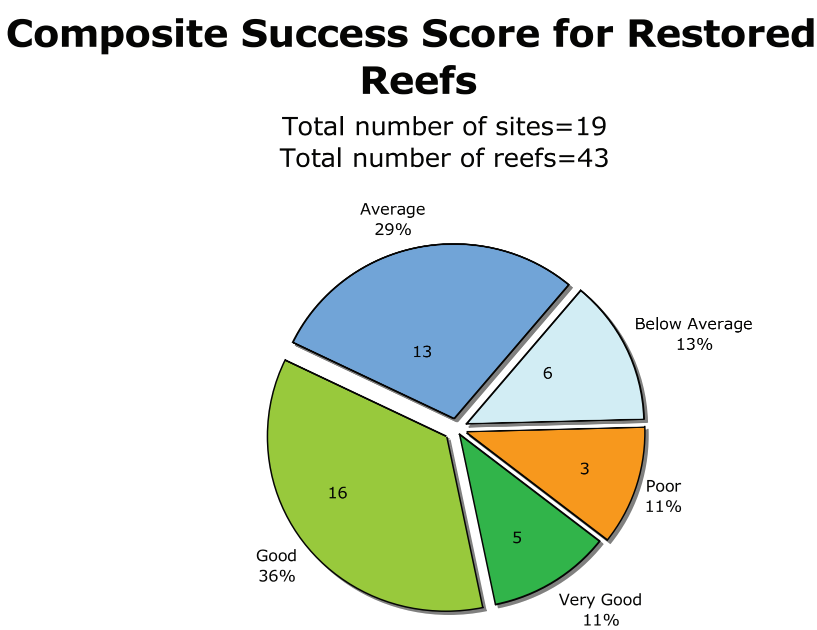


Figure 9. Composite success ratings of 43 reefs obtained by averaging scores for footprint retention and oyster population. Composite scores range from 1 (Poor) to 5 (Very Good).

Evaluation of Success in Relation to Planting year, Planting date, and Site Attributes

Planting year

In order to ascertain any potential relationship between success and planting year, reefs were evaluated for success based on the year they were planted (Table 15). Twenty-two of the 23 reefs planted in 2002 could be assessed for success. Seven reefs (32%) scored '4' on the success scale, nine (41%) scored '3', three scored '2,' and three reefs scored '1.' All the reefs that scored 1 were at the same site, Bull Creek in Beaufort County.

Of the 18 reefs planted in 2003, only nine were assessed for both footprint and oyster populations. None of the nine scored below average. Five (56%) scored '4,' and one reef scored '5.' Of the 11 reefs planted in 2004, seven were evaluated for success. Three of these scored '2' (Below average), 1 scored '3,' and three scored '4' (Good). Of the nine reefs planted in 2005, five were assessed for success. Four of these scored '5' (Very good) and 1 scored '4' (Good).

An ANOVA on ranks (Kruskal-Wallis test) could not detect a significant difference in success among planting years (p=0.385).

Time of planting

Within a given year, reefs were constructed over a 5-6 month period (roughly May-September). In order to ascertain any potential relationship between reef success and time of planting, 2002-2005 reefs were assigned to three groups based on the time they were planted (Table 15). All reefs designated as 'Early' were planted in June; all reefs designated as 'Mid' were planted between 1 July and 15 August, and all reefs designated as 'Late 'were planted after 15 August of a given year. Data were compared using Kruskal-Wallis Rank-sum ANOVA. There was not a significant difference in success related to planting date (p=0.189). The median success score for 'Early' sites was '4,' that for 'Mid' sites was '3,' and that for 'Late' sites was '3.5.'

Site Attributes

Success was evaluated in relation to the following site attributes: creek width, shoreline slope, firmness, and substrate type (Table 15). Additionally we evaluated two subjective attributes (boat traffic and wave energy) that were not quantified but were estimated from field observations over a number of years (Table 16).

Reefs were categorized in one of four creek width groups: 'Very small' (<55 m), 'Small' (55-100 m), 'Medium' (101-200 m), and 'Large' (>200 m) and compared using a Kruskal-Wallis test. There was no significant difference in success related to creek width (p=0.315).

Reefs were categorized in one of three shoreline slope categories: 'Low' (<5°), 'Medium' (5-8°), and 'High' (>8°). There was no significant difference in success rates among the slope categories (p=0.319, Kruskal-Wallis). These categories are arbitrary and relevant only to this study as the steepest slope was only 11°.

Reefs were categorized in one of five sediment firmness categories: 'Soft,' 'Medium,' and 'Hard.' Soft sites were those where an average person sank more than 8 inches when walking on the surface. Medium sites were those where an average person sank 2-8 inches. Firm sites are those where an average person sank less than two inches. Most of the restoration sites were of medium firmness. There was no difference in success rates among sites sorted by bottom firmness (Kruskal-Wallis, p=0.13).

Reefs were grouped into three substrate categories: 'Mud,' 'Mud/Shell,' and 'Shell/Sand.' The majority of the restoration sites were mud/shell substrate. There was a significant difference between success rates in the three substrate categories (Kruskal-Wallis, p=0.034) with 'Mud' substrate most likely to be successful and 'Shell/Sand' least likely (Table 15).

Reefs were grouped in one of four boat traffic categories: 'Low,' 'Med,' 'Med/High,' or 'High.' Boat traffic was based on field observations and some past knowledge, but was not quantified as Walters et al. (UCF) had in Florida in Mosquito Lagoon. There was a significant difference in success rates among the reefs in the different boat traffic categories (Kruskal-Wallis, p=0.002) with 'High' boat traffic sites less likely to be successful than any other category (Table 16). 54% of 'High' boat traffic sites ranked 'Below Average' and none ranked 'Very Good.'

Reefs were grouped into one of four qualitative "energy" categories: 'Low', 'Med', 'Med-High', and 'High'. Energy includes boat wakes, wind-driven waves and current. Sites were classified based on field observations made during this study and during shellfish surveys over the last decade. Energy was not quantified at any of the sites. There was a significant difference in success rates among the reefs in the different energy categories (Kruskal-Wallis, $p<0.001$) with 'High' energy sites less likely to be successful than any other category (Table 16). 50% of 'High' energy sites ranked 'Below Average' and none ranked 'Very Good'.

Table 15. Restoration success based on year planted, time planted, and site attributes. The Planting Time grouping evaluates the success of reefs planted 'Early' in the oyster recruitment period (June), 'Mid' in the oyster recruitment period (1 July-15 August), and 'Late' in the oyster recruitment period (after 15 August of any year). Shoreline slope categories are 'High' slope (8-11^o), 'Medium' slope (5-8^o), and 'Low' slope (<5^o). Substrate firmness categories are 'Soft,' 'Medium' and 'Firm.' Substrate composition categories are 'Shell and/or Sand,' 'Mud/Shell,' and 'Mud.' Creek width categories are 'Very small' (<55 m), 'Small' (55-100 m), 'Medium' (101-200 m), and 'Large' (>200 m). The total number of reefs for each category and the number and percent of total ranking Poor, Below Average, Average, Good, and Very Good are listed. Sites were not selected based on attributes but were categorized after the fact.

Grouping variable	Total number of reefs		Poor		Below Average		Average		Good		Very Good	
Year planted	Planted	Assessed	#	%	#	%	#	%	#	%	#	%
2002	23	22	3	14	3	14	9	41	7	32	0	0
2003	18	10	1	10	0	0	3	30	5	50	1	10
2004	11	8	1	12	3	37	1	12	3	37	0	0
2005	9	5	0	0	0	0	0	0	1	20	4	80
Planting time												
Early	13		0	0	2	18	1	9	8	64	2	9
Mid	17		3	17	4	22	6	33	2	11	2	17
Late	15		2	12	0	0	6	38	6	44	1	6
Slope												
Low	18		2	11	3	17	4	22	5	28	4	22
Medium	9		0	0	0	0	4	44	5	56	0	0
High	18		3	17	3	17	4	22	6	33	1	6
Firmness												
Soft	3		0	0	0	0	0	0	2	67	1	33
Medium	30		3	10	5	17	8	27	10	33	4	13
Hard	12		2	17	1	8	5	42	4	33	0	0
Substrate												
Mud	10		0	0	1	10	2	20	3	30	4	40
Mud/Shell	26		3	0	4	15	7	27	11	42	1	6
Shell/Sand	9		2	22	1	11	4	44	2	22	0	0
Creek width												
Very small	16		0	0	3	19	4	25	8	50	1	6
Small	7		1	14	0	0	1	14	4	57	1	14
Medium	13		3	23	2	15	2	15	3	23	3	23
Large	9		1	11	1	11	6	67	1	11	0	0

Table 16. Restoration success in relation to boat traffic and total energy (boats, wind, current). The total number of reefs for each category and the number and percent of total ranking Poor, Below Average, Average, Good, and Very Good are listed.

Grouping variable	Total number of reefs	Poor		Below Average		Average		Good		Very Good	
Boat traffic		#	%	#	%	#	%	#	%	#	%
Low	14	1	7	2	14	1	7	5	36	5	36
Med	3	0	0	0	0	2	67	1	33	0	0
Med - High	15	0	0	1	7	5	33	9	60	0	0
High	13	4	31	3	23	5	38	1	8	0	0
Energy											
Low	10	0	0	2	20	0	0	3	30	5	50
Medium	4	0	0	0	0	2	50	2	50	0	0
Med - High	13	0	0	0	0	5	38	8	62	0	0
High	18	5	28	4	22	6	33	3	17	0	0

Recruitment Potential Using Trays

Recruitment potential at restoration sites varied significantly among years (ANOVA: $p < 0.001$) with the 2004 mean recruitment almost three times that in 2003 (Figure 10). Both 2004 and 2005 recruitment were significantly higher than 2003 recruitment. For all tray recruitment sites assessed statewide, oyster densities in 2005 were highest (Figure 10) but were not significantly different from those in 2004. Both 2004 and 2005 recruitment potentials statewide were significantly higher than either 2002 or 2003 recruitment potentials (ANOVA, $p<0.001$). Within years, recruitment potential varied significantly among SRFAC sites in all years except 2004 (Table 17). In 2002, the mean recruitment potential at five restoration sites was 4,226/m^2, ranging from a low of 1,792/m^2 (Hamlin Creek) to a high of 7,530/m^2 (Leadenwah Creek). In 2003, mean recruitment potential at twelve restoration sites was 3,047/m^2, ranging from a low of 1,081/m^2 (Leadenwah) to a high of 5,598 m^2 (Pinckney). In 2004, the mean recruitment potential at seven SRFAC sites was 7,274/m^2, ranging from a low of 3,428/m^2 (Murrells Inlet) to a high of 10,757/m^2 (Pinckney). In 2005, the mean recruitment potential at 14 restoration sites with trays was 5,976/m^2, ranging from a low of 302/m^2 (Cole Creek) to a high of 9,599/m^2 (Ashe Island).

Table 17. Variation in oyster recruitment potential among SRFAC sites for each year. P-value is shown for one-factor ANOVA comparing sites within each year.

Year	Number of sites	Mean Recruitment	Minimum	Maximum	P-value
2002	5	4,226	1,792	7,530	0.01
2003	12	3,047	1,081	5,598	0.01
2004	7	6,686	3,428	10,757	0.32
2005	14	5,976	302	9,599	0.04

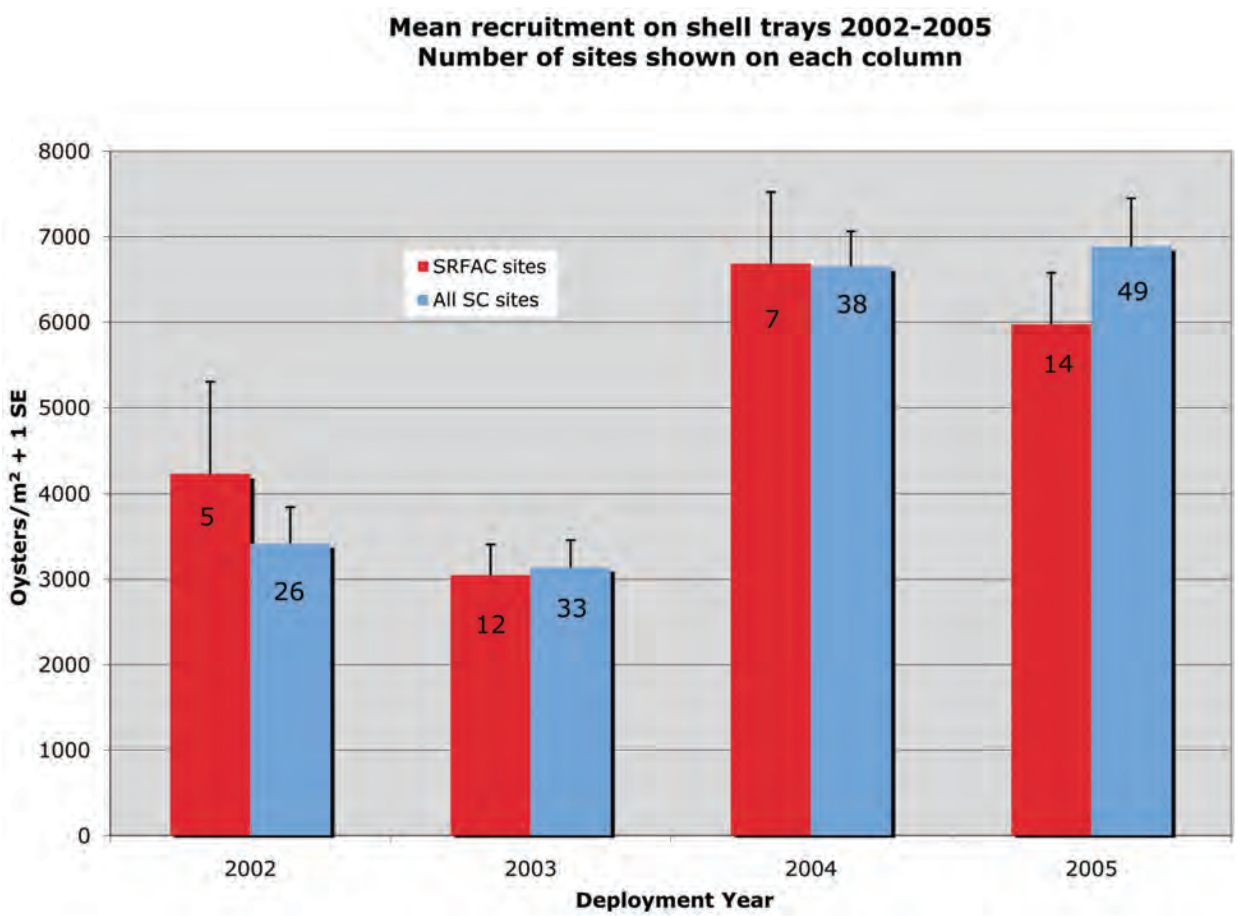


Figure 10. Oyster recruitment potential (mean oysters/m^2+1SE) at SRFAC sites and all South Carolina sites monitored from 2002-2005 using shell trays deployed for 9-11 months. The number of sites is shown in each column.

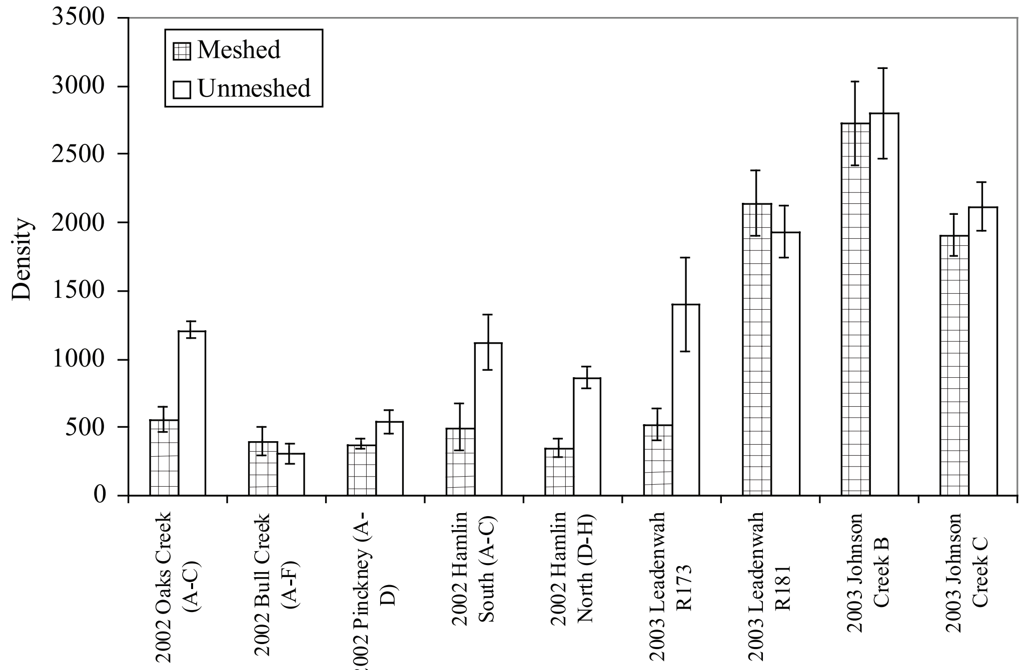


Figure 11. Mean oyster density (live oysters/m^2±1SE) for meshed and unmeshed treatments at Year Two. Data for 2002 reefs were calculated from 2004 population collections. Data for 2003 reefs were calculated from 2005 population collections. See Table 18 for sample sizes and actual mean values.

Mesh Stabilization Treatments

A total of nine sites had oyster density data that could be used to compare oyster densities between meshed and unmeshed areas at two years post-reef construction (Figure 11; Table 18). Using randomized block ANOVA, we found that unmeshed areas had significantly higher oyster density than meshed areas ($p<0.001$). Our blocking factor of site was also significant ($p<0.001$) indicating that oyster density significantly differed among the sites with oyster densities at the two Johnson Creek (S108) sites and Leadenwah (R181) being the highest.

Table 18. Reef sites with Year Two recruitment data for meshed and unmeshed treatments. Data for 2002 reefs were calculated from 2004 population collections. Data for 2003 reefs were calculated from 2005 population collections. The number of quadrat samples collected and used in calculating mean values is given for meshed and unmeshed treatments. Mean (±1SE) for meshed and unmeshed means.

Reef site	No. of Samples Collected		Mean # of Live Oysters/m^2			
	Meshed	Unmeshed	Meshed	±1SE	Unmeshed	±1SE
2002 Oaks Creek (A-C)	7	13	564	92.5	1,214	62
2002 Bull Creek (A-F)	24	24	401	103.2	307	72.1
2002 Pinckney (A-D)	10	10	378	37	545	86.8
2002 Hamlin South (A-C)	11	11	501	174.2	1,124	200
2002 Hamlin North (D-H)	16	16	353	66	861	79
2003 Leadenwah R173	4	4	523	113.5	1,399	347.3
2003 Leadenwah R181	4	4	2,143	239.1	1,931	189.1
2003 Johnson Creek B	4	4	2,728	309	2,801	334.3
2003 Johnson Creek C	4	4	1,907	153.2	2,121	176.1

A total of five sites had oyster density data that could be used to compare oyster densities between meshed and unmeshed areas at three years post-reef construction (Figure 12; Table 19). Using randomized block ANOVA, we found that oyster density did not differ significantly between unmeshed and meshed areas (p=0.76). Our blocking factor was significant (p<0.001) indicating that oyster density significantly differed among the five sites with higher oyster densities at the two Johnson Creek (S108) sites than the other three sites.

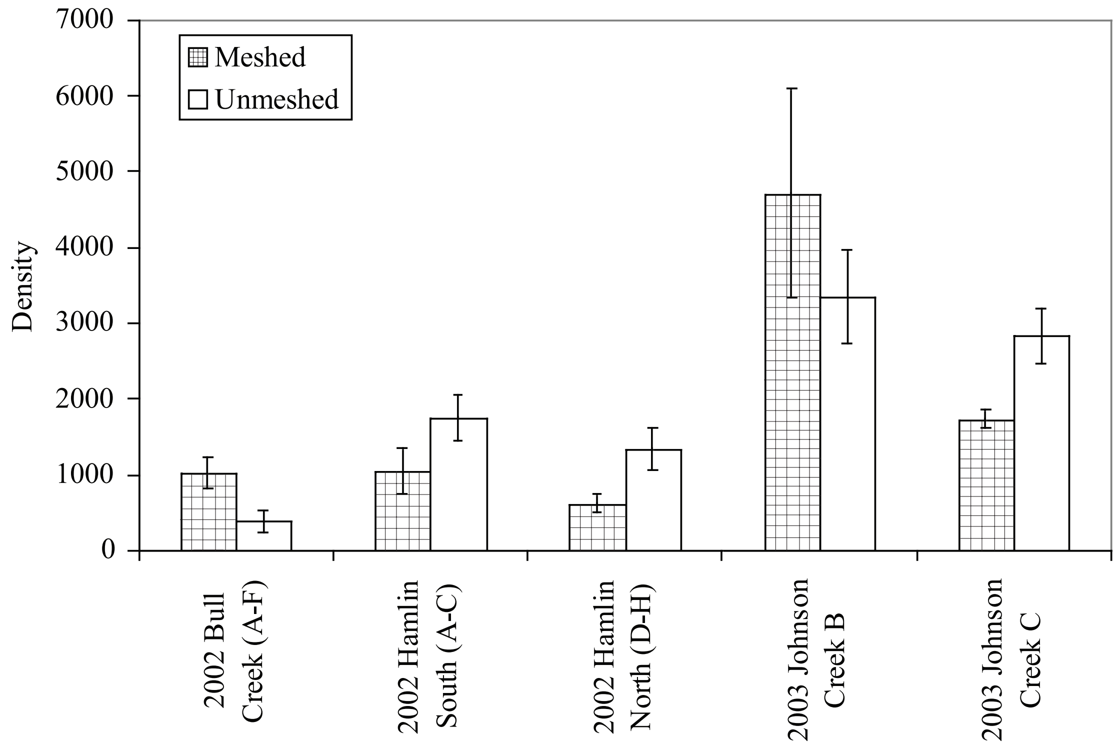


Figure 12. Mean oyster density (number of live oysters/m²±1SE) for meshed and unmeshed treatments at Year Three. Data for 2002 reefs were calculated from 2005 population collections. Data for 2003 reefs were calculated from 2006 population collections. See Table 19 for sample sizes and actual mean values.

