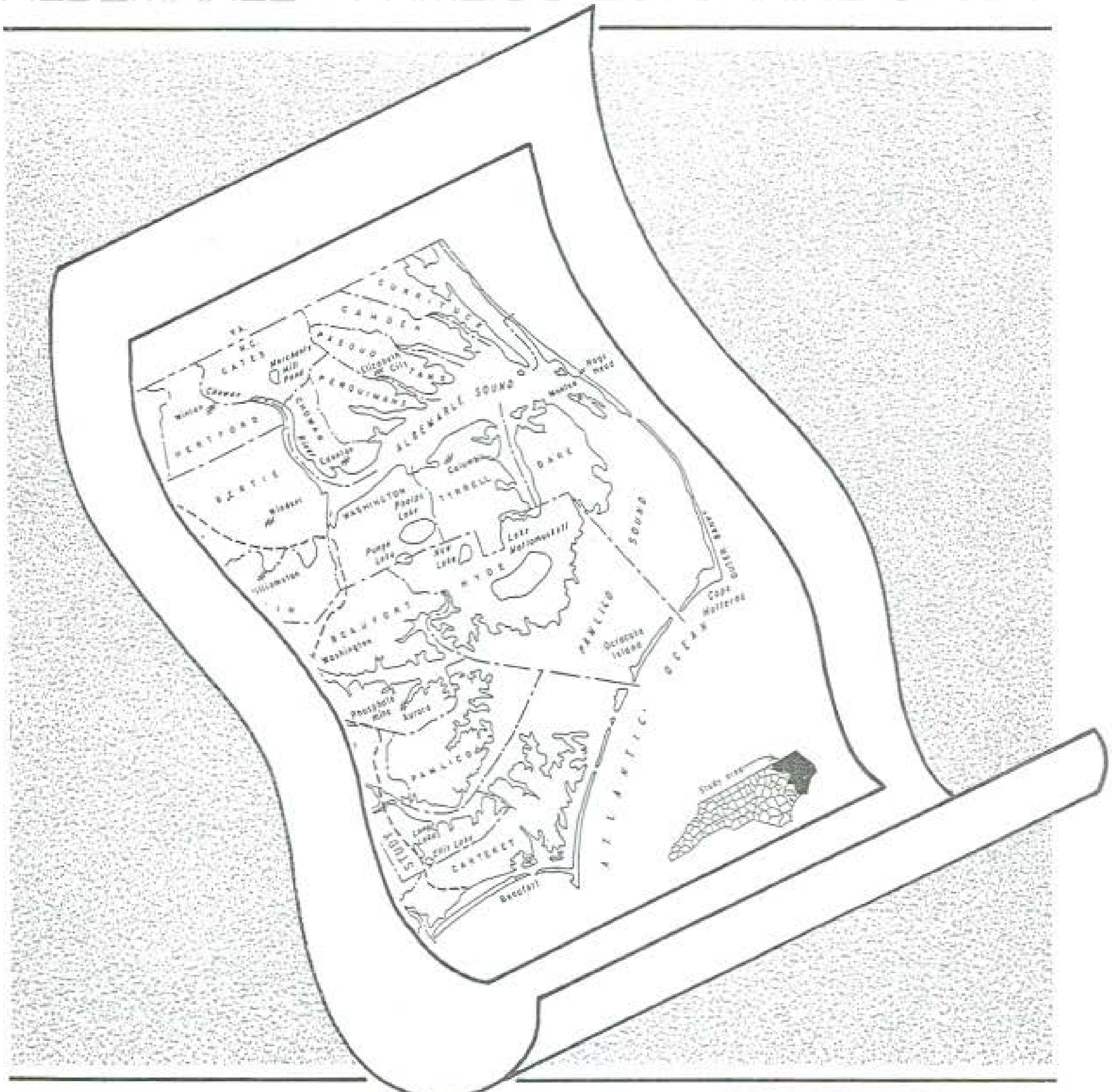
September 1991 Project No. 90-08

RECRUITMENT AND GROWTH OF THE EASTERN OYSTER,

crassostrea virginica, In North Carolina

ALBEMARLE - PAMLICO ESTUARINE STUDY



Funding Provided By
North Carolina Department of Natural Resources and Community Development
Environmental Protection Agency National Estuary Program

ALBEMARLE-PAMLICO ESTUARINE STUDY

EXECUTIVE SUMMARY

RECRUITMENT AND GROWTH OF THE EASTERN OYSTER, *Crassostrea virginica* IN NORTH CAROLINA

by

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PROJECT 90-88

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PURPOSE

The oyster industry in North Carolina is based on the success of populations of the eastern oyster Crassostrea virginica. Wild populations were an important source of high-quality oysters at the turn of the century. However, overharvesting and a lack of an effective management program have lead to a precipitous decline in harvest since that time. Annual landings have decreased from 1.5-1.8 million bushels from 1890-1900, to less than 300 thousand bushels since 1960. This pattern of decline is similar to other oyster producing regions of the eastern United States.

In order to increase the size of North Carolina's oyster populations, the North Carolina Division of Marine Fisheries (NCDMF) initiated a program of shell planting in the late 1940's. Such programs have been shown to be effective means of increasing oyster density when over-harvesting and excess siltation removes the hard substrata necessary for oyster settlement. However, the success of a particular shell planting will vary depending on spatial and temporal patterns in the settlement, growth, and survival of oysters. Although these patterns have been studied intensively along the east coast of the United States, relatively little is known of North Carolina waters.

We undertook the present study to determine how the environment (location, depth, and salinity) affected oyster demography (recruitment and growth) in the coastal waters of North Carolina. Recruitment here is defined as larval settlement and survival of spat for up to three weeks. We were interested in identifying the conditions for the highest production in order to evaluate the efficacy of the State's cultch planting program. Is cultch presently being planted in those areas with the highest potential yields? What is the best time for the planting of cultch? What other steps can be taken to enhance yield? Answers to these questions are necessary if North Carolina's oyster industry is to regain some of its previous strength.

RESULTS/CONCLUSIONS

From 1988 to 1990, we investigated the effects of location, salinity, and depth on recruitment and growth of the eastern oyster Crassostrea virginica in Pamlico and Core Sounds, North Carolina. We measured length and density of spat settling on oyster cultch deployed at deep (~3 m) and shallow (~1 m) depths at 6 sites in areas with low salinity and 6 sites in areas with high salinity. These data were compared with similar data taken at some of these sites by the North Carolina Division of Marine Fisheries since 1981 as part of their cultch planting program.

Recruitment was generally greater in the high salinity sites, compared to the low salinity sites. Recruitment was less at shallow depths compared to deeper depths. In all three years the highest recruitment occurred in August and September, corresponding to the months of maximum water temperature. Recruitment was highly variable in space and time, but appeared to diminish from 1988 to 1990. Recruitment was reduced by sedimentation and a variety of sessile organisms. All sites appeared to have a similar potential for growth.

RECOMMENDATIONS

1. As nearly as possible, cultch planting should be done in the fall (August-September), when oyster recruitment is highest.

2. Except when local conditions produce high quality oysters in very shallow waters, cultch planting should be restricted to deeper depths (>1-2 m) where oyster recruitment is highest.

3. The NCDMF should consider a program of transplanting spat from "seed" areas of high recruitment to "grow-out" areas where present recruitment might be lower. Such a program would require initial studies of cost/benefit ratios, including oyster survival and the possible transfer of oyster diseases.

4. There is a clear need for more detailed information on the recruitment and survival of oysters in North Carolina waters. Such data are necessary in order to make sure cultch is planted at all suitable sites and to implement the transplanting program suggested above.

5. Recruitment must be related to the location and density of existing beds in order to understand the high spatial and temporal variation in recruitment. A survey of the location and extent of adult oyster stocks in North Carolina is a necessary precursor to this effort.

RECRUITMENT AND GROWTH OF THE EASTERN OYSTER, *Crassostrea virginica*, IN NORTH CAROLINA

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ABSTRACT

From 1988 to 1990, we investigated the effects of location, salinity, and depth on recruitment (settlement and survival for 3 weeks) and growth of the eastern oyster Crassostrea virginica in Pamlico and Core Sounds, North Carolina. We measured length and density of spat settling on oyster cultch deployed at deep (~3 m) and shallow (~1 m) depths at 6 sites in areas with low salinity and 6 sites in areas with high salinity. These data were compared with similar data taken at some of these sites by the North Carolina Division of Marine Fisheries since 1981 as part of their cultch planting program.

Recruitment was generally greater in the high salinity sites, compared to the low salinity sites. Recruitment was less at shallow depths compared to deeper depths. In all three years the highest recruitment occurred in August and September, corresponding to the months of maximum water temperature. Recruitment was highly variable in space and time, but appeared to diminish from 1988 to 1990. Recruitment was reduced by sedimentation and a variety of sessile organisms. All sites appeared to have a similar potential for growth.

Management implications of the data are discussed, but decisions must await more detailed information on oyster ecology.

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SUMMARY AND CONCLUSIONS

Oyster recruitment was generally greater along the eastern edge of Pamlico Sound and in Core Sound in the high salinity sites, compared to the low salinity sites along the western side of Pamlico Sound. Recruitment was also less at shallow depths where mats were located immediately adjacent to the shore, compared to deeper depths located some distance from shore. Finally, recruitment was greater to bottom surfaces of shells.

Oyster recruitment undergoes enormous variation in space and time, but seems to have declined in recent years along the western edge of Pamlico Sound.

Spat density in the fall reflected patterns in the intensity of recruitment. Thus, greater numbers of spat were found on the bottom surfaces of shells, deeper locations, and at sites where recruitment was highest. However, in many instances fall spat densities were reduced by the presence of other sessile organisms and the degree of sedimentation.

