EFFECTS OF EXPOSURE ON THE POPULATION DYNAMICS OF THE EASTERN OYSTER, *Crassostrea virginica* (GMELIN, 1791), IN GEORGIA

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By Justin Manley, Alan Power and Randal Walker

Marine Extension Service, University of Georgia, Shellfish Research Laboratory,
20 Ocean Science Circle, Savannah, Georgia 31411-1011

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Abstract

This study examines recruitment, growth rate, shell morphology and mortality for eastern oysters, *Crassostrea virginica* (Gmelin, 1791), grown on commercial spat sticks in three locations of differing exposure to storm and boat waves in St. Catherine's Sound, Georgia. Locations included a small sheltered tidal creek, a partially sheltered site and a non-sheltered site within the sound. Recruitment occurred at all sites from May through October 2006. Two peak oyster recruitment events occurred at all sites; June and August. On a seasonal basis, no significant differences ($p=0.12$) in oyster spat recruitment occurred between sites, however, a general trend revealed higher settlement with increased exposure. The highest mean seasonal settlement value occurred at the open sound site with 165.57 ± 32.73 spat per 0.01 cm^2 settling per month. Mean seasonal spat recruitment was 106.14 ± 26.65 per 0.01 cm^2 and 92.69 ± 19.84 per 0.01 cm^2 in the partially and sheltered sites, respectively. By March 2006, oysters obtained shell heights ranging from 60.6 mm from the non-sheltered site in the sound to 72.2 mm in the sheltered creek. Oysters on sticks from the sheltered creek site were consistently greater in shell height than oysters from the partially and unsheltered sites. No significant differences in oyster mortality occurred between treatments from September 2006 to March 2007, except in December 2006, when mortality was higher at the partially sheltered site. Mean monthly mortality of oysters on sticks ranged from 2.7% in December at the open sound and sheltered creek sites to 17.3% at the partially sheltered site in January 2007. Oysters on sticks at the site with least exposure and the lowest recruitment rates attained the largest size and maintained a relatively low oyster mortality rate. Commercial spat stick treatments represent an environmentally sustainable oyster cultivation technique that can increase commercial oyster productivity in Georgia, substantially enhance oyster brood stock and likewise increase habitat capacity for several reef associated and migratory invertebrate and vertebrate species.

Introduction

Oysters, *Crassostrea virginica* (Gmelin, 1791), play important commercial and ecological roles in coastal Georgia. Harvesting oysters for human consumption occurred long before the arrival of Europeans to America (Thomas 2008). Georgia once led the nation in oyster harvesting in 1908 with over 3.6 million kg of meat landed and processed at thirteen canneries (Harris 1980). Today, the industry has limited production which has resulted in a market that supplies only local demand for fall and winter oyster roasts. During 2008 the Georgia shellfish industry harvested 5,973 kg of oyster meat valued at $56,321 (Georgia Department of Natural Resources). Presently, oyster harvest is flat and has little impact on local oyster stocks; however intense oyster harvest during the early 1900's is implicated in a major reduction in the existing natural oyster population (Galtsoff and Luce 1930, Harris 1980; Walker and Cotton 2001). Drake (1891) reported 688 hectares of oysters in Georgia, while Harris (1980) reported 121 hectares. Oyster reef area along the Duplin River, Georgia has decreased from 8.9 ha in 1891 to 4.3 ha by 2000 (Drake 1891; Walker and Cotton 2001). Though the decrease in live oyster areas may be partially the result of variations in research methodology, it is clear that developing methods and technologies to cultivate large quantities of live oyster shell stock for commercial purposes is both an environmental and economic necessity.

From an environmental standpoint, oysters are an indicator species that reflect the health of their surrounding ecosystem. Oyster reefs provide nesting habitat, settlement areas and refuge for numerous species of fish and invertebrates (Wenner *et al.* 1996; Breitburg 1999; Coen *et al.* 1999; Coen and Luckenbach 2000; Posey *et al.* 1999; Peterson *et al.* 2003; Grabowski and Powers 2004). As filter feeders oysters improve water quality by enhancing nutrient cycling and reducing turbidity through biodeposition (Brooks 1891; Newell 1988; Newell *et al.* 2002; Pietros and Rice 2003; Newell and Koch 2004; Newell *et al.* 2004). Oyster reefs provide structural stability within estuaries and aid in the dispersion of wave energy in a relatively soft mud environment and can shield salt marsh (*Spartina alterniflora*) habitat from erosion associated with heavy boat traffic and winter storms (Coen and Luckenbach 2000).

Natural oyster reefs occur throughout the medium to high saline areas of the estuaries in Georgia. Most reefs in Georgia occur within the intertidal zone starting at the two-hours above-mean-low-water mark and may extend to 130 cm above the mean-low-water mark (Bahr and Lanier 1981). Oyster reefs in the southeastern U.S. have the greatest density and biomass of east coast stocks (Dame *et al.* 1984). They range in size from a few small isolated clumps to massive solid mounds of both living and dead shell (Bahr and Lanier 1981) which may occur for hundreds of meters along creek and river banks. Oyster reefs occur anywhere from small feeder creeks to areas in the open sound. Oyster reefs occur wherever oysters can successfully attach to any hard substrate within the soft mud substrates that dominate coastal Georgia's estuaries. Once established, new recruits will settle on the existing oyster and with each passing year the reef will expand until centuries later massive reefs are in place.