Table 19. Reef sites with Year Three recruitment data for meshed and unmeshed treatments. Data for 2002 reefs were calculated from 2005 population collections. Data for 2003 reefs were calculated from 2006 population collections. The number of quadrat samples collected and used in calculating mean values is given for meshed and unmeshed treatments. Mean (±1SE) for meshed and unmeshed means.

Reef site	**No. of Samples Collected**		**Mean # of Live Oysters/m²**			
	Meshed	Unmeshed	Meshed	±1SE	Unmeshed	±1SE
2002 Bull Creek (A-F)	8	8	1,026	208.2	385	146.5
2002 Hamlin South (A-C)	6	6	1,049	295.7	1,761	301.5
2002 Hamlin North (D-H)	6	6	619	123.5	1,346	273.1
2003 Johnson Creek B	4	4	4,718	1,373.3	3,344	618.6
2003 Johnson Creek C	4	4	1,738	114.7	2,832	371.2

Shell Planting Depth and Change over Time

At Hamlin Creek, where different shell types were planted at different depths, the 3-inch whelk plot had less area (61%) remaining after 4 years than the other plots, which were similar to each other and averaged an increase in footprint. Density of recruited oysters was not significantly different after 1 or 2 years but after 4 years the deeper plots had significantly more oyster accumulation. The same was true on the South Carolina plots planted at shallow or deep depths at Pinckney Island. At that site the shallow plot had better footprint retention (82%) than the deep plot (45%) after 4 years.

In 2002, six reef sites were monitored for changes in shell depth (Table 20). For this project, Bull Creek (R008) was divided into two parts: Bull Creek North (R008, A-C) and Bull Creek South (R008, D-F). The other reef sites monitored for changes in depth included Pinckney (R036, 037, A-D), Hamlin Creek South, Hamlin Creek North, Oaks Creek, and Clambank. Shell depth was monitored on a quarterly basis for all sites and the actual number of months over which shell depth was measured ranged from 14 (at Clambank, R351) to 21 (at Pinckney, R036, 037). The greatest decrease in shell depth occurred at Bull Creek North (R008) where mean shell depth decreased by 10.47 cm (or 4.1”) for meshed samples (-0.55 cm/month). The greatest increase in shell depth occurred at Oaks Creek (S354) where mean depth increased by 2.97 cm (or 1.17”) for unmeshed samples (0.21 cm/month).

In 2002 reefs, no apparent pattern occurred for depth change between meshed and unmeshed treatments (Figure 13). At two sites (Bull Creek North, R008, and Hamlin North, R252) mean shell depth decreased more for meshed areas. At two sites (Bull Creek South, R008, and Hamlin South, R252) mean shell depth was greater for unmeshed areas than meshed areas. At two sites (Pinckney, R036-037, and Oaks Creek, S354) mean shell depth increased more for unmeshed areas than meshed areas as shell moved around with waves and currents. At one site (Clambank, R351) mean shell depth increased for meshed areas and decreased for unmeshed areas (Figure 14).

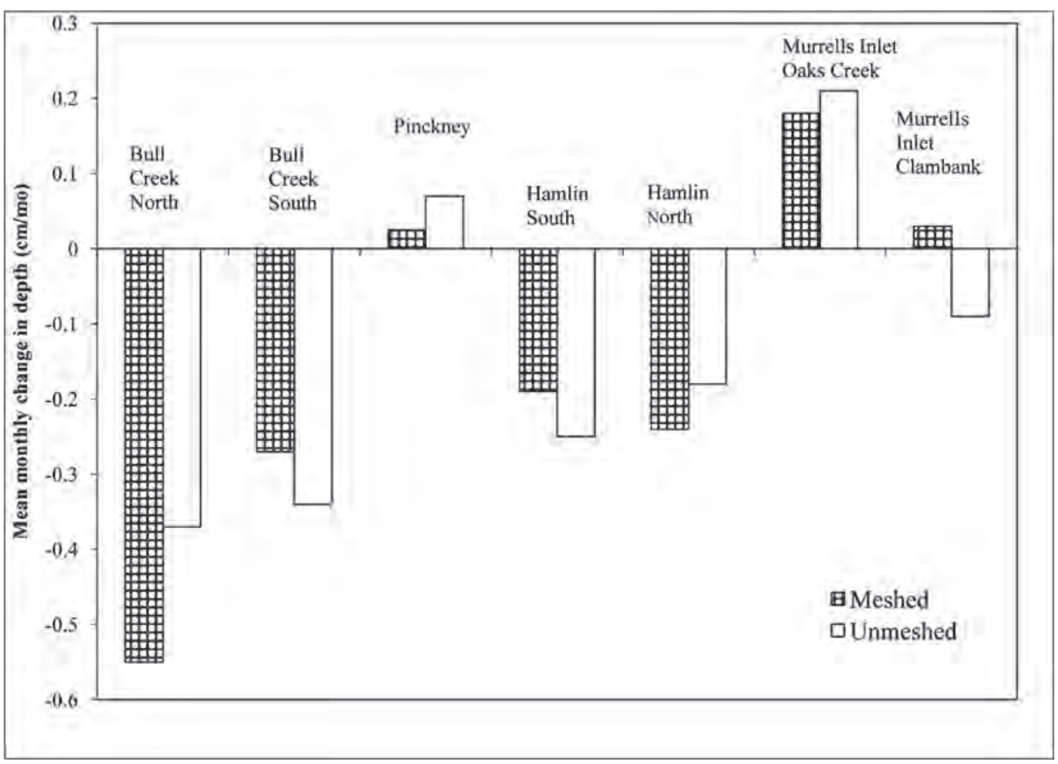


Figure 13. The average monthly change in depth for meshed and unmeshed treatments at the 2002 reefs. A negative number for change in depth means that restoration shell depth decreased from the initial depth. See Table 20 for actual values.

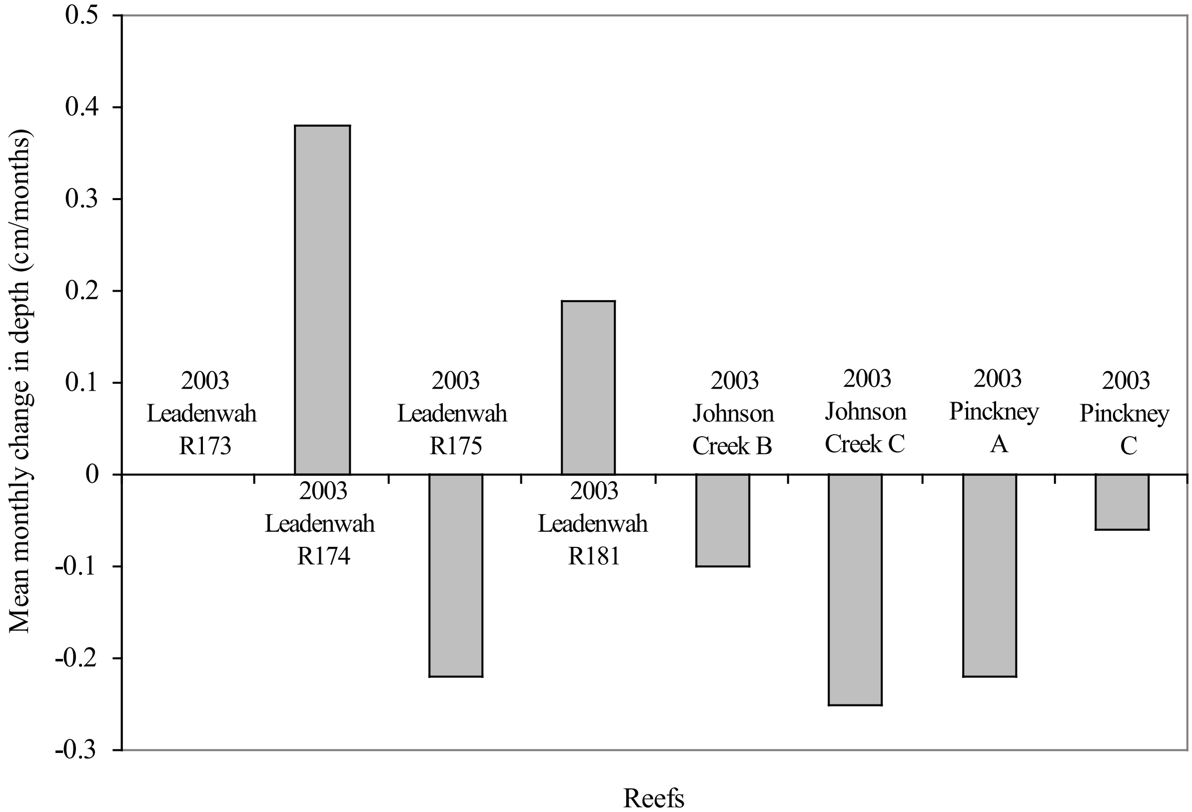


Figure 14. Mean monthly change in shell depth on the 2003 reefs. A negative value represents a decrease in shell depth from initial depth measurements, a positive value a net gain in depth. See Table 21 for raw values.

Table 20. Monthly change in depth for each of the 2002 reefs measured. The number of months depth was measured is listed for each site. The number of depth poles includes all poles at a site that were measured from the initiation of the depth pole experiment until the final measurement. The mean difference in depth was calculated by subtracting the initial depth measurement from the final depth measurement (cm) for each pole and then calculating a mean for each site. The monthly change in depth was calculated by dividing the mean difference by the total number of months that elapsed between the initial and final depths measurements. Values are given for meshed and unmeshed treatments.

Reef	No. of months depth measured		No. of depth poles		Mean difference (Final depth – Initial depth in cm)		Difference/month (cm/month)	
	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed	Meshed	Unmeshed
2002 Bull Creek North	19	19	14	14	-10.47	-7.08	-0.55	-0.37
2002 Bull Creek South	19	19	16	20	-4.08	-6.47	-0.27	-0.34
2002 Pinckney A and C	21	21	10	8	0.56	1.5	0.025	0.07
2002 Hamlin South	18	18	10	10	-3.5	-4.58	-0.19	-0.25
2002 Hamlin North	18	18	18	18	-4.25	-3.3	-0.24	-0.18
2002 MI Oaks Creek	14	14	14	14	2.46	2.92	0.18	0.21
2002 MI Clambank	14	14	28	15	0.36	-1.27	0.03	-0.09

In 2003, eight reef sites were monitored for changes in shell depth (see Table 21; Figure 14). These sites were Leadenwah R173, R174, R175, R181, Johnson Creek B, C, and Pinckney A and C. In this year class, shell changes were not monitored for meshed versus unmeshed treatments so all results are for unmeshed reefs. Shell depths were monitored on a quarterly basis for all sites and the actual number of months over which shell depth was measured ranged from 6 months (at Leadenwah, R175, and Johnson Creek, B and C) to 9 months (at Leadenwah, R173, R174, and R181). The greatest decrease in shell depth occurred at Pinckney A where mean shell depth loss was -1.78 cm (-0.22 cm/month). The greatest increase in shell depth occurred at Leadenwah R174 where mean shell depth increase was 3.44 cm (0.38 cm/month). At one site (Leadenwah R173) mean shell depth change was 0 cm (Figure 14).

Table 21. Monthly change in depth for each of the 2003 reefs measured. The number of months depth was measured is listed for each site. The number of depth poles includes all poles at a site that were measured from the initiation of the depth pole experiment until the final measurement. The mean difference in depth was calculated by subtracting the initial depth measurement from the final depth measurement (cm) for each pole and then calculating a mean for each site. The monthly change in depth was calculated by dividing the mean difference by the total number of months that elapsed between the initial and final depths measurements. Only unmeshed depths were reported for this year.

Reef	No. of months depth measured	No. of depth poles	Mean difference (Final depth – Initial depth in cm)	Difference/month (cm/month)
2003 Leadenwah R173	9	18	0	0
2003 Leadenwah R174	9	36	3.44	0.38
2003 Leadenwah R175)	6	6	-1.33	-0.22
2003 Leadenwah R181	9	39	1.67	0.19
2003 Johnson Creek B	6	18	-0.61	-0.1
2003 Johnson Creek C	6	18	-1.5	-0.25
2003 Pinckney A	8	18	-1.78	-0.22
2003 Pinckney C	8	30	-0.47	-0.06

Shell ('Cultch') Type

We initially attempted to establish treatments at restoration sites that would allow us to compare the efficacy of different shell types for restoration. However, the difficulty of procuring enough shell of each type to have replication within sites, as well as the logistical difficulty of deploying multiple shell types within a site, made this problematic. In most cases the data could not be analyzed for these reasons. Those that could be analyzed did not reveal any consistent patterns of recruitment, shell retention or spat growth.

In 2004, we established an experiment using shell trays to evaluate recruitment on the different shell types. Mean total oyster recruitment among the three different shell types was not significantly different (one-way ANOVA, p=0.31) (Figure 15). The number of recruits per shell was significantly greater on whelk shell (p=0.004), but this was offset by the fact that there were significantly fewer total shells in the whelk-filled trays (p=0.003). Whelk trays averaged (±1SE) 186 (±5.9) shells/tray (range from 179-198), with a mean of 20 oysters recruited per shell. South Carolina shell trays averaged 432 (±63) shells/tray (range from 335-550), with a mean of 5 recruits/shell. Finally, Gulf oyster trays averaged 534 (±38) shells/tray 534 (range from 495-610), with a mean of 6 recruits/shell.

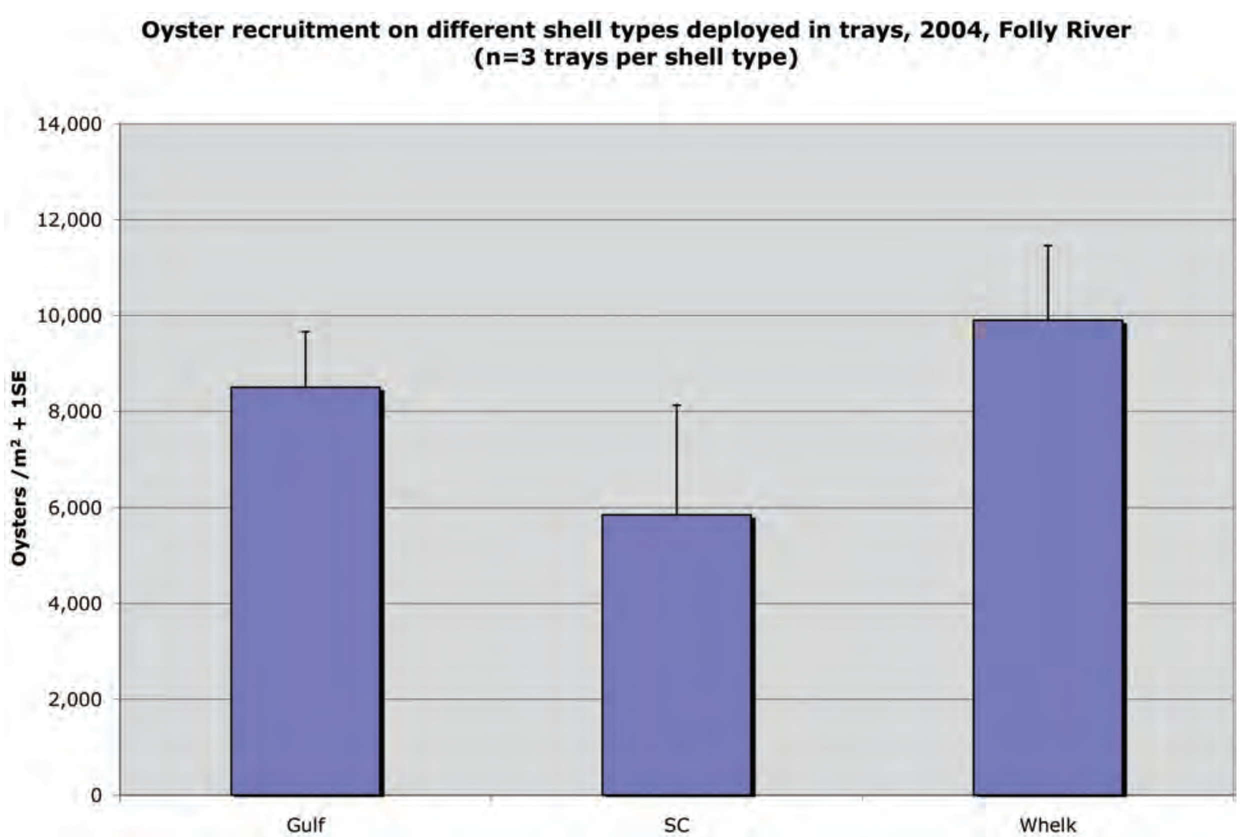


Figure 15. Mean recruitment of oysters (#/m²) to three shell types deployed in triplicate trays.

Mesh Underlay

The 2003 and 2005 pilot jute underlayment experiments were inconclusive. At Leadenwah Creek, employing a limited test (2 plots of meshed and unmeshed with underlayment and one with no underlayment), some differences between the plots were noted, but these appear to be related more too uneven shell planting than to the mesh or underlayment use.

Shell Quarantine

Both the amount of oyster tissue present and parasite abundance declined precipitously after one month and were virtually eliminated by three months. For shucked oysters, no tissue remained after 1 month, while for unshucked oysters tissue remained even after 3.5 months but no *P. marinus* (Dermo) could be detected. After one month, even in unshucked oysters, *P. marinus* had declined by 99% and it was questionable whether the few remaining spores were viable. The results support the recommendation that the quarantine of shell for one month or more can dramatically reduce the potential risk of spreading *P. marinus* when planting oyster shell (=cultch) from other geographic areas. This recommendation (Bushek et al. 2004) is applicable to virtually any region, but several parameters such as effects of climatic conditions and shell pile configuration should be taken into consideration. There is also the possibility that other pathogens not studied here may persist after 30 days. South Carolina typically errs on the side of caution and has been quarantining shell for at least 90 days prior to planting.

Evaluation of Current and Potential Shell Stabilization Materials

UV measurements supported the contention that the UV inhibiting-plastic overlying sheet did indeed reduce incident UV values by 96% for UVA & 98% for UVB, as compared to adjacent measurements in the direct exposure (control) treatment. Tensile strength (see Figure 16), from highest to lowest at beginning of the experiments was: Jute>DelStar (white)>Internet (black, stabilized)>Tenax (Radix, green). Mesh tensile strength values greatly decreased over time, as expected. Also, environmental stresses caused some of the mesh types to break down at a more rapid pace than others. The samples from field sites degraded at a slower rate than those samples placed on the land-based plywood Fort Johnson platforms. Meshes deployed at the three field sites showed very little, if any UV-associated damage. Meshes recovered from these sites were not brittle, had good color, and changed very little from the time they were deployed (besides some strand breakage). Damage on these sites seems solely attributable to wave and current action, which was sufficient in all sites to destroy the jute mesh, and at the Charleston harbor site to destroy all but the small-diameter bio-degradable, white mesh from DelStar Technologies, possibly because the smaller diameter mesh has more material per unit area and is thus potentially stronger. Water and mud appear to be acting as a significant filter to UV. Non-UV stabilized Tanex© (Radix) mesh seems to be the most sensitive to UV light. Jute mesh was the most sensitive to wave action.

Meshes tested to date degrade too quickly to be of use for stabilizing shell. Mesh needs to stabilize the shell until oyster spat and mussels accumulate in great enough numbers to provide shell stabilization. We hope that one or more manufacturers will take up the challenge to develop a material that is eco-friendly but meets the needs of shellfish restoration practitioners. As an update, the supplier of most of the bag mesh currently used by community restoration programs across the U.S., ADPI, Inc., is no longer in business and several other firms have not been able to make a consistent product.

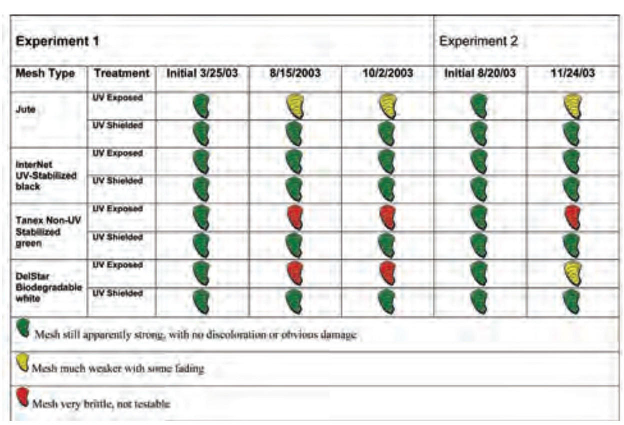


Figure 16. Summary of overall results of two experiments evaluating four meshes under different UV exposures. All materials were also assessed for tensile strength by Tenax, Inc.

