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The Fishery Value of Salt Marsh Restoration Projects

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ABSTRACT

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We assessed the benefits of different wetland restoration techniques for fishery resources by comparing habitat complexity, fishery support, and construction costs among five salt marsh restoration projects in Galveston Bay, Texas. The restoration projects included marsh terracing at Galveston Island State Park (GISPT) and Pierce Marsh Preserve (PMPT), mound construction at Jumbile Cove (JC), and marsh island construction north of Galveston Island along Interstate Highway 45 at I-45 East Marsh (I45EM) and I-45 West Marsh (I45WM). The projects were located in shallow estuarine waters and used bottom sediments or upland soils to construct intertidal areas that were planted with smooth cordgrass *Spartina alterniflora.* We used a Geographic Information System (GIS) and high-resolution aerial photography to classify areas into land (marsh vegetation) and water and applied fishery density models to assess fishery support. These models were developed to describe fine-scale distribution patterns for brown shrimp *Farfantepenaeus aztecus,* white shrimp *Litopenaeus setiferus,* and blue crab *Callinectes sapidus* across shallow estuarine habitat types (emergent marsh and shallow open water) of the Galveston Bay estuary. Restoration sites ranged in size from 6.9 ha (I45EM) to 68.2 ha (GISPT). Construction costs ranged from \$362,250 (GISPT) to \$74,200 (I45EM). Costs standardized to 1 ha for comparison among projects were \$40,608 (I45WM), \$11,875 (JC), \$10,685 (I45EM), \$8,771 (PMPT), and \$5,310 (GISPT). The I45WM project contained the greatest percentage of marsh vegetation (68%), whereas the two terracing projects had the smallest percentage (PMPT = 18%, GISPT = 19%). More of the constructed marsh in the terracing projects, however, was vegetated marsh edge (located within 1 m of the marsh shoreline) than in other projects (PMPT = 29%, GISPT = 25%, I45EM = 20%, JC = 11%, I45WM = 9%), and this habitat type supports the greatest densities of fishery species. Based on our modeling analysis, overall fishery support was greatest for the two I-45 projects, followed by the PMPT terracing project. Estimates of standing crop (number of animals) standardized to 1 ha ranged between 22,246–30,863 for brown shrimp, 21,773–33,139 for white shrimp, and 17,240–24,927 for blue crab. The two terracing projects and I45EM had higher fishery-benefit:cost ratios (ratio of standardized net fishery value to standardized project cost) than the other projects. Although marsh terraces composed of small cells supported the highest nekton populations, terraces constructed of medium cells were more cost-effective than terraces composed of either small or large cells. Based on our modeling results, all five restored sites supported relatively high populations of fishery species compared to prerestoration conditions. However, restoration sites did not support populations equivalent to a reference marsh system. Restoration projects should maximize the area of marsh vegetation and create a high degree of water-marsh interspersion to provide the most benefit for fishery species.

ADDITIONAL INDEX WORDS: *Restoration methods, marsh terracing, restoration mounds, fishery species, Galveston Bay, habitat value, penaeid shrimps, blue crab, GIS.*

INTRODUCTION

An important ecological function of coastal marshes is their support of fishery populations (Boesch and Turner, 1984; Kneib, 1997). Salt marshes in the northern Gulf of Mexico are essential nursery areas for brown shrimp *Farfantepenaeus aztecus,* white shrimp *Litopenaeus setiferus,* blue crab *Callinectes sapidus,* and other estuarine-dependent species, as this habitat type provides food for growth and structure that increases survival (Zimmerman *et al.,* 2000; Minello *et al.,* 2003).

More than half of the total area of wetlands in the conterminous U.S. has been lost over the last two centuries (Dahl, 1990). Loss rates were particularly high for coastal marshes in Louisiana and along the upper Texas coast (BRITSCH and Dunbar, 1993; White and Tremblay, 1995), and much of this loss was due to the conversion of brackish and salt marshes to open water (Dahl *et al.,* 1991).

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In response, a variety of restoration methods have been developed to return these open-water areas to marsh (TURNER and STREEVER, 2002).

A major goal of coastal marsh restoration is to increase habitat for fishery species. Yet, coastal marsh restoration projects are seldom assessed for fishery support. Recently, MINELLO and ROZAS (2002) developed a modeling approach to estimate fishery populations in coastal marshes that could be used to assess fishery support for restoration projects. The models use fine-scale density relationships with landscape-scale patterns of marsh and water to estimate population sizes for fishery species in salt marsh systems. While we recognize that true fishery value of a marsh system is more complicated and involves long-term production, we believe that population estimates for marsh systems can be a surrogate for fishery value.

The cost of wetland restoration can be widely variable (TURNER and STREEVER, 2002). Projects should be assessed for cost-effectiveness to ensure that we maximize wetland functional value. Estimating nekton populations provides a mechanism for assessing fishery benefits derived from a project and developing benefit:cost ratios. Information on the cost-effectiveness of different restoration methods should be useful in making decisions on the type of restoration projects to use under different conditions and in the design of future projects.

We examined five salt marsh restoration projects within the Galveston Bay system that were constructed using a variety of methods. Our objective was to compare these projects in terms of habitat complexity, fishery support, and construction costs. In addition, we compared these restored sites with pre-construction conditions and a reference marsh site. We also compared habitat complexity and fishery support in marsh terraces of three cell sizes that were constructed at Galveston Island State Park.

MATERIALS AND METHODS

Study Area

The marsh restoration sites were located within the Galveston Bay system on the upper Texas coast (Figure 1). Tides within the study area are predominantly diurnal, and the mean tidal range is approximately 0.3 m (ORLANDO *et al.*, 1991). Intertidal vegetation in the study area is dominated by smooth cordgrass *Spartina alterniflora* Loisel. We used the Elmgrove Point marsh as a reference site with which to compare the five restoration sites in our study. This site is located in East Bay on the northwest shore of the Bolivar Peninsula (Figure 1) and has been examined in detail by MINELLO and ROZAS (2002).