All sites included here appear to have similar potential for growth.

RECOMMENDATIONS

1. As nearly as possible, cultch planting should be done in the fall (August-September), when oyster recruitment is highest.

2. Except when local conditions produce high quality oysters in very shallow waters, cultch planting should be restricted to deeper depths (>1-2 m) where oyster recruitment is highest.

3. The NCDMF should consider a program of transplanting spat from "seed" areas of high recruitment to "grow-out" areas where present recruitment might be lower. Such a program would require initial studies of cost/benefit ratios, including oyster survival and the possible transfer of oyster diseases.

4. There is a clear need for more detailed information on the recruitment and survival of oysters in North Carolina waters. Such data are necessary in order to make sure cultch is planted at all suitable sites and to implement the transplanting program suggested above.

5. Recruitment must be related to the location and density of existing beds in order to understand the high spatial and temporal variation in recruitment. A survey of the location and extent of adult oyster stocks in North Carolina is a necessary precursor to this effort.

INTRODUCTION

The oyster industry in North Carolina is dependent on the abundance of wild populations of the eastern oyster Crassostrea virginica. At the turn of the century, good quality oysters were harvested from natural populations (Winslow 1889; Grave 1903). However, the lack of an effective management program and overharvesting have lead to a precipitous decline in harvest since that time. Annual landings have decreased from 1.5-1.8 million bushels from 1890-1900, to less than 300 thousand bushels since 1960 (Fig. 1). This pattern of decline is similar to other oyster producing regions of the eastern United States (Krantz and Meritt 1977; MacKenzie 1983; Hargis and Haven 1988; Kennedy 1989).

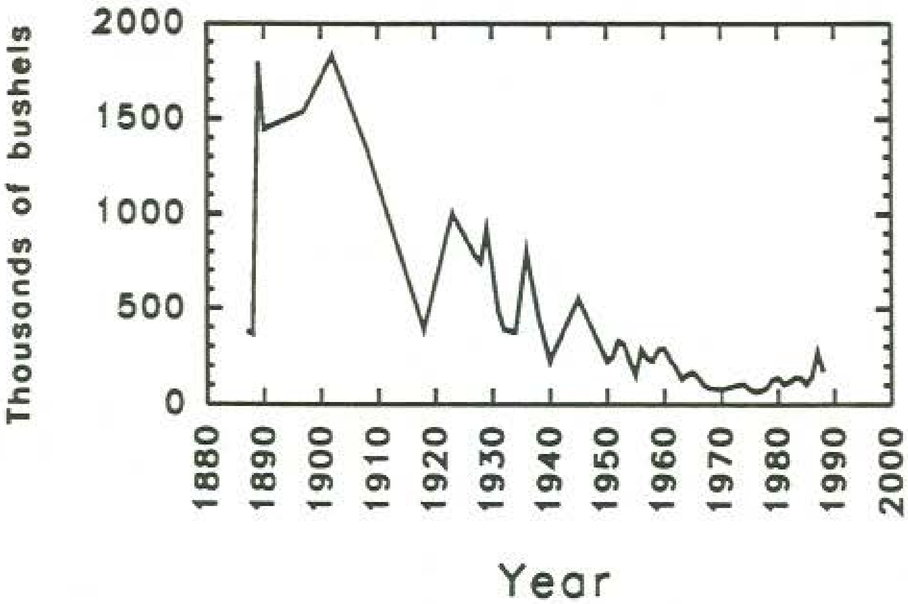

Figure 1. North Carolina oyster landings by year, 1887-1988. Bushels are U.S. standard bushels. Source: Fishery Statistics of the United States and the North Carolina Division of Marine Fisheries.

In order to increase the size of North Carolina's oyster populations, the North Carolina Division of Marine Fisheries (NCDMF) initiated a program of cultch planting in the late 1940s (Munden 1975; 1981). Such programs have been shown to be an effective means of increasing oyster density when over-harvesting removes the hard substrata necessary for oyster settlement (Ulanowicz et al. 1980; MacKenzie 1983; Abbe 1988). However, the success of a particular cultch planting program will vary depending on spatial and temporal patterns in the settlement, growth, and survival of oysters. Although these patterns have been studied intensively along the east coast of the United

States (Loosanoff and Nomejko 1956; MacKenzie 1970; Hidu and Haskin 1971; Hidu 1978; Haven et al. 1981; Kennedy and Breisch 1981; Haven and Fritz 1985; Abbe 1986; Hargis and Haven 1988), relatively little is known of North Carolina waters (Chestnut and Fahy 1953; Munden 1975; 1981; Ortega 1981).

We undertook the present study to determine how the environment (location, depth, and salinity) affected oyster demography (recruitment and growth) in the coastal waters of North Carolina. Recruitment here is defined as larval settlement and survival of spat for up to three weeks. We were interested in identifying the conditions for highest production yield in order to evaluate the efficacy of the State's cultch planting program. Is cultch presently being planted in those areas with the highest potential yields? What is the best time for the planting of cultch? What other steps can be taken to enhance yield? Answers to these questions are necessary if North Carolina's oyster industry is to regain some of its previous strength.

MATERIALS AND METHODS

The study was carried out in Pamlico and Core Sounds, between Cape Hatteras and Cape Lookout, North Carolina (Fig. 2). Pamlico Sound is shallow, with a mean depth of 5 m, dominated by lunar tides in the east, and wind-generated flow in the west (Epperly and Ross 1986). Core Sound is similarly shallow and dominated by lunar tidal flow. The Neuse and Pamlico rivers discharge into western Pamlico Sound, creating a salinity gradient from west to east (Epperly and Ross 1986). In western Pamlico Sound annual variation in salinity is from 10-30 $^{o}/_{oo}$, whereas salinity in eastern Pamlico Sound and in Core Sound remains higher, especially near oceanic inlets. These waters are shallow enough so that wind mixing generally precludes vertical stratification (Giese et al. 1979).

During March and April, 1988, we established 12 study sites in Pamlico and Core Sounds to determine the effects of location, salinity, and depth on oyster recruitment and growth. Most of these sites have been included in the NCDMF's cultch planting program since 1981 (M. Marshall, NCDMF personal communication). Indeed, we used the NCDMF marker buoys whenever possible to mark our study sites. Our sample unit consisted of 2.5cm mesh vexar (plastic) mesh cut into 40 X 40 cm square mats. Sixteen oyster shells (~9 cm in length) were drilled at each end and tied to each mat with plastic ties. Mats were deployed at a site in a horizontal orientation approximately 10 cm off the bottom; the corners were tied to steel concrete reinforcing bars (rebar) driven into the bottom.

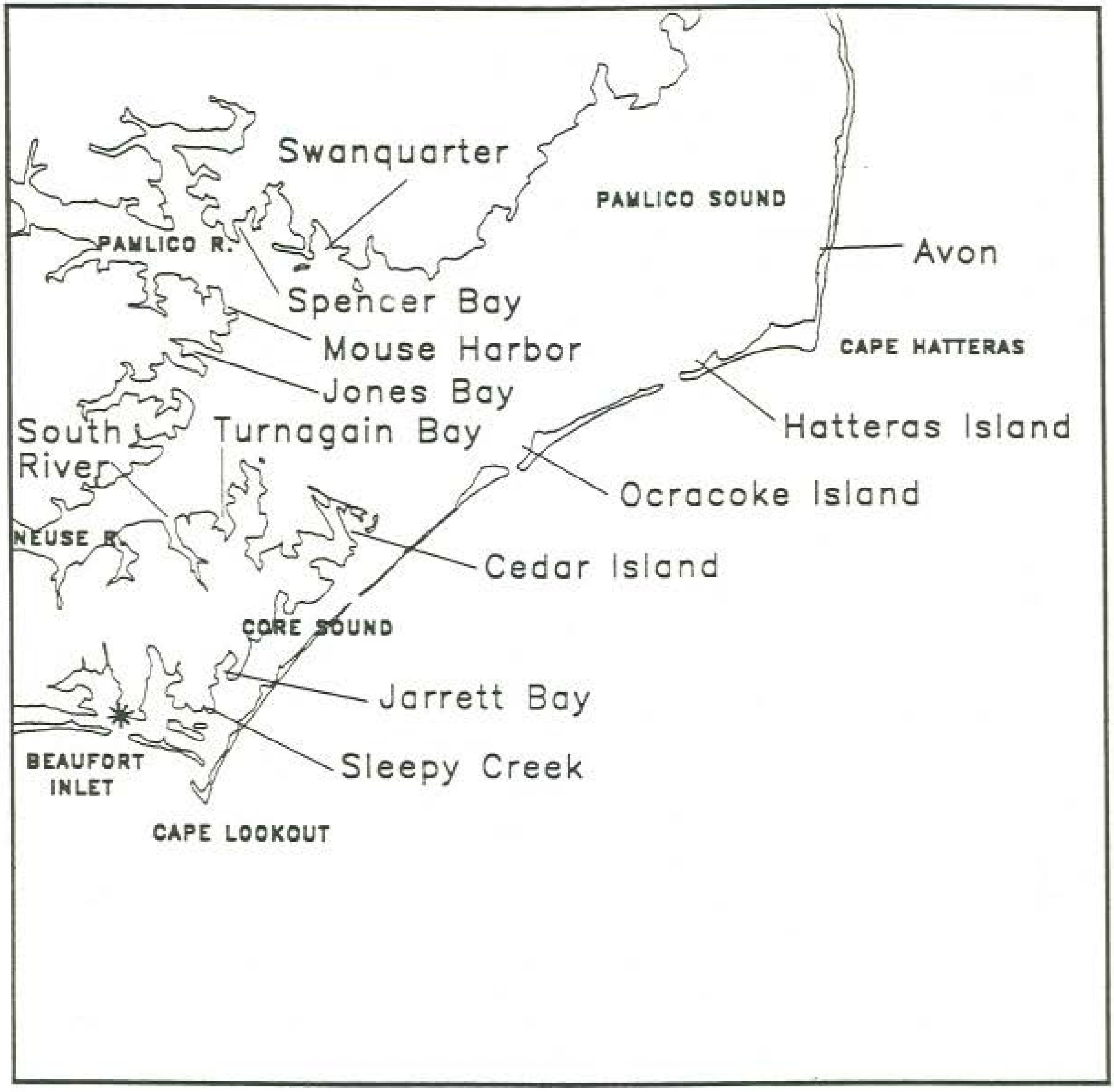

Figure 2. Map of coastal North Carolina showing locations of study sites. High salinity sites include Avon, Hatteras Island, Ocracoke Island, Cedar Island, Jarrett Bay, and Sleepy Creek. Low salinity sites include Swanquarter, Spencer Bay, Mouse Harbor, Jones Bay, Turnagain Bay, and South River. The location of the Duke University Marine Laboratory near Beaufort Inlet is indicated by an "*".