Large industrial scale commercial harvest of wild oysters even from highly productive pristine estuary systems, such as those that currently exist in Georgia, could not be sustained over a long period. Many successful oyster industries in the United States rely on strategies that implement wild spat collection and cultivation or as is observed on the West Coast of the U.S., the hatchery production and cultivation of non-native oyster spat (Matthiessen 2001). The combination of wild oyster spat collection and their subsequent cultivation, in Georgia, could potentially remove any negative impacts of the industry on the natural environment by relieving harvesting pressure of natural stocks. Using wild oyster spat also prevents the possible transport of disease from one geographic area to another which could potentially occur when using hatchery produced oyster spat from other locations. Overall, oyster cultivation has a net positive effect on the local ecosystem through habitat provision, native oyster brood stock enhancement, water quality improvement, nutrient removal, and shoreline stabilization. Fiscally, mariculture is a relatively new and unrealized area of the Georgia economy and may provide great potential for the economic growth in the state's coastal communities.

There are now well defined ways to grow large volumes of cluster (roast) oysters in Georgia using commercial spat sticks, as well as, PVC and rebar coated in cement deployed in high densities (81 sticks/m^2) (Manley 2007; Manley *et al.* 2008). While conducting oyster habitat restoration research on Sapelo Island, Manley (2007) determined that oysters attained legal harvest size (76 mm) on high density spat stick treatments in approximately 9-10 months after peak summer oyster recruitment. Therefore oysters would be legally harvestable approximately 11-12 months after cultch materials (stick treatments) were deployed. It is important to note that oyster biomass on stick treatments more than doubled from January 2005 (approximately 40 kg or 88 lbs of harvestable product) to January 2006 (approximately 155 kg or 341 lbs of harvestable product) (Manley 2007). This translates into approximately 6.5 bushels (assuming a 50 lb bushel) of cluster oysters per square meter treatment per two year period. Research has highlighted improved methods of cultivating single oysters and maximizing oyster production. Many studies have attempted to control oyster spat fouling (Adams *et al*. 1989, Moroney and Walker 1998, 1999), as well as, identifying ideal location and methods for oyster spat collection and grow-out on shellfish leases (Manley *et al*. 2008; Manley *et al*. 2009).

To determine the potential success of cultivating wild oyster spat on commercial spat sticks in $81/m^2$ densities for commercial oyster production, a comparison must be made to the industry standard which is currently wild harvest. This study examines oyster settlement, growth, and mortality rate on natural oyster reef and commercial spat sticks in areas exposed to different degrees of physical wave energy generated by storms and boat traffic. Research was conducted in three distinct areas: a creek area sheltered from major wind and wave action, an area partially sheltered from wind and wave action, and an area in the sound fully exposed to wind and wave action.

Materials and Methods

Three sites in St. Catherines Sound were used to examine how exposure to winds and boat wakes affects oyster spat recruitment (Figure 1). Site 1 was on the north bank of the Medway River near the junction of Bear River in St Catherines Sound and completely exposed to wind and wave energy. This site was characterized by a sandy-mud substrate flat and was adjacent to naturally occurring fringing oyster reef. Site 2 was on the north bank at the mouth of a small shallow salt-marsh unnamed creek that opened into the sound. Site 2 was characterized by soft mud substrate and periodic heavy sedimentation. Site 2 was partially sheltered and only exposed to wind and wave energy during east and southeast winds. The only naturally occurring oysters near site two were located on a patch reef at the mouth of the creek. Site 3 was located approximately 0.5 km northwest from the open sound on the north bank of a moderate sized unnamed salt marsh creek. Site 3 was characterized by soft mud substrate. Oysters occurred as naturally fringing reef near the mouth of this creek. Although Site 3 was located in a moderate sized tidal creek, it was completely sheltered with almost no exposure to significant wind and wave action.

To evaluate oyster recruitment, three 1-m long, 1.9-cm diameter commercial spat sticks composed of longitudinally grooved PVC pipe embedded with chips of calcium carbonate (Aquatic Eco-systems, Inc.) were deployed monthly at sites 1, 2, and 3 in St. Catherines Sound. At each site three spat collectors were driven into the mud substrate along the creek bank so that 61 cm of the stick was above the substrate surface. Spat collectors were first deployed prior to the oyster reproductive season (Heffernan *et al.*, 1989) during March 2006 within the intertidal zone at the two hours above mean-low-water mark in alignment with naturally occurring oyster reefs. Spat collectors were gathered monthly and replaced with new collectors. Oyster recruitment monitoring was terminated December 2006.

Oyster recruitment rates were quantified per $0.01m^2$ sample. Three 12.5 cm length sections of each collector were manually counted for the number of spat attached per stick for each replicate stick. Thus, a total of 9 sections were counted per site per month to determine oyster recruitment rates.

To evaluate oyster growth and mortality, three replicate plots of 81 commercial spat sticks per meter square were established at each site on 2 March 2006. Plots were deployed at the three sites adjacent to a natural oyster reef. Monthly, 32 oysters were selected randomly from each of three replicate stick plots (N = 96) per site. Additionally, one spat stick per replicate was collected monthly to determine oyster mortality rate. Oyster shell height (distance from hinge to lip in mm) and length (maximal anterior-posterior dimension of the shell parallel to the hinge) were determined using Vernier calipers. As an indicator for shell morphology related to growth, the oyster shell height to length ratio was determined by dividing oyster shell height by shell length. Oyster mortality was determined as a percentage of the number of dead articulated oysters versus live oysters.

St. Catherines Sound is a high salinity sound since it receives no major freshwater inflow from rivers. Salinity and water temperature were collected at this site monthly using a refractometer and hand held thermometer, respectively.

