Optimum Size for Planting Hatchery Produced Oyster Seed

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Final Technical Report
Grant No. NA86RG0073
Project No. R/LR-46-NSI-2

Abstract

The ability of hatcheries to produce oyster seed for stocking a variety of oyster culture operations is well established. Hatchery produced seed has not gained acceptance along the Gulf Coast primarily because survival of seed is poorly understood, particularly in relation to cost. The present study focuses on determining optimum size of seed for planting and relating survival to costs. Over a two year period several size classes of hatchery produced oyster seed (single spat and spat set on whole shell) were planted at two sites (low and high salinity) and monitored for survival and growth along with temperature, salinity, and dissolved oxygen. Laboratory studies examined the survival of seed size classes at low dissolved oxygen concentrations, and for several common predators.

In Year 1 field experiments, four size classes of oyster seed (≤ 5 mm, 6-10 mm, 11-15 mm and 16-20 mm) were planted at the two sites in replicated plots during August of 1999. All seed oysters of both setting types were lost to predation, primarily by the oyster drill, *Stromonita haemastoma*, at the high salinity (Dauphin Island) site within one month. Survival rates at the low salinity site (Fish River Reef) ranged from 42 to 62% for spat set on whole shell after 32 weeks. Most of the mortality could be attributed to predation by oyster drills and crabs. There was no significant difference in survival among the four size classes tested. Single spat experienced near total mortality within the first two weeks. Periods of low dissolved oxygen (< 1 ppm) were observed at the Fish River Reef site, lasting from 0.5 to 19.5 hours, but no oyster seed mortality could be attributed to these short-term events.

In Year 2 field experiments, three size classes of oyster seed (<15 mm, 15 - 25 mm and > 25 mm) were planted at two sites in replicated plots during September of 2000. Low dissolved oxygen events were absent and both sites had similar temperature and oxygen levels. After 6 weeks, almost all oysters in unprotected plots, regardless of size or location, were dead. Oyster seed held in protective bags suffered 20–70% mortality. Oyster drills were prevalent on the both the unprotected plots and the protective bags. Within the protective bags, spat set on whole shell survived significantly better than single oysters.

In laboratory predation experiments, oyster drills ate more large (> 25mm) single oyster seed than the other two size classes (< 15 mm and 15-25 mm) and than seed set on whole shell. When oyster drills were provided oyster seed set on whole shell only, they ate more of the largest size class. A similar study using blue crabs resulted in more medium and small oysters being consumed than the largest size class and more single oysters were consumed than those set on whole shell.

Survivorship of the three size classes of single oyster seed when exposed to hypoxic conditions (dissolved oxygen 0.01- 0.23 ppm) in a series of laboratory tests ranged from 100% after 72 hrs to 0% after 144 hrs. The mean estimated LT-50's for the three size classes of oyster seed (<20mm, 22-34mm, >35mm) were 99.37 h, 93.62 h, 93.03 h respectively, with no apparent relation between size and survival.

While there may be some size refuge from blue crab predation, there was no size refuge from oyster drill predation over the range of sizes tested for oyster seed and in fact oyster drills may prefer larger seed oysters. Unprotected single seed oysters have little chance of survival regardless of size and were preferred in predation studies. Seed oysters can survive anoxic conditions for periods of 90 to 100 hours with no clear relation to size. For the conditions

encountered during this study and the range of seed oyster sizes used, there is no economic advantage in paying more for larger seed.

Introduction

Stable and consistent supplies of seed oysters are critical elements for growth of the oyster industry in the Gulf of Mexico region. Natural production of spat and seed is often high, but can vary greatly on both spatial and temporal scales as a result of a variety of abiotic and biotic factors.

May (1972) associated limited oyster spawning and spat sets in Mobile Bay from 1969 to 1971 with extended periods of low salinity in the spring and low dissolved oxygen conditions in the summer. Low salinity has been shown to inhibit gametogenesis and it has been suggested that the inhibition could be related to variations in food availability at lower salinities (Butler, 1949; Loosanoff, 1953).

Estuaries and bays frequently exhibit seasonal salinity and temperature stratification that can lead to bottom waters becoming anoxic or hypoxic for extended periods. Fortunately, oysters have a remarkable capability to regulate their oxygen consumption rate when exposed to declining oxygen tensions. Many researchers have examined the physiological effects of oysters exposed to varying oxygen tensions (Shumway and Koehn, 1982; Baker and Mann, 1992; Llanso, 1992; Willson and Burnett, 2000) and oxygen consumption in oysters (Mitchell, 1914; Nozawa, 1929; Galtsoff and Whipple, 1931; Sparck, 1936; Gaarder and Eliassen, 1955; Collier, 1959; Hammen et al., 1962; Galtsoff, 1964; Dame, 1972, Bernard, 1974; Newell et al., 1977; Rodhouse, 1978).

Although oysters have the ability to regulate oxygen uptake over a wide range of temperature and salinity regimes, low salinity and high temperature have the most profound effects on oxygen consumption (Shumway and Koehn, 1982). In a study conducted by Andrews (1982) oysters on natural beds died when they were exposed to prolong periods of low salinity (<5 ppt) because they were unable to feed and respire. Furthermore, Shumway and Koehn (1982) reported that at any given salinity, the oxygen consumption rate increased significantly with each 10°C rise in temperature. In addition, sensitivity to hypoxia increases with temperature owing to an increase in the metabolic rate at elevated temperatures (Stickle et al., 1989). Also, adult oysters can survive anoxic conditions longer than larval stages because adults can use their large reserve of glycogen in anaerobic metabolism (Widdows et al., 1989). Consequently, early oyster developmental stages may be very vulnerable to hypoxic waters. Low oxygen levels may also affect oyster larval settlement. Baker and Mann (1992) demonstrated that hypoxic (1.5 $mgO_2\ l^{-1}$, 20% of air saturation) and anoxic (< 0.07 mg $O_2\ l^{-1}$ <1% of air saturation) conditions can significantly reduce oyster larvae settlement and also adversely effect juvenile growth and survival. Anoxic conditions also severely reduce ingestion rates in post-settlement spat (Baker and Mann, 1994).

Predation also plays a major role in curtailing the production of natural seed oysters. Oyster seed are most vulnerable to predation when they are young post-set juveniles. Major predators on young oysters include xanthid and portunid crabs, oyster drills, and black drum. The oyster drill (Stromonita haemastoma) is a very efficient predator and is responsible for consuming large quantities of oyster spat. In Mobile Bay, Alabama, 85% of the oysters in a high salinity area were killed by oyster drills during a nine month period (September 1968 – May 1969) while young oysters in a low salinity area during the same time period experienced little mortality (May and Bland, 1970). According to Butler (1954), oyster drills prefer oysters only if other prey is scarce or not available. Laboratory studies revealed that oyster drills preferred

mussels over oyster spat, and barnacles, clams, and hydroids over larger oysters (Butler, 1954; Gunter, 1979). As an opportunistic feeder, the oyster drill with it's well-developed sensory perception, appears to be able to recognize the value of the prey item and select the item that will result in optimal growth (Palmer, 1983;1984). In laboratory feeding experiments conducted by Brown and Richardson (1987), oyster drill feeding rates and efficiency increased with oyster drill size and density. Larger oyster drills were more efficient because they had the ability to forage on both small and large oysters. Although larger oyster drills have the ability to feed on larger oysters, they prefer oyster spat and the smaller oysters (Butler, 1954; Gunter, 1979). Butler (1954) observed a large oyster drill consume week old spat at the rate of 86 day^{-1} along with small barnacles. Although a small, single oyster drill was not able to forage on larger oysters, groups of small oyster drills could work together to successfully attack larger oysters (Brown and Richardson, 1987). The only effective deterrent against oyster migration is salinity. Oyster drills are usually not present in areas having a sustained salinity <15 ppt.

Although oyster drills have received a lot of attention as a primary predator of oysters, predation by portunid and xanthid crabs may in some cases be even more destructive to adult oysters and spat. Large portunid (85.5 mm CW) and xanthid (34.4 mm CW) crabs have been shown to have predation rates as high as 16.7 and 22.5 spat $crab^{-1}$ day^{-1}, respectively (Bisker and Castagna, 1987). In a study involving floating cages, blue crabs (Callinectes sapidus) were recorded to consume up to 19 spat $crab^{-1}$ day^{-1}. In addition, blue crabs were responsible for high mortalities (79 – 99%) of experimentally planted cultchless oyster spat in Chesapeake Bay, Maryland during a period of one month (Krantz and Chamberlin, 1978). In laboratory studies conducted by Krantz and Chamberlin (1978), large blue crabs (100mm - 150mm CW) were able to consume cultchless oysters up to 40mm in shell length while smaller individuals (65mm - 80mm CW) were unable to consume cultchless oysters larger than 25mm. Laboratory feeding studies showed that blue crabs had little difficulty in handling and manipulating cultchless oysters (Krantz and Chamberlin, 1978). The shell edges of cultchless oyster were easily chipped away eventually exposing the animal while cultchless spat were easily manipulated to the crab's mouth. On the other hand, blue crabs had a lot more difficulty damaging the shell of spat set on a large piece of cultch. Consequently, manipulating the spat toward the mouth was greatly impaired by any size of cultch.

Advances in hatchery technology and the ready production of spat set on microcultch (singles) and spat set on whole shell (clumps) seed provide significant opportunities for increasing both the stability and the supply of seed for public and private reefs. Hatcheries can produce either diploid or triploid oyster seed. Triploid seed has advantages in growth, quality, and yield (Allen and Downing, 1986; Allen and Downing, 1991; Shpigel et al., 1992) and possibly shelf life during summer months when diploid oysters are in poor condition from spawning. In the future, hatcheries may produce genetically selected or altered stocks that have superior growth, are disease resistant or have other desirable characteristics. One obstacle to acceptance of hatchery produced seed is the unknown survival rate of various size seed in both cultchless and remote set form. Producers cannot make informed decisions on costs versus benefits of using hatchery-produced seed without estimates of seed survival rates.

Hatchery produced seed planted on natural bottoms face many of the same hazards previously discussed for natural seed production; salinity extremes, low dissolved oxygen, and predators. Hatchery produced seed planted in Bon Secour Bay, Alabama in 1979, suffered approximately 99% mortality after only three months which was attributed to heavy rains in the spring of 1979 (Eckmayer, 1983). Predation by xanthid and portunid crabs on hatchery produced

seed has been shown to be directly proportional to crab size and inversely proportional to oyster size (Bisker and Castagna, 1987). With hatchery and open water nursery systems, we hypothesize that it is advantageous to raise oyster seed to a refuge size that is less susceptible to predation and water quality-related stress. The key is to determine the most appropriate size oyster seed for planting. Consideration must be given to the increased cost of growing seed in a nursery system for an extended period versus the expected low survival of directly planting very small seed on natural bottoms. Seed costs from commercial hatcheries increase dramatically as seed size increases, ranging from \$5.00 1000^{-1} for 1.5-2.4mm seed up to \$40 1000^{-1} for 20 - 25 mm seed (Frank M. Flowers & Son Inc, and New England Shellfish Nursery price lists).

The objectives of the present study were to determine the optimum size of hatchery produced oyster seed for planting on bay bottoms and to relate optimum size to costs of producing various size seed.

Materials and Methods

Two sets of field experiments were conducted between May 1999 and May 2001 that examined the survival and growth of several different size classes of hatchery produced oyster seed (spat set on whole shell and spat set on micro-cultch) at two different sites (low and high salinity). In addition, survival time (LT - 50s) was determined for juvenile oysters set on micro-cultch exposed to anoxic conditions in the laboratory. Predation rates and refuge size were also examined for blue crabs and oyster drills on three different size classes of oysters set on shell and on micro-cultch in the laboratory.

Sources of Oysters

Crassostrea virginica spat were produced in late spring and early summer each year of the study. Spat set on whole shell were produced from "eyed" larvae obtained from the Louisiana State University (LSU) oyster facility, Grand Isle, Louisiana. The larvae were transferred to the Alabama Department of Conservation and Natural Resources, Marine Resources Division, Claude Peteet Mariculture Center, Gulf Shores, Alabama for setting. Each batch of larvae was transferred to one of two, 946 L circular tanks containing filtered (1μm) seawater (12 ppt). The bottom of each tank was covered with 20 mesh bags filled with oyster shell. For the first 48 hours, the larvae were allowed to set using gentle aeration to facilitate settlement onto the bagged oyster shell. After this time, filtered seawater (12ppt) was pumped through the tanks for an additional five days. During the setting period, the diet consisted of naturally occurring algae supplemented with microalgae paste (Reed Mariculture, Inc, San Jose, CA), (10 ml paste $tank^{-1}$; density = 100,000 cells ml^{-1}) daily. After larvae were set for one week, the bagged oyster shell was transferred to racks located in an outdoor brackish-water (12 ppt) reservoir.

Single oysters set on micro-cultch were obtained from the same batches of larvae but set at the LSU oyster facility then transferred to racks in an outdoor brackish-water (12 ppt) reservoir in Gulf Shores. In year 1, four size classes of oysters (≤ 5 mm, 6 - 10 mm, 11 - 15 mm, 16 - 20 mm) were selected for field experiments and preliminary laboratory experiments on anoxia exposure. Three size classes of oysters were selected for year 2 field experiments and predation experiments (<15mm, 15-25mm, >25mm) and anoxia exposure experiments (<20mm, 22-34mm, >35mm).

Field Experiments

Year 1

The study involved both a high and low salinity sites. The low salinity site was located within Fish River Reef, Bon Secour Bay, Alabama and the high salinity site was located near the WR1 day beacon piling, Mississippi Sound, Alabama (Fig. 1). Six experimental units were constructed out of 3 mm PVC (polyvinyl chloride) sheets (Fig. 2). Each unit (23 cm high x 122 cm long x 86 cm wide) was fabricated using PVC cement and PVC corner bracing. For stability, the units were partitioned at the midpoint of the long side. Along the entire bottom edge of each unit, a series of holes were drilled and a 183 cm x 122 cm section of polypropylene mesh (diagonal mesh = 3.8 cm x 3.2 cm) was secured to the bottom of the unit using cable ties. The mesh extended beyond the edges of the experimental unit forming a "skirt". In addition, a series of evenly distributed holes (n = 12 –14) were drilled along the top edge. Three experimental units (replicates) were deployed at the Mississippi Sound and Fish River Reef sites on July 23 and July 26, 1999, respectively. To secure each unit, a 40 cm screw anchor was screwed into the substrate near each corner and attached with cable ties. Eight bushel bags of oyster shells were spread around the perimeter of the unit on top of the polypropylene mesh "skirt" to a height equal to the top edge of the experimental unit wall. Approximately ½ bushel bag of oyster shell was evenly distributed on top of the polypropylene mesh inside the experimental unit (Fig. 2).

Each experimental unit was designed to hold four plastic tubs (56 cm long x 40 cm wide x 15 cm high). On the bottom of each tub, five, 2.5 cm drainage holes were drilled. A sheet of fiberglass screening (square mesh = 1 mm) was secured with silicone sealant to the bottom inside surface of each tub which was then filled with an 10 cm layer of oyster shell. Directly above the layer of oyster shell, a piece of rigid plastic grate material (square mesh = 1.5 cm), covered with fiberglass screening was caulked into place around the inside edge of each tub. The plastic grate created a flat surface for the placement of oysters (set on shell and set on micro-cultch) approximately 3.8 cm below the top edge of the tub (Fig. 2).

Prior to deploying the tubs, the oysters set on whole shell were culled to ≤ 6 spat per internal shell surface. Each shell was then drilled and tagged with a colored (red, green, black, white) cable tie keyed to size class (≤ 5 mm, 6 - 10 mm, 11 - 15 mm, and 16 - 20 mm). Each experimental unit consisted of four tubs, one for each of the four size classes, hence; each experimental unit represented one replicate. Single oysters (n = 150) and oysters set on whole shell (n = 150) from each size group were randomly assigned to a tub in each experimental unit. On August 12 and 13, 1999, all six experimental units (24 tubs, 7200 oysters) were stocked, three in Mississippi Sound and three at Fish River Reef. Each tub was secured to holes in the top edge of the experimental unit wall using cable ties.

On August 17, 1999, the oysters (set on whole shell and single oysters) were observed to be scattered and partially buried due to wind-driven surge at the Mississippi Sound site. Consequently, the experimental units were relocated to a deeper site near Range Marker D, in Mississippi Sound, Alabama (Fig. 1) on August 26, 1999. Tubs were restocked at the new site with a total of 150 oysters (75 set on whole shell and 75 single oysters). To address this unexpected problem, oysters set on shell were cable tied to a 1m length of nylon line (5 mm diameter) which was then secured to the tub using cable ties at opposite corners. This procedure was duplicated at the Fish River Reef site for consistency.

After stocking, each tub was sampled every two weeks for the first month, after which monthly sampling was conducted. Sampling consisted of bringing each tub on board the boat where the total number of oysters set on whole shell per tub were counted and the length of 30

randomly selected oysters were measured. The single oysters were counted and measured similarly. Oysters at Fish River Reef were sampled on August 27, September 10, September 24, October 19, November 19, December 17, 1999, January 14, and March 28, 2000. Sampling at Dauphin Island took place on September 9, September 23, and October 22, 1999.

Water temperature (º C), dissolved oxygen (DO in mg l^{-1}), and salinity (ppt) were recorded 10 cm above the substrate at each site every half hour using Hydrolab MiniSonde water quality multiprobes (Hydrolab Corporation®, Austin, Texas). Each multiprobe was attached to a piling (Howe and Page, 2000) near the containment units. Multiprobes were exchanged and calibrated weekly. Water temperature, salinity and DO were recorded using a YSI 85 hand-held instrument whenever the multiprobes were exchanged to obtain a vertical water column profile (surface, 1 m, 2 m, and near bottom).