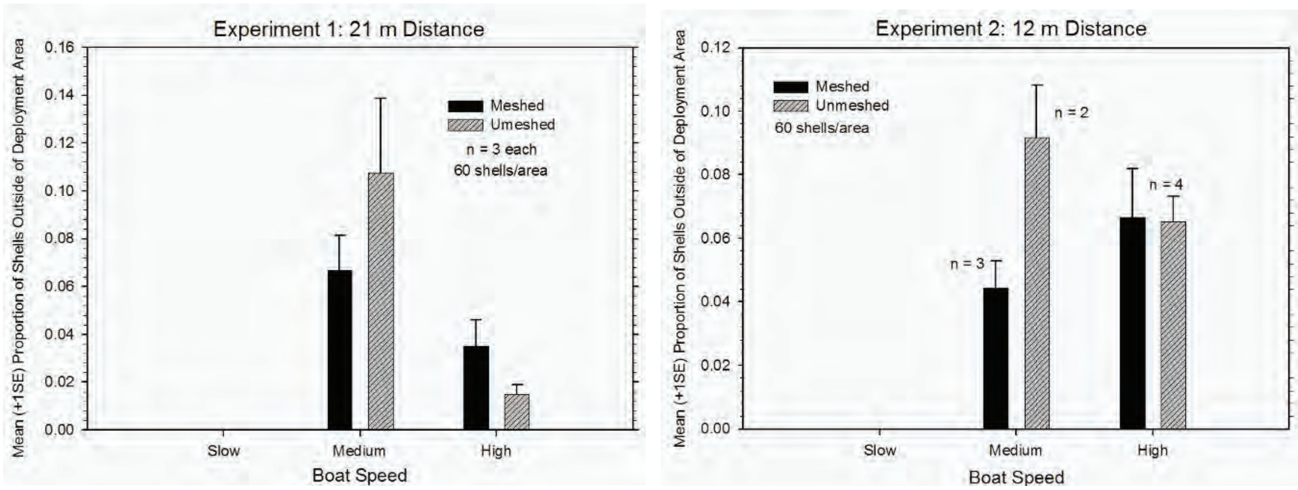


Figure 17. Summary of two boat wake trials with meshed and unmeshed shell.

Effects of Boat Wakes on Shell Movement with and without Mesh

Field trials building upon prior and current work and methods with Florida scientists from University of Central Florida (Drs. Walters and Sacks) demonstrated that shell under mesh, regardless of distance or wave energy (function here of boat speed) moved significantly less than unmeshed shell at our study site. Measurements of Gulf oyster shell used ranged from 66-116 mm shell height with individual shells weighing from 21.5 to 117 g each. The overall conclusions were that no matter what wake distances from reefs were used, (narrow tidal creek) all tested vessels moved simulated oyster shell, although shell dispersal was significantly reduced for smaller, 17-19’ Whalers and 15-17’ Duracraft, all moving at no wake speeds of ≤5.3 mph.

Our two experiments used average boat distances from shore of 21 m and 12 m. For the 21 m distance, speeds utilized with our 20’ Privateer and a 115 hp, 2-stroke engine ranged from no-wake speeds of 3.2 mph (n=3), medium speeds of 16.3 mph (n=3, not on plane), and top mean speeds of 29.3 mph on plane (n=3) over the nine trials. For the closer 12 m-from-shore trials, speeds ranged from no-wake speeds of 3.4 mph (n=3), medium speeds of 18.5 mph (n=2, not on plane), and top mean speeds of 28.5 mph on plane (n=4) over the nine trials. This study site had a moderate slope (10.4^{o}). In both the close (12 m) and more distant (21 m) experiments, shell did not move at no-wake speeds (approx. 3 mph); however, at medium speeds (16-18 mph) not on a plane, significantly more shell (nearly 2x) moved without mesh than with mesh, with a greater proportion moving at the closer distance also (Figure 17). Note that this simple assessment did not include shell that moved within its ¼ m^2 deployed quadrat area, just the proportion of the 60 shells that moved outside of the original placement. Including those additional flipped shells in the results would increase the impacts even more for the unmeshed trials (Figure 17). Results suggest that stabilizing shell with a mesh overlay, while generally preventing shell from being completely lost with time, also limits shell movement on a smaller scale, allowing sediment to build-up more quickly and thereby reduce the shell surface exposed to recruiting oysters, especially if timing between shell planting and oyster recruitment is extended more than a few weeks.

DISCUSSION AND OVERVIEW

Oyster Recruitment Findings (Reefs and Trays)

Accumulation of oysters onto constructed reefs is critical to their success as future oyster resource sites for recreational harvesting. If restoration is for other ecosystem services such as brood stock sanctuaries, or for habitat or filtering, these need to be viewed and assessed differently but oyster recruitment will still be a primary goal (Coen and Luckenbach 2000, Luckenbach et al. 2005, Coen et al. 2007, Grabowski and Peterson 2007, Brumbaugh and Toropova, 2008, Powers et al. in press). Recruitment patterns can vary significantly among years, sites and within sites, or reefs, even at a micro-scale (Bartol and Mann 1997, Bartol et al. 1999).

Oyster recruitment potential using deployed trays varied significantly among years and among SRFAC sites within years, except for 2004 when the SRFAC site recruitments were not significantly different. For all recruitment sites statewide, the 2005 recruitment was highest. As a point of reference, looking at oyster recruitment (density and size) across the entire spectrum of sites (most sites changed each year) where trays were deployed during the same period of time as the SRFAC sites, densities ranged from a low of 276 oysters/m^2 to a high of 10,756 oysters/m^2. In general, the SRFAC sites were in the medium to upper end of the recruitment potential range.

Oyster recruitment potential was always higher than actual recruitment of oysters to adjacent SRFAC reefs (Figure 18). This may be due to differences in when trays are deployed versus the reefs themselves, to differences in sedimentation, or to shell movement on the reef as opposed to in the tray where little or no movement can occur. Regardless, failure of some reefs to develop dense oyster populations does not appear to be related to larval supply.

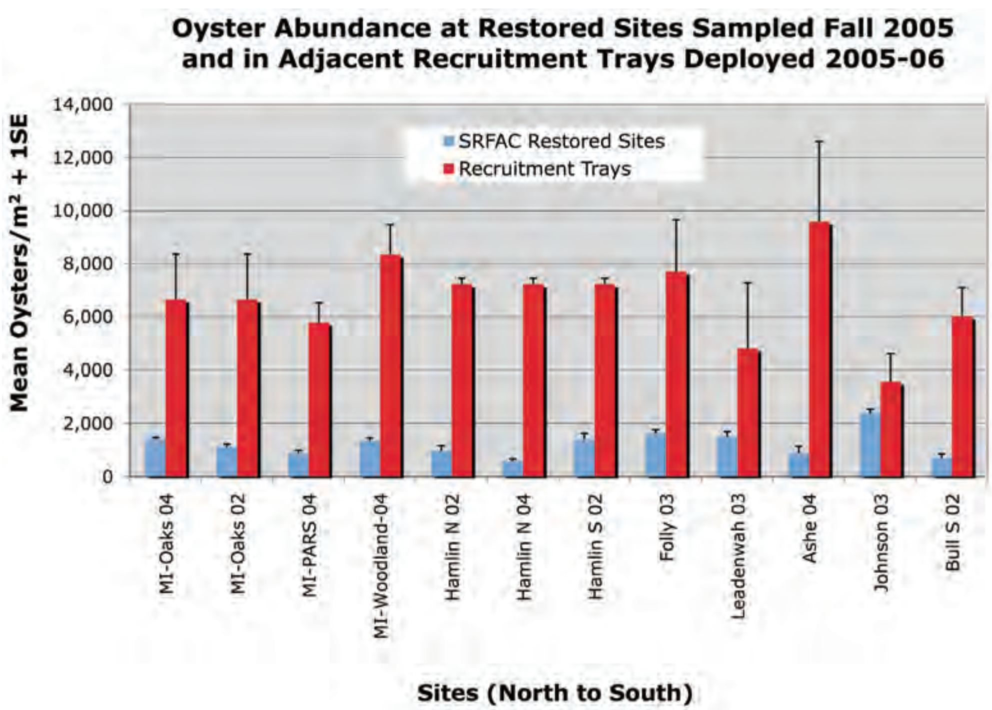


Figure 18. Oyster abundance (#/m^2+1SE) on SRFAC reefs and adjacent recruitment trays (2005-06). Reef abundances include all oysters recruited over 1-3 years while the tray abundances represent only one year's recruitment.

SRFAC sites generally had lower oyster densities at one year of age (early recruitment) than we have seen at other restoration sites (e.g. SCORE sites) or at natural sites. Similarly, the percentage of small oysters in the final population assessment, which relates to continued recruitment, was low relative to natural populations. Twenty-four of forty-two sites were ranked 'Poor' with regards to small oyster densities, and the remainder were ranked 'Fair.' It is not clear why recruitment is lower on planted shell than on natural reefs but the fact that recruitment is lower on large-scale sites than on SCORE sites, which are composed of shell contained in mesh bags, suggests that shell movement may be a factor.

However, for resource managers, lower recruitment may be advantageous for Public Shellfish Ground planting, when the primary purpose is to enhance the resource for recreational as well as commercial harvesting. Reduced density allows for faster growth and larger oysters. In South Carolina commercial oystermen reduce high density oyster populations by a husbandry process of 'rake down' or thinning, in order to encourage more rapid growth and larger oysters (B. Anderson pers. obs., but see also Lenihan and Micheli 2000, Coen and Bolton Warberg 2005).

Mesh Experiments, Shell Stabilization and Boat Wakes

Previous use of mesh by Anderson and Yianopoulos (2003) proved successful but did not have meshed and unmeshed treatments. Although we encountered many logistical problems with mesh, we did make some interesting observations. We found that unmeshed areas of reefs had significantly higher oyster density than meshed areas at both two and three years post-construction. Additionally, we found that shell depth changes were not consistent for meshed and unmeshed areas. These results led us to conclude that, for the SRFAC sites where mesh utility was evaluated, meshing was not an effective restoration tool. This does not mean that stabilization with mesh is never a good restoration tool, but in these cases it either was not effective or we could not rigorously evaluate the treatments to determine if it was effective. .

In our mesh evaluation experiments, mesh types deployed at field sites degraded slower than those samples on our controlled experimental platforms. Meshes deployed at the three field sites showed very little, if any UV-associated damage, with little or no brittleness during deployment times with the exception of strand breakage. This damage we presume was solely a result of wave/current action. The jute mesh disassociated at all field sites, while at the Charleston Harbor site, all materials except the small diameter mesh from DelStar lost integrity. Water and mud appear to be acting as a significant filter to UV. The non-UV stabilized Tanex© (Radix) mesh seems to be the most sensitive to UV light and high wave action. Jute mesh certainly was the most sensitive to wave action. We hope to work with one or more manufacturers to develop a material that is less long-lasting, but eco-friendly for the ever-growing user base across the U.S.

Finally, boat wake field trials building upon prior and current work and methods with scientists from the University of Central Florida (Drs. Walters and Sacks) demonstrated that shell under mesh, regardless of the boat's distance from the reef (12 or 22 m) or wave energy (function here of boat speed and distance), moved significantly less than unmeshed shell at our study site. That site had a moderate slope and supported our hypothesis that stabilized shell, while generally remaining in place or not being lost completely, probably allows sediment to build-up more quickly thereby impacting shell exposure and potentially recruitment if timing between planting and oyster recruit (= ”spat”) arrival is weeks to months later. We have both direct and indirect evidence that intertidal oyster reefs protect fringing marsh shorelines (Meyer et al. 1997, Coen and Bolton-Warberg in prep.). Coen and L. Walters (UCF) have examined the issue of recreational boating in both the shallow waters of the Indian River Lagoon, in central Florida, and in the narrow tidal channels near Georgetown, South Carolina (e.g., Walters et al. 2002, 2004; Wall et al. 2005). In Florida, when the distance from shore was maximized (45 m from shore), there was very little impact on loose shell on intertidal oyster reefs, even with a jet ski traveling at 48 mph (Walters et al. 2005). However, in South Carolina, where the creek center was only 18 m from shore, observed impacts were significantly greater. Hull configuration, boat speed-over-ground, and propeller orientation interactions were all significant variables in shoreline impacts (Wall et al. 2005, L. Walters et al. 2005, Coen et al. in prep. for South Carolina).

A single pass from a 17 ft Boston Whaler with a 90 hp Evinrude motor traveling at only 9 mph displaced nearly 50% of the marked oyster shells on shore, with observed turbidity influencing water clarity (via fluorescent markers) in less than 5 cm of water such that the markers were lost for a short time (Walters et al. 2004). These results hint that under normal conditions, wakes from vessels may significantly affect the surrounding shorelines and planted shell. We hope that enhancing and restoring oysters in South Carolina, even in closed areas, will have greater impacts than just resource augmentation. It also may provide Best Management Practices (BMPs) that are more natural, less costly and less intrusive for shoreline protection then hard bulk-heading (Riggs 2001; Rogers and Skrabel 2001; Bishop and Chapman 2004; Piazza et al. 2005; Bishop 2004, 2007, NRC 2007)

Shell Types

To evaluate recruitment on the three different shell types employed during the course of the study, in 2004 we established a simple side by side experiment using replicated shell trays at a single site and along a relatively uniform shoreline. Mean total oyster recruitment on the three different shell types was not significantly different. The number of recruits per shell was significantly higher on whelk shell, but this was offset by the fact that there were significantly fewer whelk shells (by count) per tray. Whelk trays averaged 186 shells/tray, with a mean of 20 oyster recruits/whelk shell vs. 432 South Carolina oyster shells/tray with a mean of 5 recruits/shell. Gulf oyster shell trays had 534 shells/tray with a mean of 6 recruits/shell. Shell volume was constant in all the trays but the differences in shape of the various shell types results in more interstitial area in trays filled with whelk and South Carolina shells (Coen et al. 2008, in prep.). However, the recruitment per unit area of shoreline surface covered did not differ among shell types.

Shell Quarantine

From our pilot experiment evaluating shell quarantine times, we found that both the amount of oyster tissue present and parasite abundance declined precipitously after one month and was virtually eliminated by three months (Bushek et al. 2004). For shucked oysters, no tissue remained after 1 month, while for unshucked oysters, tissue remained even after 3.5 months but no *P. marinus* could be detected. After one month, even in unshucked oysters, *P. marinus* had declined by 99% and it was questionable whether the few remaining spores were viable. The results support the recommendation that the quarantine of shell for one month or more can dramatically reduce the potential risk of spreading *P. marinus* when planting oyster shell from other geographic areas. This recommendation is applicable to virtually any region, but several parameters such as effects of climatic conditions and shell pile configuration should be taken into consideration. There is also the possibility that other pathogens not studied here may persist after 30 days. SCDNR errs on the side of caution and quarantines recycled shells for at least 90 days prior to planting.

Restoration Success

In recent reviews, many restoration efforts have either lacked well-defined success criteria or focused on a single criterion such as abundance of market-sized (generally 75 mm or 3") oysters (Coen and Luckenbach 2000, Luckenbach et al. 2005). On naturally occurring reefs in South Carolina , large oysters (>75 mm) typically comprise less than 10% of the total oyster population, and the highest proportion we have observed was less than 20% (Coen and Bolton-Warberg 2005, Luckenbach et al. 2005, Coen et al. 2006, Coen et al. 2007, Powers et al. in review). Natural oyster reefs have developed over many years and yet do not have high proportions of large oysters, suggesting that, in South Carolina at least, a self-sustaining oyster population is not dominated by large oysters. An additional concern when using abundance of large oysters as a criterion is that any harvesting will skew the success evaluation. Although these restoration sites were closed by posted signs, there is no way to be sure no harvesting occurred and in some prior efforts in South Carolina there has been evidence that these signs do not necessarily deter harvesting and may even attract fishing pressure (Coen and Bolton-Warberg 2005).

Thus, one objective of this study was to propose and evaluate restoration success criteria in addition to or instead of large oysters. Here we have assessed success in terms of footprint retention and a suite of oyster population parameters. Data from long-term monitoring of natural sites provided targets for the oyster population parameters.

The large-scale restoration efforts were largely successful with 47% of the reefs scoring 'Above Average' after 1-4 years and an additional 29% scoring 'Average' (Figure 9). Only 3 reefs (11%) scored 'Poor' after removal of those that could not be evaluated adequately. Footprint scores tended to be better than population scores (Figures 7 and 8). As reefs get older their population scores (which are being compared to natural reefs which may have taken decades to develop) should improve. At the same time, sites that are experiencing any shell loss will probably have decreasing footprint retention over time.

Footprint 'retention' is an easily assessed metric that could have a large bearing on long-term sustainability of a restored reef. We assessed footprint retention on 53 reefs established between 2002 and 2005 (Figure 7) and found that 49% of the reefs had Good footprint retention (>70%) and an additional 38% had Fair retention (30-70%). These reefs were of varying ages and some were probably too young to provide an accurate indicator of long-term footprint sustainability. However, more than 50% of the 3 year old and 4 year old reefs had Good footprint retention. Reefs built in 2004 appeared to have lower footprint retention than those established in other years (mean of 48% vs. 72-98% in other years). This is probably not a year-related phenomenon but simply a matter of which sites were constructed in that year.

Restored sites also compared fairly well to natural reefs in terms of oyster population development (Figure 8). Twenty-two percent of the assessed reefs were rated ‘Good’ and 42% ‘Fair’ compared to natural populations. Given that the oldest sites were only 4 years old when assessed, whereas natural reefs may have developed over decades, this is an encouraging success rate. Whether these reefs will continue to develop well and resemble natural populations, it is too early to say. We know from more controlled research efforts (Coen et al. 2006) that undisturbed, restored sites often need a minimum of three to five years to fully approach adjacent natural areas, using two of the fisheries metrics assessed here, oyster mean density and size.

Powers et al. (2008) found varying success looking at a large number of intertidal and subtidal reefs up to 40 years old. Even areas that may not have yielded harvestable oyster populations over the duration of assessment (1-4 years) still enhanced ‘fish’ habitat and with time and some shell amendments may yield better oyster resources for harvest (Luckenbach et al. 2005, Brumbaugh et al. 2006, Coen et al. 2006, 2007, ASMFC 2007, Beck et al. in review). Continued monitoring and additional controlled research will be needed to more fully assess large-scale planting efforts in South Carolina and assure continued viability of restored areas.

Success in Relation to Planting Time and Site Attributes

Composite success scores were compared on the basis of site attributes and time of planting (Tables 15 and 16). Time of planting did not have a significant effect on success. Sites planted late in the year did not appear to be less likely to be successful than those planted early or in the middle of the recruitment period. Shell planting generally proceeds full-time during the entire recruitment season, but we were concerned that planting late in the season could be a waste of precious shell resource. However, it appears that this is not the case. Private culture permit holders often wait till late summer or early fall to plant shell in order to avoid “over-spat” which can lead to crowding and small size, with little harvest potential of marketable oysters (Bill Anderson pers. comm., but see Lenihan and Micheli 2000, Coen and Bolton-Warberg 2006).

Slope, creek width, and firmness did not affect restoration success. Since even within this study we selected sites with a view to optimizing success, we do not have a full spectrum of some attributes to examine. For example, none of the sites planted had very steep slopes. Within the narrow range of slopes tested (up to 11 degrees), slope was not a factor affecting success, but managers in South Carolina already know that planting shell on steep slopes is not successful. Nonetheless, these results confirm that our current site selection criteria are producing successful restored sites.

Site attributes that were related to success were substrate type, boat traffic, and overall energy. High energy sites are usually characterized by sand/shell substrates, as the finer particles are swept away. Thus, these three attributes are really all energy-related. Although high energy sites were less likely to be successful, intermediate energy levels (or other attributes related to those) do not appear to have an effect on success rate. In other words, there is not a linear relationship between energy and success, but rather a threshold affect above which success declines. However, energy was not actually quantified and is just estimated based on field observations so this result should be interpreted cautiously. Further study is warranted to evaluate relationships between energy at a site and restoration success.

In summary, it appears that current restoration methods and site selection criteria in use in South Carolina are establishing successful oyster reefs. However, the negative effect of boat wakes on restoration success is an alarm bell that should not be ignored. New regulations may be needed to reduce boat wakes in recently restored areas, in small creeks, or in resource areas deemed critical. The continuing and increasing shortage of natural shell materials, coupled with increased restoration activities in South Carolina and most other coastal states, makes it particularly important to find alternative substrates and/or to develop alternative planting methods which might use less shell.

RECOMMENDATIONS

Our overall recommendations to enhance the effectiveness of SCDNR's shell planting program are as follows:

(1) Restoration sites should be revisited after one year to determine if maintenance planting or other adaptive management is needed.

(2) Public grounds should be reassessed regularly to adjust restoration priorities. (E.g., if a public ground is in good condition it can be given reduced priority, whereas if one has declined in status it should be given priority for restoration.)

(3) New technology should be exploited to develop rapid and consistent monitoring methods that can expedite future efforts and allow a smooth transition to the "next generation" of managers.

(4) The shell recycling program should be expanded to reduce reliance on out-of-state shell sources.

(5) The evaluation of alternative cultch materials that are more readily available than shell should be a priority. We should investigate using non-shell foundations with shell veneers to reduce overall shell requirements.

(6) Boat wakes are a threat to natural and restored reefs. SCDNR should explore the feasibility of establishing no-wake zones or restricting large vessel traffic in shellfish growing areas, particularly in the smaller creeks.

(7) Public outreach and education activities should be continued and expanded to increase public awareness of ecological value of oyster reefs, negative effects of boat wakes, and the need to recycle shell.

(8) Studies evaluating methods of stabilizing shell against waves, currents, and boat wakes should be continued.

(9) Shell planting activities should be expanded to restore oyster habitat in additional areas such as those closed to shellfishing.