One-way Analysis of Variance (ANOVA) and Tukey's Studentized Range Test (α =0.05) using SAS for PC (SAS Institute Inc., 1989) were carried out. All proportional data were arcsine transformed prior to statistical analysis (Sokal and Rohlf 1981).

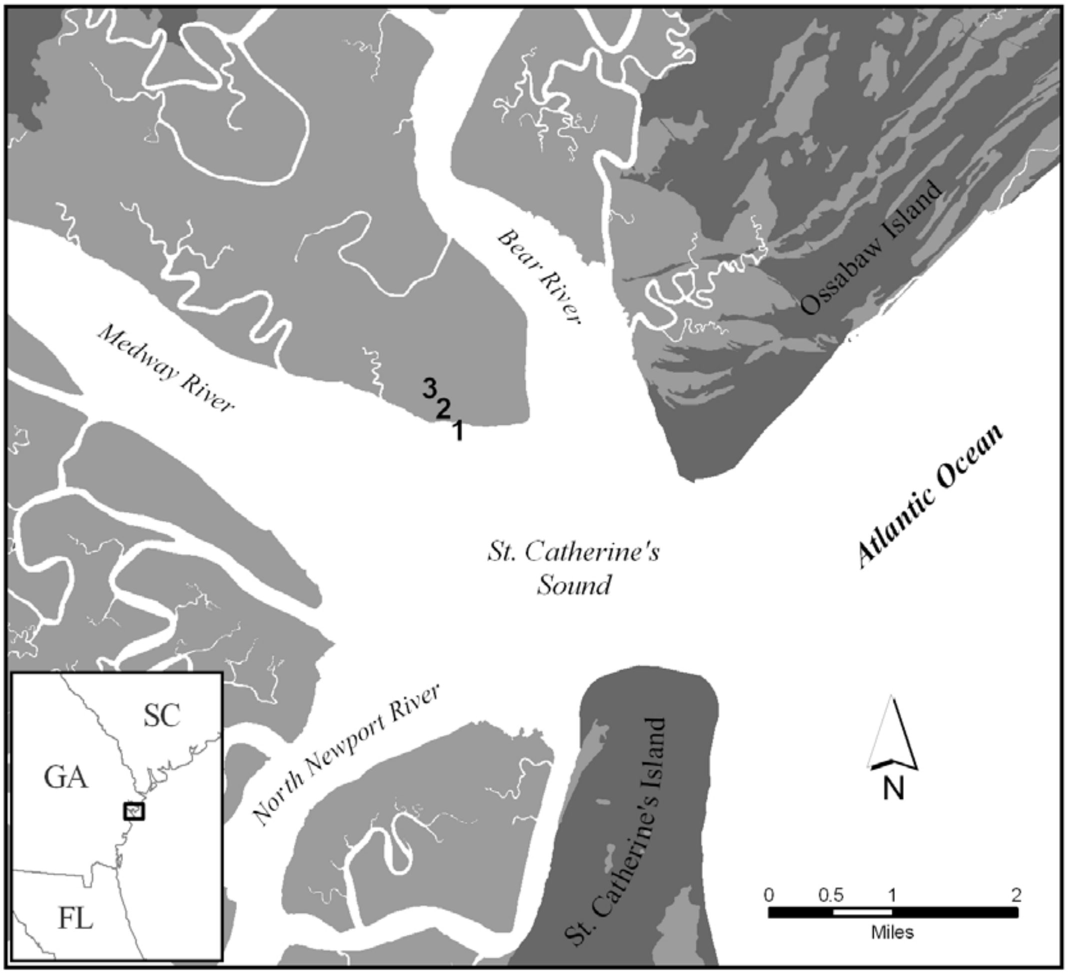

Figure 1. The study site for oyster recruitment and growth in a salt marsh area at the junction of the Medway and Bear Rivers, St. Catherine's Sound, GA.

Results

Water temperature (Figure 2) and salinity ranges (Figure 3) for the St. Catherine Sound area followed normal patterns for coastal Georgia. Temperatures ranged from summer highs of 30ºC in July to lows of 11ºC in February 2007. Temperature between sites varied only 1 degree between site

1 and sites 2 and 3 in June and September. Salinity ranged from 25.2 PSU in May to 36 PSU in October 2006. Little difference in salinities occurred between sites, with the exception of 5 PSU difference between site 1 (28 PSU) and sites 2 and 3 (23 PSU each) in June 2006.

Oyster recruitment occurred at each site each month from May to October, with two peak events in June and August 2006 (Figure 4). Overall for the season, no significant differences ($p=0.1243$) in recruitment occurred between sites (Figure 5). Highest mean seasonal value occurred at the open sound site with 165.57 ± 32.73 (S.E.) spat per 0.01 cm^2 settling per month. Mean seasonal spat recruitment was 106.14 ± 26.65 per 0.01 cm^2 and 92.69 ± 19.84 per 0.01 cm^2 in the partially and sheltered sites, respectively (Figure 5). On a monthly basis, significant differences in recruitment occurred in July ($p<0.0001$) between each site and in August ($p=0.001$). In July recruitment was low with mean spat attachment of 18.33 ± 2.43 spat per 0.01 cm^2 at the sound site which was significantly greater than the 9.0 ± 2.27 at the sheltered creek site which was different than the 1.67 ± 0.47 at the partially sheltered site. In August, the non-sheltered site in the sound (525.4 ± 31.2 spat per 0.01 cm^2) was significantly higher than the sheltered creek site (255.3 ± 59.0 spat per 0.01 cm^2). The partially sheltered site (359.8 ± 40.9 spat per 0.01 cm^2) was not statistically different from the other sites.