Restoration Sites

We assessed five restoration sites within the Galveston Bay system (Figure 1). Two projects, Galveston Island State Park Terracing (GISPT) and Pierce Marsh Preserve Terracing (PMPT), incorporated marsh terracing to convert shallow subtidal bottom to marsh (ROZAS and MINELLO, 2001). Bottom sediments at each site were excavated and used to construct terraces or ridges at marsh elevation. These ridges were arranged in a checkerboard pattern with open corners to allow movement of water and organisms through the terrace fields. Following construction, the intertidal ridges were planted with smooth cordgrass. The PMPT site was constructed in 1999 and is composed of 64 cells, each with 61-m-long sides surrounding a 0.29-ha terrace pond (Figure 2a). In addition, two rectangular (122 m by 61 m) cells were constructed in the project area (Figure 2a). Terrace cells of three different sizes were constructed at GISPT in 1999 and 2000 (Figure 2b). A total of 100 medium cells have the same dimensions as most of the PMPT terraces. In addition, 5 large cells were constructed with 122-m sides, 1.30-ha ponds, and four times the area of the medium cells; and 20 small cells were constructed with 30-m sides, 0.06-ha ponds, and approximately one-fourth the area of medium cells.

The Jumbile Cove (JC) project was constructed in 2001 and consists of 35 small islands or mounds (Figure 2c). Mounds were built using a small hydraulic dredge to excavate sandy bottom sediments off site and to pump this material into the project area. The end of the dredge discharge pipe was moved sequentially within the project area to construct each circular mound. Following construction, smooth cordgrass was planted on the intertidal mounds in August 2002.

The remaining two projects were constructed north of Galveston Island along Interstate Highway 45 (I-45) using road-construction equipment. The I-45 West Marsh (I45WM) project was constructed west of I-45 in 1999 by restoring a marsh degraded by borrow pits and a leveed disposal area. The site was restored to marsh elevation, and 12 meandering channels spaced approximately 30 m apart were excavated to create narrow

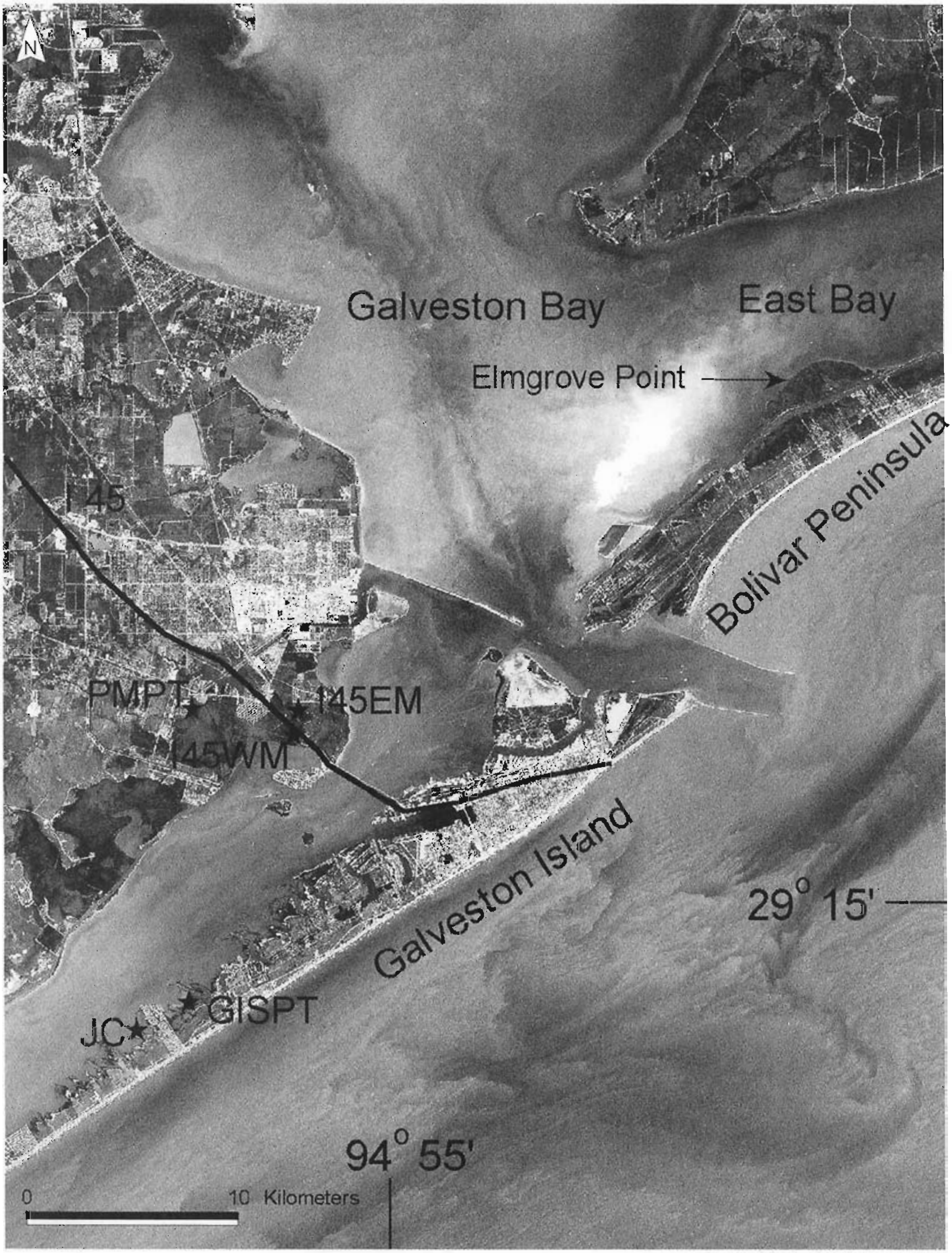

Figure 1. Locations of the five restoration sites included in our assessment and the Elmgrove Point marsh reference area in the Galveston Bay system of Texas. GISPT = Galveston Island State Park terracing site, PMPT = Pierce Marsh Preserve terracing site, JC = Jumbile Cove restoration mound site, I45WM = I-45 West Marsh site, and I45EM = I-45 East Marsh site.