ACKNOWLEDGEMENTS

This research was made possible through grant funds from South Carolina's Saltwater Recreational Fisheries License Program and SCDNR. We want to especially acknowledge Ray Haggerty and Andrew Hollis' contributions during most of the five-year program. We also wish to thank, in no order of importance, Michael Hodges, Steve Roth, Ryan Robol, Mike Yianopoulos, Andy Jennings, Chris Hardin, Jason Comer, Jim Monck, Chad Hayes, Chad Tripp, Anderson, Yvonne Bobo, Donnia Richardson, Darin Jones, Emma Gerald, Meghan Ward, Julie Nelson, Jessica Stephens, Amanda Powers, Kristen Schulte, Lee Taylor, and Claudia Jendron for all their efforts in the field and lab to make this project successful. Special thanks to Tim Bauters at the Tenax Corp. for analyzing the mesh samples with their Tensile Strength Machine, John Weinstein for assisting with the UV study, and Karen Swanson for assistance with graphics. Finally, Bob Van Dolah, David Whitaker, Wayne Waltz, John Miglarese and others provided significant input and support through SRFAC during the project's tenure. David Whitaker and Bob Van Dolah provided extensive and helpful comments to earlier drafts.

LITERATURE CITED

Anderson, F.E., 2002. Effect of wave-wash from personal watercraft on salt marsh channels. Journal of Coastal Research 37 Special Issue: 33-49.

Anderson, W.D., W.J. Keith, W.R. Tuten and F.H. Mills, 1979. A survey of South Carolina's washed shell resource. South Carolina Wildlife and Marine Resources Department Technical Rpt. No. 36, 81pp.

Anderson, W.D. and G.M. Yianopoulos, 2003. Final Report to NOAA-RC, Intertidal oyster and clam bed restoration in the ACE Basin, South Carolina using recycled oyster shell, hatchery raised clam seed, and other cultch material, Project Period, July 2000 – September 2002, 18pp.

Anonymous, 2007. Eastern Oyster Biological Review Team. Status review of the eastern oyster (*Crassostrea virginica*). Report to the National Marine Fisheries Service, Northeast Regional Office. February 16, 2007, 105 pp.

ASMFC, 2007. The Importance of Habitat Created by Shellfish and Shell Beds Along the Atlantic Coast of the U.S., prepared by L.D. Coen, and R. Grizzle, with contributions by J. Lowery and K.T. Paynter, Jr., 108pp.

Bahr, L.M. and W.P. Lanier, 1981. The ecology of intertidal oyster reefs of the South Atlantic Coast: a community profile. U. S. Fish Wildl. Serv. Program FWS/OBS/ -81/15, 105pp.

Bartol, I. K., and R. Mann, 1997. Small-scale settlement patterns of the oyster *Crassostrea virginica* on a constructed intertidal reef. Bulletin of Marine Science 61:881-897.

Bartol, I.K, R. Mann, and M. Luckenbach, 1999. Growth and mortality of oysters (*Crassostrea virginica*) on constructed intertidal reefs: effects of tidal height and substrate level. Journal Experimental Marine Biology and Ecology 237:157-187.

Beck, M.W., K.L. Heck, Jr., K.W. Able, D.L. Childers, D. Eggleston, B.M. Gillanders, B.S. Halpern, C.G. Hays, K. Hoshino, T.J. Minello, R J. Orth, P.F. Sheridan, and M.P. Weinstein, 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. BioScience 51:633-641.

Beck, M., R. Brumbaugh, L. Airoldi, A. Carranza, L. Coen, C. Crawford, O. Defeo, G. Edgar, B. Hancock., M. Kay, H. Lenihan, M. Luckenbach, C. Toropova, C. Shepard, and G. Zhang, in review. Oyster reefs at risk: a global perspective and recommendations for ecosystem revitalization. Science.

Bishop, M.J., 2004. A posteriori evaluation of strategies of management: the effectiveness of no-wash zones in minimizing the impacts of boat-wash on macrobenthic infauna. Environmental Management 34:140–149.

Bishop, M.J and M.G. Chapman, 2004. Managerial decisions as experiments: an opportunity to determine the ecological impact of boat-generated waves on macrobenthic infauna. Estuarine, Coastal and Shelf Science 61:613–622.

Bishop, M.J., 2007. Impacts of boat-generated waves on macroinfauna: towards a mechanistic understanding. J. Exp. Mar. Biol. Ecol. 343:187–196.

Bobo, M.Y., D.L. Richardson, L.D. Coen, and V.G. Burrell, 1997. A Report on the Protozoan Pathogens *Perkinsus marinus* (Dermo) and *Haplosporidium nelsoni* (MSX) in South Carolina Shellfish Populations. SCDNR-MRD-MRRI Technical Report #86, 50 pp.

Breitburg, D., L.D. Coen, M.W. Luckenbach, R. Mann, M. Posey, and J.A. Wesson, 2000. Oyster reef restoration: convergence of harvest and conservation strategies. Journal of Shellfish Research. 9:371-377.

Brumbaugh, R.D., M.W. Beck, L.D. Coen, L. Craig and P. Hicks, 2006. A Practitioners' Guide to the Design and Monitoring of Shellfish Restoration Projects: An Ecosystem Services Approach. The Nature Conservancy, Arlington, VA, 28pp.

Brumbaugh, R.D. and C. Toropova, 2008. Economic valuation of ecosystem services: A new impetus for shellfish restoration? Basins and Coasts News 2:8-15.

Brumbaugh, R.D. and L.D. Coen, 2009. Approaches for small-scale oyster reef restoration to address recruitment vs. substrate limitation: A review and comments relevant for the Olympic Oyster *Ostrea luride*. J. Shellfish Res. 28(1): 147-161.

Burrell, V.G., Jr., 1986. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic)--American oyster. U.S. Fish Wildl. Serv. Biological Report 82 (11.57), U.S. Army Corps of Engineers TR EL-82-4, 17 pp.

Burrell, V.G., Jr., 1997. Molluscan shellfisheries of the South Atlantic region of the United States. Pages 171-185 in C. L. MacKenzie, Jr., V. G. Burrell, Jr., A. Rosenfield, and W. L. Hobart, Eds. The history, present condition, and future of the molluscan fisheries of North and Central America and Europe, Volume 1: Atlantic and Gulf coasts. NOAA Technical Report No. NMFS 127, Silver Spring, Maryland.

Burrell, V.G., Jr., 2003. The Oyster Industry of South Carolina, 67pp. Self published

Burreson, E.M., N.A. Stokes, and C.S. Friedman, 2000. Increased virulence in an introduced pathogen: *Haplosporidium nelsoni* (MSX) in the eastern oyster *Crassostrea virginica*, Journal of Aquatic Animal Health 12:1-8.

Bushek, D., D. Richardson, M.Y. Bobo, and L.D. Coen, 2004. Short-term shell pile quarantine reduces the abundance of *Perkinsus marinus* remaining in tissues attached to oyster shell. J. Shellfish Res. 23:369-373.

Chose, J.R., 1999. Factors influencing bank erosion in tidal salt marshes of Murrells Inlet and North Inlet, South Carolina. M.S. Thesis, University of Charleston and MUSC. 98pp.

Coen, L.D., 1995. A review of the potential impacts of mechanical harvesting on subtidal and intertidal shellfish resources. South Carolina Division of Natural Resources, Marine Resources Research Institute, James Island, South Carolina, 46 pp. + three Appendices.

Coen, L.D., and M. Bolton-Warberg, 2003. Evaluating the impacts of harvesting practices, boat wakes and associated shoreline erosion on intertidal creek habitats in the southeastern U.S.: managers and restoration programs take note. J. Shellfish Res. 22:325.

Coen, L.D., and M. Bolton-Warberg, 2005. An examination of the impacts of various harvesting/management strategies and boat wakes on oyster bed condition, recovery rates, shoreline erosion and restoration. A Marine Recreational Fisheries Stamp Program Final Report, 96pp.

Coen, L. D., and A. Fischer, 2002. Managing the future of South Carolina's oysters: an experimental approach to evaluating current harvesting practices and boat wake impacts. Journal of Shellfish Research 21:894.

Coen, L.D. and M.W. Luckenbach, 2000. Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation? Ecological Engineering 15:323-343.

Coen, L., and R. Walker, 2005. Intertidal Oysters and the Reef-Habitat They Generate, Species account for Eastern oyster, *Crassostrea virginica.* Dept. of Interior, Comprehensive Wildlife Conservation Plan, SCDNR, 19pp.

Coen, L.D., D.M. Knott, E.L. Wenner, N.H. Hadley, and A.H. Ringwood, 1999a. Intertidal Oyster Reef Studies in South Carolina: Design, Sampling and Experimental Focus for Evaluating Habitat Value and Function. Pages 131 156, In: M.W. Luckenbach, R. Mann, J.A. Wesson (eds.), Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science Press, Gloucester Point, VA.

Coen, L.D., M.W. Luckenbach, and D.L. Breitburg, 1999b. The role of oyster reefs as essential fish habitat: a review of current knowledge and some new perspectives. Pages 438 454, in L. R. Benaka, Ed. Fish habitat: essential fish habitat and rehabilitation. American Fisheries Society, Symposium 22, Bethesda, Maryland.

Coen, L.D., M. Bolton-Warberg, Y. Bobo, D. Richardson, A.H. Ringwood, and G.I. Scott, 2004. Oyster Beds, pp. 127-147. In: R.F. Van Dolah, D.M. Sanger, and A.B. Filipowicz, eds. A Baseline Assessment of Environmental and Biological Conditions in the May River, Beaufort County, South Carolina: Final Report Submitted to the Town of Bluffton (226 pp. Overall)

Coen, L., N. Hadley, and R. Walker, 2005a. State of South Carolina's Coastal Resources, 2002-2003, Oysters and Hard Clams, SCDNR, 12pp. plus appendices.

Coen, L., N. Hadley, and W. Anderson, 2005b. State of South Carolina's Coastal Resources, 2003-2004, Oysters and Hard Clams, SCDNR, 12pp. plus appendices.

Coen, L.D., M. Bolton-Warberg, and J.A. Stephen, 2006. An Examination of Oyster Reefs as Biologically-Critical Estuarine Ecosystems. Final Report, Grant R/ER-10, Submitted to the South Carolina Sea Grant Consortium, 214pp. plus appendices.

Coen, L., K. Walters, D. Wilber, and N. Hadley, 2007a. A SC Sea Grant Report of a 2004 Workshop to Examine and Evaluate Oyster Restoration. Metrics to Assess Ecological Function, Sustainability and Success Results and Related Information, Sea Grant Publication, 27pp.

Coen, L.D., R.D. Brumbaugh, D. Bushek, R. Grizzle, M.W. Luckenbach, M.H. Posey, S.P. Powers, and G. Tolley, 2007b. AS WE SEE IT. A broader view of ecosystem services related to oyster restoration. Mar Ecol. Prog. Ser. 341:303–307.

Coen, L.D, K. Schulte, A. Powers, and L. Taylor, 2008. Evaluating oyster shell alternatives for enhancing/restoring shellfish beds and associated impacts. Presented at the 4th National Conference on Coastal And Estuarine Habitat Restoration, Providence, RI, October 11-15, 2008.

Coen, L.D, L. Walters, and P. Sacks, in prep. Evaluating natural and human factors influencing shoreline change in an estuarine river system near Bluffton, SC. Final report submitted to the Palmetto Bluff Conservancy.

Coen, L.D., D.H. Wilber, and D. Knott, in review. Development of intertidal oyster reef resident communities on natural and constructed reefs in the southeastern U.S.: Can we restore native oyster habitats? Mar. Ecol. Prog. Ser.

Crawford, R.E., N. Stolpe and M. Moore, eds., 1998. The environmental impacts of boating. Woods Hole, MA. Proceedings of a Workshop held at Woods Hole Oceanographic Institution, Woods Hole, MA USA, Dec.7-9, 1994.

Cressman, K. A., M. H. Posey, M. A. Mallin, L. A. Leonard, and T. D. Alphin, 2003. Effects of oyster reefs on water quality in a tidal creek estuary. Journal of Shellfish Research 22:753-762.

CSC, 2003, Pilot investigation of remote sensing for intertidal oyster mapping in coastal South Carolina methods comparison, NOAA Coastal Services Center, Charleston, SC. 32pp.

Dame, R., 1996. Ecology of marine bivalves: an ecosystem approach. CRC Marine Science Series, Boca Raton, 254pp.

Dame, R.F., R.G. Zingmark, and E. Haskin, 1984. Oyster reefs as processors of estuarine materials. Journal Experimental Marine Biology 83:239-247.

Dame, R., E. Haskin, and B. Kjerfve, 1984. Water flow over an intertidal oyster reef and its relationship to nutrient dynamics. Journal of Shellfish Research 4:86-87.

DeBlieu, J., M. Beck, D. Dorfman, P. Ertel, 2005. Conservation in the Carolinian Ecoregion: An Ecoregional Assessment. The Nature Conservancy, Arlington, VA, 60pp.

Dugas, R., R. Leard, and M.E. Berrigan, 1991. A partial bibliography of oyster cultch materials and resource management projects. Gulf States Mar. Fish. Comm., 12 pp.

Dumbauld, B. R., D. A. Armstrong, and T. L. McDonald, 1993. Use of oyster shell to enhance intertidal habitat and mitigate loss of dungenous crab (*Cancer magister*) caused by dredging. Canadian Journal of Fisheries and Aquatic Sciences 50: 381-390.

Ewart, J.W., and S.E. Ford, 1993. History and impact of MSX and Dermo diseases on oyster stocks in the Northeast region. NRAC Fact Sheet 200, Northeastern Regional Aquaculture Center, U. of MA., Dartmouth.

Ford, S.E., and M.R. Tripp, 1996. Diseases and defense mechanisms. In A.F. Eble, V.S. Kennedy, R.I.E. Newell, Eds., 581-660pp. The eastern oyster, *Crassostrea virginica*. Maryland Sea Grant College Park, MD.

French McCay, D.P., C.H. Peterson, J.T. DeAlteris, and J. Catena, 2003. Restoration that targets function as opposed to structure: replacing lost bivalve production and filtration. Marine Ecology Progress Series 264: 197-212.

Fulford, R.S., D.L. Breitburg, R.I.E. Newell, W.M. Kemp, and M.W. Luckenbach, 2007. Effects of oyster population restoration strategies on phytoplankton biomass in Chesapeake Bay: a flexible modeling approach. Marine Ecology Progress Series 336:43–61.

Gabet, E.J., 1998. Lateral migration and bank erosion in a salt marsh tidal channel in San Francisco Bay, California. Estuaries 21:745-753.

Galtsoff, P.S., 1964. The American oyster *Crassostrea virginica* Gmelin. U.S. Fish Widl. Serv. Fishery Bulletin 64:1-480.

Gambordella, M., L. McEachron, C. Beals, and W. S. Arnold, 2007. Establishing baselines for monitoring the response of oysters in southeast Florida to changes in freshwater input, Final Report, 176pp.

Giotta, R.E., 1999. Distribution of American oysters (*Crassostrea virginica*) in South Carolina: interacting effects of predation, sedimentation and water flow at varying tidal elevations. M.S. Thesis. University of Charleston, 98pp.

Glancy, T.P., K. T.K. Frazer, C.E. Cichra, and W.J. Lindberg, 2003. Comparative patterns of occupancy by decapod crustaceans in seagrass, oyster, and marsh-edge habitats in a northeast Gulf of Mexico estuary. Estuaries. 26:1291-1301.

Goodwin, L.K., 2007. Evaluating shoreline change on both short and long-term scales: erosion, habitat loss and relevant physical, biological and anthropogenic factors. M.S. Thesis, MES Program, College of Charleston, SC.

Goodwin, L., L.D. Coen, L. Walters, and P. Sacks, 2006. Evaluating natural and human factors influencing habitat change, for ameliorating observed shoreline losses. ICSR 2006 Abstract, Charleston, SC.

Grabowski, J.H., and C.H. Peterson, 2007. Restoring oyster reefs to recover ecosystem services. Ch. 15, pp. 281-298, in Ecosystem Engineers: Concepts, Theory and Applications, Eds., K. Cuddington, J.E. Byers, W.G. Wilson, and A. Hastings, Elsevier/ Academic Press, Netherlands.

Grizzle, R.E., J.R. Adams, and L.J. Walters, 2002. Historical changes in intertidal oyster (*Crassostrea virginica*) reefs in a Florida lagoon potentially related to boating activities. Journal of Shellfish Research 21:749-756.

Grizzle, R.E., J.K. Greene, M.W. Luckenbach, and L.D. Coen, 2006. A new in situ method for measuring seston uptake by suspension-feeding bivalve mollusks. J. Shellfish Res. 25:643-649.

Grizzle, R.E., J.K. Greene, and L.D. Coen, 2008. Seston removal by natural and constructed intertidal eastern oyster (*Crassostrea virginica*) reefs: a comparison with previous laboratory studies, and the value of in situ methods. Estuaries and Coasts. 31(6):1208-1220.

Hadley, N.H. and L.D. Coen, 2002. Community-Based Program Engages Citizens in Oyster Reef Restoration (South Carolina). Ecological Restoration 20:297-298.

Hadley, N., M. Hodges, D. H. Wilber, and L.D. Coen, In press. Evaluating Intertidal Oyster Reef Development in South Carolina Using Associated Faunal Indicators. Restoration Ecology.

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner, 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-638.

Jefferson, W.H., W.K Michener, D.A. Karinshak, W. Anderson, and D. Porter, 1991. Developing GIS Data Layers for Estuarine Resource Management. Proceedings, GIS/LIS 91, pp. 331-341.

Jordan, S.J., and J.M. Coakley, 2004. Long-term projections of eastern oyster populations under various management scenarios. Journal of Shellfish Research 23:63–72.

Kaufman, L., and P.K. Dayton, 1997. Impacts of marine resource extraction on ecosystem services and sustainability, In: Daily, G.C., (Ed.), Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, D.C., pp. 275-293.

Kennedy, V.S., R.I.E. Newell, A.F. Eble, eds., 1996. The Eastern Oyster: *Crassostrea virginica*. Maryland Sea Grant, College Park, MD, 734 pp.

Kennish, M.J., ed., 2002. Impacts of motorized watercraft on shallow estuarine and coastal marine environments. J. Coastal Res. Special Issue No. 37:1-202.

Kirby, M.X., 2004. Fishing down the coast: historical expansion and collapse of oyster fisheries along coastal margins. Proc. Natl. Acad. Sci. 101:13096-13099.

Lehnert, R.L., and D.M. Allen, 2002. Nekton use of subtidal oyster shell habitats in a southeastern U.S. estuary. Estuaries 25:1015-1024.

Lenihan, H.S., and F. Micheli, 2000. Biological effects of shellfish harvesting on oyster reefs: resolving a fishery conflict by ecological experimentation. Fishery Bulletin 98:86-95.

Lenihan, H.S., C.H. Peterson, J.E. Byers, J.H. Grabowski, G.W. Thayer, and D.R. Colby, 2001. Cascading of habitat degradation: oyster reefs invaded by refugee fishes escaping stress. Ecological Applications 11:764-782.

Lenihan, H.S., and C.H. Peterson, 2004. Conserving oyster reef habitat by switching from dredging and tonging to diver hand-harvesting. Fishery Bulletin 102:298-305.

Lotze, H.K., H.S. Leniham, B.J. Bourque, R.H. Bradbury, R..G. Cooke, M.C. Kay, S.M. Kidwell, M.X. Kirby, C.H. Peterson, and J.B.C. Jackson, 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312:1806-1809.

Luckenbach, M.W., L.D. Coen, P.G. Ross, Jr., and J.A. Stephen, 2005. Oyster reef habitat restoration: relationships between oyster abundance and community development based on two studies in Virginia and South Carolina. J. of Coastal Research Special Issue 40:64-78.

MacKenzie, C.L., Jr., 1996. History of oystering in the United States and Canada, featuring the eight greatest oyster estuaries. Marine Fisheries Review 58:1-87.

MacKenzie, C.L., Jr., V.G. Burrell, Jr., A. Rosenfield, and W.L. Hobart, Eds., 1997. The history, present condition, and future of the molluscan fisheries of North and Central America and Europe, Volume 1, Atlantic and Gulf coasts. United States Department of Commerce, NOAA Technical Report No. 127, Silver Spring, Maryland.

Meyer, D.L., E.C. Townsend, and G.W. Thayer, 1997. Stabilization and erosion control value of oyster cultch for intertidal marsh. Restoration Ecology 5:93-99.

Meyer, D.L., and E.C. Townsend, 2000. Faunal utilization of created intertidal eastern oyster (*Crassostrea virginica*) reefs in the southeastern United States. Estuaries 23:34-45.

Micheli, F., and C.H. Peterson, 1999. Estuarine vegetated habitats as corridors for predator movements. Conservation Biology 13 (4): 869–881.

Nanson, G.C., A. Von Krusenstierna, and E.A. Bryant, 1994. Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania. Regulated Rivers: Research and Management 9:1-14.

National Research Council (NRC), 2004. Nonnative Oysters in the Chesapeake Bay. National Academies Press. Washington, D.C., 325pp.

National Research Council (NRC), 2007. Mitigating shore erosion along sheltered coasts. Washington, D.C. National Academies Press, 188pp.

Nelson, K.A., L.A. Leonard, M.H. Posey, T.D. Alphin and M.A. Mallin, 2004. Using transplanted oyster beds to improve water quality in small tidal creeks: a pilot study. J. Exp. Mar. Bio. Ecol. 298:347-368.

Newell, R.I.E., 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: A Review. J. Shellfish Res. 23: 51-61.

Newell, R.I.E., W.M. Kemp, J.D. Hagy, and C.F. Cerco, J.M. Testa, and W.R. Boynton, 2007. Top-down control of phytoplankton by oysters in Chesapeake Bay, USA: Comment on Pomeroy et al. (2006). Mar. Ecol. Prog. Ser. 341:293–298.