Differences in shell height occurred each month except for January 2007 (Table 1). By March 2007, oysters obtained shell heights ranging from 60.6 mm from the non-sheltered site in the sound to 72.2 mm in the sheltered creek. Oysters on sticks from the sheltered creek site were consistently greater in shell height than oysters from the partially and unsheltered sites from October 2006 until March 2007. They were significantly larger than all others only in September and December 2006.

No clear pattern in shell height:shell length ratio (Table 2) or shell height:shell width ratio (data not shown) occurred for oysters during this study. Oysters from the sheltered creek site had the highest height:shell length ratio value six out of seven months and the second highest ratio in the other month; however no other trends were observed for either ratio.

Little significant differences in oyster mortality between treatments occurred from September 2006 to March 2007 (Table 3). Mean monthly mortality of oysters on sticks ranged from 2.7% in December at the open sound and sheltered creek sites to 17.3% at the partially sheltered site in January 2007. Significant differences in mortality only occurred in December 2006, when mortality was higher at the partially sheltered site.

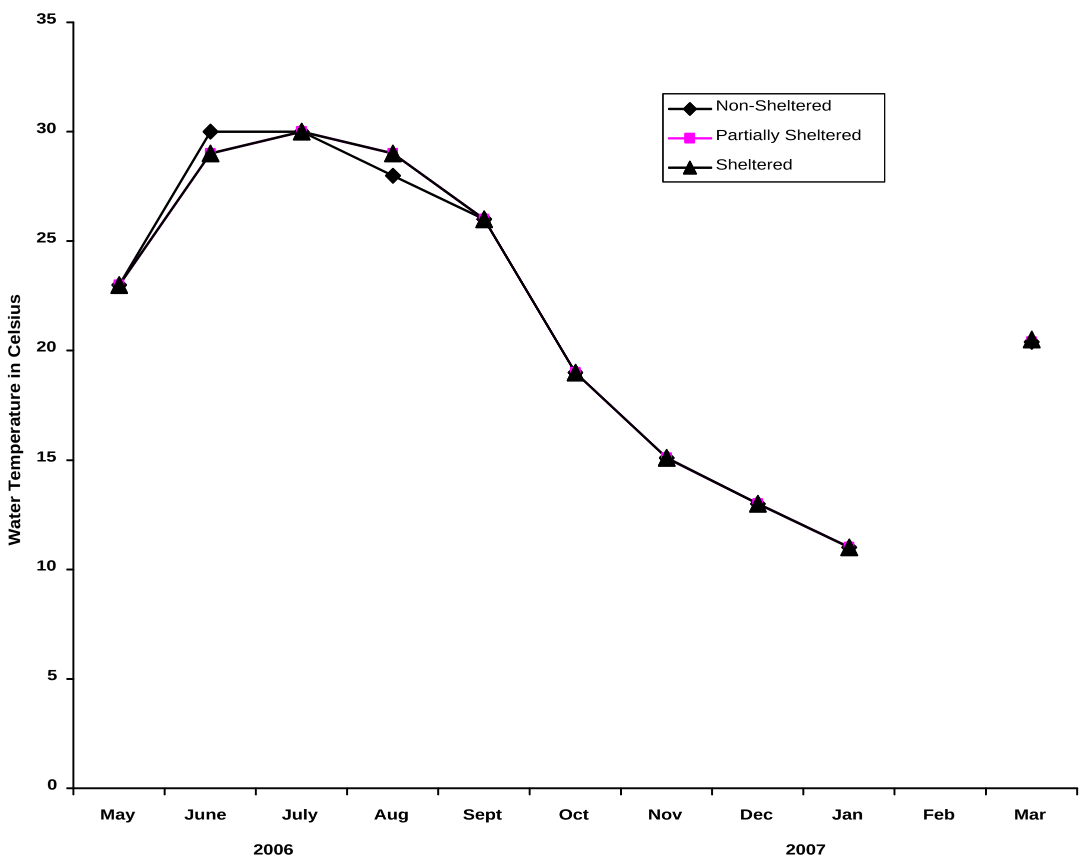

Figure 2. Monthly water temperatures for the three study sites in St. Catherine's Sounds, GA.