In 1988 six study sites were selected in areas with low salinity along the western edge of Pamlico Sound, and 6 in areas with high salinity along the eastern edge of Pamlico Sound and in Core Sound (Fig. 2). At each site we placed 12 mats at deep (~3 m) and 12 mats at shallow (~1 m) depths. At each depth 6 mats were designated "recruitment mats" and 6 were designated "permanent mats". At each census the recruitment mats were retrieved, all spat were counted, and retrieved mats were replaced with new mats. The permanent mats were retrieved, all spat were counted and measured, and the mats re-deployed. During 1988 only, we noted whether spat were located on the top or bottom surfaces of the shells. We censused each site at approximately 3 week intervals from May through October 1988. Thus "recruitment" in this paper refers to the settlement of oyster larvae and their subsequent survival for a period of up to 3 weeks.

In 1989, 6 recruitment mats were censused at each site on a similar schedule as in 1988. However, in 1988 it was evident that oyster recruitment and/or subsequent survival might have been inhibited by the presence of algae or other sessile invertebrates (e.g., tube worms, encrusting bryozoans, and tunicates). We reasoned that fouling of cultch might increase with time and that different fouling communities might develop on cultch deployed at different times (Sutherland and Karlson 1977). Therefore, in 1989 we altered our design for the permanent mats in order to determine the effect of submergence time on the accumulation of oyster spat on permanent mats. An initial set of 3 permanent mats was deployed in May. A new set of 3 permanent mats was added in July and again in August, for a total of 9 permanent mats at each of the two depths at each site. Permanent mats were sampled for numbers of spat per shell and sizes of spat at 6 weeks after deployment and when observations ended in October. In addition, shells on the permanent mats were censused for the presence of other sessile organisms 6 weeks after deployment and at the end of October. This was accomplished by noting the species present under 10 randomly spaced points distributed over an area the size of the oyster shell (e.g., Sutherland 1981). Only the lower shell surface was sampled because most settlement occurred here and sedimentation was reduced.

In 1990, 6 recruitment mats were censused at each site at 3 week intervals, as in 1988 and 1989. However, permanent mats were deployed only once in May and the number of mats at each depth and site was reduced to 3. Sampling of spat size and density on permanent mats was conducted at 3 week intervals from May to November 1990.

In all three years we also measured surface water temperature and salinity while censusing each site. These measurements are taken to represent the entire water column in the general absence of vertical stratification (Giese et al. 1979).

In order to place our data in historical perspective, we compared them with data taken by the North Carolina Division of Marine Fisheries (NCDMF) since 1981 as part of their cultch planting program. The NCDMF returned to each planting site at 3-6 month intervals for up to three years, collecting random samples of 30 shells (cultch) from planted beds and determining the number and size of spat on each shell. These data provide information on oyster density and an estimate of growth, because cultch is known to be free of oysters when planted. We report here on the interval between 1981 and 1987.

RESULTS

During our sampling intervals, water temperature in Pamlico and Core Sound fluctuated between 16°C and 30°C. Temperatures from May-November were similar at all sites and correlated well with continuous readings (Fig. 3) taken at the Duke University Marine Laboratory (DUML) dock near Beaufort Inlet (Fig. 2) ($r=0.87$, $n=239$, $P < 0.001$). However, summer temperatures at the low salinity sites tended to be somewhat higher than at the DUML dock. These sites are removed from the influence of oceanic inlets.

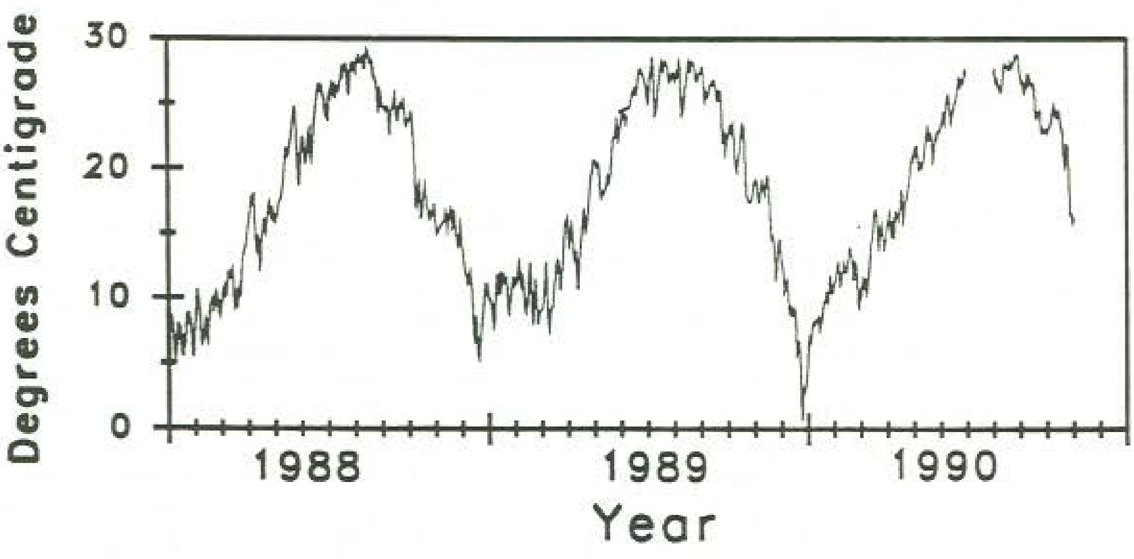

Figure 3. Daily average surface temperatures taken at the Duke University Marine Laboratory dock near Beaufort Inlet during 1988-1990.

Surface salinities were generally lower at the sites along western Pamlico Sound, compared to sites along eastern Pamlico Sound and Core Sound (Figs. 2, 4); we were successful in establishing sites in low and high salinities, respectively. During 1988, salinity at the low salinity sites increased from approximately 10 $^{o}/_{oo}$ to 25 $^{o}/_{oo}$, reflecting a summer of low rainfall and reduced fresh water input from the Pamlico and Neuse Rivers (W. Kirby-Smith, Duke Marine Laboratory, personal communication). Thus, salinity differences between the two groups of sites were less in 1988 than in 1989 and 1990 (Fig. 4). During 1989 and 1990, salinity remained low throughout the summer at the low salinity sites (Fig. 4), reflecting summers of high rainfall (W. Kirby-Smith, Duke Marine Laboratory, personal communication). Indeed, rainfall was so heavy in 1989 that salinity was reduced at the high salinity sites during September and October 1989 (note the greater variation in salinity at the high salinity sites in 1989 compared to 1988 and 1990, Fig. 4).

Although recruitment was extremely variable among sites and years (Fig. 5), some patterns are apparent. Recruitment was generally greater in the high salinity sites along eastern Pamlico Sound and Core Sound, compared to the low salinity sites along the western side of Pamlico Sound. Although recruitment peaks were observed at Swanquarter and Mouse Harbor during 1988 and 1989, most low salinity sites experienced limited or no recruitment (Fig. 5). Recruitment was generally less at shallow depths (Fig. 5) and generally greater (> 50% of the total) on the bottom surfaces of shells (Fig. 6). At the high salinity sites there was an occasional recruitment peak in June. However, recruitment at all sites tended to be concentrated in September-October (Fig. 5) when water temperatures were highest (Fig. 3). Finally, the intensity of recruitment diminished from 1988 to 1990; during 1990 recruitment was sparser or absent from many sites with substantial recruitment in previous years (Fig. 5).