Year 2

Field experiments in year 2 used the same experimental units but the experimental design was altered based on year 1 results. The experimental units at the low salinity site, Fish River Reef, remained in the original location. The experimental units located at the high salinity site, Range Marker-D, were moved to Cedar Point Reef in Mississippi Sound, Alabama (Fig. 1). This site was located near commercially productive reefs and was thought to more accurately reflect predation intensity.

The size classes of oysters used for year 2 field experiments were re-evaluated based on the year 1 results and focused on three size classes (<15mm, 15-25 mm, > 25 mm). The two setting types, spat set on whole shell and single spat remained the same. Spat set on whole shell were culled to ≤6 spat per shell, regardless of position on the shell. Each shell was drilled and tagged with a colored (red, black, white) cable tie keyed to size class.

Three replicate experimental units were deployed at each site. Each experimental unit consisted of three tubs, as previously described, and one sealed mesh oyster growing bag (19mm mesh). The tubs and bags were secured to holes in the top edge of the experimental unit wall using cable ties. Each tub and bag was stocked with spat set on whole shell (50) and single spat (50) from each of the three size classes (<15 mm, 15-24.9 mm, ≥ 25 mm) for a total of 300 oysters per tub or bag. The spat set on whole shell were cable tied to a 1 m section of nylon line (5mm diameter) which was then secured to the tubs using cable ties at opposite corners. Similarly, spat set on whole shell placed in the bag were attached to a line for consistency. The bag in each experimental unit served as a predator control. The experimental units at Fish River Reef were stocked on October 10, 2000 followed with the stocking of the Cedar Point Reef units on October 11, 2000.

The Fish River Reef site was sampled on October 25, November 15, 2000 and January 17, 2001. The Cedar Point Reef site was sampled on October 26, November 15, 2000 and January 18, 2001. On each sample date, one tub was removed from each experimental unit and returned to the lab for analysis. The bags from each experimental unit were retrieved and brought aboard the boat, analyzed, and returned to the experimental unit. Analysis consisted of counting the total number of oysters set on whole shell for each size class and measuring the height of 30 randomly selected oysters from each size class. If less than thirty oysters remained for a particular size class, all oysters were measured. Single oysters were counted and measured similarly.

Laboratory Experiments

Hypoxia Study

Year 1

A preliminary experiment was undertaken to determine the LT - 50s of single oysters exposed to hypoxic conditions. The LT-50 represents the hours needed for anoxic conditions to kill 50% of the test population. Four size classes (3 - 5 mm, 6 - 10 mm, 11 - 15 mm, and 16-25 mm) of single oysters were placed in 250 ml Erlenmyer flasks which were contained in a water bath (Boekel Industries). Hypoxic water (0.01 - 0.07 mg l^{-1}, O_2) was established by bubbling nitrogen through a reservoir tank and pumping the anoxic water through the flasks at the rate of 250 ml hr^{-1}. Water temperature was maintained at 30° C ± 2° by the water bath and heaters in the reservoir. The salinity was maintained at 15 ppt. The water used in this setup was filtered (1μm) seawater.

One hundred twenty oysters (30 of each size class) were randomly assigned among twenty flasks each with six oysters. Forty control oysters were divided among eight flasks that were supplied with normoxic water (DO = 5.4 to 5.5 mg l^{-1}). Time of death was recorded when oysters gaped.

Year 2

Based on inherent problems with the initial experimental design, a less complex method for determining LT - 50s for anoxia was designed in year 2. The new experimental design involved two, independent, closed, recirculating systems consisting of two, 208 l reservoirs, 8 PVC chambers, and a water bath (Fig. 3). The source of water in this setup consisted of filtered and UV sterilized seawater (salinity = 15 ppt). Hypoxic water (DO = 0.02 – 0.23 mg l^{-1}) was established in reservoir A by bubbling nitrogen in at a rate of 0.5 l min^{-1}. A latex diaphragm allowed excess gas to vent from the reservoir. Normoxic water (DO = 6.02 – 6.84 mg l^{-1}) in reservoir B was maintained through continuous aeration. A submersible heater placed in both reservoirs maintained a water temperature of 30°C. The experimental chambers used in this setup were constructed from a section of PVC pipe (46 cm x 5 cm), couplers, bushings, and nylon hose fittings (Fig. 4). The volume of each chamber was approximately 1100 ml.

Four replicate trials were run for the experiment. Prior to each experimental run, three size classes (≤ 20 mm, 22-34 mm, ≥35 mm) of single oysters were acclimated to reservoir water (30º C, salinity = 15 ppt) at normoxic conditions for 24 hr in 38 l aquaria. Oysters were not fed during the acclimation period or during the experimental run. After the acclimation period, thirty oysters (10 from each size class) were placed in each of the eight PVC chambers, which were then sealed. Hypoxic water was then transferred from reservoir A using a Supreme Mag Drive Utility Pump (1325 l h^{-1}) to a gang valve where it was distributed to one of four PVC chambers designated as “experimental”. Similarly, normoxic water from reservoir B was transferred to four PVC chambers designated as “control”. After each of the eight chambers was filled with water and any trapped air released, all chambers were placed in a water bath set at 30°C. The flow of both the hypoxic and normoxic water through the chambers was adjusted at 500 ml min^{-1}. The effluent from the experimental chambers was returned to reservoir A through an air-tight fitting. The normoxic effluent was returned to reservoir B where it was vigorously aerated.

One experimental and control chamber each were removed from the water bath after 72, 96, 120, and 144 hrs. The number of dead oysters from each chamber was recorded and the remaining oysters transferred to 38 l aquaria containing normoxic, filtered, reservoir water (30°C, salinity = 15 ppt) for a 48 hours recovery period. After the recovery period the oysters

were examined again for mortality and total dead and live oysters were recorded. Four replicate trials were run for the experiment.

Predation Studies

Experimental Recirculating System Design

The predation studies took place in a closed, recirculating system consisting of nine, 38 l aquaria placed in a fiberglass trough (0.30m deep x 0.61m wide x 2.51m long) (Fig. 5) and two 208 l reservoirs. The aquaria were placed on top of PVC pipe within the trough to eliminate anoxic pockets of water. All nine aquaria and both reservoirs were filled with filtered seawater . Using a Supreme Mag Drive Utility Pump, water was drawn from one reservoir which contained an oyster shell filter and distributed to each of the nine aquaria using 9-way valve manifold. The water was allowed to over flow from each tank into the trough, which emptied into the second reservoir . Each of the nine aquaria contained an airstone and the water flow into each tank was adjusted at approximately 500 ml min^{-1}.

Oyster Drill Predation Experiment

Six plastic mesh (2 cm) cages (6.7 cm x 3.3 cm x 2.2 cm) were constructed and held together using cable ties (Fig. 6). In the bottom of each cage was a plastic mesh (0.5 cm) tray (6.5 cm x 3.1 cm x 0.5 cm) which was easily removed by opening a side panel (Fig. 6). A single cage containing a tray was placed in aquaria 4 - 9. Aquaria 1 – 3 were the control tanks and were absent of the mesh cages. Ten oysters set on whole shell and ten single oysters from each of three different size classes (<15mm, 15-25mm, >25mm; n = 60) were placed in the control aquaria 1 – 3. Similarly, 60 oysters were placed on the mesh tray inside the mesh cage in aquaria 4 - 6. The cages in aquaria 7 - 9 contained only oysters set on whole shell (n=30). After a starving period of approximately 48 hr, one oyster drill, S. haemastoma, (range = 52.9 - 67.4 mm TL) was added to each cage. At 24 hr intervals, for a total of 168 hr, the cages were removed and the number and size of dead oyster set on whole shell and single oysters were recorded. Each dead oyster was replaced with a similar size class specimen and the cage was then returned to its corresponding aquaria.

Blue Crab Predation Experiments

The experimental design used in the oyster drill predation study was also used for the blue crab predation studies. Instead of an oyster drill, one starved (~ 48 hr) blue crab, C. sapidus, (range = 156 mm - 177 mm CW) was placed in cages 4 - 9. At 72 hr intervals, for a total of 144 hrs, the cages were removed and the number and size of dead oysters (set on whole shell and singles) were recorded. Each dead oyster was replaced with a similar size class specimen and the cage was then returned to its corresponding aquaria.

Statistical Analysis

Statistical Analysis System (SAS) 6.12 was used for all statistical procedures (SAS Institute Inc., 1987).

Field Experiments

An Analysis of Variance (ANOVA) was performed to investigate the difference in mean oyster survival and height between size classes, setting type, and sites. A square root transformation (Zar, 1984) was conducted on the survival data prior to the analysis. If a significant ($P \leq 0.05$) difference in mean oyster survival or height was observed, a Tukey's

Honestly Significant Difference (HSD) Test was performed to differentiate the population means. (SAS Institute Inc., 1987).

Hypoxia Experiments

In the hypoxia exposure experiments the data from the replicate experiments were pooled and analyzed by probit analysis (SAS 1987). The data reported for the hypoxia studies are LT-50 values (hours needed for anoxic condition to kill 50% of the test population). This bioassay establishes significant differences between LT-50 values of the size classes based on non-overlap of the 95% confidence limits.

Predation Experiments

In the predation studies, the number of oysters eaten by oyster drills or blue crabs in a particular replicate was adjusted by subtracting the mean number of oysters that died in the control tanks (1 – 3) from the number of oysters eaten for each size class and oyster type (set on shell or set on micro-cultch) in the experimental tanks (4 – 9). An Analysis of Variance (ANOVA) was performed to investigate the difference in mean oyster mortality from predation between size classes and sites. A square root transformation (Zar, 1984) was conducted on the mortality data prior to the analysis. If a significant ($P \leq 0.05$) difference in mean oyster survival was observed, a Tukey's Honestly Significant Difference (HSD) Test was performed to differentiate the population means.

Results

Field Experiments

Year 1

Salinity was considerably higher than anticipated due to a very dry summer in 1999. The mean salinity at the Mississippi Sound location was 24.6 ppt (range = 14.4 – 29.2) from August 24 – October 21, 1999. The mean salinity at Fish River Reef over the same time period was only slightly lower at 21.4 ppt. The mean salinity at Fish River Reef through March 28, 1999, when experiments ended at that location was 21.7 (range = 10.7 – 29.7 ppt) (Fig. 7). At Fish River reef, there were a number of low oxygen events (< 2 ppm) with varying duration (0.5 – 131.5 hrs). Oxygen concentrations of < 1 ppm lasted from 0.5 to 19.5 hrs. Oxygen concentrations were consistently higher at the Mississippi Sound location and low oxygen events (<2 ppm) were rare and lasted for short duration (0.5 – 10 hrs)(Fig 8). Water temperature was similar between locations from August 24 – October 21, 1999 (range = 20.03 – 33.49 ^{o}C). The water temperature range for Fish River Reef through the March 28, 1999 end date was 8.19 to 31.61^{o}C (Fig. 9).

Mean survival after 32 weeks for oysters set on whole shell at Fish River Reef ranged from 42% for ≤ 5 mm seed to 62% for 11 – 15 mm seed (Fig. 10). There was no significant difference in survival among the four size classes tested ($F = 3.88$; $P > 0.0556$). Mean height of seed after 32 weeks varied from 48 mm (range = 23 – 63 mm) for the ≤ 5 mm size class to 55 mm (range = 37 – 75 mm) for the 16 – 20 mm size class (Fig. 11). There was no significant difference in height among the three larger class sizes, but the ≤ 5 mm size class was significantly smaller than the other three size classes ($F=7.27$; $P < 0.001$). Very few single spat survived the first two-week sampling period (September 10, 1999) at Fish River Reef. Predation, primarily by oyster drills and to a lesser extent crabs, appeared to be the cause of mortality. Predation by oyster drills was indicated by drill holes in empty shells, while crab predation was indicated by the presence of crushed shells. Oyster drills were present in the Fish River Reef area because of the drought conditions leading to higher than normal salinity in 1999.

All oysters set on whole shell and single oysters at Range Marker D, Mississippi Sound suffered substantial mortality during the first two weeks of the experiments (Fig. 12). By the end of one month, very few live oysters were found. The experiment at this site was terminated at this time (September 23, 1999). Predation, primarily by oyster drills, appeared to be the cause of the majority of oyster mortality.

Year 2

Salinity remained high through the fall of 2000 with the lack of any substantial rainfall events. During the experimental period from October10 to January 18, 2000, mean salinity at Cedar Point Reef was 25.81 ppt (range = 14.6 – 33.4 ppt) and would fluctuate with the tides. Salinity at Fish River Reef was consistently high with a mean of 26.9 ppt (range = 23.5 – 31.7 ppt) and remained relatively stable throughout the experimental period. (Fig.13). Dissolved oxygen was similar between sites though levels would fluctuate more at the Fish River Reef site (mean = 7.01 ppm, range = 2.96 – 11.01 ppm), while Cedar Point Reef (mean = 8.74 ppm, range = 5.3 – 19.25 ppm) remained relatively stable (Fig 14). No low oxygen events were recorded at either site during this time period. Water temperatures were similar between Cedar Point Reef and Fish River Reef, ranging from 4.88 to 25.17 ^{o}C (Fig. 15).

After one month, almost all oysters in the unprotected tubs, regardless of size, location, or setting type, were dead. The majority of the mortality occurred during the first two weeks of the experimental run (Fig. 16, 17). The cause of the mortality was related to the presence of oyster drills. The mean number of oyster drills present in the tubs at both Fish River Reef (Range=0-25.6) and Cedar Point Reef (Range=9-41.3) decreased as the number of oysters available to prey upon decreased. Cedar Point Reef typically had more oyster drills per tub than Fish River Reef on all sample dates (Fig. 18).

Smaller oysters survived the first two week sampling period slightly better than larger oysters ($F=6.31$, $P<0.01$). This difference disappeared in subsequent samples as almost all oysters in unprotected tubs were consumed. There were no differences in survival between cultch types during any sampling period, regardless of size and location ($P>0.05$). Overall there were no differences in survival between location during any sampling period ($P>0.05$) but when broken down by cultch type, oysters set on whole shell at Fish River Reef survived the first two week period slightly better than those at Cedar Point Reef ($F=8.43$, $P<0.01$). Again, this difference disappeared in subsequent samples.

Oysters placed in protective bags, regardless of size class, cultch type, and location, survived significantly better ($F=416.14$, $P<0.001$) than those in tubs but also suffered substantial mortality due to the presence of oyster drills (Fig. 16, 17). Oyster drills were able to drill oysters through the mesh bags. In the protective bags, oysters set on whole shell survived significantly better than single oysters ($F=45.29$, $P<0.001$). This difference existed among all three size classes (<15 mm, $F=4.98$, $P<0.05$; 15 - 25 mm, $F=29.96$m $P<0.001$; > 25 mm, $F=29.10$, $P<0.001$). But when analyzed by location a difference in survival between cultch types of the largest size class was not apparent (Cedar Point Reef, $F=0.97$, $P>0.3805$; Fish River Reef, $F=5.93$, $P>0.0716$). There was no significant difference in survival between size classes of oysters set on whole shell overall ($F=0.81$, $P>0.4640$) or at either location (Cedar Point Reef, $F=0.88$, $P>0.4617$; Fish River Reef, $F=1.21$, $P>0.3629$). In the case of single oysters set on micro-cultch, significantly more large oysters survived over the other two smaller size classes ($F=4.34$, $P<0.03$). When analyzed by individual location this difference was only apparent at Fish River Reef ($F=5.18$, $P<0.04$).

Few oysters in unprotected tubs survived until the end of the experiment; therefore only oyster in protected bags were used for growth analysis. Mean oyster height ranged from a high of 50.78mm for the large size class (>25 mm) of single oysters at Cedar Point reef to a low of 24.52 for the small size class (<15 mm) oysters set on whole shell at Fish River Reef. Growth rates were similar between size classes at each location (Cedar Point Reef $F=0.25$, $P>0.7843$; Fish River Reef, $F=0.75$, $P>0.4910$)(Fig. 19) and oyster height remained distinctly different between size classes over the entire experiment ($F=377.21$, $P<0.001$), within each site (Cedar Point Reef, $F=236.32$, $P<0.001$; Fish River Reef, $F=212.46$, $P<0.001$), and within each cultch type (Cedar Point Reef, Micro-cultch, $F=167.89$, $P<0.001$; Whole Shell, $F=109.14$, $P<0.001$; Fish River Reef, Micro-cultch, $F=135.17$, $P<0.001$; Whole Shell $F=121.93$, $P<0.001$)(Fig. 20, 21).

There were no significant differences in oyster height between single oysters and those set on whole shell within size classes 2 and 3 (Size 2, $F=1.01$, $P>0.3169$; Size 3, $F=1.49$, $P>0.2251$). Single oysters in the largest size class were significantly larger than oysters set on whole shell at the beginning of the experiment ($F=132.24$, $P<0.001$) and this difference was sustained through the end of the experimental period ($F=94.29$, $P<0.001$). The results of these comparisons between cultch types were consistent when analyzed within each site (Fig. 20, 21).

Within all size classes and cultch types, oysters grew to a greater mean height at Cedar Point Reef compared to Fish River Reef ($P<0.01$). This is also reflected in higher growth rates within all size classes of oysters at Cedar Point Reef compared to Fish River Reef ($P<0.01$) (Fig. 19).

Laboratory Experiments

Hypoxia Study

Year 1

The preliminary experiment indicated that general range of the LT-50s of seed oysters exposed to hypoxic conditions at 30°C, was between 94 and 98 hours with no clear relation among the size groups examined (3-5 mm, 6-10 mm, 11-15 mm and 16-25 mm).