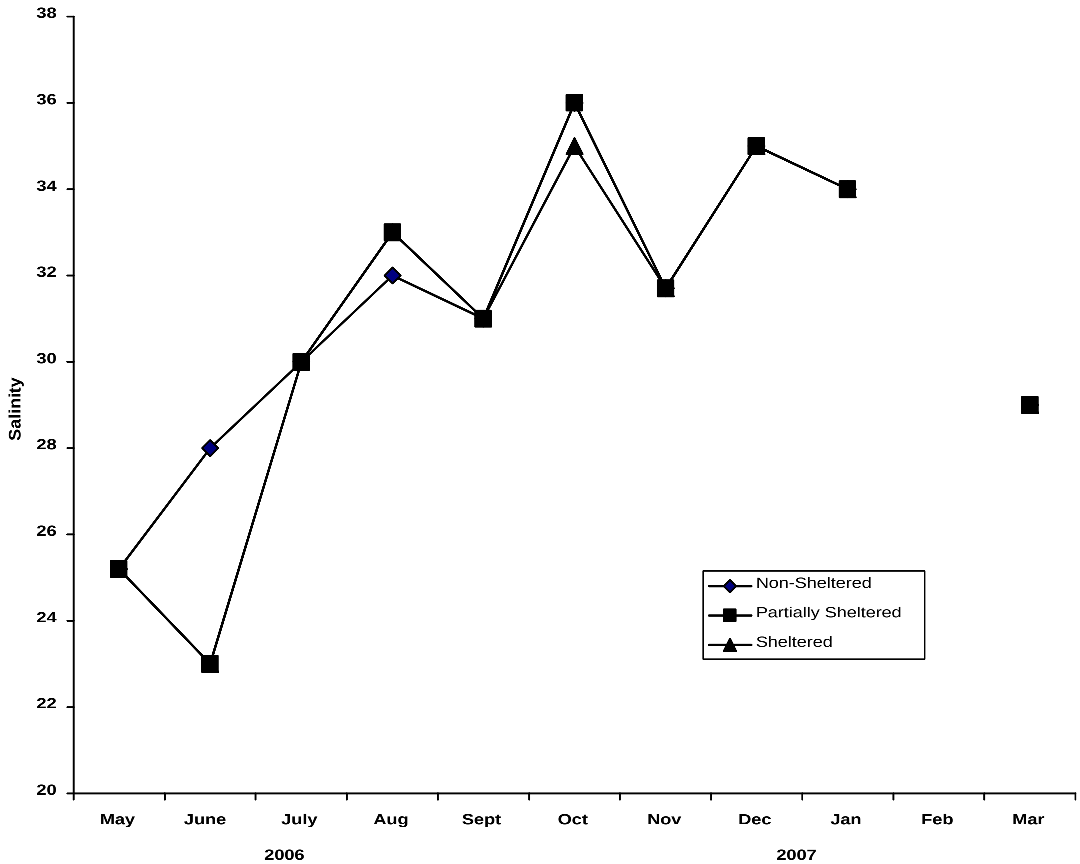

Figure 3. Monthly saline values for the three study sites in St. Catherine's Sounds, GA.

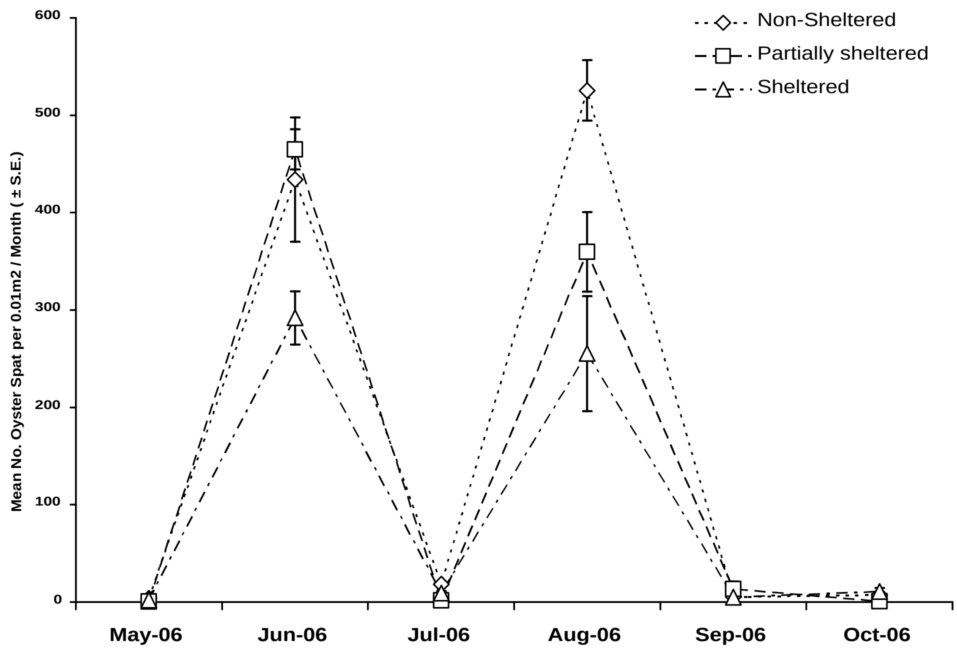

Figure 4. Monthly mean (± S.E.) oyster spat recruitment in three sites in St. Catherine's Sound, GA.