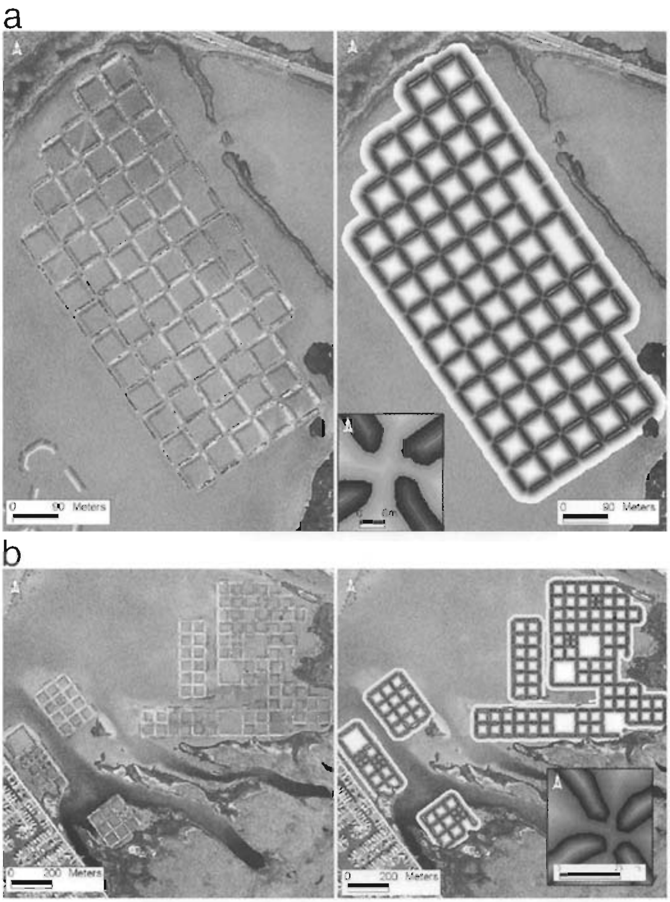

Figure 2. Aerial photographs and GIS results of land-water classifications for the five restoration sites: marsh terracing at (a) Pierce Marsh Preserve (PMPT) and (b) Galveston Island State Park (GISPT), (c) restoration mounds at Jumbile Cove (JC), and marsh islands constructed along Interstate Highway 45 at (d) I-45 West Marsh (I45WM) and (e) I-45 East Marsh (I45EM).

marsh islands (Figure 2d). The intertidal area between channels was planted with smooth cordgrass in summer 1999. East of I-45, a total of 32 marsh islands were built in 2001 at the I-45 East Marsh (I45EM) project site (Figure 2e). This project was constructed with fill from a nearby abandoned well-pad and access road using a bulldozer at low tide to move and shape the material into small (10–30 m wide), irregularly shaped islands. These intertidal islands were planted with smooth cordgrass in 2001.

Assessment Analysis Methods

Use of Fishery Density Models

We used the modeling approach of MINELLO and ROZAS (2002) to estimate potential nekton populations for each restoration project and the Elmgrove Point reference site. This approach is based on the development of regression models that describe fine-scale (1–10 m) nekton density patterns within a marsh system in relation to the peak density at the vegetated marsh edge. For densities within marsh vegetation, we used refined versions of the models described by MINELLO and ROZAS (2002); the models were modified to include their validation data. For shallow open water, we used models developed from a comparable study (unpublished data) where we estimated mean nekton densities in spring, summer, and fall of 2000 in marsh edge vegetation and on nonvegetated bottom at 1, 5, 15, 25, and 50 m from the marsh edge. The nonlinear regression models from this study