Year 2

In most instances, little mortality was noted among all size classes of oysters in the hypoxia exposure experiment until the 72 h sampling interval. Mortality of all oysters in all size classes was usually noted at the 144 h sampling interval (Fig 22). The estimated LT-50 from probit analysis for all oysters combined was 95.374 h. Within the large (>35mm), medium (22-34mm), and small (<20mm) size classes, LT-50s were 93.032 h, 93.616 h, and 99.366 h respectively. Though LT-50s were inversely proportional to size, there were no significant differences in LT-50 between the size classes as indicated by the overlap of the 95% confidence limits (Fig. 23).

Predation Studies

Oyster Drill Predation Experiments

During the 168 h predation study, the water parameters were as follows: mean water temperature = 20.8 ± 0.5 °C (range = 20.3 – 21.6 °C), mean salinity = 24.5 ± 0.7 ppm (range = 23.3 – 25.2 ppm), and mean DO = 7.5 ± 0.4 mg l^{-1} (range = 6.9 – 7.9 mg l^{-1}). The mean length of the oyster drills used throughout these laboratory studies was 60.3 ± 3.7 mm (range = 52.9 – 67.4 mm).

In general, oyster drills tended to select larger oysters to prey upon over smaller oysters in tanks with both cultch types and in tanks with only oysters set on whole shell. Oyster drills preyed more heavily on large (>25 mm) single oysters than on the other two size classes (≤ 15 mm and 16-25 mm) and more than on all size classes of oysters set on whole shell (Fig. 23). When oyster drills were provided oysters set on whole shell only, they ate considerably more of the larger size class (Fig. 24). Oyster drills ate significantly more large and medium oysters set on whole shell than small oysters set on whole shell in the combined cultch type treatment ($F=29.59$, $P>0.001$).

Blue Crab Predation Experiments

During the 144 hr predation study, the water parameters were as follows: mean water temperature = 22.5 ± 0.6 °C (range = 21.8 – 22.9 °C), mean salinity = 26.6 ± 0.3 ppm (range = 26.3 – 26.9 ppm), and mean DO = 6.63 ± 0.3 mg l^{-1} (range = 6.41 – 6.97 mg l^{-1}). The mean carapace width (CW) of the blue crabs used throughout these laboratory studies was 166.3 ± 7.9 mm (range = 156 - 177 mm).

In tanks with both cultch types, blue crabs ate more middle size class (15-25 mm) single oysters than the other two size classes (<15 mm and >25 mm) and more than all size classes combined of oysters set on whole shell (Fig. 25). No large oysters set on whole shell and very few large single oysters were eaten in tanks with both cultch types. Blue crabs ate more single oysters than oysters set on whole shell in all size classes. When blue crabs were offered oysters set on whole shell only, they ate very few oysters. No medium size class oysters were eaten in these tanks and slightly more of the small size class (≤15mm) oysters were eaten than large size class (>25mm) oysters (Fig. 26). Due to the low number of replicates and high variability within treatments, the only significant difference was more small oyster were eaten as opposed to large oysters set on whole shell in the tanks with both cultch types ($F=7.41$, $P>0.024$).

Discussion

Oyster drills are a major predator of eastern oysters in Mobile Bay. Population densities ranging from zero in low salinity areas to as high as 27,000 individuals hectare^{-1} in high salinity areas have been reported in Mobile Bay (Hofstetter, 1977). Field studies conducted by MacKenzie (1977) documented that oyster drills require salinities greater than 15 ppt, while at salinities below 10 ppt they become immobile, and exposure to 7 ppt for up to 1 to 2 weeks is lethal (Galtsoff, 1964). However, laboratory studies have shown that oyster drills can tolerate salinities as low as 5 ppt at 20° for up to 10 days (Stickle and Howey, 1975). Typically, the Mississippi Sound area behind Dauphin Island has a higher salinity than the Fish River Reef area in Bon Secour Bay and therefore has a higher concentration of oyster drills. Drill densities escalated in the 1999 and 2000 at both locations due to drought conditions. Consequently, in year 1 of this study, high mortality of both oysters set on whole shell and single oysters occurred in less than two weeks at the Range Marker D, Mississippi Sound study site (mean salinity = 24.6 ppt). In addition, due to higher than normal salinities at Fish River Reef (mean salinity = 21.4 ppt), we can assume that predation by oyster drills at this site was higher than normal.

Although total mortality of single oysters was observed at Fish River Reef in Year 1 field experiments, some of the oysters set on whole shell survived throughout the study. It is interesting to note that the largest size class of oysters set on whole shell did not exhibit the highest percent survival. In Year 2 field experiments, oyster drills again were the major cause of

oyster mortality at both Cedar Point Reef and Fish River Reef. Unprotected tubs suffered almost complete mortality within a month. Results from the unprotected tubs showed a similar lack of selection in terms of predation by size class as in year one though there was some indication that smaller oysters survived slightly better the first two weeks of the experiment.

Oysters held in protective bags in Year 2 survived somewhat better but also suffered significant mortality attributed to oyster drill predation. Again, there was no difference in survival based on size class for oyster set on whole shell. In fact, the only case where larger oysters survived better than the smaller size class was micro-cultch oysters in protective bags at Fish River Reef in Year 2.

Studies have shown that foraging efficiency increases with both oyster drill size and age (Brown and Richardson, 1987). Consequently, prey size selection differs for different size classes of oyster drill. However, even though smaller oyster drills are not able to successfully prey upon larger oysters, they can group together to successfully prey upon larger oysters (Garton, 1986; Brown and Richardson, 1987). The results from field experiments suggest that for the most part, there was a lack of size refuge from predation by oyster drills at the size classes of oysters tested (Year1 - ≤ 5 mm, 6 - 10 mm, 11 - 15 mm, 16 - 20 mm; Year2 - 5-14mm, 15-25mm, >25mm). In the case where larger oysters survived better than the smaller size classes of single oysters in protective bags at Fish River Reef in Year 2, can probably be related to the size structure of the oyster drill population in this area. With drought conditions in 1999 and 2000 oyster drills began to recruit to the Fish River Reef area where they are seldom found during normal rainfall years. Most drills in the area were small and had probably recruited to the area recently. These smaller drills may have had a harder time drilling the largest size class of single oysters through the protective bags. At Cedar Point Reef, where there was a wide range in the size structure of the oyster drill population, there was no significant difference in survival between size classes within a particular cultch type. Laboratory predation experiments reiterated the lack of a refuge size for oysters from predation by oyster drills. In the controlled laboratory setting oyster drills actually tended to consume more of the larger size classes of oysters.

Evidence of crab predation was noted in Year 1 field experiments, though it was not a major contributing factor to mortality in the field experiments. Crab predation may have been more of a factor had oyster drills not been so abundant. Laboratory predation experiments with blue crabs indicated the potential for refuge size with the majority of oysters being consumed from the two smaller size classes. Bisker and Castagna (1987) noted that larger blue crabs (mean cw =85.5) and were capable of preying significantly on oyster in a large size class (19.3-31.4mm) but predation rates drastically increased as oyster size decreased. We had similar results in consumption of smaller size classes of oysters in our study using considerably larger blue crabs (mean cw=166.3) but saw little predation on the largest size class oyster (>25mm).

Cultch type may be one of the more important decisions when planting oysters. In Year 1 field experiments, oysters set on both cultch types suffered complete mortality at the Mississippi Sound site but at the Fish River Reef site oysters set on whole shell survived significantly better than single oysters. In this instance the oysters set on whole shell are provided refuge by being more concealed and obscured by the shell they are set on and also predators may have a harder time manipulating oyster. In Year 2 field experiments, oysters set on whole shell survived better than single oysters when held in protective bags. Mortality of oysters in protective bags can almost certainly be attributed to oyster drills. Again, single oysters are more exposed to oyster drills feeding through the bags while those set on whole shell are

afforded protection by the bag and the shell configuration. The refuge afforded oysters set on whole shell was demonstrated in the laboratory predation experiments also. When give a choice, both oyster drills and blue crabs consumed more single oysters as opposed to oysters set on whole shell.

In the Maryland portion of the Chesapeake Bay, Krantz and Chamberlin (1978) suggested that cultchless oysters may be of little value when planted directly on bottom due to crab predation and there use should be limited to protective containers. A similar conclusion can be reached based upon the results from field and laboratory predation experiments presented here. Oyster set on whole shell should survive better planted directly on bottom as opposed to single oysters. Single oysters are better suited to an environment protected from predation and even then, care must be taken to insure that protective containers are not accessible by oyster drills.

Periodic low dissolved oxygen events have been documented in the Fish River Reef area (Saoud et al., 2000) and along the eastern shore of Mobile Bay (May, 1972; Turner et al., 1987; Schroeder et al., 1990). Austin (1954) and Ryan (1969) reported flood tides moving eastward and northward along the eastern side of the Bay and ebb tides moving southward along the western side. According to May (1973) and Turner *et al*. (1987), density stratification results in the isolation of bottom waters in Mobile Bay, which coupled with high biological oxygen demand (BOD) in the sediment leads to oxygen depletions. Based on these reports, during periods of stratification, a rising tide would push low oxygen water toward the eastern shore and the Fish River Reef area. In the summer of 1999, prior to deployment of oysters for Year 1 field experiments, there were two periods of extended low dissolved oxygen conditions recorded at Fish River reef. The longest incident lasted 130 h. Oysters deployed in an experimental array in a separate study during this time suffered total mortality due to these summer anoxic events (Saoud et al., 2000).

Fish River Reef was selected for this study in part to look at size dependent survival of oyster seed related to anoxic conditions. During the two field experimental periods, no long-term low dissolved oxygen events occurred and no oyster mortality could be attributed to anoxic conditions. Laboratory experiments were conducted to further investigate the relationship between oyster seed survival and exposure to anoxic conditions. Several studies have shown that oyster tolerance to anoxia decreased with increasing temperature (Dunnington, 1968; Andrews, 1982; Shumway and Koehn, 1982; Stickle *et al.*, 1989). Stickle *et al.* (1989) reported LT_{50} values of over 28 days for oysters in anoxic conditions at temperatures of 10 ^{o}C and three days for oysters at 30 ^{o}C. Oysters buried in anoxic sediment survived for more than 5 weeks at temperatures less than 5 ^{o}C, but only 4 days at temperatures greater than 25 ^{o}C (Dunnington, 1968). An experimental temperature of 30^{o}C was chosen for the laboratory experiments to simulate the extreme conditions oyster seed would experience during the summer in Mobile Bay. At the sizes tested (>35mm, 22-34mm, <20mm) there were no differences in the LT-50 of seed exposed to anoxic conditions though the LT-50s were inversely proportional to oyster seed size. This would indicate that there is no benefit to selecting a particular size class of oyster seed for planting in areas susceptible to low dissolve oxygen conditions. Areas such as Fish River Reef where there exist the possibility of long term low oxygen events (>100 h) coinciding with high summer water temperatures, it is probably not practical to plant seed directly on bottom. These type areas may be more suited to off-bottom oyster aquaculture to get seed out of low dissolved oxygen conditions in bottom waters.

Conclusions

The present study reiterates the fact that choosing a location for planting oyster should be carefully considered. Water conditions and predator abundance should be weighed when investigating planting sites. Results from this study indicate that oysters set on whole shell would be preferable to single oysters for planting directly on water bottoms. Whole shell cultch appears to provide some measure of protection to young oyster spat. Single oysters are more susceptible to predation when planted on open water bottoms.

There appears to be little justification for buying larger seed in terms of gaining a refuge from predation when planting directly on water bottoms. While there may be some size protection from blue crab predation there was no size refuge from oyster drill predation over the range of sizes tested here for oyster seed set on whole shell. In fact, oyster drills may prefer larger seed oysters. Drought conditions during this study led to dramatic increase in oyster drill predation. Their impact on planted seed is well documented here. The Cedar Point Reef area that is the heart of the commercial oyster harvest in Alabama probably would not have benefited from any type of oyster seed planting program during this time period due to the large numbers of oyster drills. In areas subject to heavy blue crab predation, it would be beneficial to leave oysters set on whole shell in their setting bags until the oysters reach a size of approximately 25mm before planting on bottom. The study also showed no benefit to buying larger seed for use in areas subject to hypoxic conditions. Seed oysters can survive hypoxic conditions for periods of 90 to 100 h with no clear relation to size.

Analysis of survival for oyster seed set on whole shell from year one of this study and the published price of oyster seed of various sizes indicated there was no advantage in paying more for larger seed. Even though the smallest seed had the lowest nominal survival, the cost per oyster after 32 weeks was still lowest for the smallest seed size (<5 mm). The cost of the largest seed (16-20 mm) after 32 weeks was about 5 times higher per oyster than the smallest seed. For the conditions encountered during this study and the range of seed oyster sizes used, there is no economic advantage in paying more for larger seed. The preferable method for planting on open bottom waters suggested here would be to purchase oyster larvae from a hatchery and use remote setting techniques to set larvae on whole oyster shell and then plant on bottom. An alternative would be to purchase oyster seed from the hatchery that is already set on whole shell and plant directly on bottom. The use of single oysters should be limited to use in protective containers in an aquaculture type setting.

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Fig. 1. Study sites for Year 1 and Year 2 field experiments in Mobile Bay, Alabama.

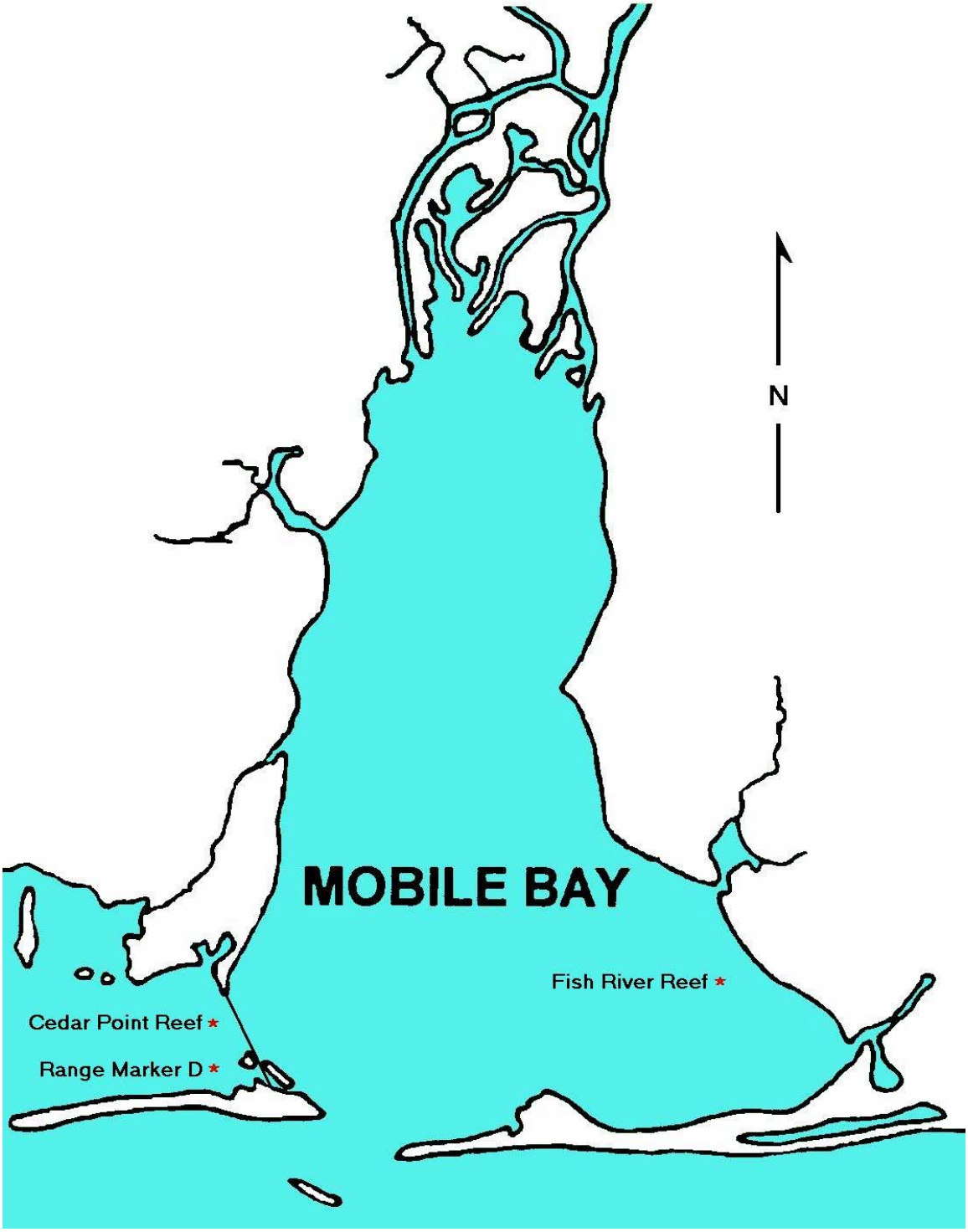

Fig. 2. Experimental units used for Year 1 and Year 2 field experiments.