Accumulation of oyster spat on the permanent mats reflected the recruitment patterns observed on recruitment mats. Thus greater numbers (> 50% of the total) accumulated on the lower surfaces of shells during 1988 (Fig. 6) and other years (S. Ortega, personal observation). Similarly, in October of each year greater numbers of spat were found at the deep sites and the highest accumulations were observed at Swanquarter (1988), Avon (1989), Hatteras Island and Sleepy Creek (Figs. 5, 7). However, there is considerable evidence that shells on permanent mats were not as attractive to oyster larvae as the newly submerged shells on recruitment mats. Maximum densities on permanent mats were much lower than those observed on recruitment mats (note the different ordinate scales in Figs. 5 and 7). There was little accumulation of spat on permanent mats in Swanquarter and Mouse Harbor during 1989 (Fig. 7), even though larvae were abundant at these sites in September 1989 (Fig. 5). Fewer spat accumulated

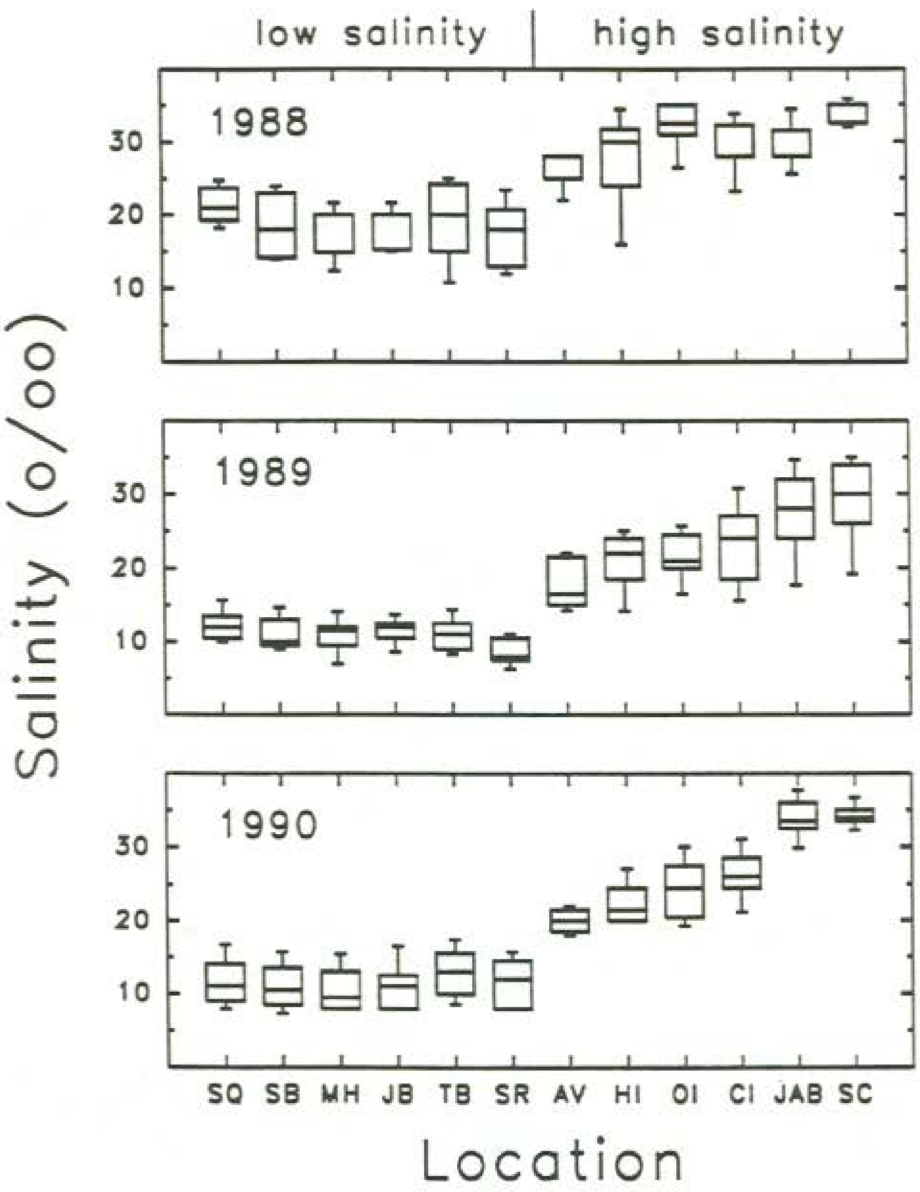

Figure 4. Box plots (Tukey 1977) of surface salinities taken at each census of the study sites during 1988-1990. SQ - Swanquarter, SB - Spencer Bay, MH - Mouse Harbor, JB - Jones Bay, TB - Turnagain Bay, SR - South River, AV - Avon, HI - Hattaras Island, OI - Ocracoke Island, CI - Cedar Island, JAB - Jarrett Bay, SC - Sleepy Creek.

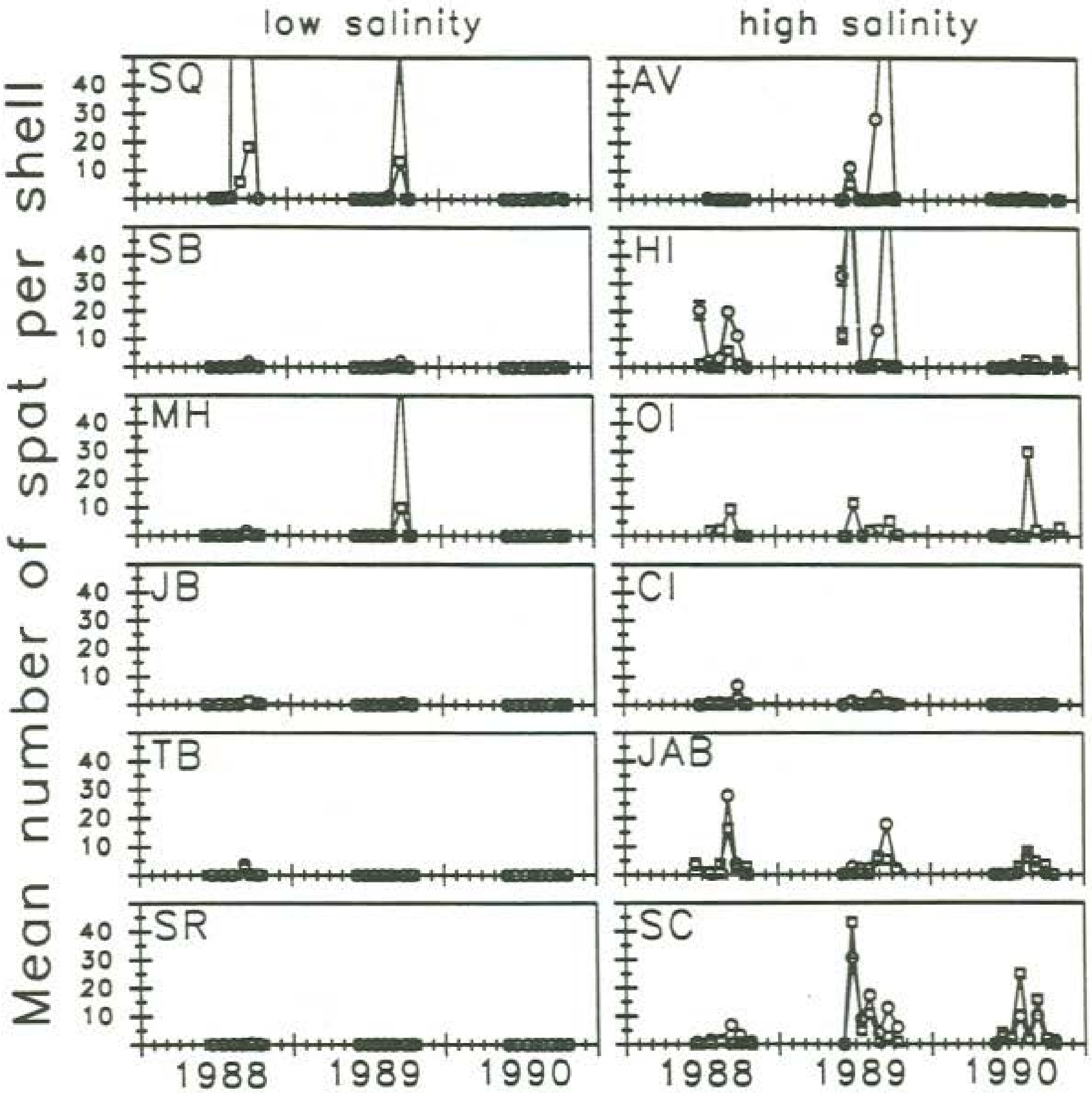

Figure 5. Mean density (± SE) of spat on the recruitment mats measured during the census of each site. Circles = deep depths, squares = shallow depths. A symbol is present for each sample date even if no spat settled. Site designations as in Fig. 4.