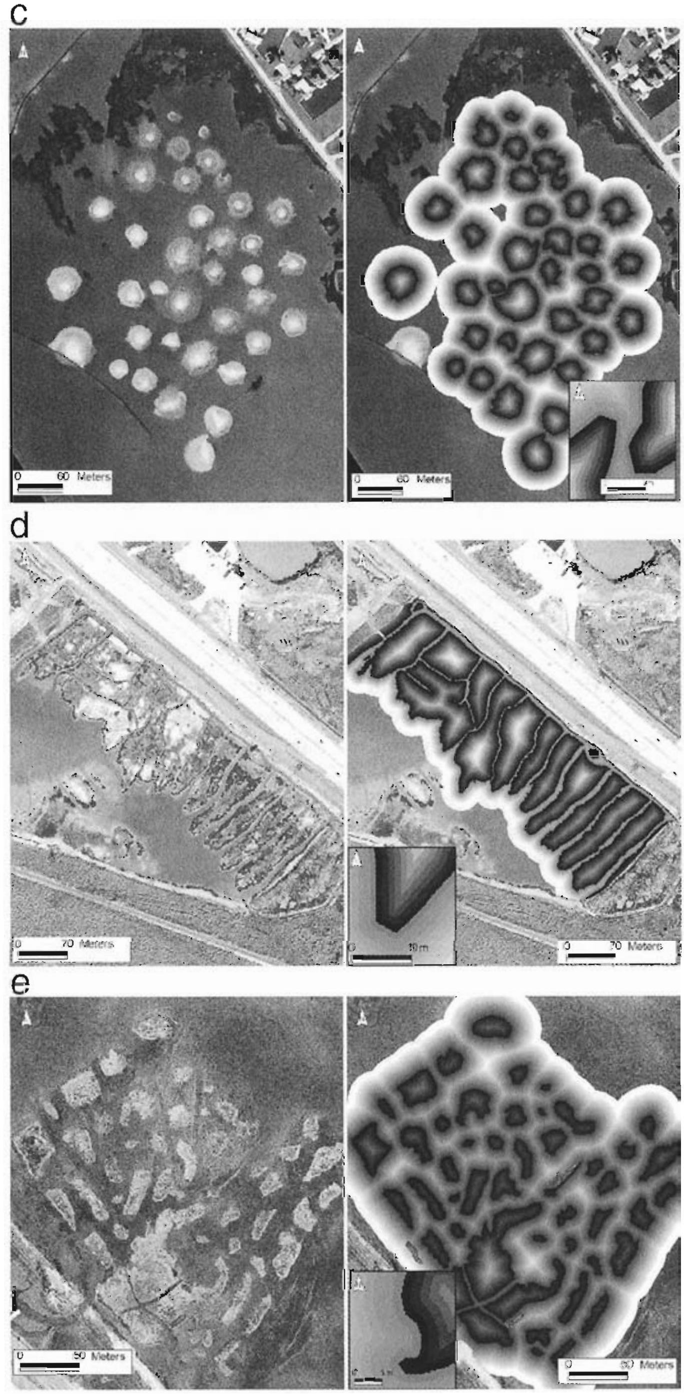

Figure 2. Continued.

described the decline in density from the marsh edge out into open water.

All of the models (brown shrimp, white shrimp, and blue crab) predict nekton densities within a marsh system based on the density at the vegetated marsh edge. We used marsh edge densities derived from 1,566 enclosure samples collected in the lower portion of the Galveston Bay system (mean annual salinity = 15–30 ‰) on various projects between 1982 and 1997. Mean densities were estimated for periods when a species was abundant in the Galveston Bay system. These densities in marsh edge vegetation (and the seasonal abundance periods) were 13.5 brown shrimp per m^2 (April–September), 11.3 white shrimp per m^2 (June–November), and 6.8 blue crabs per m^2 (April–October).

GIS Classification and Analysis of Habitat Complexity and Fishery Support

We calculated the areas of vegetation and water at different distances from the marsh edge with ArcView 3.2a (ESRI, Redlands, California) using a process similar to that described by MINELLO and ROZAS (2002). Base maps of each project site were constructed in a Geographic Information System (GIS) from digital georeferenced aerial images (scale = 1:14,000) taken December 14, 2001, by Landiscor Aerial Information (Houston, TX). We drew a 25-m buffer around restored marsh in project areas to define the boundary of each project site. The base map for the reference site was constructed in a GIS from a 1-m ground-resolution Digital Orthophoto Quarter Quadrangle (DOQQ) image analyzed by the U.S. Geological Survey from a color-infrared photograph (1:40,000 scale) taken February 5, 1995.

We generated habitat layers in vector format for each project site. First, we digitized the areas of water and vegetation in each scene using an on-screen digitization procedure. We classified all constructed intertidal area (*e.g.,* terraces, islands) within a project scene as vegetation, assuming that all emergent land at restoration sites will eventually become vegetated with smooth cordgrass and be available for use by nekton. We then classified the vegetation and water areas in each scene into different categories based on distance to the nearest marsh shoreline (*e.g.,* 0–1 m, 1–2 m, and so on) using Spatial Analyst 1.1 (ESRI, Redlands, California). We calculated the overall areal coverage of each distance-to-edge category within the water and marsh areas for each scene. Finally, we applied modeled densities for each distance-to-edge category using Microsoft Excel 2000 to estimate nekton populations for the entire project areas and the reference site.

We also estimated the size of fishery populations (standardized to 1 ha) at JC, GISPT, PMPT, and I45EM before any restoration projects were constructed at these sites. These sites, prior to restoration, consisted almost entirely of open water that was >25 m from the nearest marsh. Therefore, for this analysis, we estimated pre-restoration populations by multiplying the model densities of fishery species (number of individuals m^{-2}) in water >25 m from marsh by 10,000 m^2. For comparison purposes, we also calculated hypothetical nekton populations before construction for the I45WM project, as if this project was built in shallow open water. In reality, the I45WM project was built over borrow pits and a leveed disposal area.

Cost Estimates

We obtained construction costs from project managers with state and federal resource agencies or local project sponsors. Only the costs of constructing marsh platforms (*e.g.,* terraces, restoration mounds) or tidal channels were included in the project cost. We did not include the cost of building structures such as the geotextile tube barriers that were used at GISPT and JC to protect these restoration sites from erosive waves. Such structures were necessitated by site conditions and are not required for most applications of these restoration methods (*e.g.,* marsh terracing or hydraulic-dredge mound construction), yet they can add substantially to the total cost of a project. For example, the cost of installing geotextile tubes at the GISPT site was >5 times the cost of constructing the terraces. We also did not include the costs associated with planting marsh vegetation at the sites. Volunteers did most of the planting at some sites, whereas paid workers or a combination of these two labor sources were used for planting the marsh at other sites. Therefore, the actual costs incurred for planting did not represent the true cost of planting the marsh at every site. Planting costs generally increase with the proportion of marsh area at a site, but these costs usually account for only a small fraction of the total cost of a project.

Our cost estimates for terraces of different cell sizes were based on levee length as a proxy for

Table 1. *Results of habitat classification for the Elmgrove Point reference site and each restoration site. The total project area, the area that was marsh (marsh area), the proportion of the site that was marsh (percent marsh area), the total area of the site that was marsh edge (total marsh edge), and the percentage of marsh edge within marsh and over the entire site (within site) are given for each site.*

Site	Total Area (ha)	Marsh Area (ha)	Percent Marsh Area	Total Marsh Edge (ha)	Percent Marsh Edge	
					Within Marsh	Within Site
Jumbile Cove	11.8	3.6	30.4	0.4	11.1	3.4
Pierce Marsh Preserve	31.6	5.6	17.7	1.6	28.5	5.0
I-45 East	6.9	1.8	26.1	0.4	20.1	5.2
I-45 West	8.6	5.8	67.7	0.5	8.9	6.0
GISP Terraces	68.2	12.7	18.6	3.2	25.0	4.7
Elmgrove Point (Reference)	481.6	306.8	63.7	44.4	14.5	9.2

construction cost. If terraces are of similar width and height, the cost of constructing a terrace project can be determined by multiplying a fixed construction cost (per unit length of levee) for that specific site by the total length of levees to be constructed within the project area. Therefore, terrace levee length can be used as a realistic proxy for the construction cost at a particular site because the construction cost for each unit length of levee within a site is equal. We calculated levee length from hypothetical, large terrace fields composed of the three cell sizes used at GISPT by extracting the levee length from a 1-ha area imbedded within these hypothetical terrace fields.