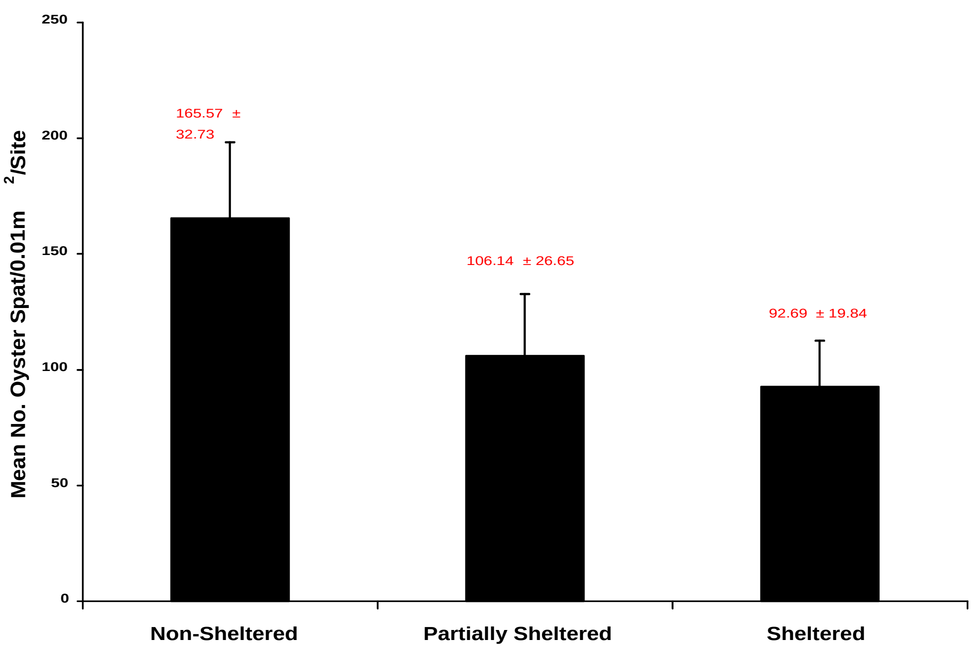

Figure 5. Seasonal mean (± S.E.) oyster spat recruitment in St. Catherine's Sound, GA

Table 1. The mean size (± S.E.) in mm of oysters from sticks at the sheltered, partially sheltered and non-sheltered sites in St. Catherine's Sound, GA. Letters below mean indicates the results of the Tukey's Multiple Range Test. Similar letters indicate no significant differences between means

Sept 2006 (p<0.0001)

	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	36.0	30.1	25.3
SE	1.04	0.77	0.64
MRT	a	b	c

Oct 2006 (p<0.001)

	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	47.2	43.9	31.6
SE	1.75	1.67	1.33
MRT	a	a	b

Nov 2006 (p<0.001)

	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	54.4	47.8	39.2
SE	2.72	2.14	1.86
MRT	a	a	b

Dec 2006 (p<0.001)

	Sheltered Creek	Partially Sheltered	Non-sheltered
Mean	65.6	52.5	51.6
SE	2.40	2.26	2.56
MRT	a	b	b

Jan 2007 (p=0.2917)

	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	69.3	63.8	63.7
SE	3.56	2.47	2.48
MRT	a	a	a

Feb 2007 (p=0.0015)

	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	73.3	69.4	59.7
SE	3.60	2.05	2.18
MRT	a	a	b

Mar 2007 (p=0.0142)

	Sheltered Creek	Partially Sheltered	Non-sheltered
Mean	72.2	68.7	60.6
SE	3.34	2.78	2.35
MRT	a	ab	b

Table 2. The mean shell height:shell length ratio (± S.E.) in mm of oysters from sticks at the sheltered, partially sheltered and non-sheltered sites in St. Catherine's Sound, GA. Letters below mean indicates the results of the Tukey's Multiple Range Test. Similar letters indicate no significant differences between means

Sept 2006 (p=0.0208)			
	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	1.99	1.89	1.80
SE	0.05	0.05	0.05
MRT	a	ab	b
Oct 2006 (p<0.0001)			
	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	2.20	2.08	1.78
SE	0.05	0.05	0.04
MRT	a	ab	b
Nov 2006 (p<0.0001)			
	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	2.28	2.09	1.87
SE	0.06	0.07	0.05
MRT	a	a	b
Dec 2006 (p=0.0316)			
	Sheltered Creek	Partially Sheltered	Non-sheltered
Mean	2.25	2.09	2.05
SE	0.06	0.06	0.06
MRT	a	a	a
Jan 2007 (p=0.0137)			
	Sheltered Creek	Partially Sheltered	Non-sheltered
Mean	2.45	2.23	2.17
SE	0.09	0.06	0.06
MRT	a	ab	b
Feb 2007 (p=0.0044)			
	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	2.37	2.31	2.13
SE	0.06	0.05	0.05
MRT	a	a	b
Mar 2007 (p=0.001)			
	Partially Sheltered	Sheltered Creek	Non-sheltered
Mean	2.52	2.42	2.20
SE	0.06	0.07	0.06
MRT	a	a	b

Table 3. The mean monthly mortality (± S.E.) in mm of oysters from sticks at the sheltered, partially sheltered and non-sheltered sites in St. Catherine's Sound, GA. Letters below mean indicates the results of the Tukey's Multiple Range Test. Similar letters indicate no significant differences between means.

Sept 2006 (p=0.9133)			
	Partially Sheltered	Sheltered Creek	Non-sheltered
Mean	7.3	7.3	4.0
SE	4.37	6.36	3.06
MRT	a	a	a
Oct 2006 (p=0.7821)			
	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	10.0	8.0	8.0
SE	1.15	3.06	4.16
MRT	a	a	a
Nov 2006 (p=0.2407)			
	Sheltered Creek	Partially Sheltered	Non-sheltered
Mean	10.0	9.3	4.67
SE	2.00	1.76	2.40
MRT	a	a	a
Dec 2006 (p=0.0004)			
	Partially Sheltered	Sheltered Creek	Non-sheltered
Mean	11.3	2.7	2.7
SE	0.67	0.67	0.67
MRT	a	b	b
Jan 2007 (p=0.1483)			
	Partially Sheltered	Sheltered Creek	Non-sheltered
Mean	17.3	10.0	5.3
SE	2.91	4.16	2.91
MRT	a	a	a
Feb 2007 (p=0.6881)			
	Non-sheltered	Sheltered Creek	Partially Sheltered
Mean	8.67	7.33	6.67
SE	0.67	1.76	2.40
MRT	a	a	a
Mar 2007 (p=0.3545)			
	Sheltered Creek	Non-sheltered	Partially Sheltered
Mean	13.3	6.0	6.0
SE	4.06	2.31	4.16
MRT	a	a	a