Peterson, C.H., J.H. Grabowski, and S.P. Powers, 2003. Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. Marine Ecology Progress Series 264:251-256.

Piazza, B.P., P.D. Banks, and M.K. La Peyre, 2005. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. Restoration Ecology 13:499–506.

Powell, E. N., J. N. Kraeuter, and K. A. Ashton-Alcox, 2006. How long does oyster shell last on an oyster reef? Estuarine, Coastal and Shelf Science 69:531-542.

Powers, S.P., C.H. Peterson, J.H. Grabowski, and H.S. Lenihan, 2009. Evaluating the success of constructed oyster reefs in no-harvest sanctuaries: implications for restoration. Marine Ecology Progress Series 389:159-170.

Riggs, S.R., 2001. Shoreline erosion in North Carolina estuaries. The Soundfront Series, UNC-SG-01-11. 68pp.

Rogers, S., and T. Skrabel, 2001. Managing erosion on estuarine shorelines. The Soundfront Series, UNC-SG-01-12, 32pp.

Rodney, W.S., and K.T. Paynter, 2006. Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay in Maryland. J. Exp. Mar. Biol. Ecol. 335:39-51.

Rothschild, B.J., J.S. Ault, P. Goulletquer, and M. Héral, 1994. Decline of the Chesapeake Bay oyster population: a century of habitat destruction and overfishing. Marine Ecology Progress Series 111:29-39.

SCDHEC 2010. 2009 Shellfish growing area status report. SCDHEC, Columbia, SC. http://www.scdhec.gov/environment/water/docs/sftrend.pdf

Smith, F.G.F., D. Loy, G. Florence, R. F. Van Dolah, W. D. Anderson, L. D. Coen, M. Finkbeiner, and B. Stevenson, 2005. South Carolina oyster bed mapping. A paper submitted to the ASPRS 2005 Annual Conference, Baltimore, Maryland, March 7-11, 2005.

Stanley, J. G., and M.A. Sellers, 1986a. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic)--American oyster. United States Fish and Wildlife Service Office of Biological Services Report No. FWS/OBS-82/11.65, and United States Army Corps of Engineers Report No. TR EL-82-4, Washington, D.C.

Stanley, D.W., and M.A. Sellers, 1986b. Species profile: life histories and environmental requirements of coastal fishes and invertebrates (Gulf of Mexico)-American Oyster. U.S. Fish Wildl. Serv. Biol Rep. 82(11.64) U.S. Army Corps of Engineers, TR EL-82-4, 25 pp.

Street, M.W., A.S. Deaton, W.S. Chappell, and P.D. Mooreside, 2005. North Carolina Coastal Habitat Protection Plan. North Carolina Department of Environment and Natural Resources, Division of Marine Fisheries, Morehead City, NC. 662pp.

Thayer, G.W., T.A. McTigue, R.J. Salz, D.H. Merkey, F.M. Burrows, and P.F. Gayaldo, Eds., 2005. Science-Based Restoration Monitoring of Coastal Habitats, Volume Two: Tools for Monitoring Coastal Habitats. NOAA Coastal Ocean Program Decision Analysis Series No. 23. NOAA National Centers for Coastal Ocean Science, Silver Spring, MD. 628pp. plus appendices.

Tolley, S.G. and A.K. Volety, 2005. The role of oysters in habitat use of oyster reefs by resident fishes and decapod crustaceans. Journal of Shellfish Research 24:1007-1012.

Van Dolah, R.F., A.F. Holland, L.D. Coen, A.H. Ringwood, M.V. Levisen, P.P. Maier, G.I. Scott, A.K. Leight, Y. Bobo, and D. Richardson, 2000. Biological Resources, Report on the status of Broad Creek/Okatee River Systems. DHEC-MRRI-NOAA-Charleston.

Van Dolah, R.F., D.M. Sanger, and A.B. Filipowicz, 2004. A Baseline Assessment of Environmental and Biological Conditions in the May River, Beaufort County, South Carolina. Final Report Submitted to The Town of Bluffton by South Carolina Department of Natural Resources, United States Geological Survey, and the National Ocean Service National Oceanic and Atmospheric Administration, Center for Coastal Environmental Health and Biomolecular Research. 243pp.

Wall, L., L. Walters, P. Sacks, and R. Grizzle, 2005. Recreational boating activity and its impact on the recruitment and survival of the oyster *Crassostrea virginica* on intertidal reefs in Mosquito Lagoon, FL. J. Shellfish Res. 24:965-974.

Walters, L.J., K. Johnson, L.M. Wall, N. Martinez, and R. Grizzle, 2002. Shell movement and juvenile survival of the oyster on intertidal reefs adjacent to waters with intense boating activity in the Indian River Lagoon, Florida. J. Shellfish Res. 21:415-416.

Walters, L., L.D. Coen, P. Sacks, J. Grevert, and J. Stiner, 2004. Boat Wakes on Intertidal Reefs of the Oyster *Crassostrea virginica*. Presented at the 33rd Annual Marine Benthic Ecology Meetings, Mobile, AL, March 2004.

Walters, L., L.D. Coen, and R. Grizzle, 2005. Impact of boat wakes on the Eastern Oyster, *Crassostrea virginica* in the southeastern United States: maximizing sustainability and restoration, Final report to Florida Sea Grant, 9pp.

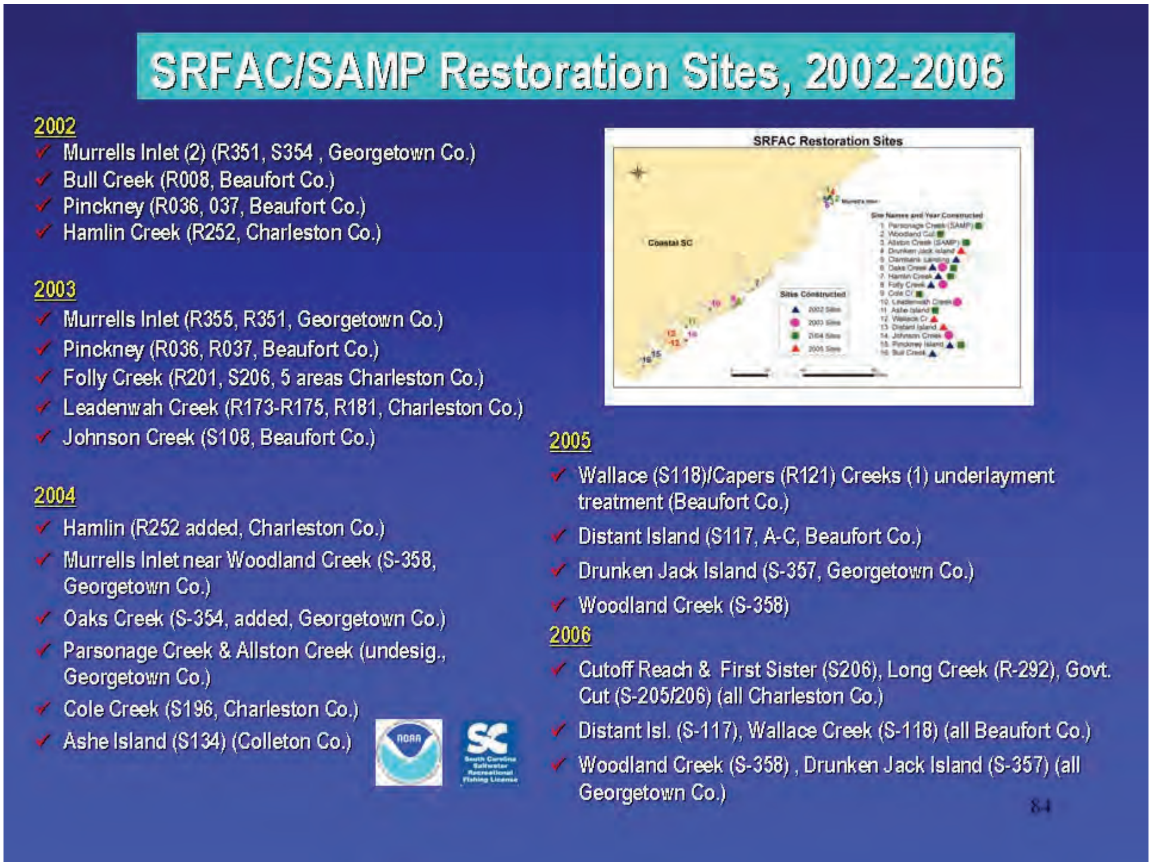
Weinstein, M.P., and D.A. Kreeger, Eds., 2000. Concepts and controversies in tidal marsh ecology. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Wells, H.W., 1961. The fauna of oyster beds, with special reference to the salinity factor. Ecological Monographs 31:266-329.

Zabawa, C., and C. Ostrum, 1980. Final Report On the role of boat wakes in shore erosion in Anne Arundel Co., MD.

Zimmerman, R., T. Minello, T. Baumer, and M. Castiglione, 1989. Oyster reef as habitat for estuarine macrofauna. NOAA Tech. Mem. NMFS-SEFC-249, 16pp.

Appendix 1. Restoration Site Descriptions and Related Tables



Appendix 1 Figure 1. Map of SRFAC and SAMP restoration sites along South Carolina's coast planted from 2002-2006. Designations in parenthesis include coastal County and State or Public Shellfish Ground Designation

2002 Sites

Clambank Landing and Oaks Creek (Georgetown County)

In Murrell's Inlet, reefs were constructed at Clambank Landing on S354, a recreational-only SSG and nearby in Oaks Creek on R351. Clambank was characterized by a flat intertidal bank (0°), soft-medium sediments, and medium wave energy (Table A1.1, A1.2). Portions of the Clambank site are adjacent to a boat landing and may be subjected to resulting boat wakes, but the landing is quite shallow and inaccessible on low tides and generally only small boats utilize it. The Oaks Creek site had firmer sediments and in some areas an overlying layer of horizontal dead shell, with a moderate slope (8°). Although there is a fairly high volume of recreational boat traffic along Oaks Creek, the restoration site is separated from the main channel by a sandbar which provides some protection from boat wakes. Both sites are located on fringing shorelines with adjacent Spartina marsh. The creek is approximately 50 m wide at Clambank and 80 m wide at the Oaks Creek site. Both sites were planted in late June 2002, which is early in the recruitment season. A total of approximately 4,100 bushels of shell was planted at the two sites.

Hamlin Creek (Charleston County)

Two sites on Hamlin Creek within R252, designated as Hamlin North and South, were planted in September 2002, late in the recruitment season. Both sites had medium sediment firmness with some pre-existing horizontal dead shell and occasional isolated clusters of live oysters. Wave energy at both sites was estimated as medium to high due to moderately heavy boat traffic. Hamlin South has a channel width of 40 m with a moderate slope of 7°. Hamlin North is 37 m wide with a relatively steep shoreline (9°). Both have fringing intertidal banks with adjacent Spartina marsh. A total of approximately 1,429 bushels of shell was deployed at Hamlin North and South. (Table A1.1, and A1.2)

Bull Creek (Beaufort County)

Two sites were planted on Bull Creek within R008 in Beaufort County. This site has a relatively steep shoreline (10-11º) and medium to firm sediment composition. Prior to planting, a layer of horizontal dead shell was covered with a large amount of sedimentation. Bull Creek is approximately 69 m wide and has heavy boat traffic. (Table (Table A1.1, and A1.2). Approximately 4,100 bushels were planted in July 2002 which is the middle of the recruitment season.

Pinckney Island (Beaufort County)

A total of 1,000 bushels of shell was planted on two adjacent PSGs (R036 and R037) on Mackay Creek at Pinckney in late July 2002 in the middle of the recruitment season. This site was characterized by a wide and gently sloping (0º) intertidal bank with firm sediment composition. This site is heavily harvested since it is one of the few PSGs in the state which is accessible without a boat and there were few, if any, live oysters prior to planting. The shoreline has a layer of horizontal dead shell. This site has extremely heavy boat traffic, being adjacent to one of the busiest boat landings in the state, and strong currents due to the large channel width (630 m).

Table A1.1. SRFAC planting area descriptions for 2002 reefs. The presence of pre-existing dead/live oyster shell is given in the Substrate column. The level of wave energy experienced by a site from boats is given in the Boat traffic column and the wave energy from currents and wind is given in the Current/wind column (L = low wave energy, M = medium wave energy, and H = high wave energy). The sediment firmness of a site is given in the Sediment firmness column (S = soft, M = medium , and F = firm). Channel width was measured from high tide of one shoreline to the high tide line of the opposite shore.

County	Site	Substrate	Current/ wind	Boat traffic	Sediment firmness	Bank slope (degrees)	Channel width (m)
Georgetown	Clambank S354	Mud	M	M	S-M	0	50
Georgetown	Oaks Creek R351	Mud/shell, scattered clusters	M-H	M-H	M	8	80
Charleston	Hamlin Creek South R252	Mud/shell, scattered clusters	M-H	M-H	S-M	7	40
Charleston	Hamlin Creek North R252	Mud/shells, scattered clusters	M-H	M-H	S-M	9	37
Bluffton	Bull Creek R008	Mud/shell, scattered clusters	H	H	M	10-11	150
Bluffton	Pinckney R036 and R037	Sand/shell	H	H	M-F	0	630

Table A1.2. 2002 Shell Planting and Experimental Treatments. In the Date planted column, Early = Before July 1; Mid = July 1-August 15; and Late = After August 15. The Planting location column indicates where in the intertidal zone shell was planted. The Planted shell types column indicates which restoration shell was planted at a site (W = whelk, SC = South Carolina oyster shell, and G = Gulf oyster shell). All depths in cm. The Mesh treatments column indicates if experimental meshing occurred at a site. Numbers in parentheses in the Shell volume column are estimated bushels based on area x depth calculations.

Site	Date planted (relative to recruitment period)	Planting location within intertidal zone	Shell volume planted (U.S. Bu.)	Area planted (m^2)	Initial shell depth (± 1SD)	Planted shell type(s)	Mesh treatments deployed
Clambank S354	23 June 2002 Early	Mid to low	2,050 (727)	476	5.1 (2.9) (n = 43)	W	Y
Oaks Creek R351	23 June 2002 Early	Mid to low	2,050 (821)	924	5.7 (2.8) (n = 28)	G and W	Y
Hamlin Creek South R252	19 Aug. 2002 Late	Mid to low	730 (587)	146	14.2 (4.8) (n = 20)	W, SC, and G	Y
Hamlin Creek N R252	19 Aug. 2002 Late	Mid to low	699 (618)	209	11.4 (4.8) (n = 36)	G and W	Y
Bull Creek R008	25 July 2002 Mid	Mid to low	4,100 (2,942)	615	16.8 (7.6) (n = 64)	G, SC, and G/W mix	Y
Pinckney R036 and R037	30 July 2002 Mid	High to low	1,000 (698)	245	11.8 (3.8) (n = 18)	SC and G/W mix	Y

2003 Sites

Murrells Inlet (Georgetown County)

Approximately 3,280 bushels of shell were planted at Clambank (R351) and Oaks Creek (S354) in September 2003 late in the recruitment season. The sites were adjacent to those described above and planted in 2002 and had similar characteristics (Tables A1.3 and A1.4).

Folly Creek (Charleston County)

Approximately 8,294 bushels of shell were planted on S206 in Folly Creek in June 2003, early in the recruitment period. This site has a relatively steep bank (9°), medium to firm sediment composition, and moderate to high wave energy due to boat traffic. Channel/creek width ranges from 80-220 m (Tables A1.3 and A1.4).

Folly River (Charleston County)

Approximately 1,428 bushels of shell were planted on R201 in Folly River in June 2003 early in the oyster recruitment season. This site has a moderate slope (8°) and relatively firm sediment composition with a layer of horizontal dead shell. Located near the popular Folly River boat landing, it experiences heavy boat traffic, from large as well as small boats, and strong currents due to the wide channel (230 m) and proximity to the ocean (Tables A1.3 and A1.4).

Leadenwah Creek (Charleston County)

In Leadenwah Creek, 5,135 bushels of shell were planted at four sites (R173, R174, R175, and R181) in July 2003, in the middle of the recruitment season. Characteristics of these four adjacent sites varied (Appendix Tables A1.3 and A1.4). R173, located on a relatively wide creek (350 m) had a relatively moderate slope (8°), soft to medium sediment firmness, some overlying horizontal dead, and medium wave energy. The R174 site, located on a narrow stretch of creek (55 m wide) was flat, had soft sediments with no pre-existing shell matrix, and low wave energy. The R175 site was steep (11°) with medium to firm sediments and some patchy horizontal dead shell. Located on a relatively small creek (105 m) it experienced more boat traffic than R174 but less than R173. The R181 site had a 7° slope with soft to medium sediment firmness and some pre-existing horizontal dead shell. The creek width was 150 m with moderate boat traffic.

Johnson Creek (Beaufort County)

Approximately 4,876 bushels of shell were planted in Johnson Creek on S108 in late August 2003, towards the end of the recruitment season. Shell was planted in three areas (designated A, B and C for monitoring purposes) which were similar in pre-construction characteristics. All had a moderate (7^o) to steep (9.5^o) sloping shoreline, soft to medium sediments, a pre-existing horizontal dead shell matrix, and low wave energy with light boat traffic. Channel width ranged from 65-122 m (Appendix Tables A1.3 and A1.4).

Pinckney Island (Beaufort County)

Approximately 2,672 bushels of whelk shell were planted at Pinckney Island (R037) in late August, towards the end of the recruitment period. This site is characterized by a gentle (0^o) to very moderate (<7^o) slope, firm sediment composition, a pre-existing dead shell layer, high wave energy due to heavy boat traffic, and strong currents (Tables A1.3 and A1.4).

Table A1.3. SRFAC planting area descriptions for 2003 reefs.The presence of pre-existing dead/live oyster shell is given in the Substrate column. The level of wave energy experienced by a site from boats is given in the Boat traffic column and the wave energy from currents and wind is given in the Current/wind column (L = low wave energy, M = medium wave energy, and H = high wave energy). The sediment firmness of a site is given in the Sediment firmness column (S = soft, M = medium , and F = firm). Channel width was measured from high tide of one shoreline to the high tide line of the opposite shore.

County	Site	Substrate	Current/wind	Boat traffic	Sediment firmness	Bank slope (degrees)	Channel width (m)
Charleston	Leadenwah Creek R173	Mud	M	M	S-M	8	350
Charleston	Leadenwah Creek R174	Mud	L-M	L-M	S	0	82
Charleston	Leadenwah Creek R175	Mud	L-M	L-M	M-F	11	153
Charleston	Leadenwah Creek R181	Mud	M	M	S- M	7	160
Charleston	Folly Creek S06A	Mud	M-H	M-H	M-F	9	80-220
Charleston	Folly Creek S206B	Mud	L-M	L	S	9	50-220
Charleston	Folly Creek S206C	Mud	M-H	M-H	M-F	9	80-220
Charleston	Folly Creek S206D	Mud	M-H	M-H	S	9	80-220
Charleston	Folly River R201	Shell/mud	H	M-H	F	8	230
Charleston	Johnson S108A	Shell/mud	M	L	S	7	203
Charleston	Johnson S108B	Shell/mud	M	L	S-M	9.5	46
Charleston	Johnson S108C	Shell/mud	M	L	S-M	9	47
Bluffton	Pinckney Island R037A	Sand/shell	H	H	F	7	630
Bluffton	Pinckney Isl. R037 B,C	Sand/shell	H	H	F	1	630
Georgetown	Clambank R351	Mud	L	L-M	S-M	0	50-80
Georgetown	Oaks Creek S354	Mud/shell	M	M-H	M-F	8	37

Table A1.4. 2003 Shell Planting and Experimental Treatments. In the Date planted column, Early = Before July 1; Mid = July 1-August 15; and Late = After August 15. The Planting location column indicates where in the intertidal zone shell was planted. In the Planted area column, "not defined" means that the original footprint was not measured because it did not appear to be there. All depth values in cm. The Planted shell types column indicates which restoration shell was planted at a site (W = whelk, SC = South Carolina oyster shell, and G = Gulf oyster shell). The Mesh treatments column indicates if experimental meshing occurred at a site. NM = not measured.