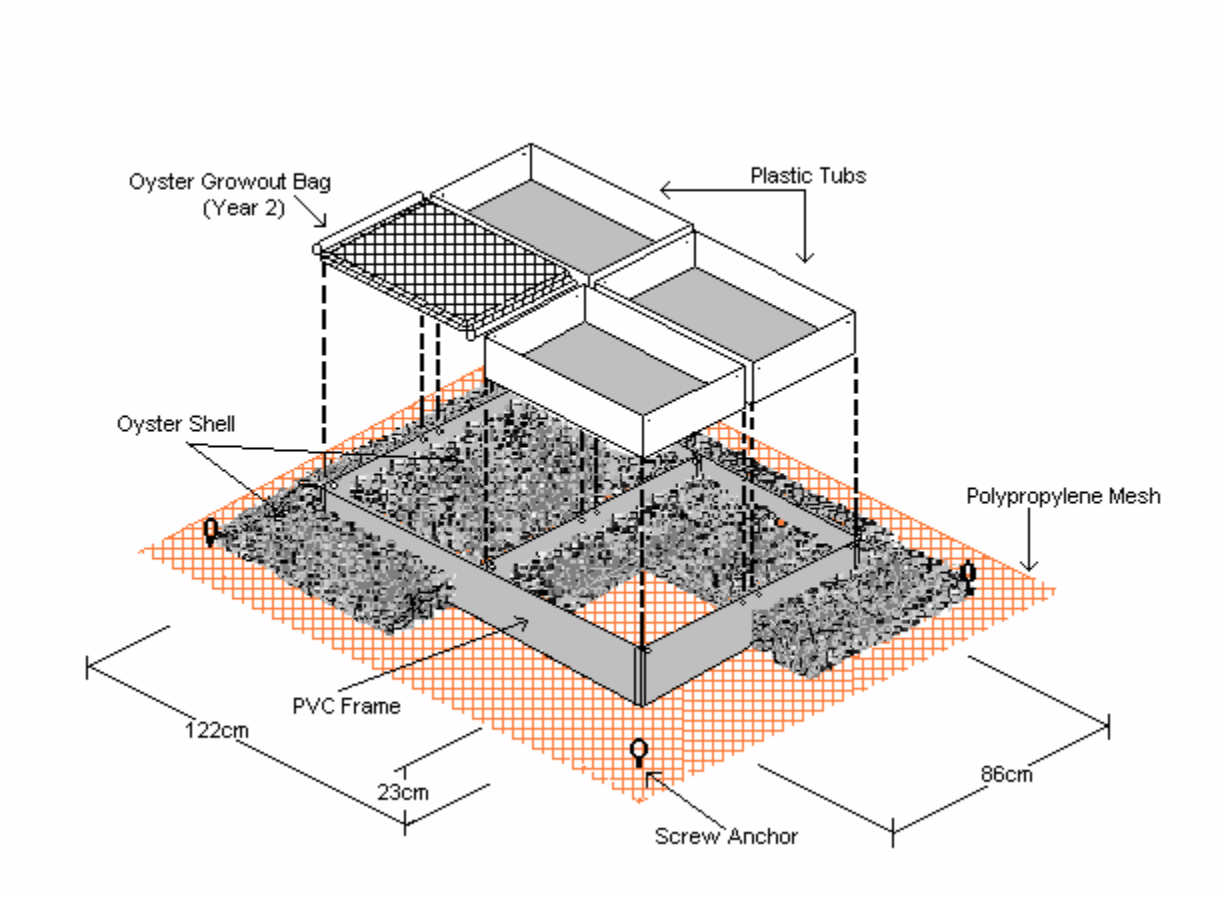

Fig. 3. A schematic diagram of the closed recirculating system used for Year 2 hypoxia experiments.

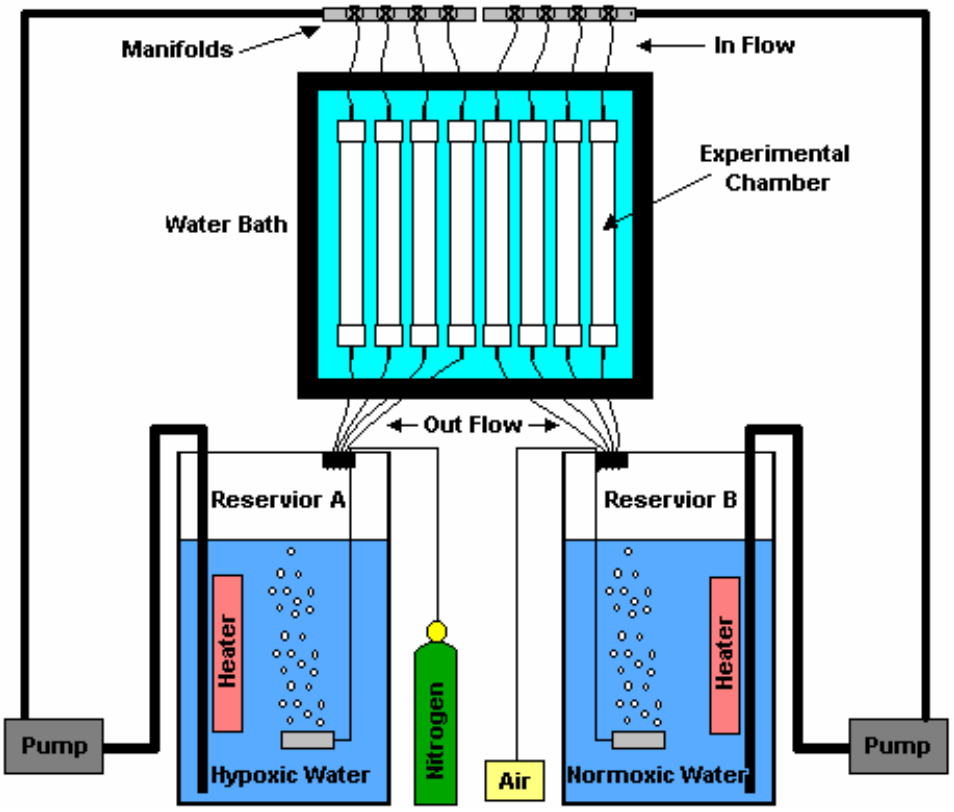

Fig. 4. The PVC experimental chambers used to determine the survival time (LT-50s) of juvenile oysters exposed to hypoxic conditions.

Fig. 5. A schematic diagram of the closed, recirculating system used for both the oyster drill and blue crab predation experiments.

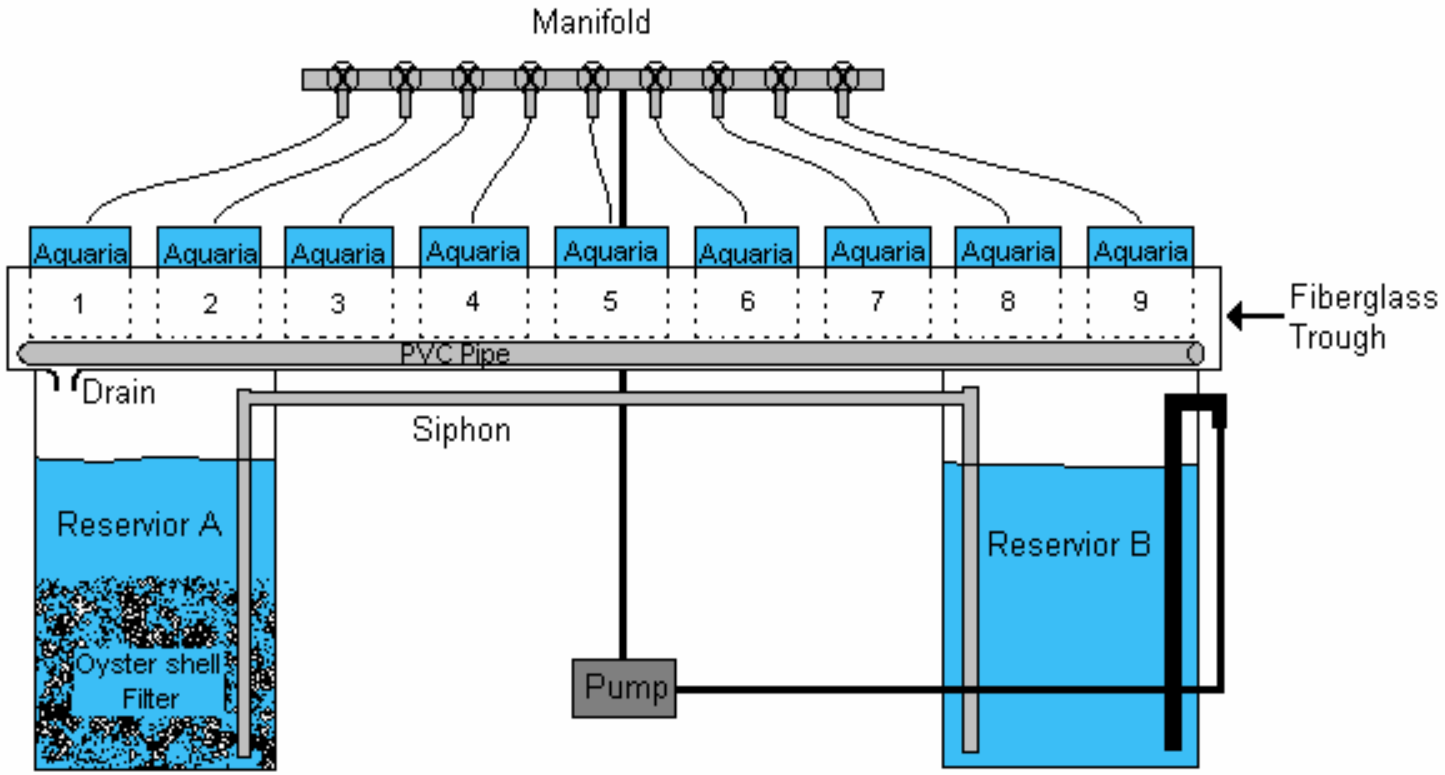

Fig. 6. The plastic mesh cages and trays used in both the oyster drill and blue crab predation experiments.

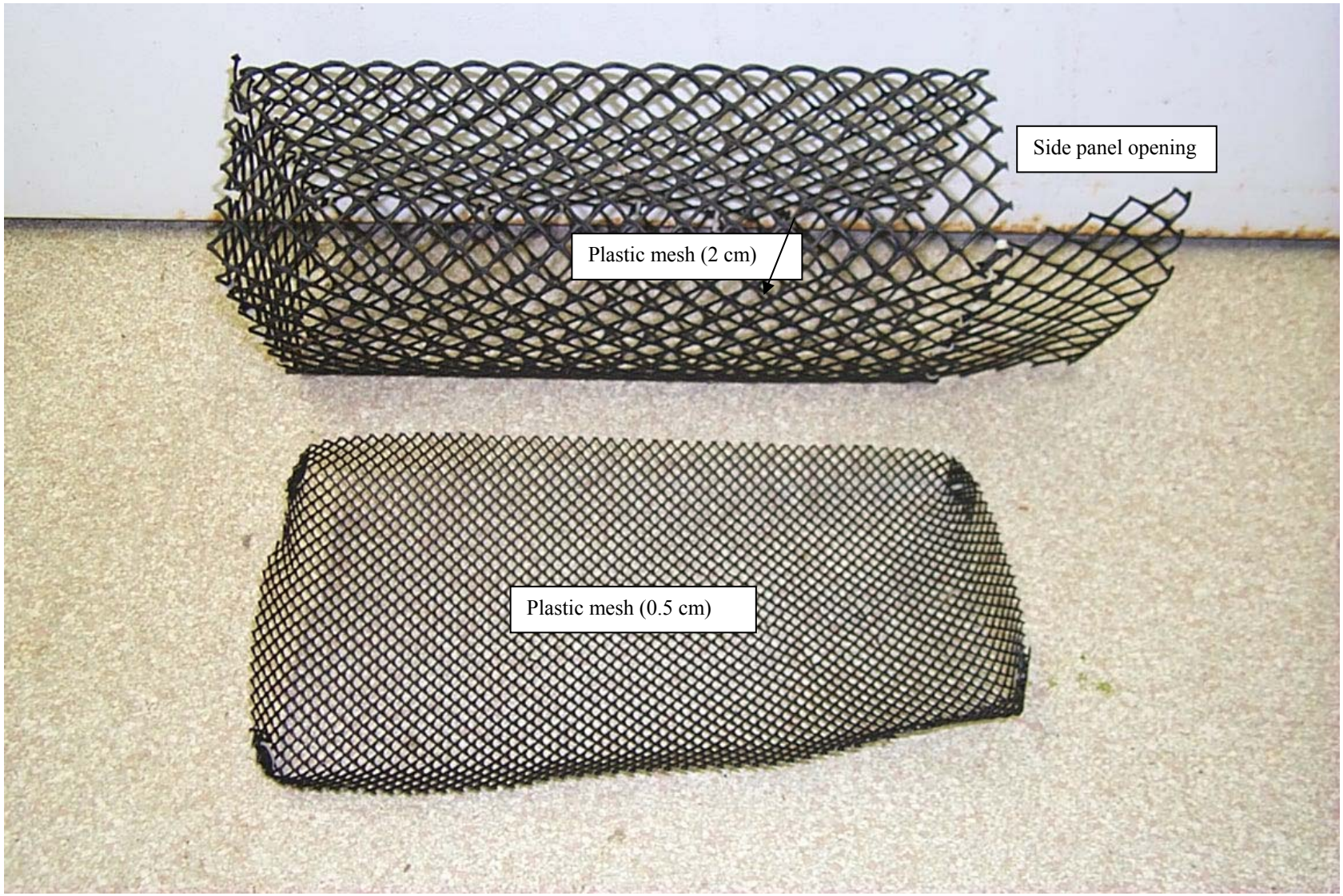

Fig. 7. Salinity (ppt) recorded at Fish River Reef and Range Marker D, Mississippi Sound, for Year 1 field experiments.

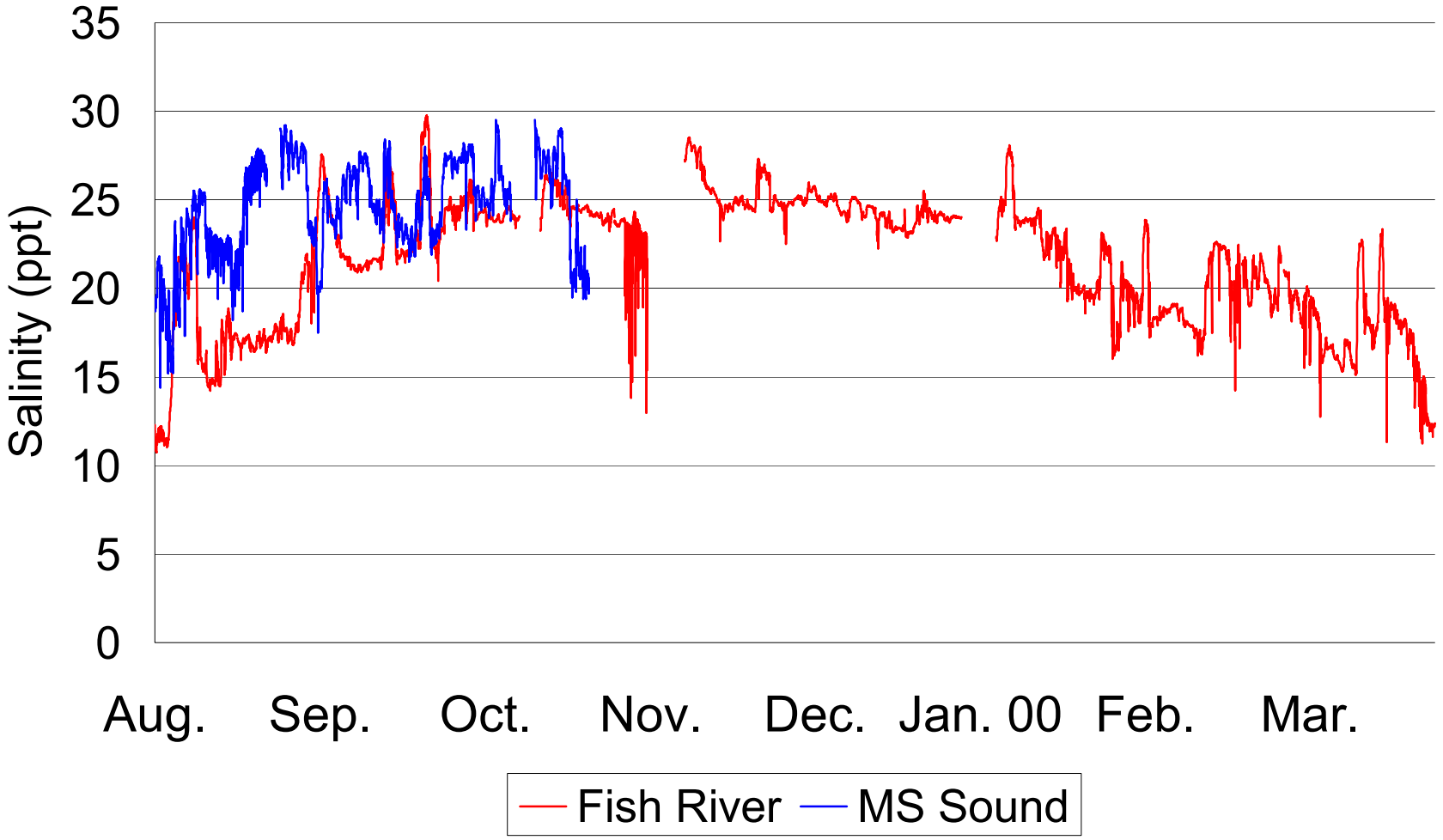

Fig. 8. Dissolved oxygen (ppm) recorded at Fish River Reef and Range Marker D, Mississippi Sound, for Year 1 field experiments.