Fishery Benefits

Using our density models and land-water configurations, we calculated the projected standing crops (per hectare) of brown shrimp, white shrimp, and blue crab for each restoration project. Species-specific fishery benefits were then calculated as the difference between these estimates and the estimates for 1 ha of shallow open water that was replaced by the project. After standardizing project costs to a per ha basis, we summed the fishery benefits for the three nekton species and calculated a benefit:cost ratio by dividing standardized benefits by costs; this ratio is expressed as number of nekton per U.S. $1.00 of construction cost. Benefit:cost ratios used to compare marsh terrace fields of different cell size were determined by dividing the sum of fishery benefits by the length of terrace levee estimated for a 1-ha area.

RESULTS

Classification and Habitat Complexity

The area encompassed by the restoration projects included in our study ranged from 6.9 ha (I45EM) to 68.2 ha (GISPT), and habitat complexity (marsh-water pattern) differed substantially among sites (Table 1). The I45WM project contained the greatest percentage of marsh vegetation (68%). The two marsh terracing projects consisted mostly of open water; the percentage of marsh at the terracing sites was 19% and 18%.

Marsh edge, that portion of the marsh area within 1 m of the shoreline, composed 9% to 29% of the vegetated area among projects (Table 1). Marshes at the two terracing projects contained the highest percentage of marsh edge, whereas the marsh at the I45WM site had the smallest proportion of this habitat type. This vegetated marsh edge, as a percentage of the entire project area, was highest at the I45WM and I45EM sites; the JC site had the lowest percentage of marsh edge (Table 1).

Habitat complexity in marsh terraces differed with cell size (Table 2). Small cells were > 35% marsh, whereas medium and large cells were 28% and 13% marsh, respectively. The percentage of marsh edge (both within marsh and within each cell) increased as cell size decreased (Table 2).

Fishery Support

Based on our modeling analysis, overall fishery support (expressed as standing crop or number of animals per ha of project area) was greatest for the two I-45 projects, followed by the PMPT terracing project (Table 3). Standardized standing crop ranges for the restored sites were 22,246–30,863 brown shrimp ha^{-1}, 21,773–33,139 white shrimp ha^{-1}, and 17,240–24,927 blue crab ha^{-1}; estimates for each species were highest for I45WM and lowest for JC (Table 3). Variability associated with these population estimates is difficult to assess because of the large number of potential sources (MINELLO and ROZAS, 2002).

Table 2. *Results of habitat classification for marsh terrace cells of three sizes. Small terrace cell has 30-m sides and a 0.06-ha pond, medium cell has 61-m sides and 0.29-ha pond, and large cell has 122-m sides and 1.30-ha pond. The total area, the area that was marsh (marsh area), the proportion of the cell that was marsh (percent marsh area), the total area that was marsh edge (total marsh edge), and the percentage of marsh edge within marsh and over the entire cell (within cell) are given for each cell size.*

Cell Size	Total Area (m^2)	Marsh Area (m^2)	Percent Marsh Area	Total Marsh Edge (m^2)	Percent Marsh Edge	
					Within Marsh	Within Cell
Small	920.1	324.6	35.3	100.5	31.0	10.9
Medium	4,001.6	1,106.1	27.6	273.8	24.8	6.8
Large	14,906.7	1,951.3	13.1	431.7	22.1	2.9

We calculated that a 1-ha area of open water >25 m from marsh would support 6,431 brown shrimp, 2,400 white shrimp, and 7,623 blue crab; these represent estimates of pre-restoration populations (standardized to 1 ha) for the sites. Post-restoration population estimates for brown shrimp, white shrimp, and blue crab were up to an order of magnitude higher than these pre-restoration estimates (Figure 3). Prior to restoration, the I45WM site likely would have supported even fewer animals because this area was composed of borrow pits and a leveed disposal area that was inaccessible to fishery species.

Based on our modeling estimates, the Elmgrove Point reference site supported higher nekton populations than the five restoration sites (Table 3). This reference site would support 37,748 brown shrimp, 38,606 white shrimp, and 26,680 blue crabs ha^{-1}, according to our models (Table 3). These values differed slightly from the estimates we reported previously (MINELLO and ROZAS, 2002) for the same site because we refined our earlier methodology to include models for open water.

Our modeling analysis showed that nekton populations increase as terrace cell size decreases (Table 4). For example, white shrimp population estimates for a 1-ha terrace field of small cells were 1.5 and 2.8 times higher than those for 1-ha terrace fields of medium and large cells, respectively. Likewise, estimates of brown shrimp and blue crab populations for a standardized terrace field composed of small cells were higher than those for terrace fields of medium or large cells (Table 4).