Site	Date planted (relative to recruitment period)	Planting location within intertidal zone	Shell volume (U.S. Bu.)	Planted area (m^2)	Planted shell depth (cm ± 1 SD)	Planted shell types	Mesh treatments deployed
Leadenwah Creek R173	18 July 2003 Mid	High to low	1,613	297	3.4 + 3.4 (n =18)	W,SC,G	Y
Leadenwah Creek R174	17 July 2003 Mid	High	651	133	5.9+4.4 (n = 36)	W	Y (underlay)
Leadenwah Creek R175	23 July 2003 Mid	Mid to low	1,290	564	2.3+2.3 (n = 6)	G,W	N
Leadenwah Creek R181	16 July 2003 Mid	High to low	1,581	492	2.5 + 3.1 (n = 39)	W,SC,G	N
Folly Creek S06A	23 June 2003 Early	Mid	2,328	619	13.3 (calculated)	G,W	N
Folly Creek S206B	10 June 2003 Early	High to low	1,197	316	13.3 (calculated)	G,W	N
Folly Creek S206C	19 June 2003 Early	Mid	3,519	1,089	11.4 (calculated)	W,SC,G	N
Folly Creek S206D	20 June 2003 Early	Mid	1,250	Not defined	5.9 (calculated)	SC,G	N
Folly River R201A	25 June 2003 Early	High	700	564	4.4 (calculated)	W	N
2003 Folly R201B	25 June 2003 Early	High	728	Not defined	NM	SC	N
Johnson S108A	21 Aug. 2003 Late	High to low	3,307	789	7.8 + 5.2 (n = 27)	W,G	Y
Johnson S108B	19 Aug. 2003 Late	High to low	784	190	4.4 + 3.1 (n = 18)	W,G	Y
Johnson S108C	19 Aug. 2003 Late	High to low	785	168	5.8 + 4.7 (n = 18)	W,G	Y
Pinckney R037A	29 Aug. 2003 Late	High to low	1,414	512	4.7 + 2.4 (n = 18)	W	N
Pinckney R037B	29 Aug. 2003 Late	High to low	454	27	NM	W	N
Pinckney R037C	29 Aug. 2003 Late	High to low	804	368	4.8 + 3.0 (n = 18)	W	N
Clambank R351	16 Sep 03 Late	Mid	2,465	411	NM	G	N
Oaks Creek R351	16 Sept. 2003 Late	High to mid	815	190	NM	G	N

2004 Sites

Murrell's Inlet multiple sites (Georgetown County)

In Murrell's Inlet, reefs were constructed at Oaks Creek (354) and Woodland Cut (S358). The Oaks Creek site was characterized by a moderate intertidal slope (8^{o}), soft to medium sediment composition firmness, a pre-existing horizontal dead shell matrix, and medium wave energy due to moderate boat traffic. The channel width was 80 m. Approximately 3,787 bushels of shell were planted at Oaks Creek in June 2004 early in the recruitment season. The Woodland Cut sites (A and B) were characterized by a gentle ($2\text{-}3^{o}$) intertidal slope, firm sediment composition, a horizontal dead shell matrix with vertical growth, and medium to high wave energy due to high wind energy. The channel width was 56 m. Approximately 2,325 bushels of shell were planted at Woodland Cut in June 2004 (Table A1.5 and A1.6).

Two sites were planted with funding from the Murrells Inlet Special Area Management Plan on undesignated grounds in Parsonage Creek and Allston Creek. The Parsonage Creek sites (A and B) were characterized by a gentle intertidal slope (1.5^{o}), medium sediment composition firmness, some pre-existing shell on the intertidal bank, some vertical live oyster growth along the marsh line, and low to medium wave energy due to light to moderate boat traffic. The channel width was ~28 m. Approximately 1,500 bushels of shell were planted at Parsonage in June 2004, early in the recruitment season. The Allston Creek sites (C and D) were characterized by a gentle intertidal slope (1.5^{o}), medium sediment composition firmness, some horizontal dead shell was present and vertical growth of oysters occurred along the marsh. This site experienced medium wave energy due to moderate boat traffic and the creek width was 20 m. Approximately 1,900 U.S. bushels of shell were planted at Allston in June 2004 (Table A1.5 and A1.6).

Hamlin Creek (Charleston County)

In 2004, additional shell plantings were made in Hamlin Creek (R252) at the sites designated Hamlin North and South. The North Hamlin site was characterized by a steep intertidal slope (9^{o}), medium sediment composition firmness, and some pre-existing horizontal dead shell with some vertical growth of oyster along the marsh line. This site experienced medium wave energy due to moderate boat traffic and had a channel width of 37 m. The South Hamlin site was characterized by a moderate intertidal slope (7^{o}), extremely soft sediment composition firmness, pre-existing patchy horizontal dead shell, and high wave energy due to heavy boat traffic. The channel width was 40 m. Approximately 2,055 bushels shell were planted at North and South Hamlin in July 2004 midway through the recruitment season (Tables A1.5 and A1.6).

Cole Creek (Charleston County)

Approximately 6,200 bushels of shell were planted at Cole Creek (S196) in October 2004, after the recruitment season (Tables A1.5 and A1.6). The Cole Creek site was characterized by a gentle intertidal slope (4^{o}), firm sediment composition, some pre-existing horizontal shell with vertical oyster growth in the marsh line, and high wave energy due to this site's close proximity to the Atlantic Ocean and a lack of any protective barrier.

Ashe Island (Colleton County)

Approximately 2,200 bushels of shell were planted at Ashe Island (S134) in October 2004, after the end of the recruitment season (Tables A1.5 and A1.6). The Ashe Island site was characterized by a gentle intertidal slope (2^{o}), firm sediment composition, some pre-existing horizontal oyster shell with some vertical oyster growth in the marsh line, and low wave energy due to light boat traffic. The channel width was 320 m.

Table A1.5. SRFAC planting area descriptions for 2004 reefs.The presence of pre-existing dead/live oyster shell is given in the substrate column. The level of wave energy experienced by a site from boats is given in the Boat traffic column and the wave energy from currents and wind is given in the Current/wind column (L = low wave energy, M = medium wave energy, and H = high wave energy). The sediment firmness of a site is given in the Sediment firmness column (S = soft, M = medium , and F = firm). Channel width was measured from high tide of one shoreline to the high tide line of the opposite shore.

		Substrate	Current/ wind	Boat traffic	Sediment firmness	Bank slope (degrees)	Channel width (m)
Georgetown	Oaks Creek S354	Mud/shell	M-H	M	S-M	8	80
Georgetown	Woodland Cut S358	Mud/shell	L-M	L	F	2.5	35
Georgetown	Parsonage Creek UD	Mud/shell	L	L	M	1.5	28
Georgetown	Allston Creek UD	Mud	L	L	M	1.5	20
Charleston	Hamlin Creek North R252	Mud	M	M-H	M	9	37
Charleston	Hamlin Creek South R252	Mud/shell	H	M-H	S	7	40
Charleston	Cole Creek S134	Sand	M-H	L	F	4	80
Colleton	Ashe Island S196	Mud/shell	L	L	F	2	320

Table A1.6. 2004 Shell Planting and Experimental Treatments. In the Date planted column, Early = Before July 1; Mid = July 1 - August 15; and Late = After August 15. The Planting location column indicates where in the intertidal zone shell was planted. In the Planted area column, "not defined" means that the original footprint was not measured because it did not appear to be there. The Planted shell types column indicates which restoration shell was planted at a site (W = whelk, SC = South Carolina oyster shell, and G = Gulf oyster shell). The mesh treatments column indicates if experimental meshing occurred at a site.

Site	Date planted (relative to recruitment period)	Planting location	Shell volume (U.S. Bu.)	Planted area (m^2)	Planted shell depth (cm ± SD	Planted shell type(s)	Mesh treatment
Oaks Creek	16 June 2004 Early	Mid to low	3,787	539	17.1 ± 10.5 (n = 21)	G	N
Woodland Cut A	25 June 2004 Early	High to low	2,325	667	12 ± 11.3 (n = 8)	W, G, and SC	N
Woodland Cut B	25 June 2004 Early	High to low	2,325	667	6.8 ± 5.1 (n = 8)	W, G, and SC	N
Parsonage Creek (A-B)	25 June 2004 Early	High to low	1,499	245	5.2 ± 2.0 (n = 8)	W, G, and SC	N
Allston Creek (C-D)	26 June 2004 Early	High to low	1,941	457	4.5 ± 2.2 (n = 8)	W, G, and SC	N
Hamlin Creek North	23 July 2004 Mid	High to low	879	203	5.7 ± 5.3 (n = 15)	G and SC	N
Hamlin Creek South	23 July 2004 Mid	High to low	1,174	316	4.5 ± 5.7 (n = 15)	G and SC	N
Cole Creek	2 Oct. 2004 Late	High to low	6,204	440	13.6 ± 18.2 (n = 21)	G and SC	N
Ashe Island	20 Oct. 2004 Late	High to low	2,227	370	Not defined	G	N

2005 Sites

Distant Island (Beaufort County)

In the Distant Island area (S117) three sites were selected for reef construction (Appendix Table 1-4a). The Distant Island A site had a gentle (2o) intertidal slope, medium to firm sediment composition, some pre-existing shell, and live horizontal oyster growth in the marsh line. This site experienced low wave energy due to light boat traffic. The channel width was 135 m. Approximately 4,380 bushels of shell were planted at Distant Island A in June 2005 early in the recruitment season. The Distant Island B site had a gentle intertidal slope (1^o), medium to firm sediment composition, some pre-existing shell, live vertical oyster growth in the marsh line, and low wave energy due to light boat traffic. The channel width was 32 m. Approximately 10,800 bushels of shell were planted at Distant Island B in July 2005, early in the recruitment season. The Distant Island C site had a gentle intertidal slope (2^o), soft to medium sediment firmness composition, some pre-existing patchy shell, and live horizontal oyster growth in the marsh line. This site experienced low wave energy due to light boat traffic and had a channel width of 135 m. Approximately 4,380 bushels of shell were planted at Distant Island C in June 2005 (Table A1.7 and A1.8).

Wallace-Capers (Beaufort County)

In the Wallace-Capers Creek area three sites were selected for reef construction. The Wallace A site on S 118 had a gentle (2^o) intertidal slope, soft sediment composition firmness, a dead and live patchy horizontal shell matrix, and medium wave energy due to moderate boat traffic. The channel width was 180 m. Approximately 4,250 bushels of shell were planted at Wallace A in late July 2005, towards the middle of the recruitment season. The Wallace B site (S118) had an extremely gentle intertidal slope (<1^o), very firm sediment composition, some patchy dead horizontal shell matrix with vertical oyster growth along the marsh line, and low wave energy due to light boat traffic. The channel width was 204 m. Approximately 9,900 bushels of shell were planted at Wallace B in July 2005. The Wallace C site (R121) site had a gentle intertidal slope (4^o), soft sediment composition firmness, no pre-existing shell, and low wave energy due to light boat traffic. The channel width was 98 m. Approximately 1,200 bushels of shell were planted at Wallace R121 in early August 2005 (Table A1.7 and A1.8).

Murrell's Inlet: Drunken Jack and Woodland Cut (Georgetown County)

At Murrell's Inlet, reefs were constructed in two areas, Drunken Jack Island (S357) and Woodland Cut on S358 (Table A1.7 and Al.8). Drunken Jack was characterized by a gentle intertidal slope, medium to firm sediment composition, some dead and live pre-existing horizontal shell, and high wave energy due to heavy boat traffic. The channel width was 90 m. Approximately 8,100 bushels of shell were planted at Drunken Jack in September 2005, late in the recruitment season. The Woodland Cut site was characterized by a gentle intertidal slope (2^o), very firm sediment composition, some pre-existing horizontal dead shell, and medium wave energy due to moderate boat traffic and moderate wind energy. The channel width was 50 m. Approximately 3,575 bushels of shell were planted at Woodland Cut in September 2005, late in the recruitment season.

Table A1.7. SRFAC planting area descriptions for 2005 reefs.The presence of pre-existing dead/live oyster shell is given in the shell substrate column. The level of wave energy experienced by a site from boats is given in the Boat traffic column and the wave energy from currents and wind is given in the Current/wind column (L = low wave energy, M = medium wave energy, and H = high wave energy). The sediment firmness of a site is given in the Sediment firmness column (S = soft, M = medium , and F = firm). Channel width was measured from high tide of one shoreline to the high tide line of the opposite shore.

County	Site	Shoreline substrate	Current/wind	Boat traffic	Sediment firmness	Bank slope (degrees)	Channel width (m)
Georgetown	Drunken Jack S357	Mud	H	H	M-F	2	90
Georgetown	Woodland Cut S358	Mud/shell	M-H	M	F	2	50
Beaufort	Distant Island A S117	Mud	L	L	M-F	2	110
Beaufort	Distant Island B S117	Mud	L	L	M- F	1	85
Beaufort	Distant Island C S117	Mud	L	L	S-M	2	130
Beaufort	Wallace A S118	Mud	M	M	S	2	170
Beaufort	Wallace B S118	Shell?	L	L	F	1	125
Beaufort	Wallace R121	Mud	L	L	S	4	120

Table A1.8. 2005 Shell Planting and Experimental Treatments. In the Date planted column, Early = Before July 1; Mid = July 1 and August 15; and Late = After August 15. The Planting location column indicates where in the intertidal zone shell was planted. The Planted Shell Types column indicates which restoration shell was planted at a site (W = Whelk, SC = South Carolina oyster shell, and G = Gulf oyster shell). The mesh treatments column indicates if experimental meshing occurred at a site. NM = not measured.

Site	Date planted (relative to recruitment period)	Planting Location	Shell Volume (U.S. Bu.)	Planted area (m^2)	Planted Shell Depth (cm +1SD)	Planted Shell Types	Mesh Treatments
Drunken Jack S357	29 Sept 05 Late	High to low	8,103	940	NM	G and SC	N
Woodland Cut S358	29 Sept 05 Late	High to low	3,577	608	NM	G and SC	N
Distant Island A S117	6 Jun 05 Early	High to low	4,382	1,006	NM	G	N
Distant Island B S117	7 Jul 05 Mid	High to low	10,814	1,958	NM	W	N
Distant Island C S117	6 Jun 05 Early	High to low	4,382	1,098	NM	G	N
Wallace A S118	29 Jul 05 mid	High to low	4,248	1,986	NM	G	Underlay
Wallace B S118	29 Jul 05 mid	High to low (on sandbar)	9,913	4,242	NM	G	N
Wallace C R121	9 Aug 05 mid	High to low (on mudbar)	1,200	275	NM	G and W	Underlay

2006 Sites

Drunken Jack and Woodland Cut (Georgetown County)

A total of 6,969 bushels of Gulf and SC shell were planted on S357 and S358 in August, late in the recruitment season. The Drunken Jack site was similar to the 2005 site but was in an area estimated to have higher boat traffic and wave energy in general. The Woodland Cut site was also similar to the 2005 site (See Table A1.9).

Long Creek (Charleston County)

A total of 5,293 bushels of seed oysters were relayed from the Santee River to R292 in September, late in the recruitment season. This site has a soft muddy substrate (Table A1.9).

First Sisters Creek, Governors Cut and Cutoff Reach (Charleston County)

First Sisters Creek (S206) was planted with 6,400 bushels of Gulf and South Carolina shell in late June, in the middle of the recruitment season. This site has a mud substrate but is relatively firm and is exposed to only moderate boat traffic. 8,087 bushels of mixed shells were planted at Cutoff Reach (S206) and Governors Cut (S205 and S206) in mid-September, very late in the recruitment period. The Cut-off Reach site was firm with a shell base. This site has medium current and wind energy but is exposed to heavy boat traffic. The Governors Cut site was middy but relatively firm. This site is potentially exposed to high boat traffic and high energy from currents and wind.

Distant Island and Wallace (Beaufort)

The Distant Island site (S117) was planted with 6,696 bushels of Gulf shell and had a sandy bottom and was firm. This site is exposed to moderate energy from wind, currents or boats. Wallace Creek (S118) was planted with 16,263 bushels of Gulf shell and was also sandy and firm, but is assumed to be exposed to higher boat traffic (Table A1.9).

Table A1.9. SRFAC planting area descriptions for 2006 reefs. The presence of pre-existing dead/live oyster shell is given in the Substrate column. The level of wave energy experienced by a site from boats is given in the Boat traffic column and the wave energy from currents and wind is given in the Current/wind column (L = low wave energy, M = medium wave energy, and H = high wave energy). The sediment firmness of a site is given in the Sediment firmness column (S = soft, M = medium , and F = firm. Channel width was measured from high tide of one shoreline to the high tide line of the opposite shore. NM= Not Measured.

County	Site	Shoreline substrate	Current/ wind	Boat traffic	Sediment firmness	Bank slope (degrees)	Channel width (m)
Georgetown	Drunken Jack S357	Mud	M	L	F	NM	90
Georgetown	Woodland Cut S358	Sand	M	M	F	NM	50
Charleston	Long Cr R292	Mud	M	L	S	NM	NM
Charleston	Governors Cut S205/206	Mud	H	H	F	NM	NM
Charleston	1st Sister Creek S206	Mud	M	M	F	NM	NM
Charleston	Cutoff Reach S206	Shell	M	H	F	NM	NM
Beaufort	Distant Island S117	Sand	M	M	F	NM	110
Beaufort	Wallace S118	Sand	M	H	F	NM	170

Appendix 2. Mesh Treatment Design and Layout for 2002 Sites

Murrells Inlet: Clam Bank Landing S354

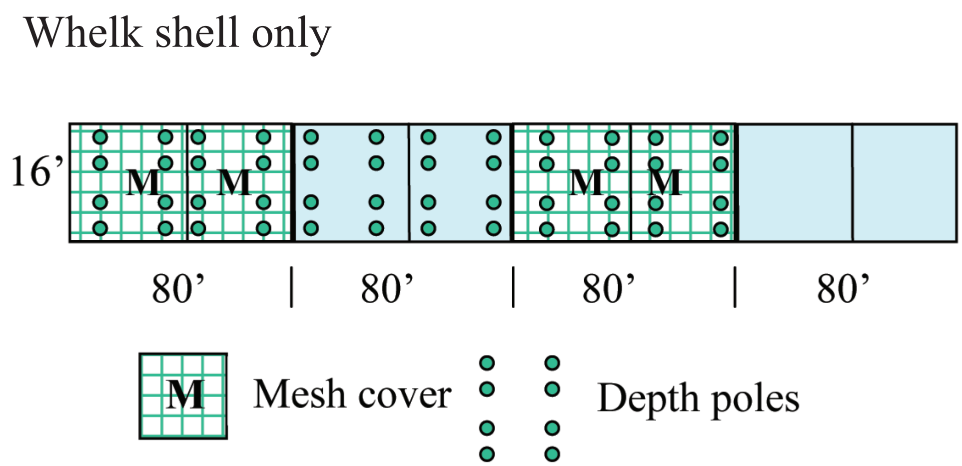


Figure A2.1. Mesh and shell layout at Clam Bank Landing S354 in 2002.

The site at Clambank Landing was subdivided into 4 sections (designated A, B, C and D for monitoring purposes) and half of each subsite was covered with mesh (Figure A2.1). Sixteen depth poles were installed in each subplot. All of the Clambank Landing subsites were designated to be planted with Whelk shell, but in reality all three shell types were used (Figure A2.2).

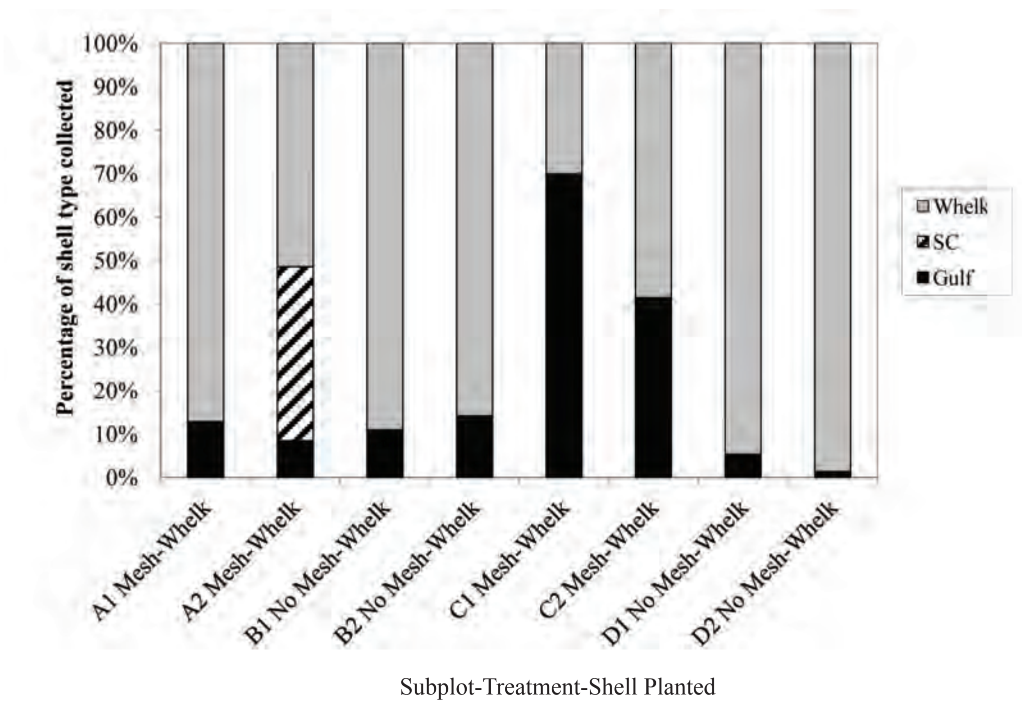


Figure A2.2. Actual shell type planted in each subplot at Clambank 2002. Meshed and unmeshed sections of each subplot were evaluated separately for shell type composition. All plots were intended to be whelk shell only.

Murrels Inlet Oaks Creek

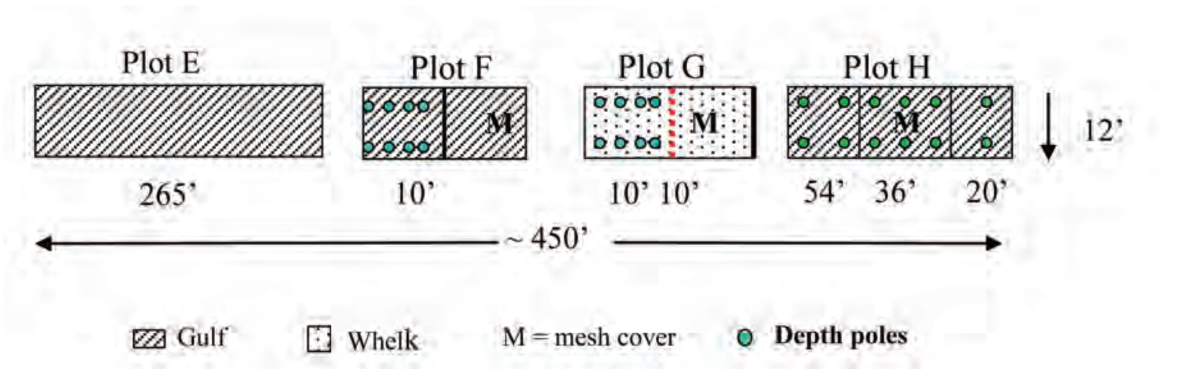


Figure A2.3. Mesh and shell type layout at Oaks Creek.