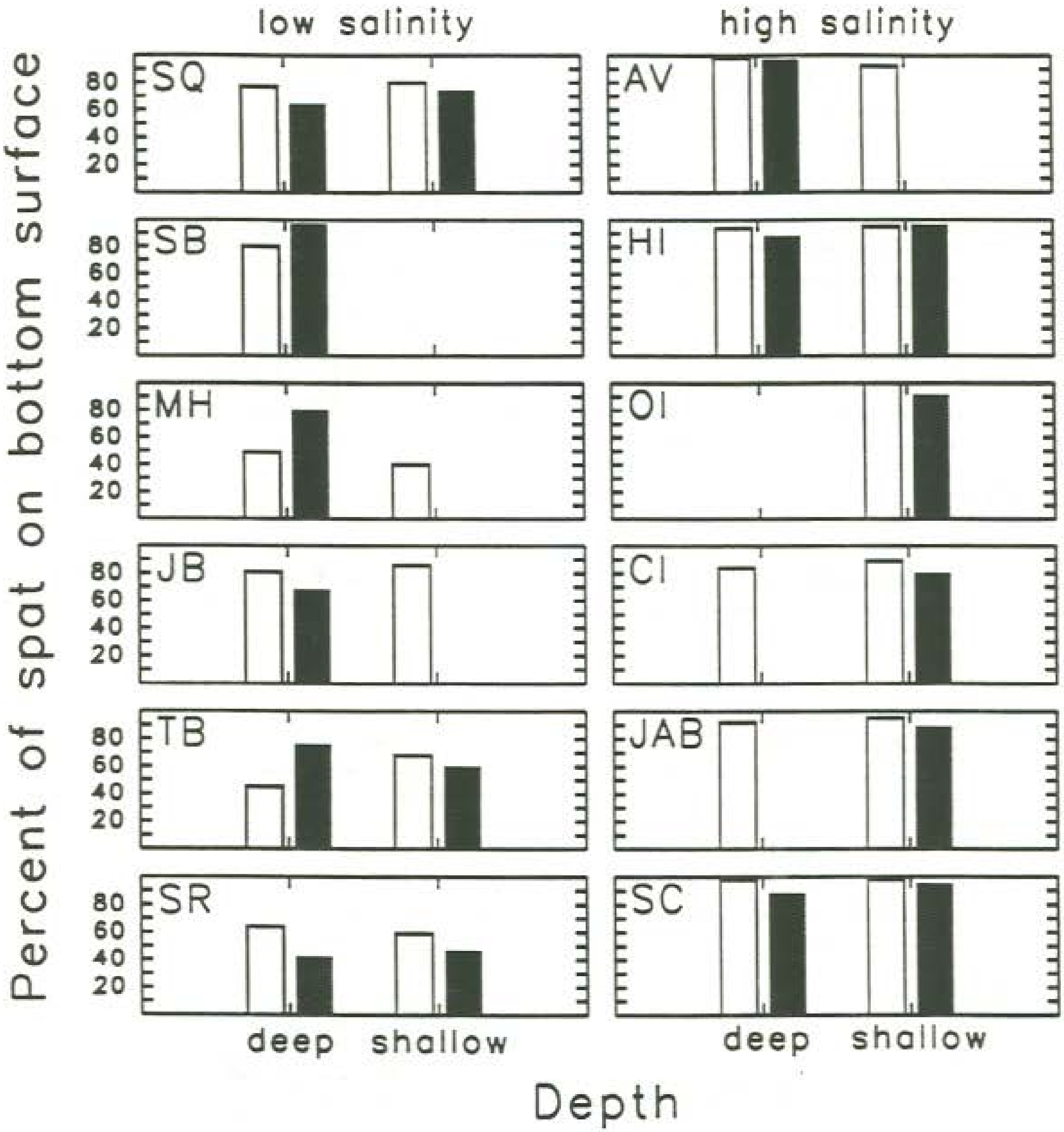

Figure 6. Percent of spat recruiting to the bottom of shells tied to recruitment mats (clear bar) and accumulating on the bottom of shells tied to permanent mats (filled bar) at each site during 1988. Recruitment data are pooled over the entire recruitment season, from May to October, data from permanent mats were taken at the end of the recruitment season in October. The absence of a bar indicates no recruitment or accumulation of spat. Site designations as in Fig. 4.

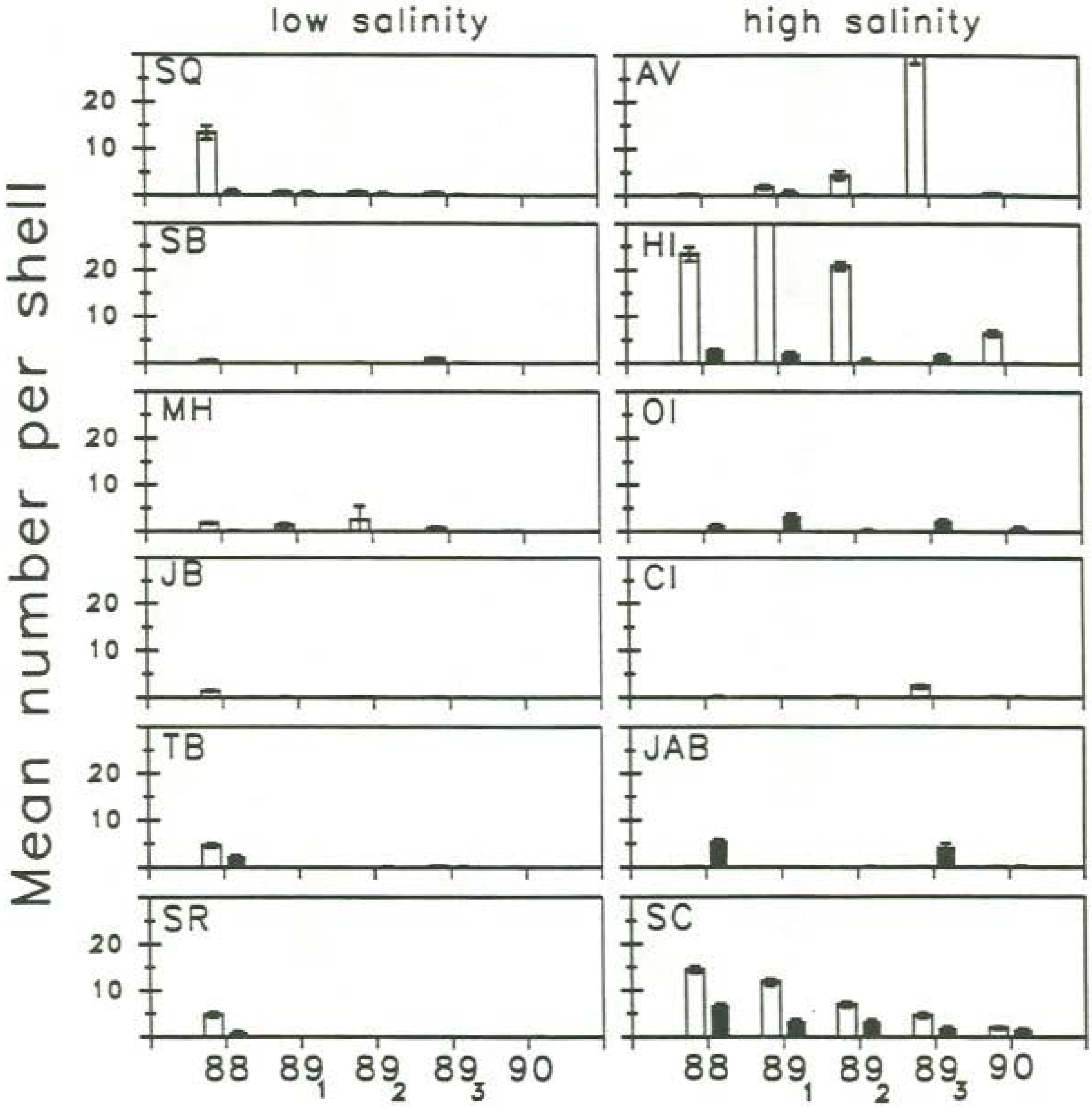

Figure 7. Mean density (± SE) of spat accumulated onto permanent mats at each study site. Data were taken at the end of the recruitment season in October 1988, 1989, and 1990. 89_1 = deployed in May, 89_2 = deployed in July, 89_3 = deployed in August.

on permanent mats in Sleepy Creek in 1989 compared to 1988 (Fig. 7), even though recruitment was higher during 1989 (Fig. 5). Apparently, these reduced densities were not due to intra-specific competition or predation occurring after settlement; data from 1988 indicate that densities on permanent mats increased monotonically to the October levels reported in Fig. 7.

Figure 8 more clearly illustrates the enhanced attractiveness to oyster larvae of newly submerged, clean shells compared to "old" shells which have become fouled with sediment and sessile organisms. If spat had accumulated on permanent mats at the same rate as they recruited to recruitment mats, spat density in October on the permanent mats would have been equal to the cumulative recruitment on recruitment mats; the values in Figure 8 would lie along the dotted line. Instead, most values fall below the dotted line, indicating much lower than expected accumulation of spat on permanent mats (Fig. 8).

The fouling community that interfered with oyster recruitment was less diverse at the low salinity sites than at the high salinity sites (Figs. 9, 10). At both deep and shallow depths, the lower surfaces of shells at most low salinity sites were initially coated by a thick layer of sediment, ciliate protozoans, and diatoms (e.g. Bacillaria paradoxa, Nitzschia sp., and Navicula spp.), a mixture we called "alg" for algal mat (Figs. 9, 10). At Swanquarter, Spencer Bay, and Mouse Harbor this algal mat was mixed with barnacles (Balanus spp.) and an encrusting bryozoan Schizoporella unicornis. These sessile animals persisted through October, while at Turnagain Bay and South River the algal mat had almost disappeared by October, leaving much bare space (Figs. 9, 10).

A higher diversity of sessile animals were observed at both depths at the high salinity sites than at the low salinity sites. Oysters were a common component of the fouling community, together with a serpulid polychaete Hydroides dianthus, Balanus spp., Schizoporella unicornis, and occasionally, the tunicate Styela plicata, the sponge Halichondria bowerbanki, and the sabellid polychaete Sabellaria vulgaris (Figs. 9, 10). The animal community tended to be more persistent than the algal mat observed at the low salinity sites; initial and final (October) abundances of animals were similar at most sites (Figs. 9, 10).