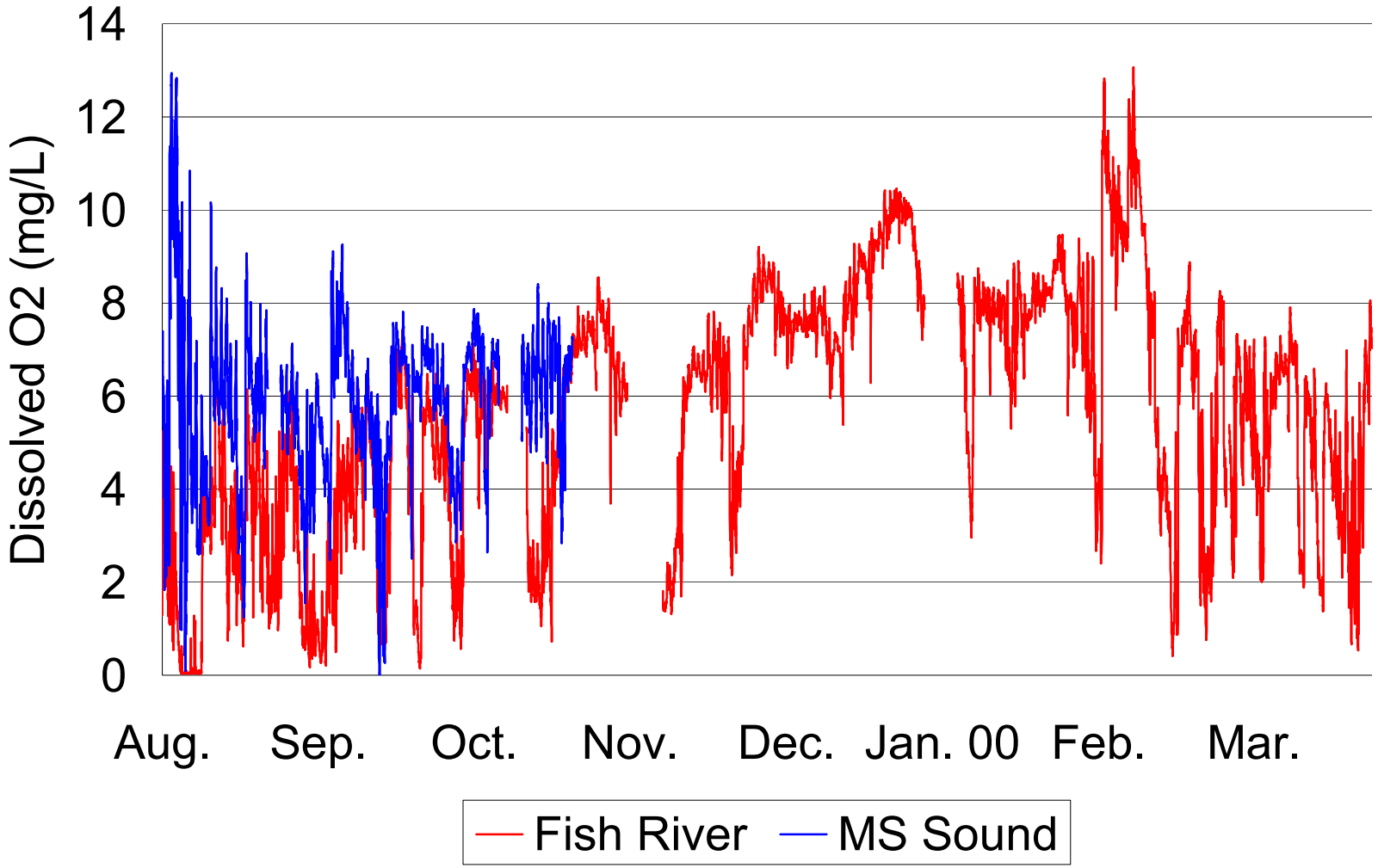

Fig. 9. Temperature (°C) recorded at Fish River Reef and Range Marker D, Mississippi Sound, for Year 1 field experiments.

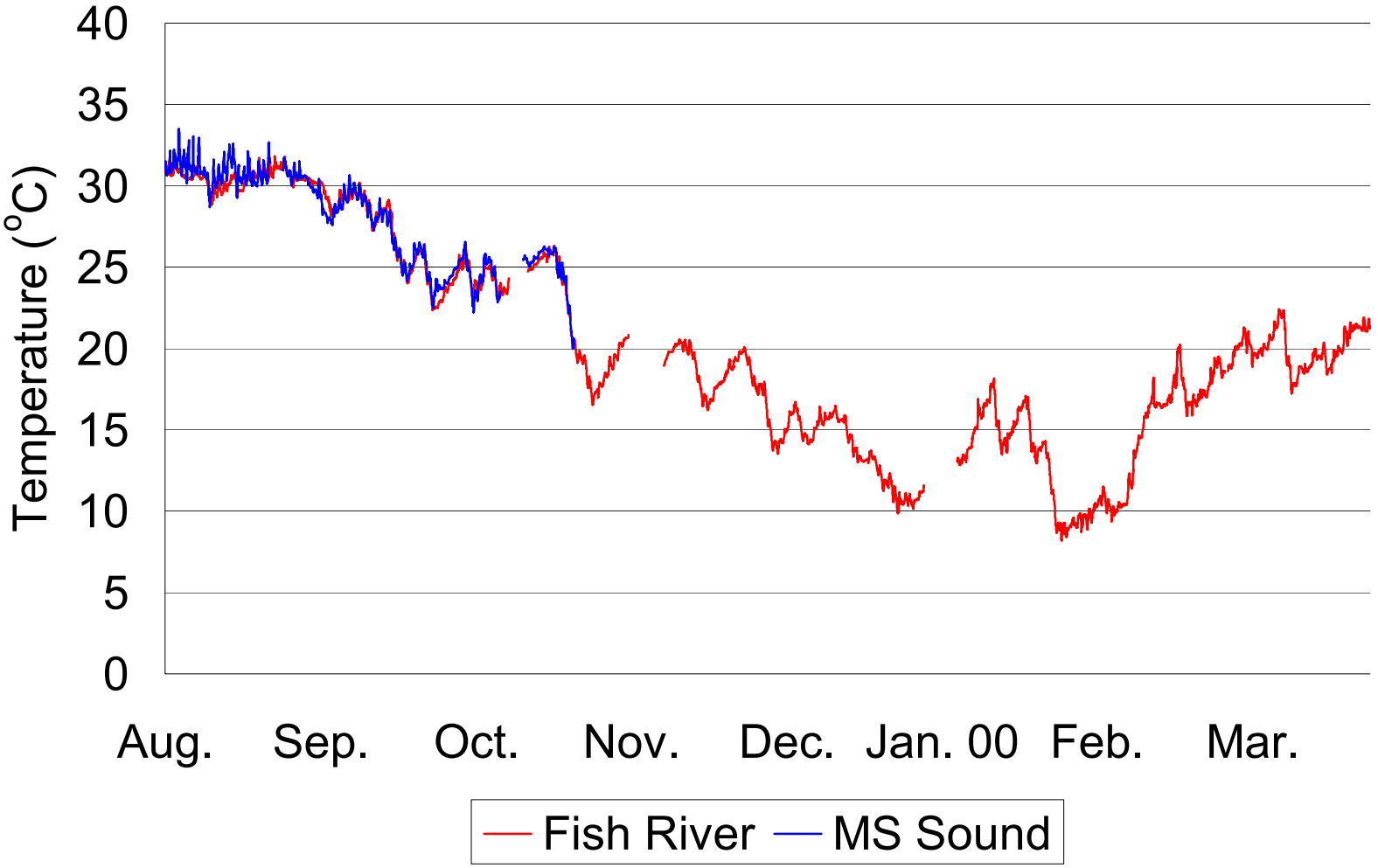

Fig. 10. Percent survival of four size classes of oysters set on whole shell at Fish River Reef from 13 August 1999 to 28 March 2000.

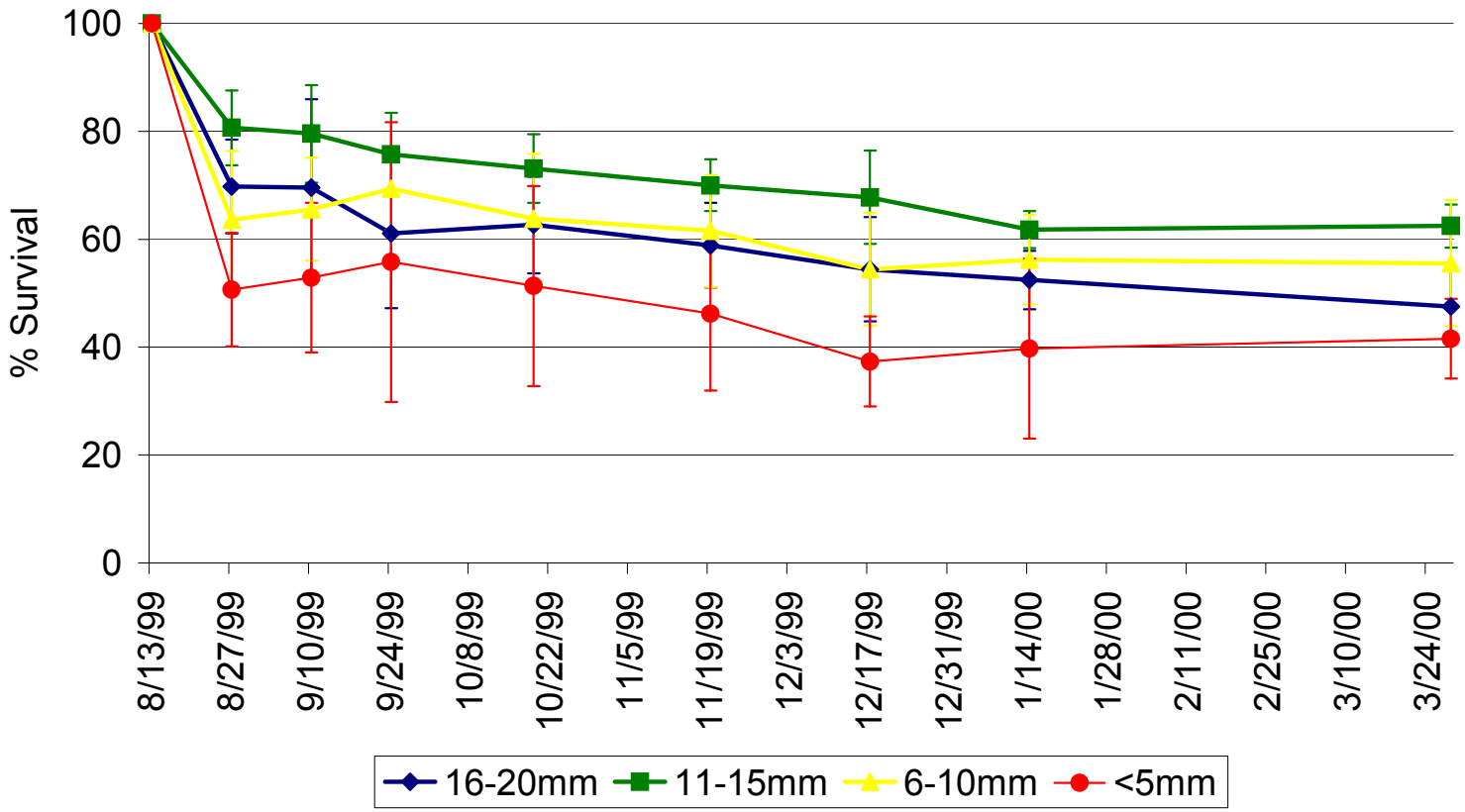

Fig. 11. Mean height (mm) of four size classes of oysters set on shell at Fish River Reef from 13 August 1999 to 28 March 2000.

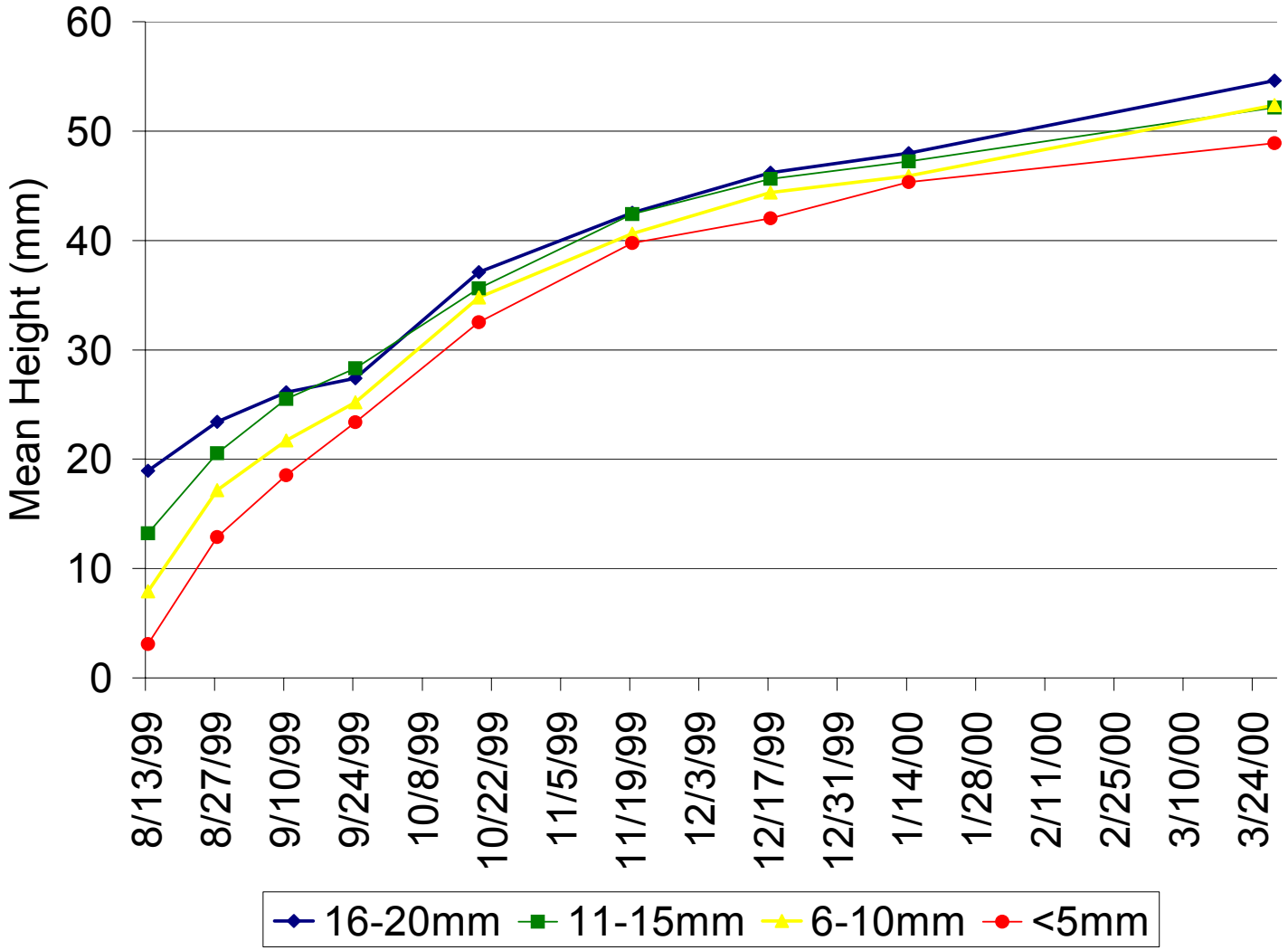

Fig.12. Percent survival of four size classes of oysters set on whole shell and micro-cultch at Range Marker D from 26 August to 22 October, 1999.

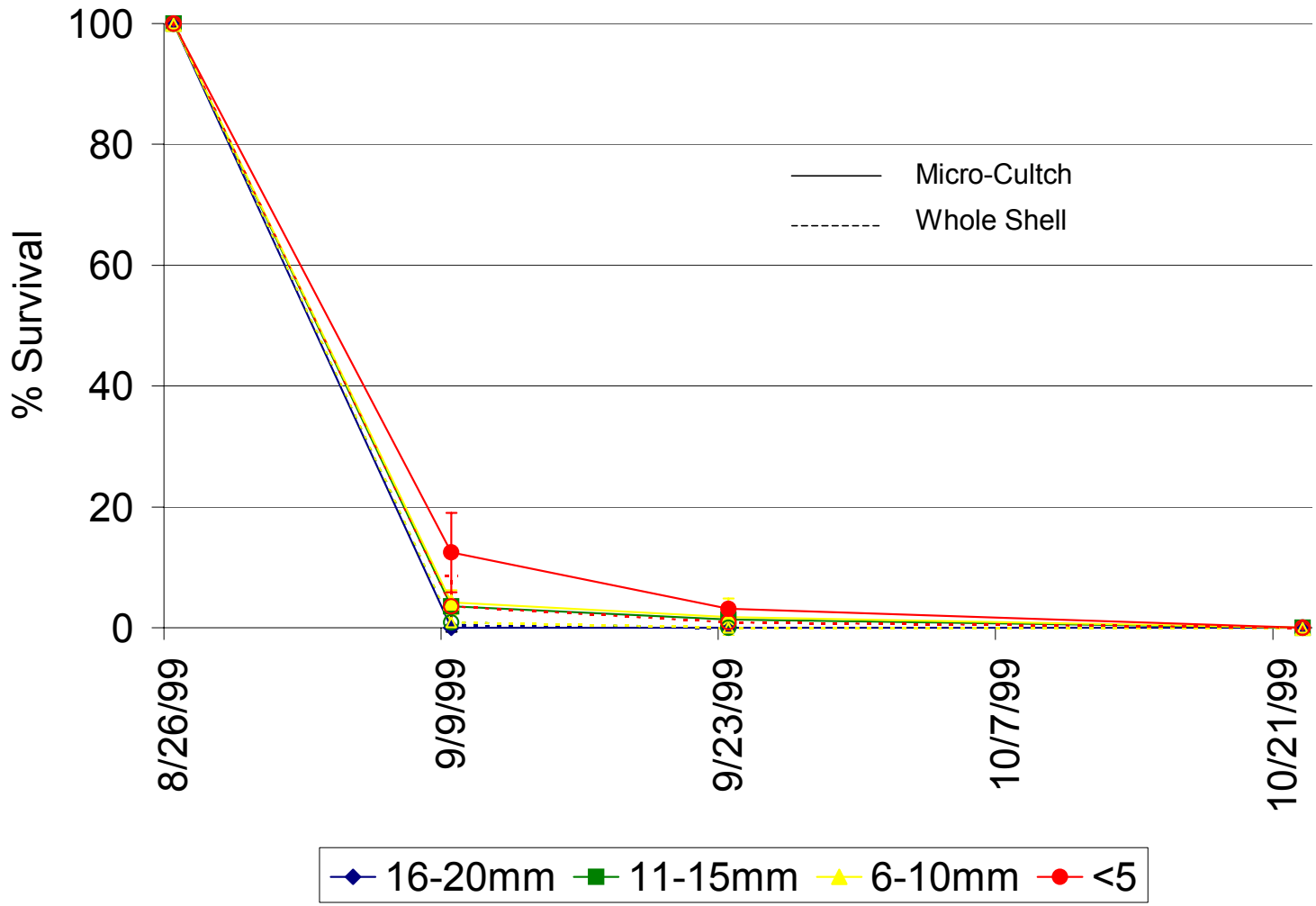

Fig. 13. Salinity (ppt) recorded at Fish River Reef and Cedar Point Reef for Year 2 field experiments. Hydrolab malfunction at Fish River Reef on December 18, 2000.