The Oaks Creek planting included four subplots (E, F, G, and H, Figure A2.3). The Oaks Creek site was planned to have replicated meshed and unmeshed plots of two shell types (Gulf, whelk). Due to a shortage of whelk shell, only one small area was planted with whelk (subplot G). Subplots F and H, both planted with Gulf shell primarily, were each partially meshed. Subplot E was planted with Gulf shell and remain unmeshed. We conducted shell counts after planting to determine the actual type of shell present (Figure A2.4). We were unable to evaluate the effect of shell type for Oaks Creek 2002 reef because the actual planted shell deviated too much from the original experimental design.

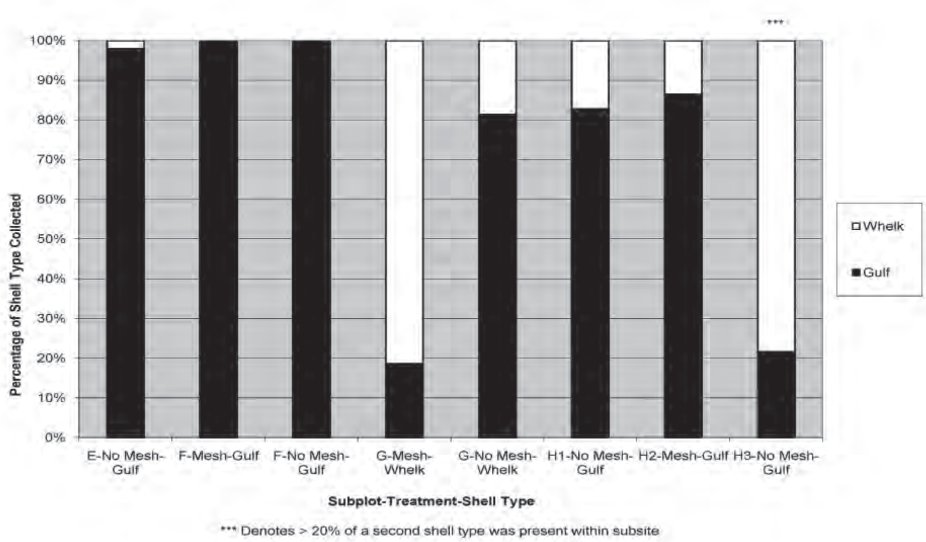


Figure A2.4. Actual shell types planted at Oaks Creek. X-axis labels indicate intended shell type.

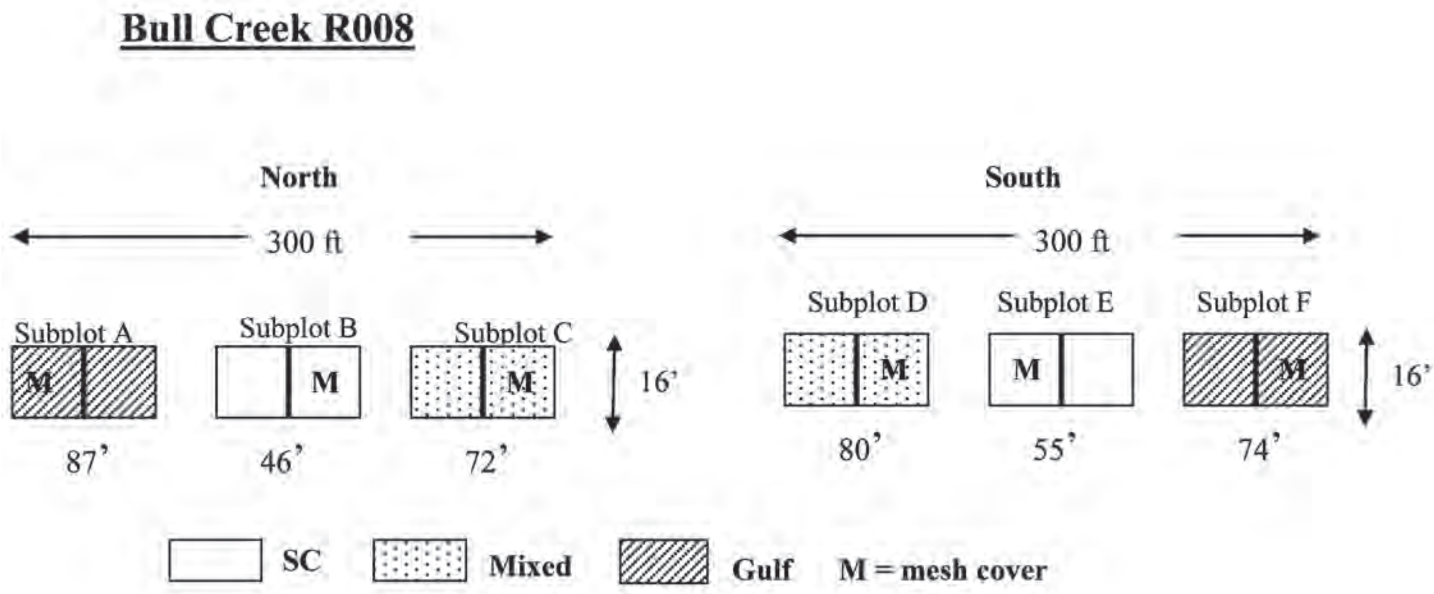


Figure A2.5. Mesh and shell type layout at Bull Creek (North and South).

The Bull Creek sites included Bull Creek North (subplots A-C) and Bull Creek South (D-E). The experimental design specified that two subplots were to be planted with each shell type (one subplot of each of the three shell types at Bull North and one of each at Bull South), with one half of each subplot covered with mesh (Figure A2.5). Depth poles were used to evaluate changes in shell depth in meshed and unmeshed plots. We were unable to evaluate the effect of shell type for Bull Creek 2002 reef because the actual planted shell deviated too much from the original experimental design (Figures A2.6 and A2.7).

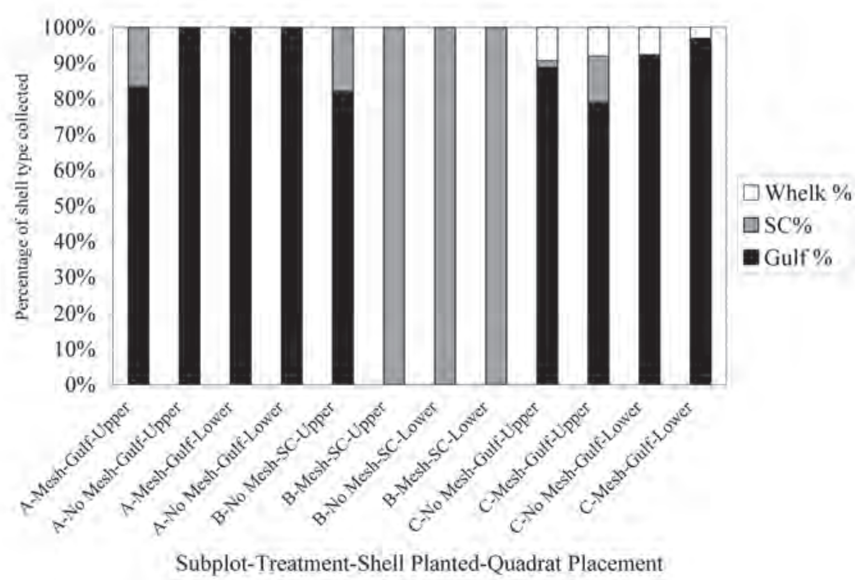


Figure A2.6.Actual shell type planted for each subplot at Bull Creek North. Intended shell is indicated in x-axis label. Meshed and unmeshed sections of each subplot were evaluated separately for shell type composition. Upper and lower sections of the bank were sampled within each subplot.

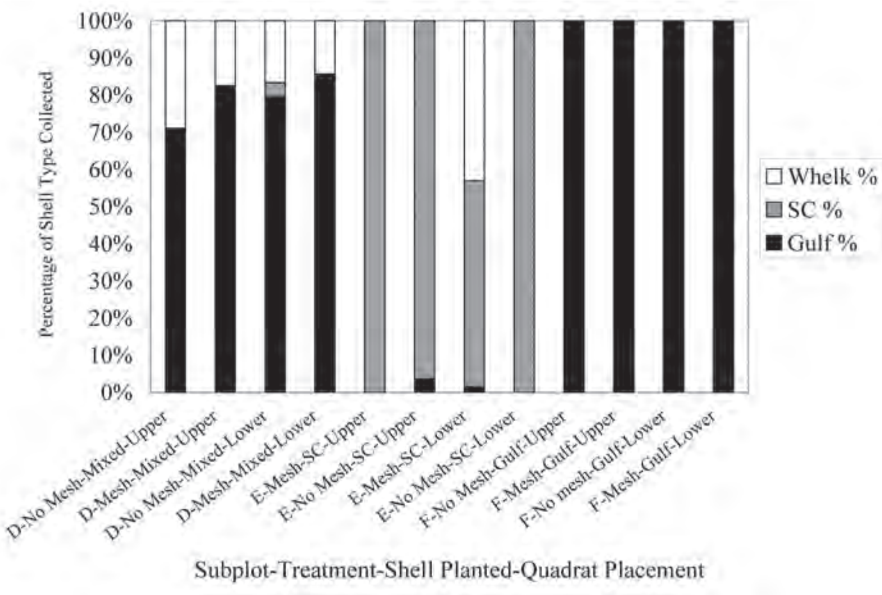


Fig A2.7. Percentages of shell type planted for each subplot section at Bull Creek South. Meshed and unmeshed sections of each subplot were evaluated separately. Subplots were also evaluated for upper and lower regions. X-axis labels indicated intended shell type for each subplot section

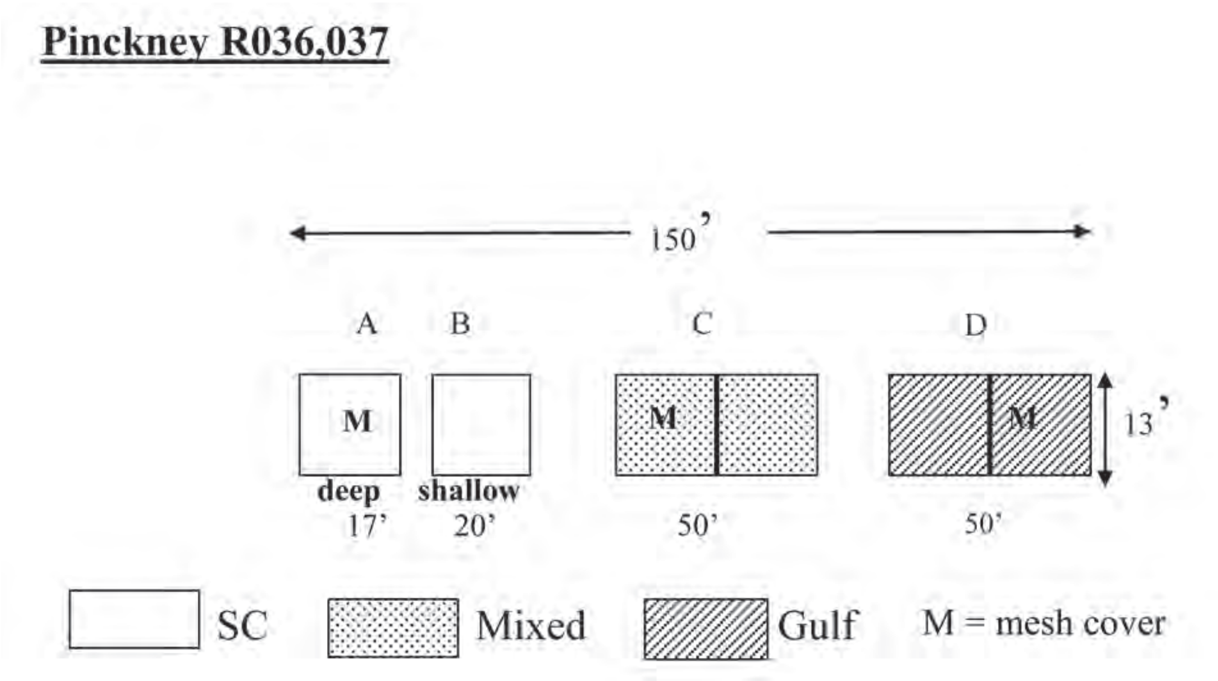


Figure A2.8. Mesh and shell type design at Pinckney.

The experimental design for Pinckney included three shell types (Figure A2.8): SC, Gulf and a mixture of the two. One half of each subplot was to be covered with mesh. The SC plot was planted at two different depths. Actual shell planting differed from the design and we were unable to evaluate the effect of shell type at this site (Figure A2.9).

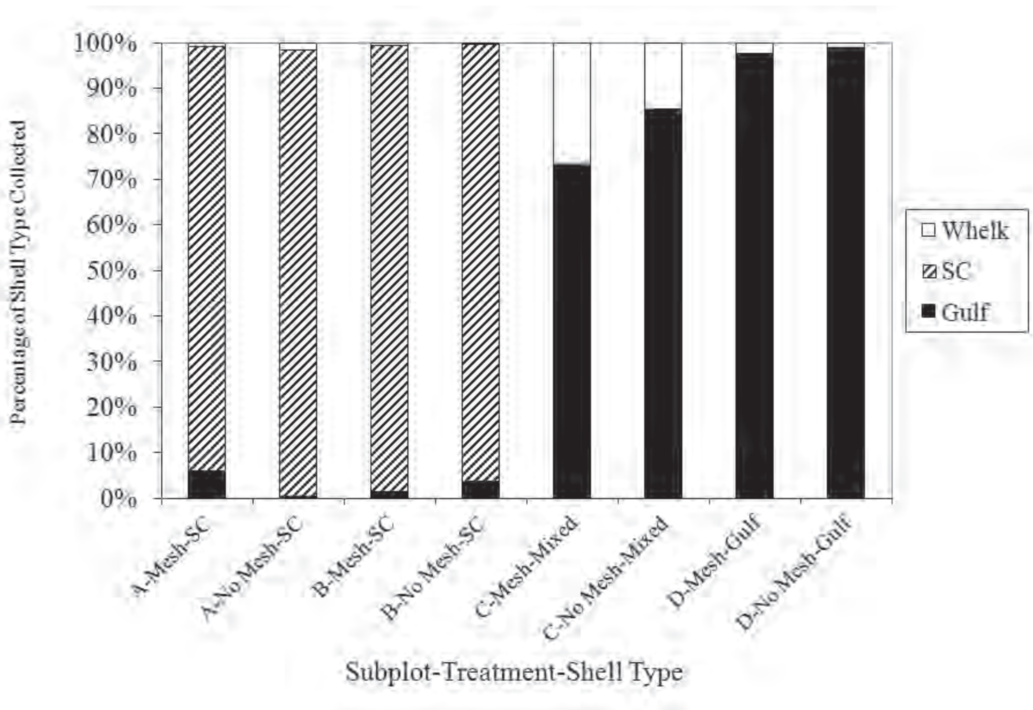
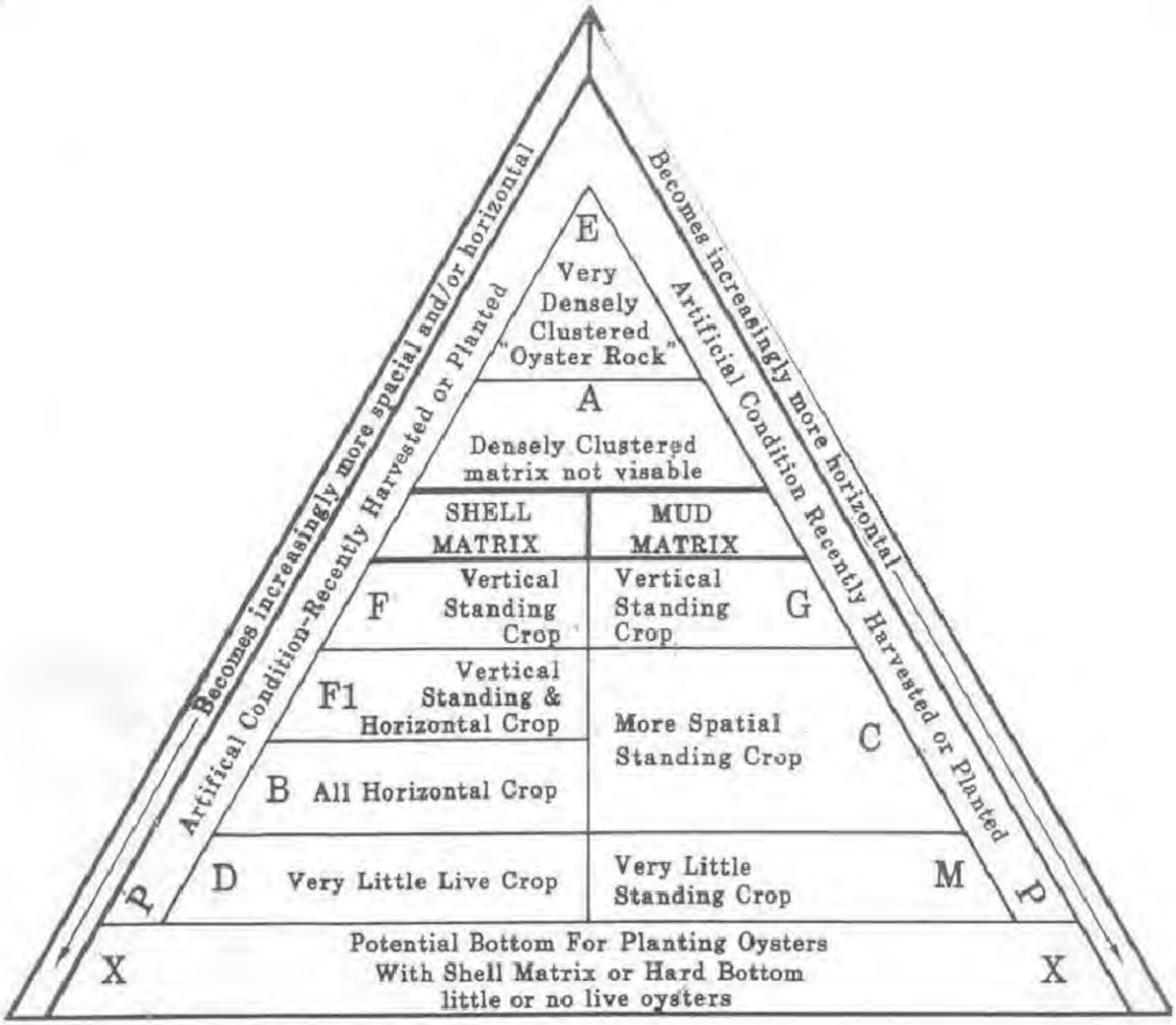
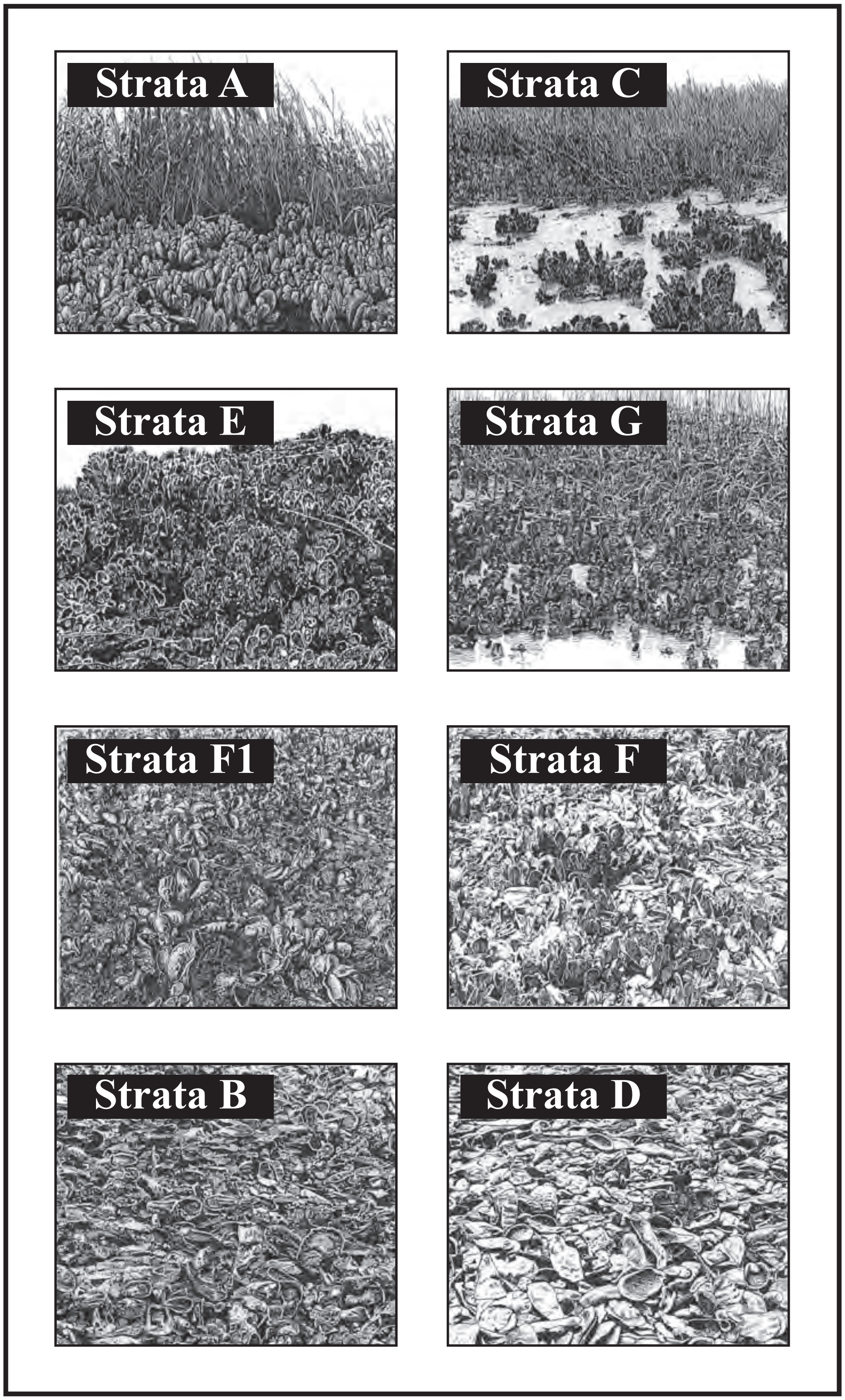


Figure A2.9. Actual shell type in each subplot at Pinckney. The x-axis labels indicate intended shell type.