Table 3. *Estimates of standing crop (number of animals) for brown shrimp, white shrimp, and blue crab populations in restoration project areas and the Elmgrove Point reference site. Standing crops are standarized for 1 ha of the site area.*

Site	Brown Shrimp (number/ha)	White Shrimp (number/ha)	Blue Crab (number/ha)
Jumbile Cove	22,246	21,773	17,240
Pierce Marsh Preserve	27,296	25,698	17,978
I-45 East	28,997	28,815	19,775
I-45 West	30,863	33,139	24,927
GISP Terraces	26,490	24,807	17,823
Elmgrove Point (Reference)	37,748	38,606	26,680

Construction Costs

The cost of constructing these restoration projects was related to the method used to build each project, initial site conditions, and project size (Table 5). Total construction costs ranged from $74,200 (I45EM) to $362,250 (GISPT). Based on costs standardized to 1 ha of project area, the two

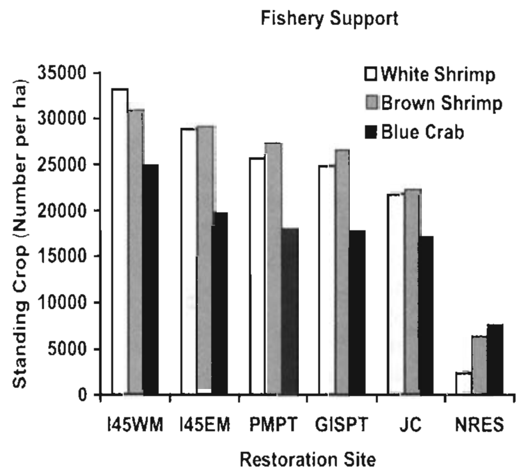

Figure 3. Population estimates for white shrimp, brown shrimp, and blue crab in a standard 1 ha area for the five restoration projects and a non-restored area (NRES) of shallow water >25 m from the nearest marsh which represents the pre-restoration condition. See legend of Figure 1 for restoration project acronyms.

Table 4. *Estimates of standing crop (number of animals) for brown shrimp, white shrimp, and blue crab populations in terraces of three cell sizes (small, medium, and large). Standing crops are standarized for 1 ha of the site area.*

Site	Brown Shrimp (number/ha)	White Shrimp (number/ha)	Blue Crab (number/ha)
Small Cell	47,062	48,503	28,661
Medium Cell	34,362	32,735	22,120
Large Cell	19,639	17,113	14,411

marsh terracing projects were the least costly to build, and the I45WM site was the most expensive (Table 5). The demolition of levee walls at the I45WM site added considerably to the project cost.

The cost of constructing marsh terraces increased as cell size decreased, because the length of terrace levees within a unit project area increases as cell size decreases (Table 6). For example, the length of terrace levees per ha in a terrace field of small cells is 3.3 and 1.8 times greater than that in terrace fields of large or medium cells, respectively (Table 6).

Fishery Benefit:Cost Assessment

The ratio of standardized fishery value to standardized project cost varied almost 6-fold among sites (Table 5). The two marsh terracing projects were more cost-effective than the other projects we assessed. The I45WM project was the least cost-effective.

Although nekton populations increased substantially as terrace cell size decreased, cost (length of levees) increased faster than population size for small cells (Table 6). Therefore, the benefit:cost ratio for terraces composed of small cells was less than that for terraces of medium cells. Based on our modeling analysis, terrace fields constructed of medium cells are more cost-effective to construct than terrace fields composed of either small or large cells (Table 6).

DISCUSSION

Our analysis indicated that restoration successfully improved fishery habitat at all five sites that we examined. Our models show that these sites should support relatively high populations of fishery species compared with pre-restoration conditions. The I45EM, GISPT, PMPT, and JC sites were estimated to support 9 to 14 times more white shrimp than an equal area of shallow open water, the composition of these sites before restoration. These restored sites also supported more than three times the population of brown shrimp and more than twice the population of blue crab that we estimated for the sites prior to restoration. The difference in fishery support between pre- and post-restoration conditions at the I45WM site was likely even greater than that at the other sites because much of this site was leveed and inaccessible to fishery species prior to restoration. Levees and other structures that restrict tidal exchange can severely limit habitat use by fishery species (McGovern and Wenner, 1990; Rogers *et al.*, 1994; Rozas and Minello, 1999).

Our model estimates of fishery populations increased as the proportion of marsh edge increased at a site. Numerous studies have documented that penaeid shrimps and blue crab are concentrated in flooded shoreline vegetation, and these species reach much higher densities in the marsh edge than in other shallow water habitat types (Zim-

Table 5. *Project costs and fishery benefits. Construction costs, fishery benefits, and benefit-cost ratios are given for each project site. Standardized construction costs were estimated by dividing the total construction costs by the total project area. Standardized net standing crops for each species were derived by subtracting the standing crops for that species estimated for 1 ha of open water (6,431 brown shrimp, 2,400 white shrimp, and 7,623 blue crab) from the standardized standing crops for that species at each site. Standardized total nekton standing crops were calculated by summing the standardized net standing crops of the three species for each site. The benefit : cost was derived by dividing the standardized total nekton standing crops by the standardized cost for each project.*

Site	Total Project Cost ($)	Standardized Cost ($, cost/ha)	Standardized Net Standing Crop			Standardized Total Nekton Standing Crop	Standardized Benefit : Cost (nekton per $)
			Brown Shrimp	White Shrimp	Blue Crab		
Jumbile Cove	140,375	11,875	15,815	19,373	9,617	44,805	3.8
Pierce Marsh Preserve	277,000	8,771	20,865	23,298	10,355	54,518	6.2
I-45 East	74,200	10,685	22,566	26,415	12,152	61,133	5.7
I-45 West	350,000	40,608	24,432	30,739	17,304	72,475	1.8
GISP Terraces	362,250	5,310	20,059	22,407	10,200	52,666	9.9

Table 6. *Comparison of fishery benefits for terraces of three cell sizes (small, medium, and large). Length of terrace levees standardized to 1 ha of a hypothetical terrace field (Standardized Levee Length), fishery benefits, and benefit-cost ratios are given for each cell size. Standardized levee lengths were estimated by determining the total length of levees within a 1-ha area for each cell size. Standardized net standing crops for each species were derived by subtracting the standing crops for that species estimated for 1 ha of open water (6,431 brown shrimp, 2,400 white shrimp, and 7,623 blue crab) from the standardized standing crops for that species for each cell size. Standardized total nekton standing crops were calculated by summing the standardized net standing crops of the three species for each cell size. The benefit : cost was derived by dividing the standardized total nekton standing crops by the standardized levee length (SLL) for each cell size.*