Numbers to the right of the graphs in Figures 9 and 10 are estimates of the percent of successful recruitment on the permanent mats, an index of the ease with which oyster spat were able to invade the existing fouling community. They represent the spat density in October expressed as a percent of the cumulative recruitment on the recruitment mats during the same interval. For example, at the deep depth at Sleepy Creek, the mean density in October on the permanent mats submerged from May

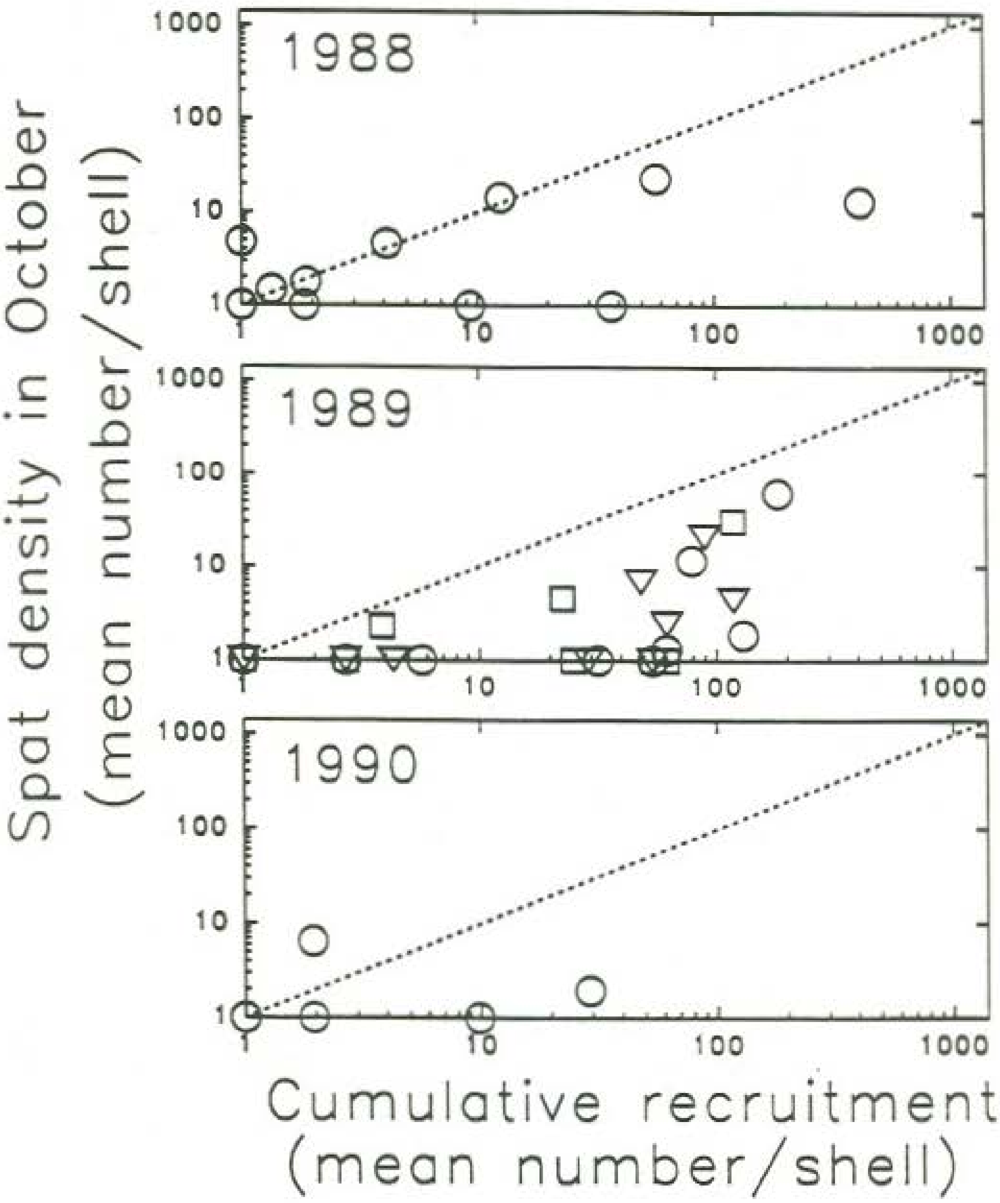

Figure 8. Relation between spat density in October on permanent mats, and cumulative recruitment over the same time interval on recruitment mats. Only data from the deep depth at each site are included. ○ - May-October, ▽ - July-October, □ - August-October. Values < 1 are set to 1.

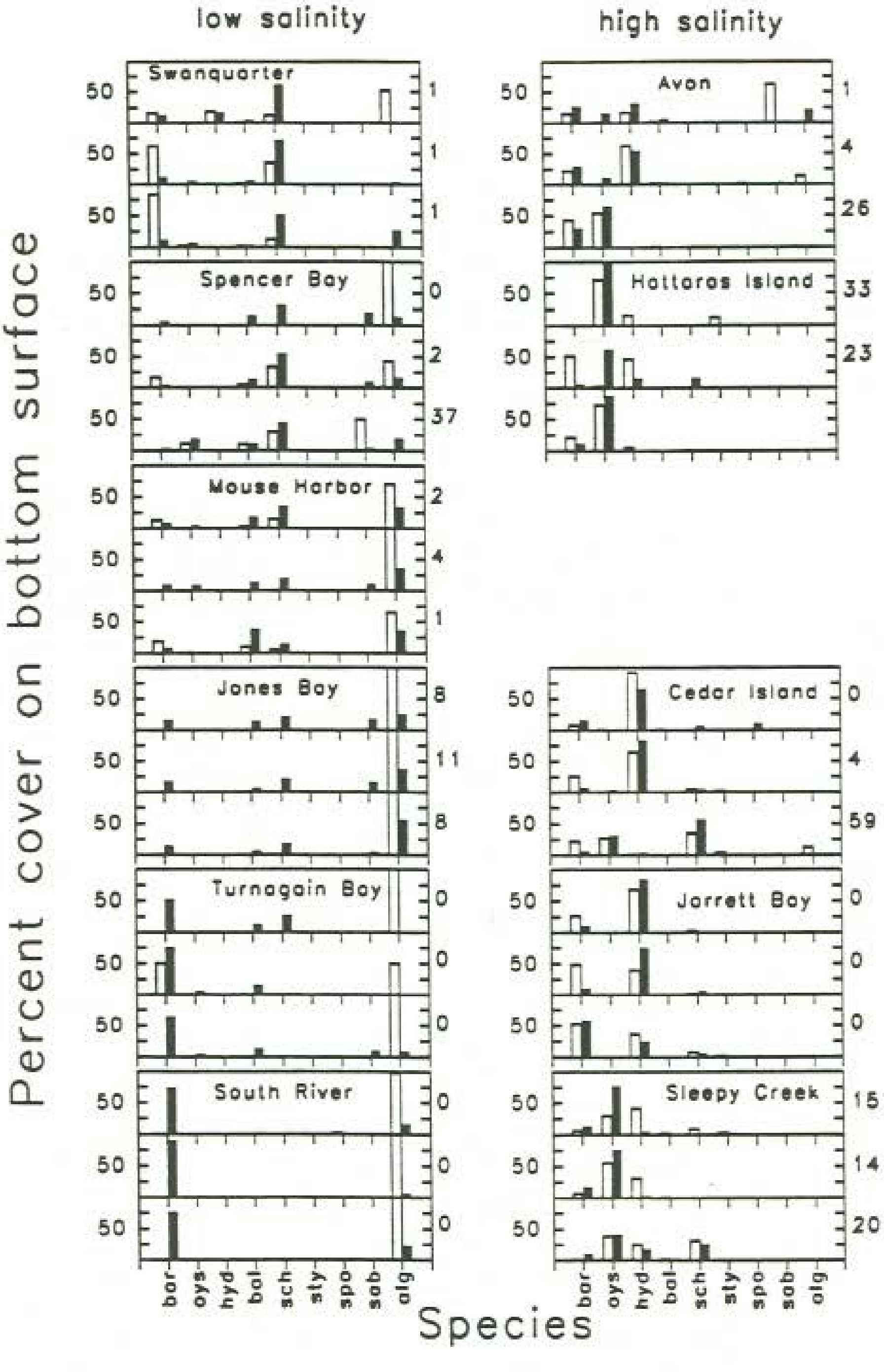

Figure 9. Percent cover of sessile organisms on the bottom surface of shells on permanent mats at deep depths in 1989. The top, middle, and bottom graph for each site represent mats deployed in May, July, and August, respectively. Open bar = census completed 6 weeks after submergence, solid bar = census completed in October. bar = bare, oys = Crassostrea virginica, hyd = Hydroides dianthus, bal = Balanus spp., sch = Schizoporella unicornis, sty = Styela plicata, spo = Halichondria bowerbanki, sab = Sabellaria vulgaris, alg = sediment, ciliate protozoans and diatoms (e.g., Bacillaria paradoxa, Nitzschia sp., and Navicula spp.). Numbers to the right of each graph are an index of successful recruitment (mean density of spat in October on permanent mats/cumulative recruitment on recruitment mats during each interval, expressed as a percentage). No data are available for Ocracoke Island.