Appendix 3. South Carolina Oyster Strata Definitions

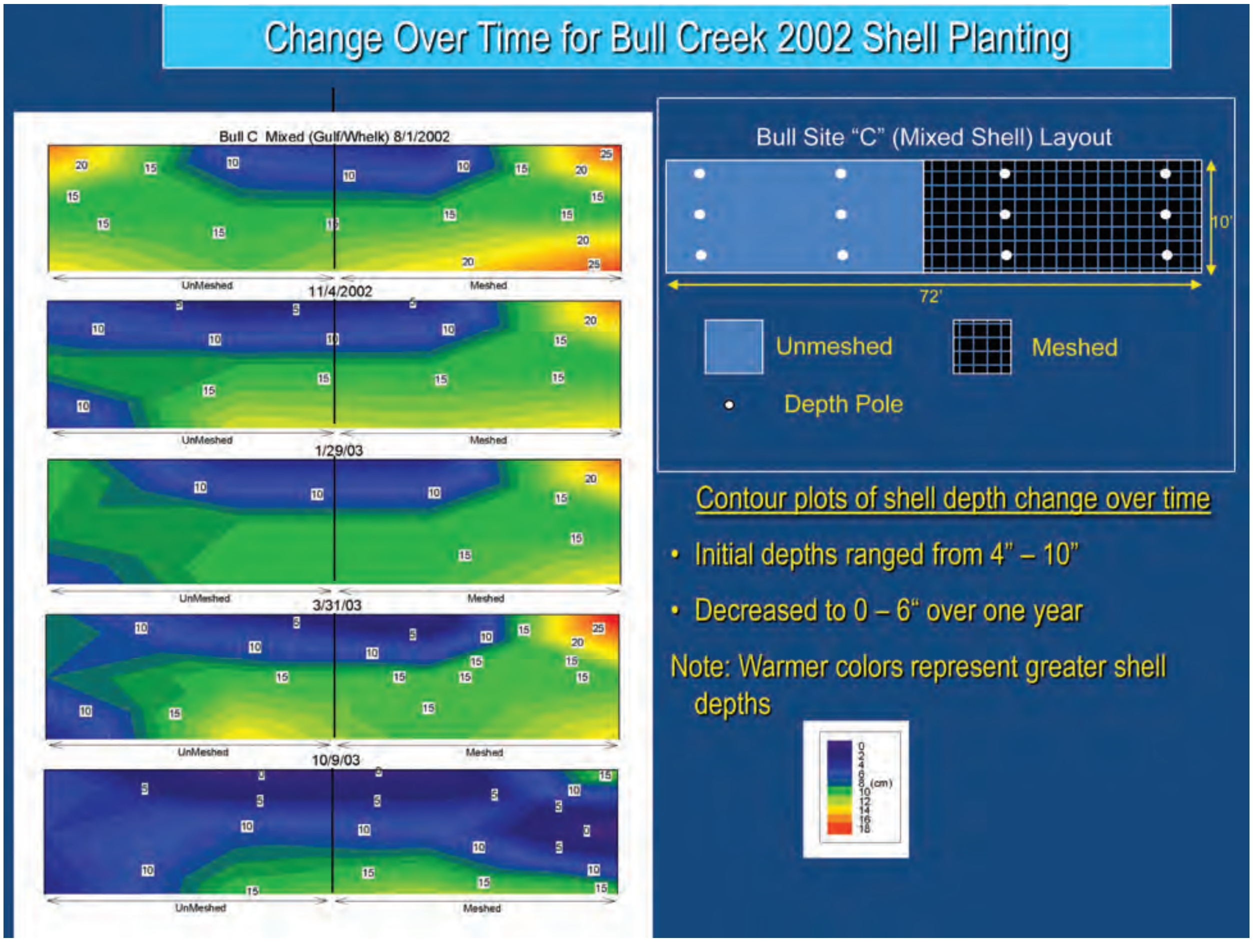


A diagrammatic representation of the strata types developed by OFM during their statewide assessment program in the 1980s. The two major dividing regimes revolve around increasing vertical clusters of oysters and whether the intervening matrix between the clusters is shell or mud.



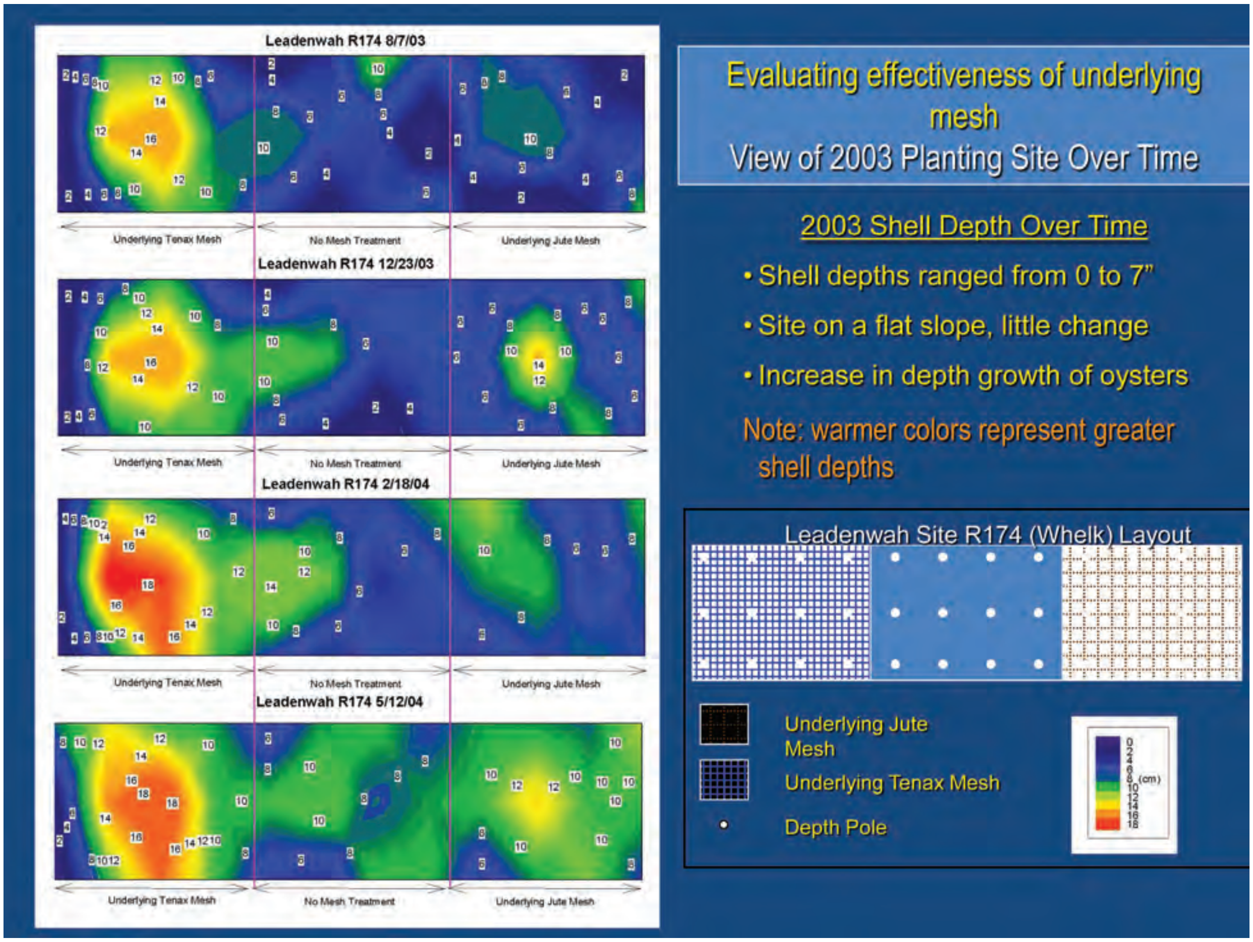
Eight of the most shell-dominated strata types developed by SMS-OFM during their statewide assessment program in the 1980s. These are pen and ink idealized-drawings.

Appendix 4. Contour Plots Depicting Changes in Shell Depth over Time



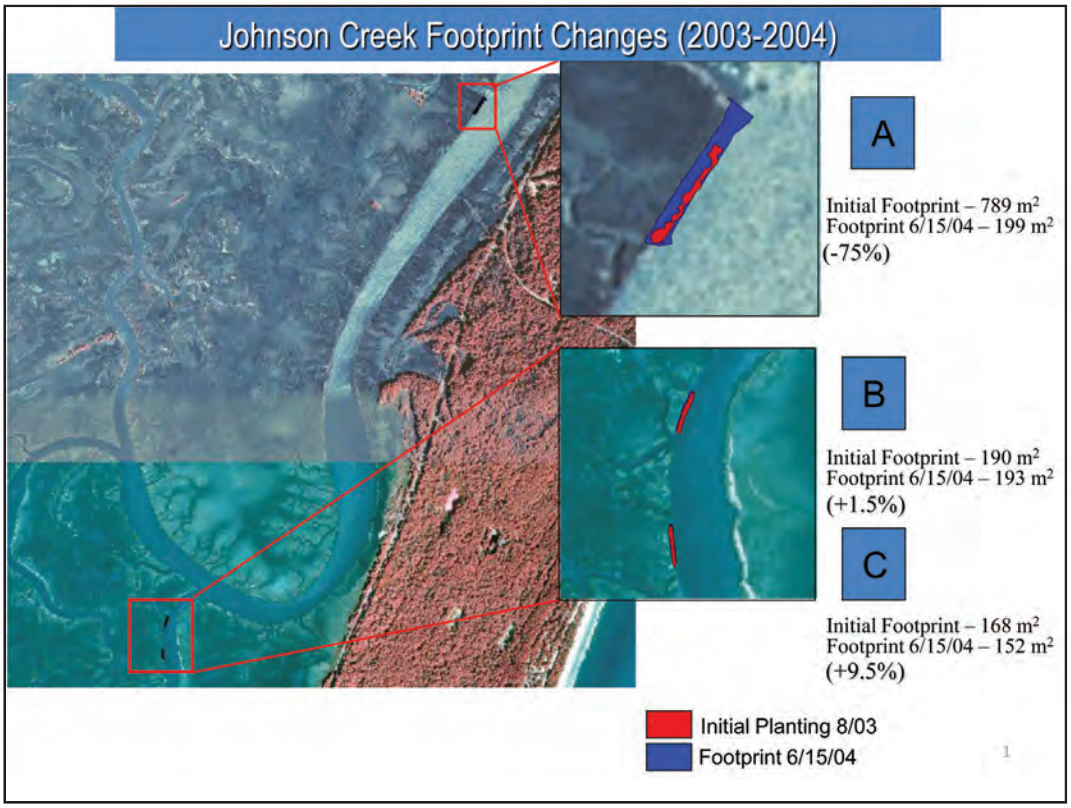
The contour plots above depict the change in restoration shell depth over time for Bull Creek C. The left side of each plot represents the unmeshed portion of reef C and the right side represents the meshed portion. Ultimately, shell depth appeared to decrease for both meshed and unmeshed areas.

Contour Plots Depicting Changes in Shell Depth over Time



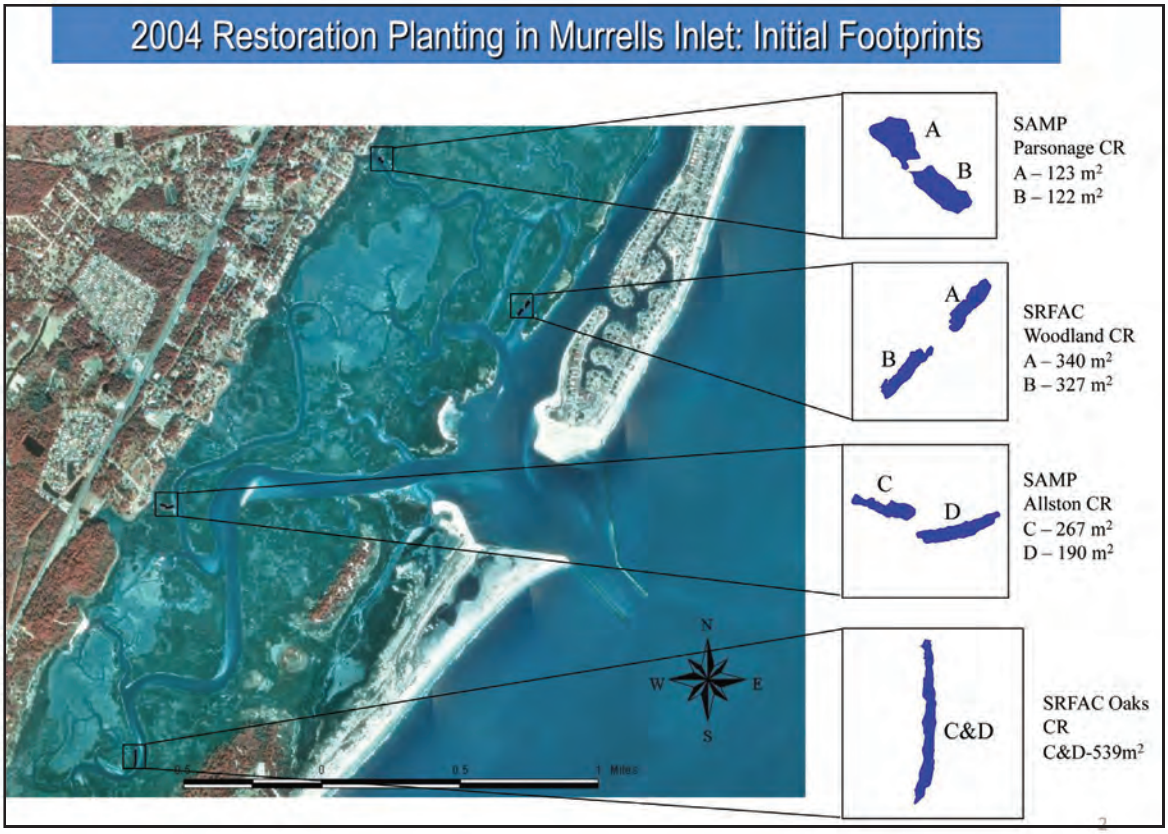
The contour plots above depict the change in restoration shell depth over time for Leadenwah R174. The left side of each plot represents the meshed portion of the reef, the middle represents the unmeshed portion, and the right side represents the meshed underlayment portion. Ultimately, shell depth appeared to increase for the three areas.

Appendix 5. Examples of SRFAC and SAMP Reef Footprint Changes over Time from Aerial Imagery



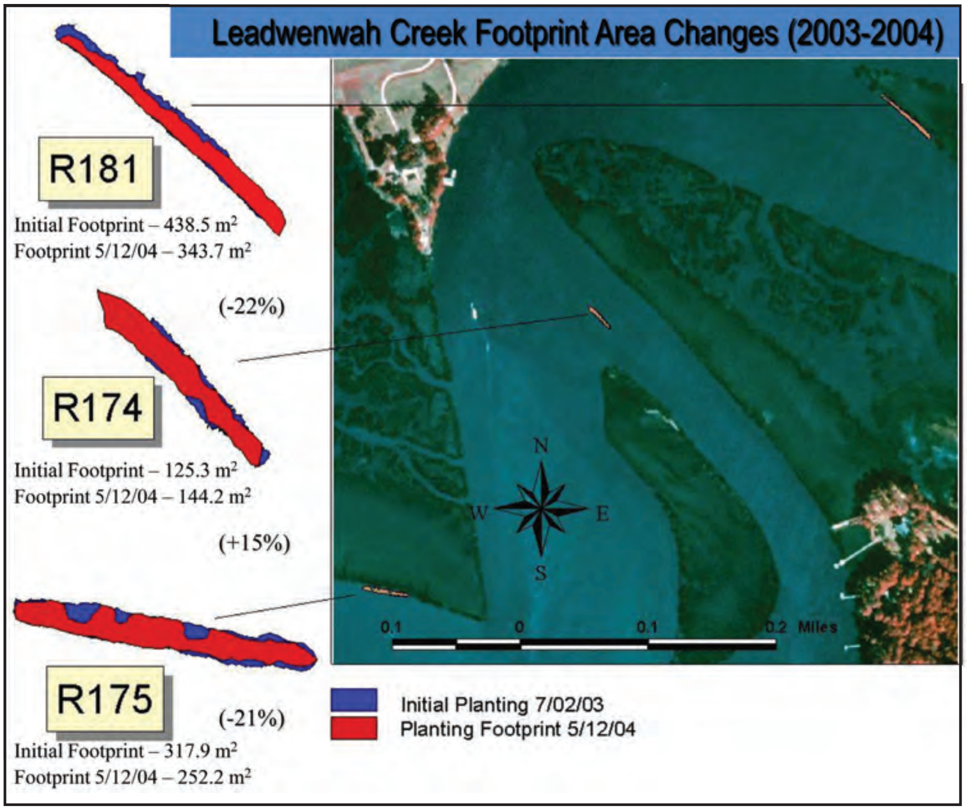
Aerial imagery of the three Johnson Creek sites. Johnson Creek reefs were constructed in 2003. Within one year of planting, Site A had lost more than 70% of the initial reef footprint. Sites B and C were used for evaluating mesh and were not used in the evaluation of footprint change over time.

Examples of SRFAC and SAMP Reef Footprint Changes over Time from Aerial Imagery



Aerial imagery of the four sites in Murrells Inlet planted in 2004. By the end of 2006 all four sites had less than 60% area remaining from the initial footprint size.

Examples of SRFAC and SAMP Reef Footprint Changes over Time from Aerial Imagery



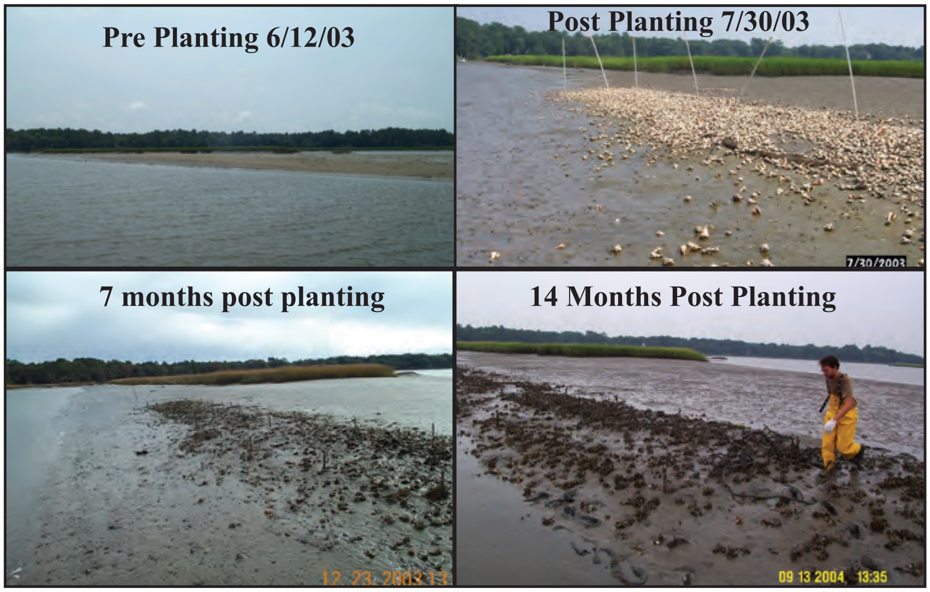
Aerial imagery of three sites planted in Leadenwah Creek in 2003. These sites were evaluated for mesh and could not be used in the assessment of footprint change. This is because only the inner portions of the reefs, where the mesh treatments existed, were measured for size and not the whole footprint area. However, even within the inner portion of these reefs, this imagery illustrates that footprint area decreased within the first year.

Walking Footprints

Areas surveyed using Trimble ProXR mapping grade GPS. Each footprint is walked and resampled over time. Areas were then saved as ArcView shape files.

Appendix 6. Photographic Examples of Changes in SRFAC Reefs Over Time

Leadenwah 2003 Site R174



Leadenwah R174 is above average on the success scale. A relatively small area was planted with shell. At Year 2 (2005), oyster densities were moderately high and growth was good. At three years of age approximately 98% of the footprint remained with good vertical oyster growth.

Examples of Changes in SRFAC Reefs over Time

Johnson Creek A was planted thinly and heavy siltation occurred by 4 months post-planting. This site never recovered from the siltation and is considered a failure.

Examples of Changes in SRFAC Reefs over Time

Pinckney A was planted late in the oyster recruitment season of 2003. After three years, the footprint area has decreased by about 50%. This site is considered below average.

Total cost: $663.00
Total copies: 50
Cost per copy: $13.26

Printed on Recycled Paper
10-7382