Site	Total Area of One Cell (ha)	Standardized Levee Length (m/ha)	Standardized Net Standing Crop			Standardized Total Nekton Standing Crop	Standardized Benefit : Cost (nekton per SLL)
			Brown Shrimp	White Shrimp	Blue Crab		
Small Cell	0.09	491	40,631	46,103	21,038	107,772	219
Medium Cell	0.40	267	27,931	30,335	14,497	72,762	272
Large Cell	1.49	149	13,208	14,713	6,788	34,709	234

MERMAN *et al.*, 1984; ZIMMERMAN and MINELLO, 1984; MINELLO *et al.*, 1994; PETERSON and TURNER, 1994; CICCHETTI, 1998; HOWE *et al.*, 1999; MINELLO, 1999; ROZAS and ZIMMERMAN, 2000). Therefore, the size of these nekton populations increases with the amount of marsh edge present at a site (MINELLO and ROZAS, 2002). Our population models express this edge-density relationship, and project realistic estimates of fishery populations at the landscape scale (MINELLO and ROZAS, 2002).

The projected populations of fishery species at the restored sites were not equivalent to those at the reference marsh at Elmgrove Point. Although each project was designed to create a considerable amount of marsh edge, the restoration sites contained less marsh edge than the reference marsh (3.4–6.0% vs 9.2% of total area). These results indicate that restoration projects can be further improved to benefit fishery species by increasing the amount of marsh edge.

Based on our assessment, marsh terracing was the most cost-effective restoration method. Marsh constructed using the terracing method contains a relatively high proportion of marsh edge, and marsh terraces are relatively inexpensive to build. The I45WM site contained a greater proportion of marsh edge (6% of total site area) than the other sites and therefore supported the highest fishery populations, but it was very expensive to construct. Heavy equipment was required to move a large amount of material to restore the site, making this project the least cost-effective of the five projects we assessed. Initial site conditions, however, were mainly responsible for the project cost. This design could be constructed at a considerably lower cost if initial site conditions were more favorable.

Two different restoration techniques were used at I45EM and JC to construct small marsh islands. The JC site was less cost-effective than I45EM for two reasons. The cost of constructing the mounds with hydraulic dredging at JC was about 11% higher than constructing islands at the I45EM site with earth-moving equipment. Further, although the JC site contained a greater proportion of marsh than the I45EM site, the proportion of marsh that was marsh edge at the JC site was about half that of the I45EM site (11% vs 20%). More importantly, marsh edge represented only 3.4% of the entire JC site compared with 5.0% of the I45EM site. The islands at the JC site were circular in shape, and circles have the smallest perimeter-to-area ratio of any geometric surface. Consequently, the irregularly shaped islands at I45EM contained more marsh edge (perimeter), and therefore, could support higher fishery populations than the circular mounds at JC. The I45EM project ranked just behind the two terracing projects in cost-effectiveness. This site is projected to support relatively high fishery populations, but the construction method used at the I45EM site was more expensive than that used to build marsh terraces.

Design changes could improve the fishery value of marsh restoration projects. The terracing projects at GISPT and PMPT contained a large amount of marsh edge, but fishery species would have benefited even more had the proportion of marsh area within the terrace fields been higher (ROZAS and MINELLO, 2001). One way to increase the proportion of marsh in a terrace field is to decrease terrace cell size. Our comparison of the three cell sizes used at GISPT showed that smaller cells would support higher fishery populations than large cells. However, the cost of constructing small cells rises at a faster rate than increases in fishery support, and therefore, marsh terraces composed of small cells are less cost-effective than terraces with medium or large cells. In addition, as cell size decreases, the proportion of borrow area (or deep, disturbed bottom habitat) in a cell increases. The amount of borrow area in a terrace field is directly related to total terrace length. For example, based on the GISP terrace field, the pond area in a terrace field of small cells would be 62% borrow area compared with fields composed of medium cells (37% borrow area) or large cells (15% borrow area). If borrow areas have much less habitat value for juvenile fishery species than undisturbed areas in a terrace pond, the increased borrow area would further offset any gain in fishery support achieved by increasing the proportion of marsh in a field. Other potential negative impacts of deep borrow areas include the possibility that they harbor large fishes that may prey on juvenile fishery species and they replace shallow intertidal feeding areas for shorebirds. The slope of the intertidal area also is an important consideration in the construction of marsh habitats. The proportion of a terrace or island that is composed of low intertidal marsh decreases as slope increases. Marsh with steep slopes may provide little accessible habitat for fishery species.

The method used at JC to construct marsh (*i.e.*, off-site dredging) may have the advantage of causing less habitat disturbance to a site than marsh terracing, where borrow areas are adjacent to the terrace levees. Off-site dredging can move the borrow areas to deeper areas of the bay, where any negative effects of creating deep-water habitat may be reduced. Alternatively, borrow areas can be avoided completely where material is available and substrate conditions allow the use of bulldozers to construct marsh islands as was done at I45EM. Future projects that use these restoration methods should build marsh islands with geometric shapes that maximize the perimeter:area ratio. For example, long, narrow (10- to 30-m-wide) islands would provide much more marsh edge, and fishery support, than circular islands of equal area.

Marsh restoration projects are not built solely to benefit fishery species, although this objective is common. Other reasons for restoring marshes include providing fish (non-fishery species) and wildlife habitat, shoreline protection, sediment stabilization, water filtration, nutrient cycling, and aesthetic value (MATHEWS and MINELLO, 1994). The Jumbile Cove and I-45 projects, for example, were designed to avoid the unnatural appearance of terracing projects. The checkerboard grid used in many terrace fields is not aesthetically pleasing to many people, despite the cost-effectiveness of this restoration method.