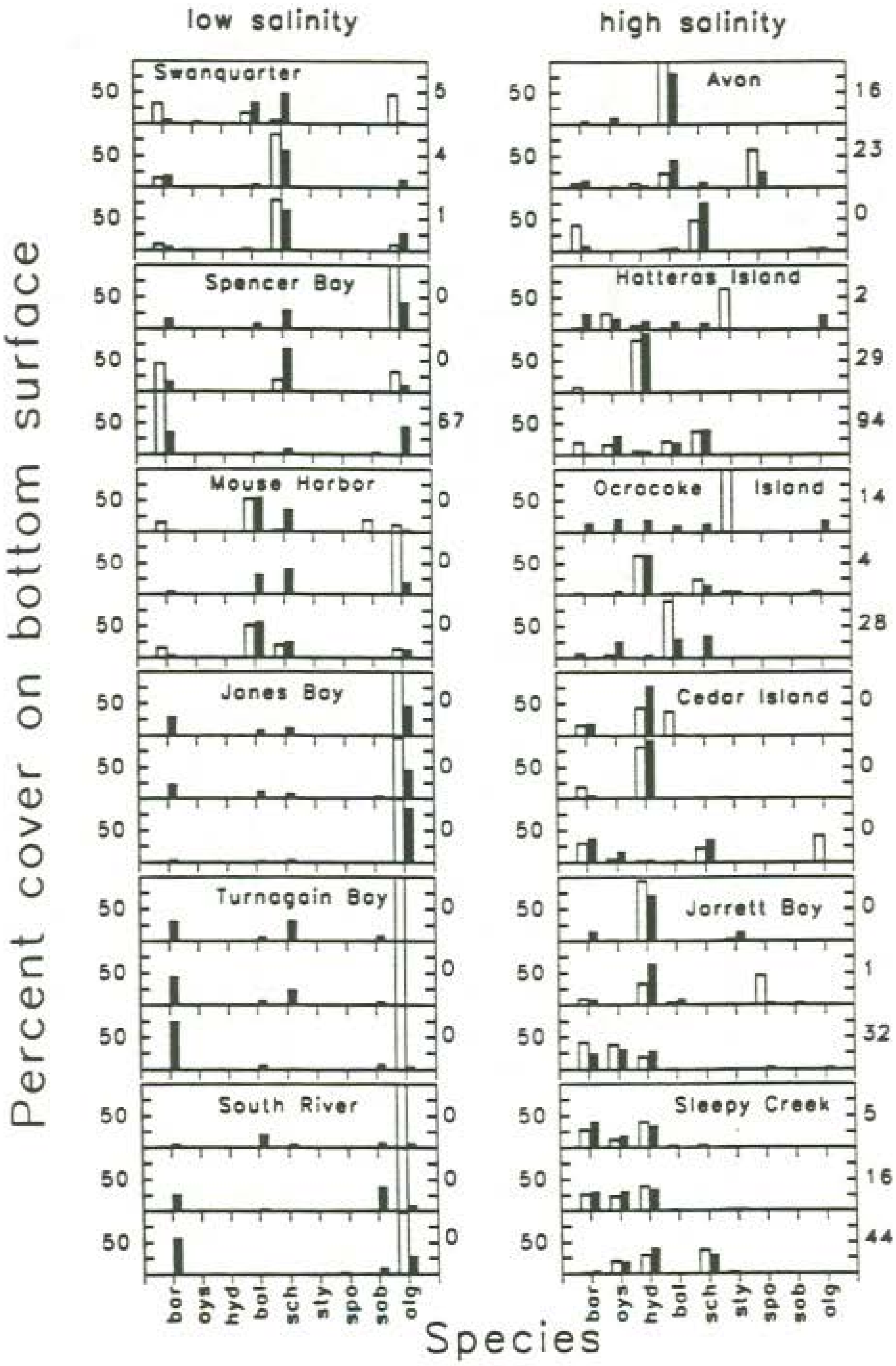

Figure 10. Percent cover of sessile organisms on the bottom surface of shells on the permanent mats at shallow depths in 1989. Rest of caption same as for Fig. 9.

through October was 12 spat per shell. Cumulative recruitment on the recruitment mats over the same interval was 79 spat/shell. Thus, our estimate of the percent of successful recruitment on these permanent mats is (12/79) X 100 = 15% (Fig. 9).

A higher percentage of available oyster larvae was able to invade the fouling community on permanent mats located at the high salinity sites (Figs. 9, 10). In addition, the percent of successful recruitment tended to be higher on permanent mats deployed later in the summer, especially at the high salinity sites (Figs. 9, 10). Note, however, that some of the "zeros" at the low salinity sites resulted from "zeros" in the denominator; at some low salinity sites there was no recruitment even on the recruitment mats (Fig. 5).

Density of spat on cultch planted by the North Carolina Division of Marine Fisheries (NCDMF) generally averaged 5 or less per shell. The one exception in 7 years was at Turnagain Bay where density increased temporarily to 25 spat per shell at the end of 1985. Some areas where we observed the highest recruitment (Hatteras Island, Jarrett Bay, and Sleepy Creek) were not used by the NCDMF during their cultch planting program in time to provide data for the period ending in 1987.

Oyster spat on permanent mats attained lengths of 10-40 mm by October (Fig. 11). There was little difference in mean length on mats submerged at different times during 1989 (Fig. 11), although this may simply indicate that recruitment to all mats was simultaneous and occurred later in the year. All sites appeared to have a similar potential for growth; the mean length of spat in October was not consistently higher at any of the 12 study sites (Fig. 11).

Our data on growth agree well with data collected by the North Carolina Division of Marine Fisheries (NCDMF). For the NCDMF data, growth rate was estimated by regressing the mean length of spat found on the 30 shells collected at each sample period, versus time since the planting of cultch. Varying numbers of regressions were possible at each site (Fig. 12), depending on the cultch planting program, with 3 to 6 observations (samples) for each regression. There was no significant difference in growth rates (mm per day) among sites (Fig. 12, slopes log transformed to homogenize variances, one-way analysis of variance, $F_{8/47} = 1.378$, Pr F = 0.231). The overall mean growth rate (slope) was 0.082 mm/day, suggesting an annual growth rate of 30 mm at all sites.

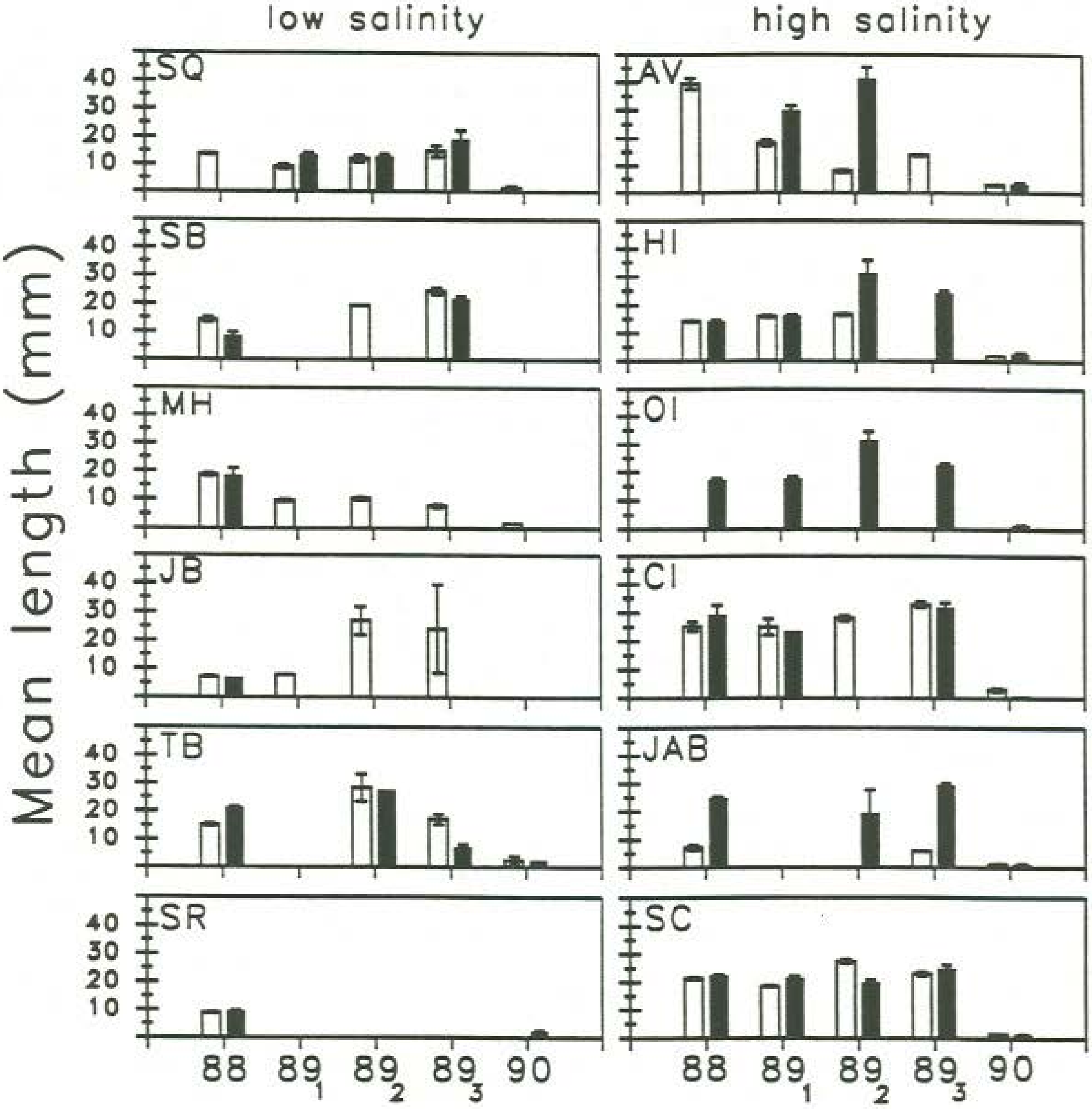

Figure 11. Mean length (± SE) of spat on the permanent mats in October. The three groups of bars for 1989 represent data from mats deployed in May, July, and August, respectively. Open bar = deep depth, closed bar = shallow depth.