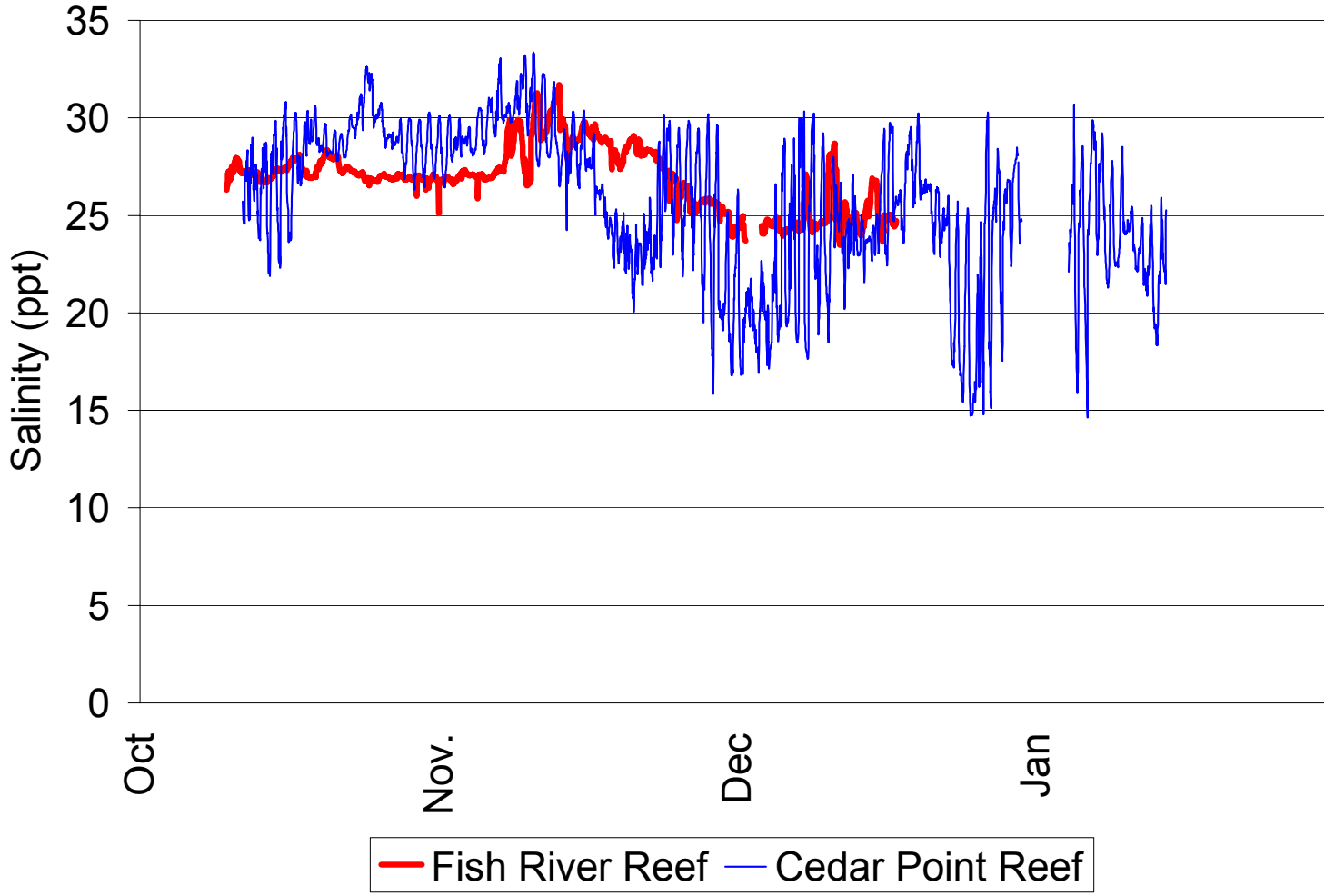

Fig. 14. Dissolved oxygen (ppm) recorded at Fish River Reef and Cedar Point Reef for Year 2 field experiments. Hydrolab malfunction at Fish River Reef on December 18, 2000.

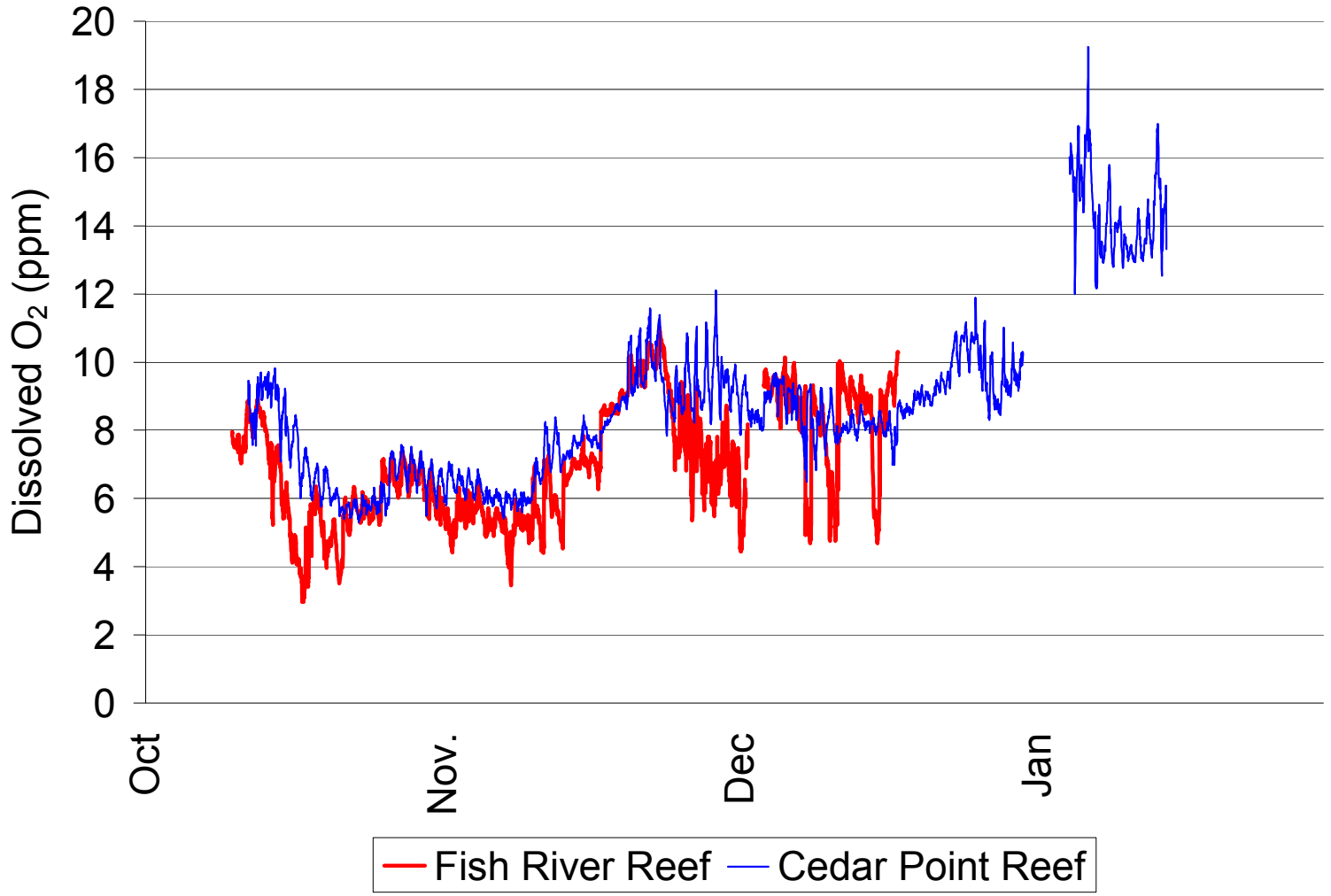

Fig. 15. Temperature (°C) recorded at Fish River Reef and Cedar Point Reef for Year 2 field experiments. Hydrolab malfunction at Fish River Reef on December 18, 2000.

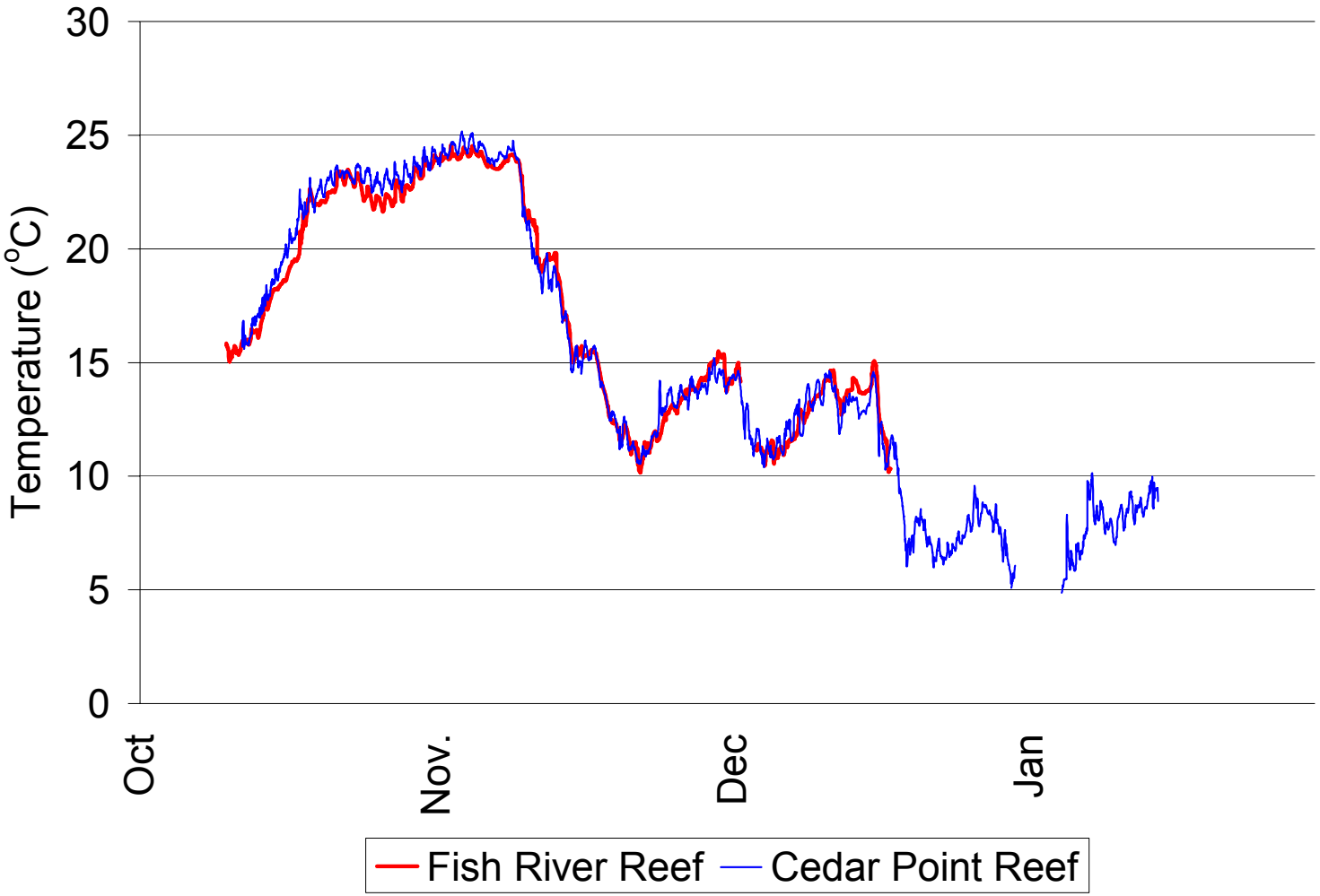

Fig.16. Percent survival of three size classes of oysters set on whole shell and single oysters held in unprotected tubs and protected bags at Cedar Point Reef, Alabama from 10 October 2000 to 18 January 2001.

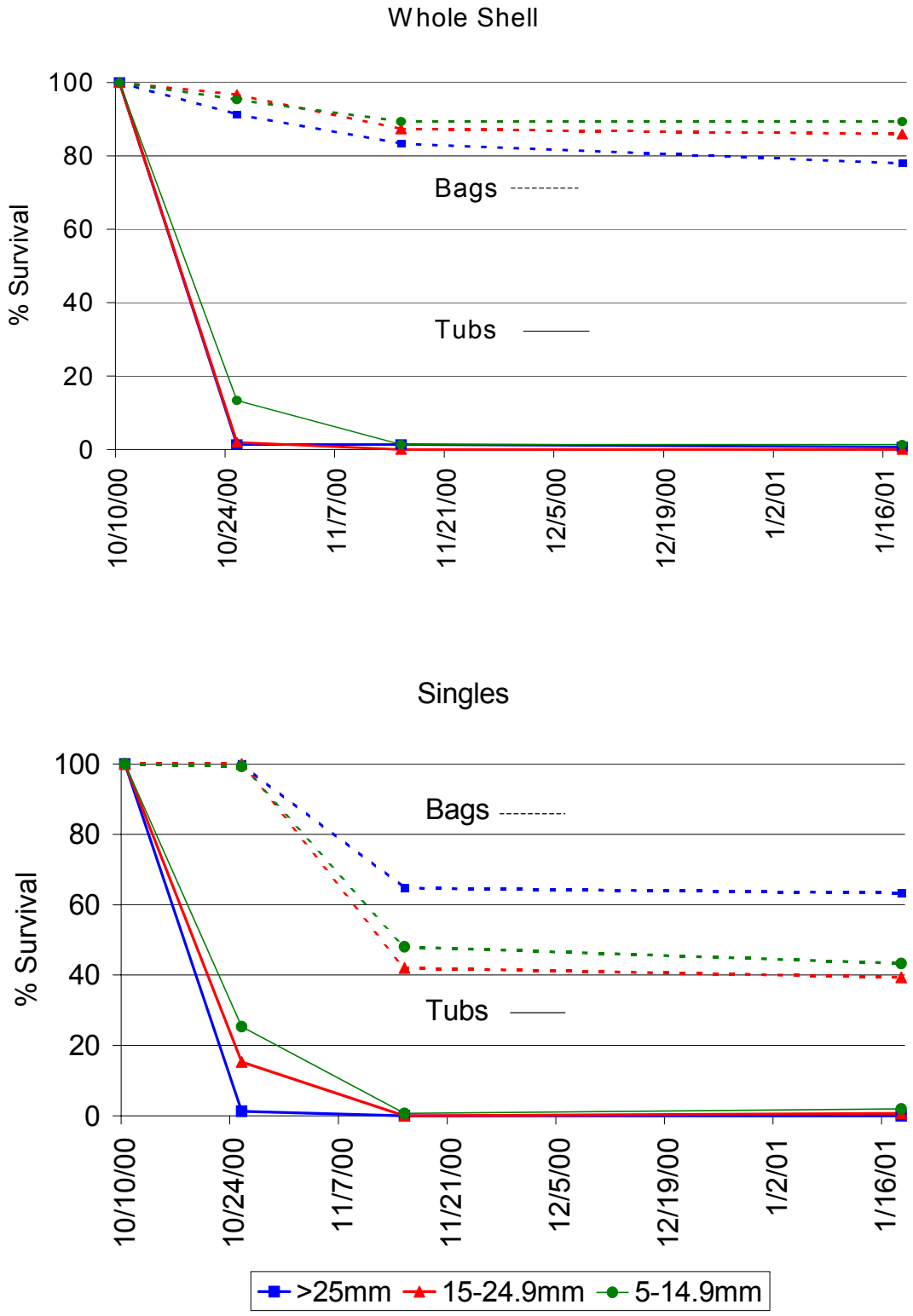

Fig.17. Percent survival of three size classes of oysters set on whole shell and single oystes held in unprotected tubs and protected bags at Fish River Reef, Alabama from 10 October 2000 to 18 January 2001.