Discussion

Several factors are involved in developing methodology for large-scale oyster cultivation in any given location. For instance, defining site characteristics such as seasonal water quality patterns, sediment type, and exposure to wind and waves are necessary to assess potential impacts on oyster survival and growth. If hatchery produced oyster spat is unavailable or not cost effective, as is the case in Georgia, larval availability for wild oyster spat collection is of great importance. Therefore monitoring local oyster recruitment patterns is paramount to determine wild spat collection sites and site selection for the reduction of spat fouling of market size oysters (Adams *et al.* 1989; Moroney and Walker 1998, 1999). It is also important to note that oyster recruitment rates in a given location could directly impact oyster growth characteristics in terms of shell morphology. This in turn may affect product quality or the shellfish market in which the oyster shell stock is sold. The intertidal oysters harvested in Georgia usually are sold as clusters to supply local oyster roasts. Intertidal oysters that generally exhibit clustered growth are a distinctly different product than the singule ovate oyster intended for consumption in the raw market as a half shell oyster. Therefore it is necessary to determine which type of product you intend to cultivate. Although a half-shell grade oyster is usually sold at a much higher price, oysters intended for the roast market may potentially be produced in greater volumes and at lower operating costs.

As indicated by oyster recruitment rates, the coastal estuary systems of Georgia are relativity pristine and highly productive and are capable of supplying oyster spat for large-scale oyster culture. The recruitment pattern of oysters during this study is consistent with previous research in Georgia. In general two patterns of recruitment occur in Georgia: one major peak recruitment period in May/June with gradually lower rates throughout the summer into fall; or two peaks, one in May/June followed by a second peak in August/September (O'Beirn *et al.* 1995, 1996a,b, 1997, Moroney and Walker 1998; Thoresen *et al.* 2005; Walker 2002-2009 Sapelo Island National Estuarine Research Reserve oyster recruitment data unpublished). An early major peak followed by a smaller peak in late summer have also been observed in a four-year study on South Carolina oysters (Kenny *et al.* 1990). During this research, there was continuous oyster recruitment from April to October with peak recruitment occurring in June and August. Similar oyster recruitment patterns were observed in Sapelo Sound during 2006 (Manley *et al.* 2009). St. Catherines Sound is close in geographical proximity to Sapelo Sound and has a similar salinity regime (Manley *et al.* 2009).

Therefore it is not unlikely that similar oyster recruitment patterns would be observed in both sound systems. Recruitment in Sapelo Sound occurred May to September with a major peak in June followed by a second peak in August. Farther south in Doboy Sound, another high salinity sound, recruitment peaked at Marsh Landings at the mouth of the Duplin River in September 2006 – an unusual recruitment event, i.e. no early peak (Walker 2002-2009 Sapelo Island National Estuarine Research Reserve oyster recruitment data unpublished).

Highlighting recent oyster recruitment research in Georgia, geographically, oyster recruitment rates are generally higher in areas located in close proximity to open sound sites versus the headwater areas of many tidal creeks (Moroney and Walker 1998; Manley *et al.* 2009). Highest recruitment rates occurred at the open sound sites in all studies. Highest recruitment in St Catherines Sound in this study was 52,540 spat/m^2 in August, while it was 98,132 spat/m^2 in June 2006 in Sapelo Sound and 48,562 spat/m^2 in September 2006 at Marsh Landing in the Dublin River at the junction of Doboy Sound (Manley *et al.* 2009; Walker 2002-2008 Sapelo Island National Estuarine Research Reserve oyster recruitment data unpublished). Generally speaking, oyster recruitment was consistently, although not statistically, lower during this research even just slightly up the creek from the unsheltered open sound site. Oyster settlement rates were consistently lower in the sheltered creek site during each peak event (Figure 4). In the Dulpin River, Sapelo Island, there is a clear pattern of little-to-no recruitment occurring in the headwaters of the river as compared to high recruitment at the mouth (Marsh Landings) and at the mid-river site, Jack Hammock. Little-to-no recruitment at the headwaters of the Duplin River was observed in two years (1992-3) of monitoring by O'Beirn *et al.* (1996a), three years (1999-2001) by Thoresen *et al.* (2005), and in eight years (2002-2009) by Walker (Sapelo Island National Estuarine Research Reserve oyster recruitment data unpublished). Moroney and Walker (1998) found that in general oyster spat recruitment was lower in the upper reaches of tidal creeks in Georgia and increased as sites occurred closer to the mouth of the creek. Likewise Manley *et al.* (2008) observed lower recruitment rates as sites moved from the open sound to rivers to small creeks.

Wave action is known to limit bivalve recruitment (Harger 1970, Ortega 1981). The effects of increased exposure to wave action within St. Catherine's Sound did not however, have any significant effect on oyster recruitment, and in fact the greatest recruitment occurred at the open sound site. Higher recruitment rates at the mouth of creeks are believed due to removal of oyster larvae from headwater areas by tidal flushing (O'Beirn *et al.* 1994; 1997; Manley *et al.* 2008). While this is a valid assumption, research by Seim *et al.* (2006) indicated that the upper reaches of some smaller tidal creeks have diminished water velocities and net movement of water over a tidal cycle. Thus, it is likely that patterns of oyster recruitment in headwater areas of well mixed estuaries may be directly related to the density of sexually mature oysters, which in most cases is low compared to densities at the mouth of creeks and areas of river confluence (Bahr and Lanier 1981). The sheltered site in this study was at the mouth of a small tidal creek where a sizeable oyster bed exists. Kenny *et al.* (1990) occasionally observed higher settlement at a site in the outer bend of a tidal creek in an area in which Bahr and Lanier (1981) believed was conducive to oyster reef formation.