Our modeling approach allowed us to assess restoration projects for fishery support. We believe that our population estimates are realistic for coastal marsh systems in the northern Gulf of Mexico. However, the estimates are based on many assumptions that could affect the model output. A discussion of possible sources of error that could influence population estimates derived from our models is presented by MINELLO and ROZAS (2002). In applying this modeling approach to restoration sites, additional sources of error should be considered. The location and size of the buffer area that is drawn around the boundary of a site could affect population estimates. We used a 25-m buffer that was mostly open water. The effect of this buffer on our population estimates was likely minimal, because the buffer area was relatively small compared with the total area of each site, and because nekton densities in open water are relatively low. To examine the potential effect of a buffer along with project size and shape on our results, we conducted an additional analysis in which all open water was removed from the calculations, and benefits and costs were estimated solely on the area of marsh constructed. We obtained the same ranking among sites in this exercise as in the original analysis (Table 7).

Our approach was based on the assumption that all of the intertidal area within the 2001 aerial images of the restoration sites would ultimately support *Spartina alterniflora* marsh because our models are based on nekton patterns established for this marsh type. In fact, portions of some restored sites may not support this marsh vegetation. For example, some of the terraces located on the outside of the terrace field at GISP are too low to support marsh vegetation because of erosion from storms that occurred after the 2001 photographs were taken, and portions of the marsh at I45WM were initially constructed too high in the intertidal zone to support *S. alterniflora*. Further, at some sites, the intertidal area capable of supporting *S. alterniflora* may have expanded since 2001 as coastal processes reworked sediments placed there to restore the sites. An analysis based on more recent aerial photography would likely

Table 7. *Ratio of Fishery Benefits to Project Costs using marsh area only. Standardized net standing crops for each species were derived by subtracting the standing crops for that species estimated for 1 ha of open water (6,431 brown shrimp, 2,400 white shrimp, and 7,623 blue crab) from the standardized standing crops for that species in marsh at each site. Standardized total nekton standing crops were calculated by summing the standardized net standing crops of the three species for each site. The benefit : cost was derived by dividing the standardized total nekton standing crops by the standardized cost (project cost / area of marsh constructed) for each project.*

Site	Standardized Net Standing Crop			Standardized Total Nekton Standing Crop (number/ha)	Standardized Cost (cost/ha marsh)	Standardized Benefit : Cost (nekton per $)
	Brown Shrimp	White Shrimp	Blue Crab			
Jumbile Cove	39,606	43,275	27,257	110,138	$39,069	2.8
Pierce Marsh Preserve	88,770	81,898	47,372	218,041	$49,482	4.4
I-45 East	65,869	64,757	38,552	169,178	$40,994	4.1
I-45 West	30,919	35,519	22,940	89,378	$59,983	1.5
GISP Terraces	82,603	77,599	45,174	205,376	$28,501	7.2
Elmgrove Point (Reference)	42,285	43,592	26,349	112,226		

yield different estimates of fishery populations for all the sites, but a change in their ranking is unlikely because the proportion of the affected area within each site is small relative to the total project area.

The nekton densities used for the vegetated marsh edge in the models also will affect the results. The densities we used were based on mean values documented for natural habitats in Galveston Bay, Texas. Densities of fishery species in restored marsh may be different from those in natural habitat. In fact, densities of penaeid shrimps and blue crab can be significantly lower in constructed marsh than natural marsh (MINELLO and ZIMMERMAN, 1992; MINELLO and WEBB, 1997; ROZAS and MINELLO, 2001). Densities in natural habitat often vary considerably over time and space as well. Therefore, our modeling approach will not give accurate estimates of populations for any particular site (natural or restored) or time. However, our models should be robust for estimating relative differences in populations among different sites because the spatial patterns (*i.e.*, edge-density relationship) for fishery species appear to be consistent in marsh systems of the northern Gulf of Mexico. Although projected population estimates may differ from reality in time and space, project rankings that result from our modeling approach should be consistent.

This modeling approach estimates the standing crop of juvenile fishery species in different marsh systems, and we are using these population estimates as a surrogate for fishery value. We recognize that fishery value is more complicated and should encompass the productivity of species derived from the marsh system and the longevity of the system. We have not incorporated these concepts into our analysis. Using estimates of productivity as a basis for comparing restoration success would be preferable to using standing crop, but productivity is far more difficult to measure, especially at multiple sites, over large spatial scales, and in open systems like an estuary. Density and standing crop reflect recruitment, mortality, and emigration of juvenile fishery species, and therefore, should be important indicators of habitat value for these species (MINELLO, 1999). Project longevity should be included in assessments of restoration projects when this information is available. Further research may provide reasonable estimates for the longevity of these relatively new restoration techniques. Other measures of fishery value also should be considered when assessing the success of restoration projects including, for example, species diversity, productivity of prey populations, and ecological values of inner marsh habitat.

Our population models included only decapod crustaceans, but models also could be developed for fishes. Gulf menhaden *Brevoortia patronus*, spotted seatrout *Cynoscion nebulosus*, and red drum *Sciaenops ocellatus* support important fisheries in the northern Gulf of Mexico and would be suitable species to include in such models. The young of spotted seatrout and red drum, like the decapods used in our models, are most abundant at the marsh shoreline (MINELLO, 1999), and we expect that populations of these two species also would increase with the amount of marsh edge at a site. Juvenile gulf menhaden are more abundant in open water than in marsh vegetation (MINELLO, 1999), and therefore may not benefit directly from restoration projects that replace shallow water habitat with marsh.

In conclusion, our results from population models indicate that the fishery value of marsh restoration projects can be quite variable. We believe that the use of population models can be a useful tool for assessing the habitat value of marsh restoration projects. In addition to providing information on benefits to fishery species, our approach provided a basis for comparing the cost-effectiveness of projects. This approach also provides a mechanism for evaluating alternative designs for future restoration projects and for designing projects that most improve fishery habitat at a reasonable cost.

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