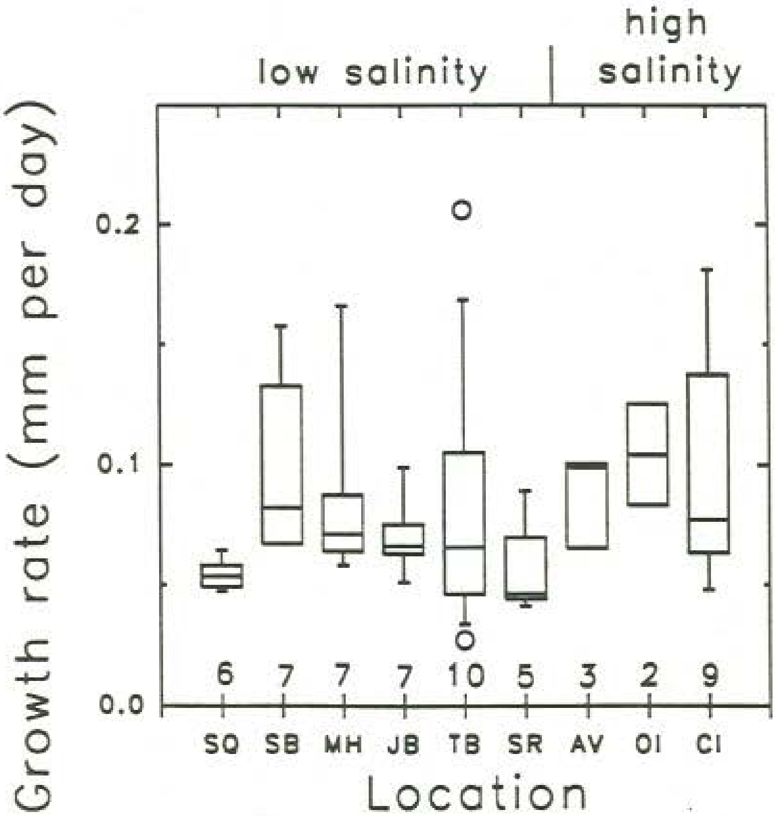

Figure 12. Box plots (Tukey 1977) of oyster growth rates estimated from data collected by the North Carolina Division of Marine Fisheries between 1981 and 1987. Growth rate estimated by regressing the mean length of spat versus time since cultch planting. Numbers indicate the number of regressions available for each site. Site designations as in Fig. 4.

DISCUSSION

An important feature of the recruitment of _Crassostrea virginica_ in North Carolina is the enormous variation in space and time (Fig. 5). Thus, recruitment was highly variable among the 12 study sites in all three years. In a given year and site, recruitment could be continuous (Sleepy Creek), or concentrated in one (Swanquarter, Mouse Harbor, Avon, Jarrett Bay) or 2 peaks (Hatteras Island). Finally, interannual variation was high; recruitment could be dense one year and absent the next (Swanquarter, Mouse Harbor, Avon, Hatteras Island). Such variation in recruitment is a common feature of oyster populations (Krantz and Meritt 1977; Haven and Fritz 1985; Abbe 1986; Kenny et al. 1990) as well as other benthic organisms with pelagic larvae (Underwood and Denley 1984).

In spite of the variation, a number of broad spatial and temporal patterns are apparent in the recruitment of oysters in North Carolina. Recruitment was generally greater along eastern Pamlico Sound and Core Sound in the high salinity sites, compared to the low salinity sites along the western side of Pamlico Sound (Fig. 5). Indeed, recruitment was lacking at many low salinity sites during all three years. Recruitment was generally less at shallow depths where mats were located immediately adjacent to the shore, compared to deeper depths located some distance from shore (Fig. 5). At all sites, recruitment was generally greater (> 50% of the total) on the bottom surface of the shells (Fig. 6), a commonly observed behavior for this species except perhaps when waters become extremely turbid (Kennedy and Breisch 1981). In all three years, recruitment tended to be greater in August and September when water temperatures were highest (Figs. 3, 6). Finally, cumulative (total) recruitment was lower in 1990 compared with 1988 and 1989 (Figs. 5, 8).

Spat density in the fall reflected patterns in the intensity of recruitment. Thus, greater numbers of spat were found on the bottom surfaces of shells (Fig. 6), deeper locations (Fig. 7), and at sites where recruitment was highest (Swanquarter in 1988, and a number of high salinity sites, Avon in 1989, Hatteras Island in 1988 and 1989, and Sleepy Creek in all 3 years) (Fig. 7). However, fall spat densities were reduced by the presence of other sessile organisms and the degree of sedimentation. Thus, maximum densities on the permanent mats were generally much lower than cumulative recruitment on the recruitment mats (Fig. 8). The combination of algal turf and sediment characteristic of low salinity sites appeared especially inhibitory to oyster settlement. Estimates of the percent of successful recruitment (numbers to the right of Figs. 9 and 10) are an index of the ease with which oyster spat were able to invade the existing fouling community. In only 3 instances did this estimate exceed 10% in the low salinity sites, compared with 16 instances in the high salinity sites (Figs. 9, 10). In 1988, spat densities increased monotonically on the permanent mats, suggesting that reduced settlement, rather than post-settlement mortality, was responsible for the lower than expected fall spat densities.

Fall spat density of Crassostrea virginica in North Carolina appears to have declined in recent years along the western edge of Pamlico Sound where our low salinity sites are located. From 1985-1987, the North Carolina Division of Marine Fisheries (NCDMF) reported spat densities of 2-5 spat per shell at our low salinity sites. In our study, fall spat density on the permanent mats at these same sites was very low or zero from 1988-1990, except for Swanquarter, Turnagain Bay and South River in 1988 (Fig. 7). More evidence for a decline in spat density comes from the fall oyster shoal survey of 84 sites in western Pamlico Sound, conducted by the North Carolina Department of Natural Resources and Community Development (NCDNR&CD) in Washington, NC (Sean McKenna and Greg Judy, personal communication). Survey data indicate a general decrease in the density of spat in 1989 compared to 1988. The survey includes data from Swanquarter Bay, Spencer Bay, Mouse Harbor, and Jones Bay since 1983. Only in Mouse Harbor was recruitment greater in 1989 compared to recent years (S. McKenna and G. Judy, NCDNR&CD, personal communication).

Present data are insufficient to determine the cause for the apparent decline in fall spat density in western Pamlico Sound. The algal turf/sediment fouling community appears to inhibit spat recruitment and/or survival, but it is unclear whether this fouling community is a new feature of the region, e.g., reflecting decreasing water quality. It also appears that recruitment is diminishing in western Pamlico Sound even on the continuously replenished, "clean" oyster shells on recruitment mats. Thus, the reduction in fall spat density could reflect a diminished supply of larvae, implying an adult population reduced by predators (McKenzie 1981), disease (Kennedy, 1989), or overharvesting (Hargis and Haven 1988; Kennedy 1989). There is little reason to suspect a recent increase in the numbers of oyster predators. However, the polyhaline disease, Perkinsus (= Dermocystidium) marinus (Dermo), has been reported in the Pamlico Sound (M. Marshall, North Carolina Division of Commercial Fisheries, personal communication) and is a significant cause of mortality in 1 to 2 year old oysters. In addition, harvesting of adult stocks continues to remove both adult populations and habitat (shells of adults) for spat and juveniles. Indeed, the recent declines in North Carolina's oyster harvest provide direct evidence for a reduction in the size of the adult population. It appears likely that oyster populations along the western edge of Pamlico Sound and perhaps other areas in North Carolina, have suffered a fate similar to those in the Chesapeake Bay, where overharvesting and disease have destroyed oyster habitat and decimated adult populations (Kennedy and Breisch 1983; Hargis and

Haven 1988; Kennedy 1989; Heral et al. 1990).

All sites included here appear to have a similar potential for growth. The mean length of spat in October was not consistently higher at any of the 12 study sites (Fig. 11) nor were there any significant differences in growth rates measured by the North Carolina Division of Marine Fisheries during their cultch planting program (Fig. 12). At all sites, spat attained sizes of 10-40 mm during the first year and would reach marketable size (75 mm) by the end of 3 years (Figs. 11, 12). This contrasts with data from the Chesapeake Bay where regional differences in oyster growth are marked (Kennedy and Breisch 1981).

The oyster industry in North Carolina does not systematically transplant spat from "seed" areas to "grow-out" areas, a traditional practice in the Chesapeake Bay (Kennedy 1989). However, data presented here suggest that such a practice could greatly enhance current levels of production in North Carolina. Cultch could be initially deployed at a few high salinity sites where recruitment is greatest and later moved to low salinity sites for grow-out. A large number of grow-out sites is available where growth is high, but where present recruitment is very low. Lowered salinity at these sites might reduce problems with oyster predators and other sources of mortality (Wells 1961), including the diseases MSX and Dermo (Ford 1985; Héral et al. 1990).

There is a clear need for more detailed information on the recruitment and survival of oysters in North Carolina waters. Data must be systematically accumulated from all oyster producing areas in the state to identify sites with the highest natural recruitment, greatest growth, and lowest mortality. The present study is only the beginning of thisnecessary task. Such data are necessary in order to make sure cultch is planted at all suitable sites and to implement the transplanting program suggested above. Recruitment must also be related to the location and density of existing beds in order to understand the high spatial and temporal variation in recruitment. For example, it is possible that recent declines in recruitment may be related to reductions in parental stock from pollution, disease, and overfishing. Recent declines in yield suggest that the task is urgent as well as necessary.

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APPENDIX

Latitude and longitude of study sites

Site	Latitude	Longitude
Swanquarter	35° 21.4′	76° 18.5′
Spencer Bay	35° 23.9′	76° 28.0′
Mouse Harbor	35° 18.3′	76° 29.7′
Jones Bay	35° 13.7′	76° 33.1′
Turnagain Bay	34° 58.8′	76° 29.2′
South River	34° 58.2′	76° 34.8′
Avon	35° 20.5′	75° 31.0′
Hatteras Island	35° 13.8′	75° 40.9′
Ocracoke Island	35° 7.3′	75° 58.6′
Cedar Island	34° 59.4′	76° 17.5′
Jarrett Bay	34° 47.5′	76° 29.3′
Sleepy Creek	34° 43.5′	76° 31.4′