Growth potential in the local oyster industry is currently restricted due to the limited production capabilities associated with the conventional method of wild oyster harvest. A shift to a cultivation based industry would provide an avenue for industry expansion as shellfish lease areas could be utilized with greater efficiency and environmental sustainability. Developing a consistent, cost effective method of producing large volumes of quality live shell stock is the first step. During this research oyster settlement, growth, shell morphology, and survival on alternate cultch material (commercial spat sticks) were compared among areas to physical energy (wind and wave). The primary purpose was to determine if high densities of commercial spat sticks could produce large volumes of live oysters for the oyster roast market or sack trade. Another aim was to establish a better cultivation-based harvest technique that was capable of substantially out producing the current method of harvest (culling of wild oysters with hand held implements). This research demonstrates that oysters on stick treatments grew to market size in a year and exhibited greater survival rates than that expected for wild oysters on the bottom.

The larger size of oysters on sticks versus those in natural beds is also consistent with earlier research. Moroney and Walker (1998) showed that oysters cultured off-bottom in the intertidal zone grew larger and had higher survival rates than oysters placed directly on the intertidal bottom. Off-bottom oysters are not affected by shifting sediments as much as those on the bottom. In an oyster restoration project, Manley (2007) showed that oysters settling on sticks projecting above the bottom grew larger than oysters that settled off oyster shell held in crab traps and mesh bags near or on the bottom. Oysters that settled on shells held in mesh bags lying on the surface grew the least. Shifting sediments filled the spaces between shells held in traps while shells in mesh bags were almost completely buried. Lenihan (1999) observed that 81% of variability in oyster growth and mortality was explained by physical conditions and the flow environment alone. Greater water movement over stick structures likely resulted in higher exposure to nutrient-rich water and improved oyster feeding associated with feces removal and nutrient re-suspension. The localized carrying capacity of live oysters within each 3-dimensional stick treatment was likely increased in direct relation to increased settlement area and greater volumes of phytoplankton rich water moving through the aggregated mass of oysters. This should have provided a much greater feeding advantage to oysters on stick treatments versus natural reef since oysters on natural reef usually exist a distance much closer to the sediments in areas of reduced water flow. Therefore a reduction of feeding area on natural reef versus stick treatments could likely explain the substantial differences in oyster sizes and potential biomass within the same occupied area. This was observed by Manley (2007) when comparing live oyster biomass on sticks deployed in 81 stick/m^2 density arrangements to live oyster biomass on fresh oyster shell in mesh bags. Manley (2007) recorded that stick treatments had approximately 90% (119 kg) greater live oyster biomass than mesh bag treatments (13.5 kg). Results would have likely been comparable during this research had we compared biomass per meter square between natural oyster reef and live oysters on stick treatments. It is important to note that stick treatments not only improved local oyster brood stock but also serves essential habitat for invertebrate and vertebrate species.

Greater oyster mortalities from the natural bottom versus those on the sticks at all sites are not surprising. A host of benthic predators prey on oysters: oyster drills, *Urosalpinx cinerea* (Say, 1822); knobbed whelks, *Busycon carica* (Gmelin, 1791); lightning whelks, *Busycon sinistrum* Hollister, 1958; channeled whelk, *Busycotypus canaliculatus* (Linné, 1758); blue crabs, *Callinectes sapidus* Rathbun, 1896; mud crabs *Panopeaus herbstii* H. Milne-Edwards, 1834; and stone crabs *Menippe mercenaria* (Say, 1818). Predators would have easier access to oysters on bottom than those suspended above bottom on sticks. Oyster drills occur low in the intertidal zone in Georgia feeding on oysters at the base of reefs (Walker 1981). Whelks also prey on oysters at the base of reefs (Walker 1988, Walker *et al.* 2008). Rarely do whelks or oyster drills occur up on the reefs. Thus it is not surprising that they would not attack intertidal oysters grown off bottom on sticks. Lower mortality of oysters within the creek may be attributed to the absence of whelks in small creeks. Sediment accumulation increases mortality on natural and manmade oyster reefs (O'Beirn *et al.* 2000). Oysters also were less likely to be smothered on stick treatments.

In summary, oyster recruitment, growth, and survival were excellent on commercial spat sticks at all sites regardless of exposure to wind and waves. Oysters on sticks at the site with the least exposure and the lowest recruitment rates attained the largest size and maintained a relatively low oyster mortality rate. The net positive contribution to the local ecosystem associated with a shift to cultivation using spat sticks or a similar technique could be quite significant. The cultivation of oysters using spat sticks was observed to substantially enhance oyster brood stock and likewise increase habitat capacity for several migratory invertebrate and vertebrate species. Thus, it is possible that the proper use of this environmentally sustainable oyster cultivation technique could effectively increase commercial oyster productivity in Georgia. However, a cost analysis on alternative materials, as opposed to actual spat sticks, would have to be conducted since the material costs for spat sticks is quite high (Manley *et al.* 2008). A good substitute for commercial spat sticks could be quarter inch rebar coated in cement slurry. This would bring the cost per meter square plot down from approximately 241 to 81 dollars U.S. (Savannah Steel Company 2006). The benefit to switching to rebar is not only reduced cost but reusability. One drawback to the use of rebar would be weight during transport, but this could be mitigated by onsite processing (pulling oysters off sticks and packaging onsite). Sticks could be stockpiled and collected during the following tide. This is just one possibility among many others.

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