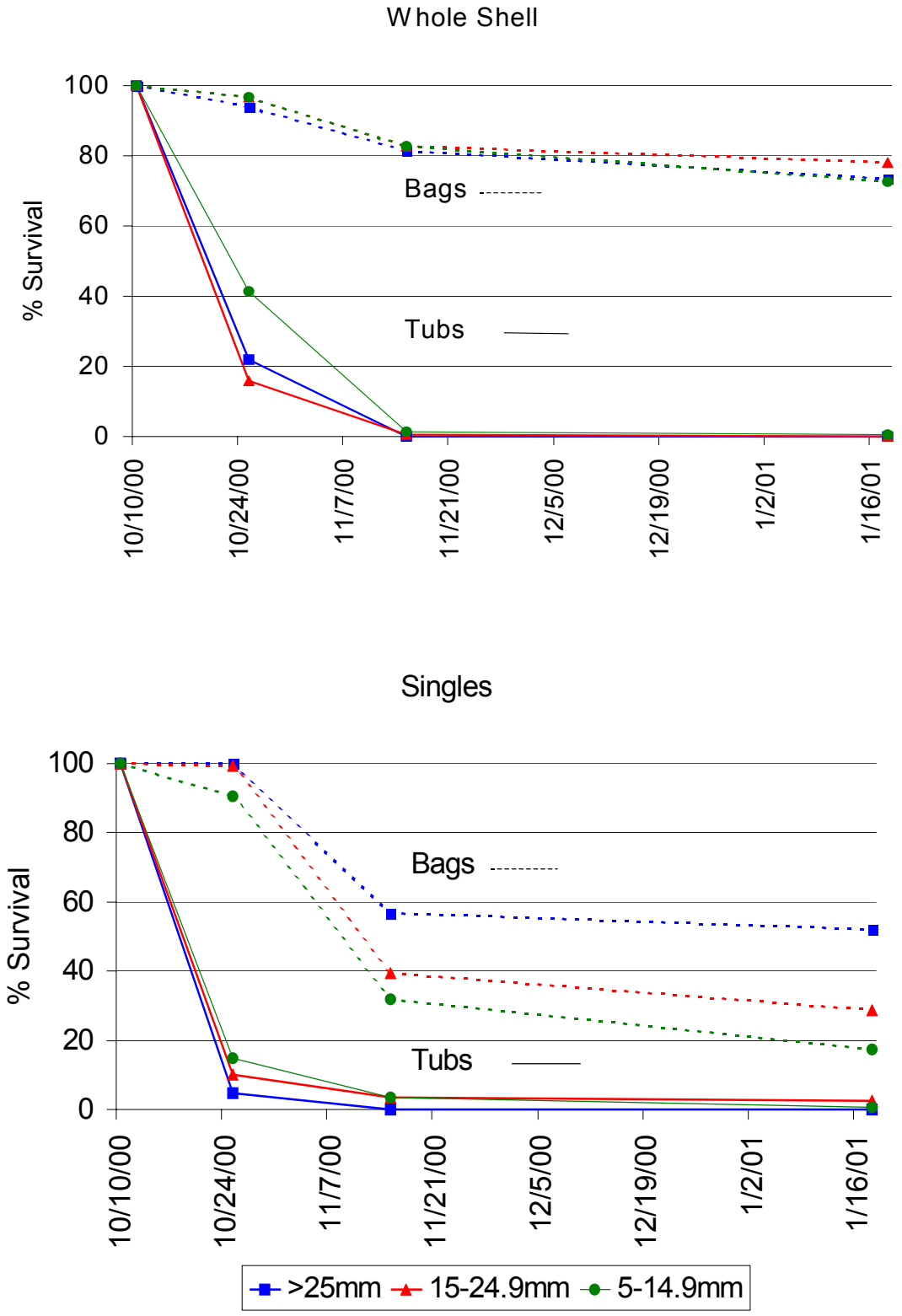

Fig.18. Mean number of oyster drills per unprotected tub at Fish River Reef and Cedar Point Reef from 10 October 2000 to 18 January 2001.

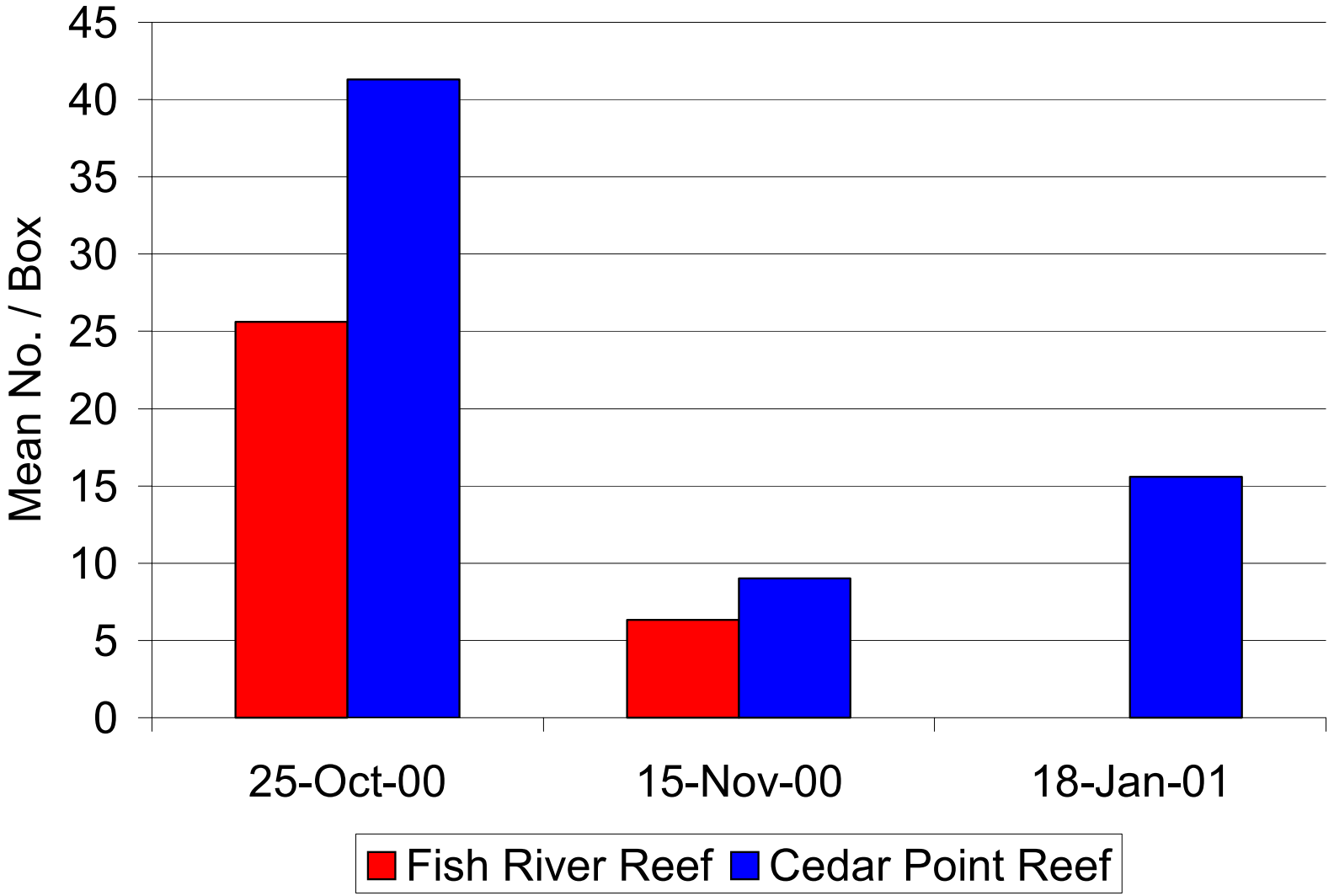

Fig. 19. Mean growth rate (mm/day) of three size classes of oysters set on whole shell and single oysters held in protected bags at Cedar Point Reef and Fish River Reef, Alabama from 10 October 2000 to 18 January 2001.

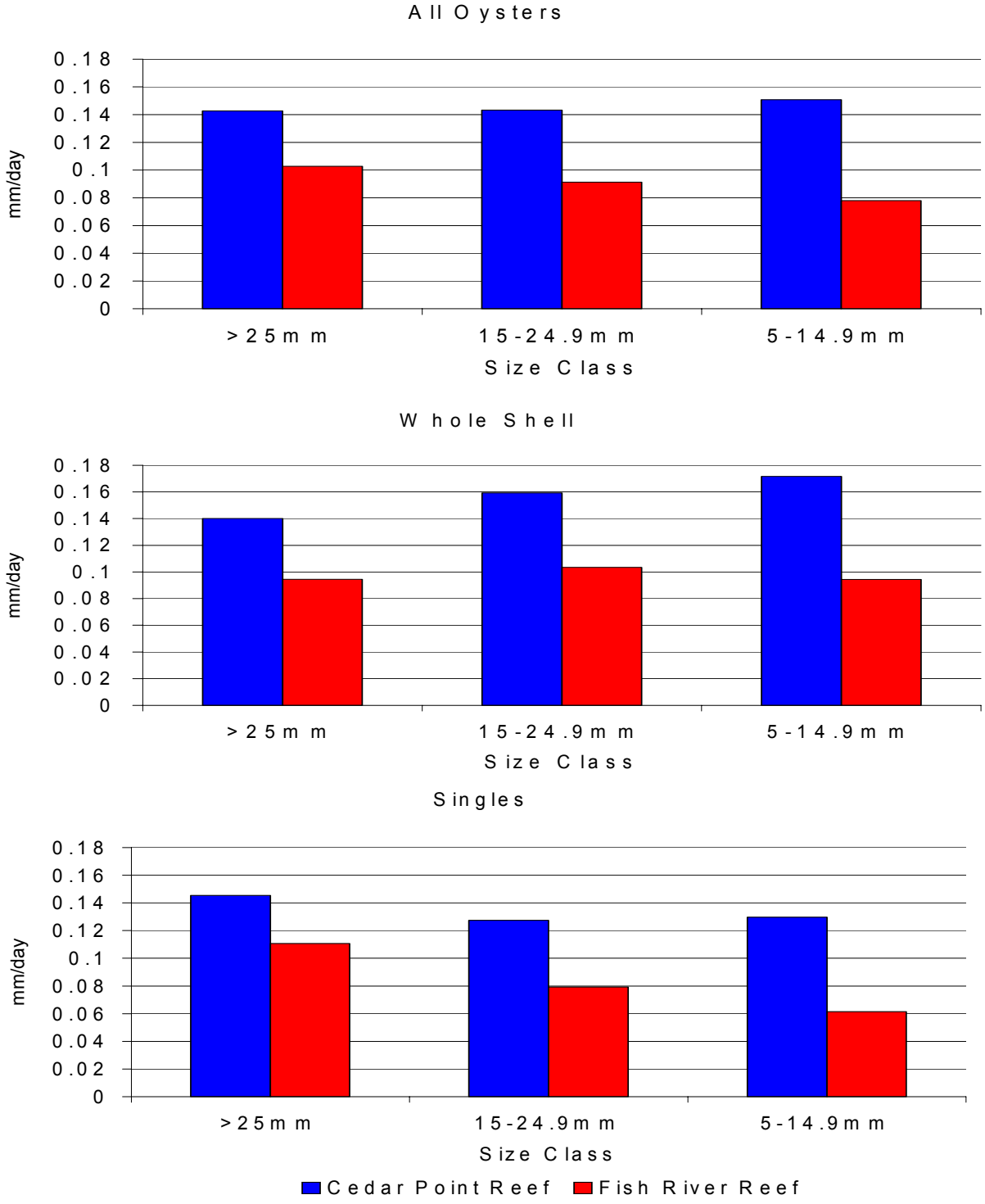

Fig. 20. Mean oyster height (mm) of three size classes of oysters set on whole shell and single oysters held in protected bags at Cedar Point Reef, Alabama from 10 October 2000 to 18 January 2001.

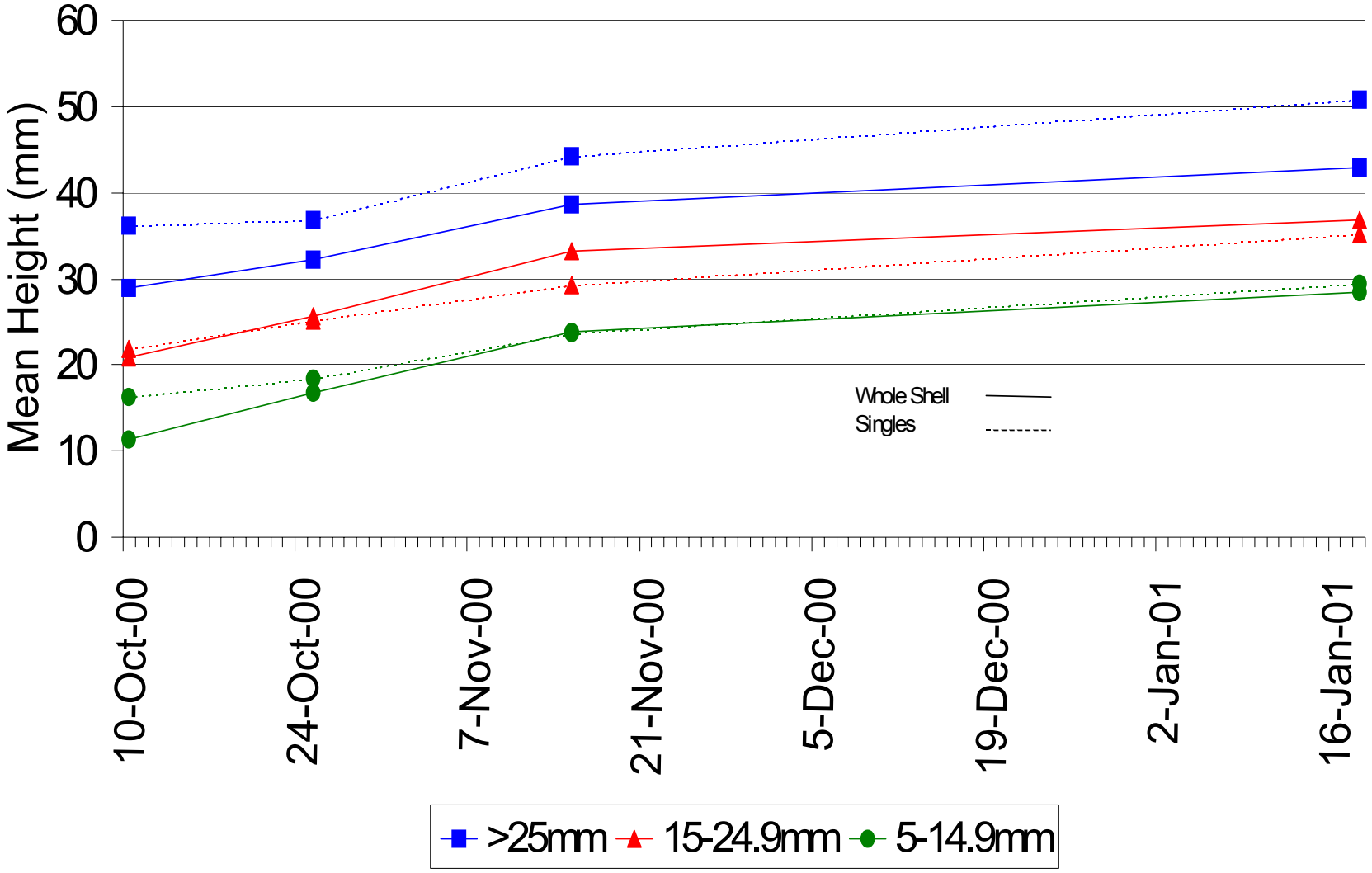

Fig. 21. Mean oyster height (mm) of three size classes of oysters set on whole shell and single oysters held in protected bags at Fish River Reef, Alabama, from 10 October 2000 to 18 January 2001.

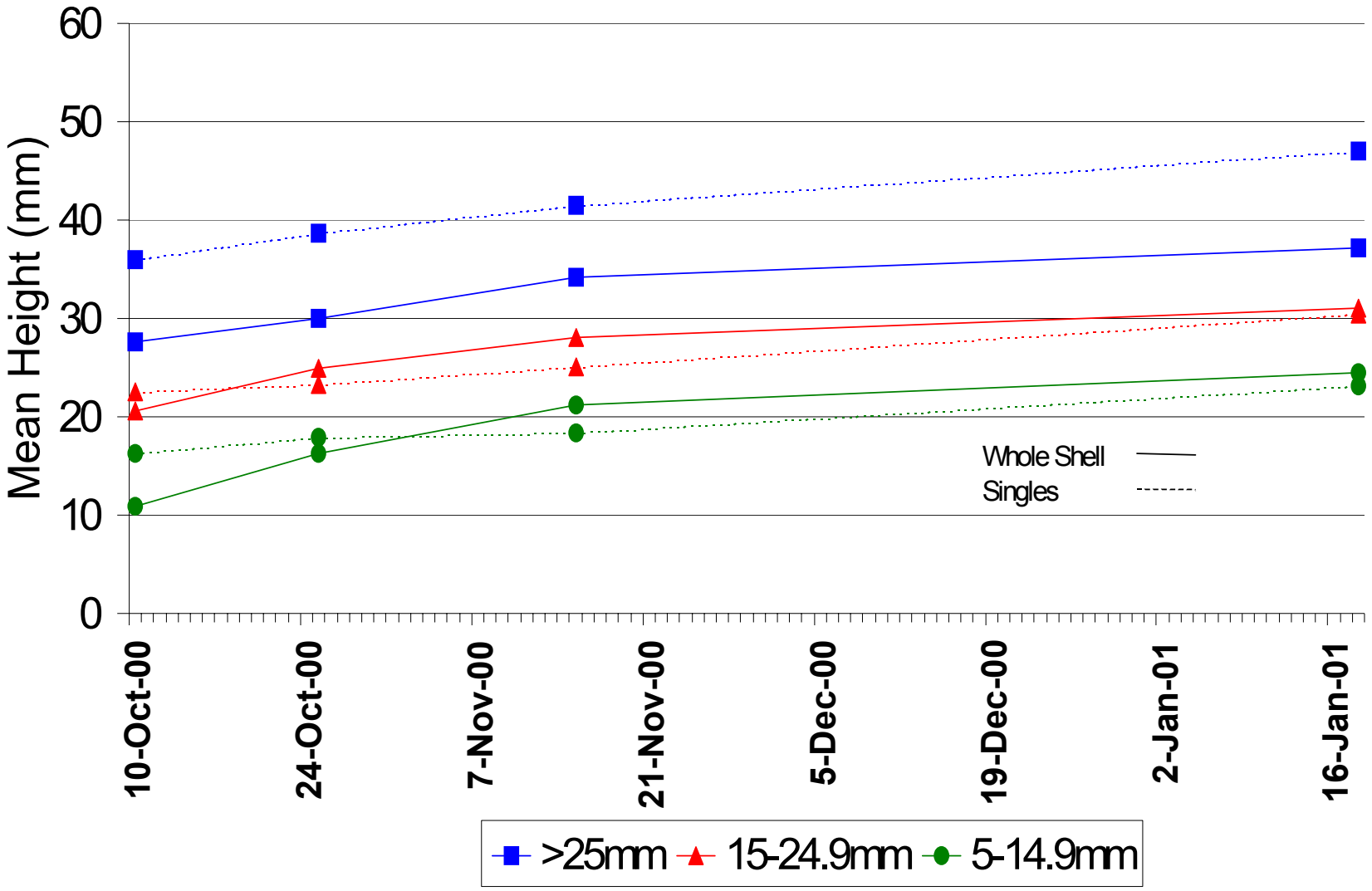

Fig. 22. Mean percent mortality of three size classes of single oysters and all oysters combined exposed to hypoxic conditions at 15 ppt salinity and 30°C temperature.

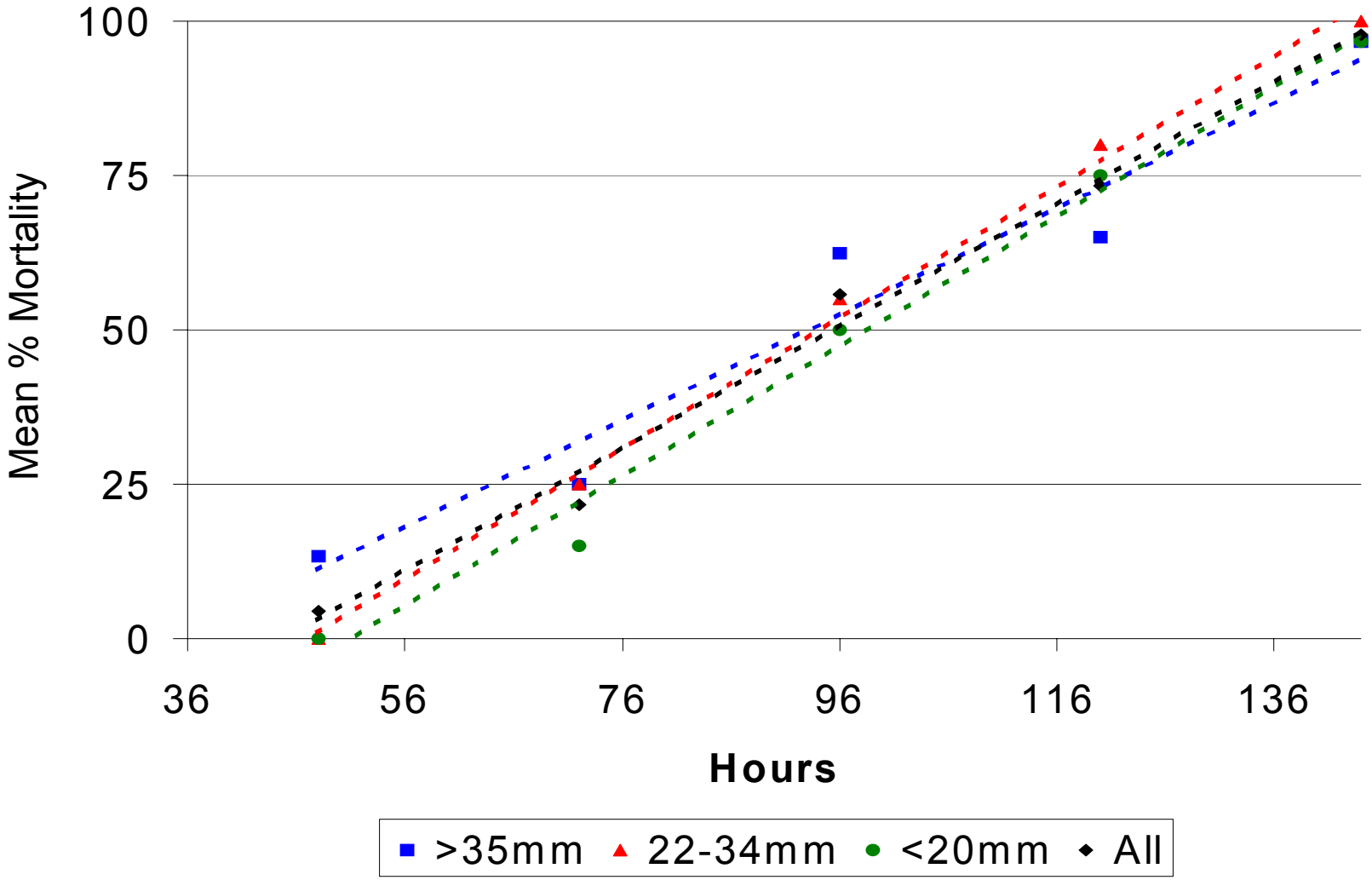

Fig. 22. LT-50s generated from probit analysis of three size classes of single oysters and all oysters combined exposed to hypoxic conditions at 15 ppt salinity and 30°C temperature.

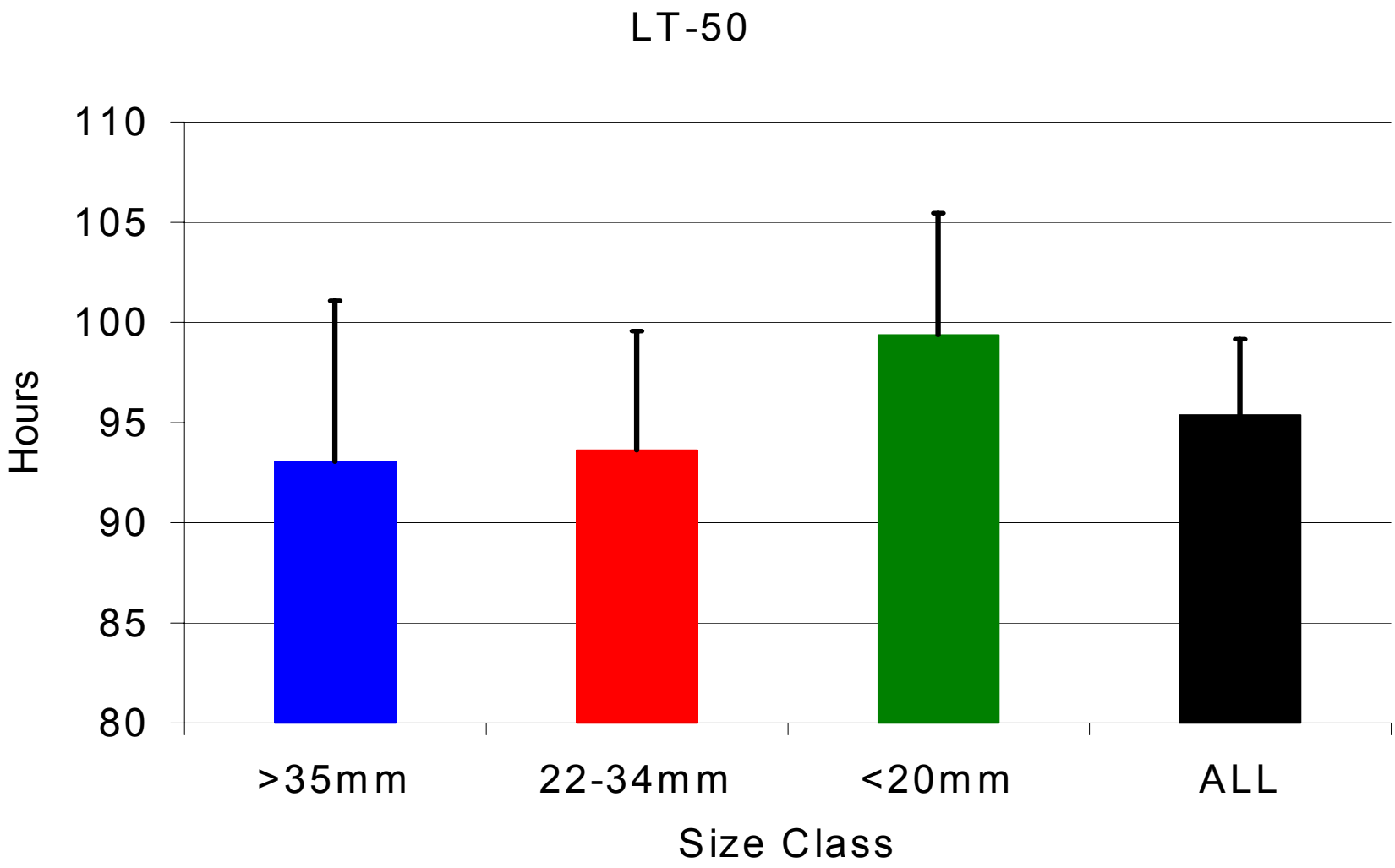

Fig. 23. The mean number of oysters eaten by oyster drills provided oysters set on whole shell and single oysters.

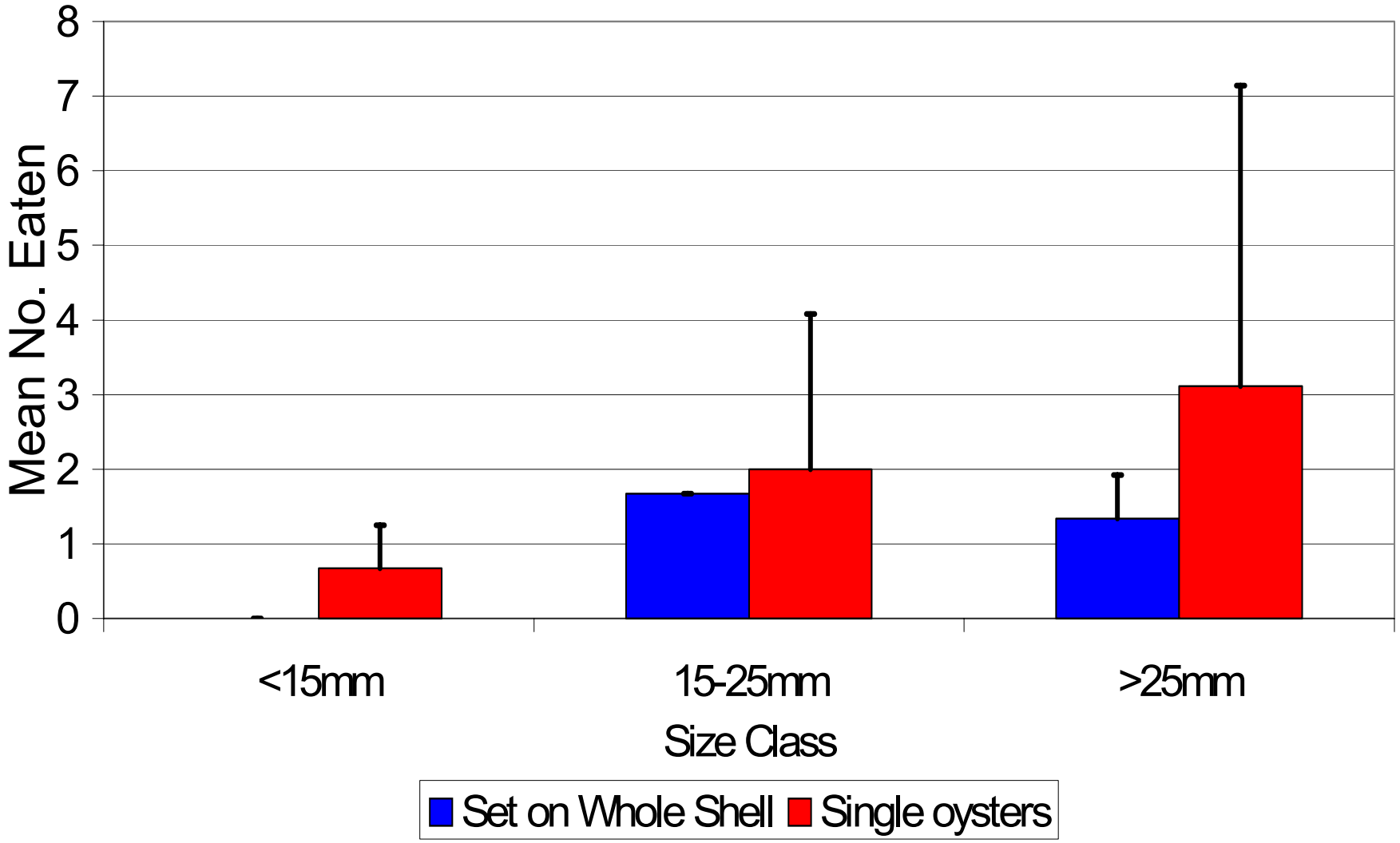

Fig. 24. The mean number of oysters eaten by oyster drills provided oysters set on whole shell only.

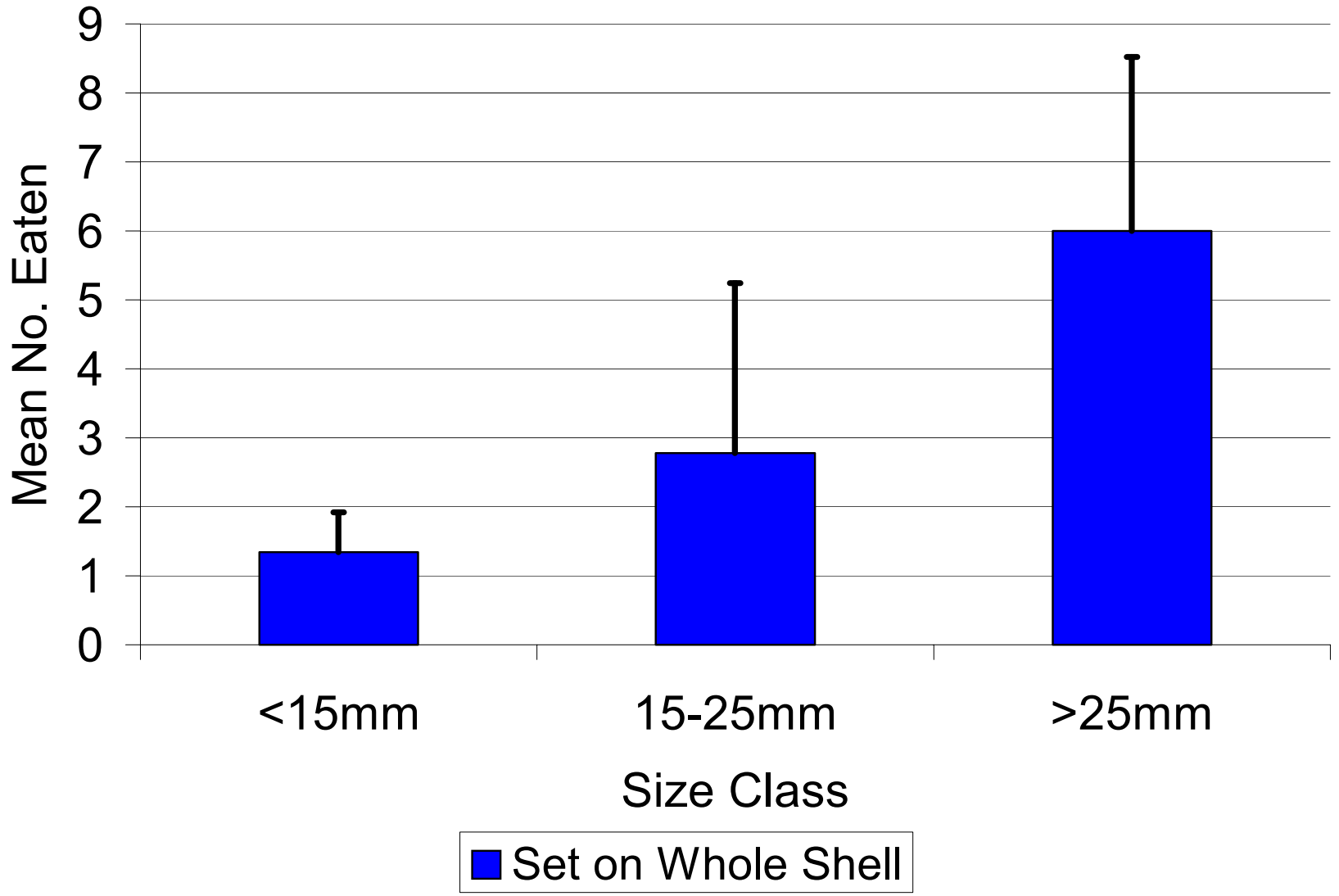

Fig. 25. The mean number of oysters eaten by blue crabs provided oysters set on whole shell and single oysters.

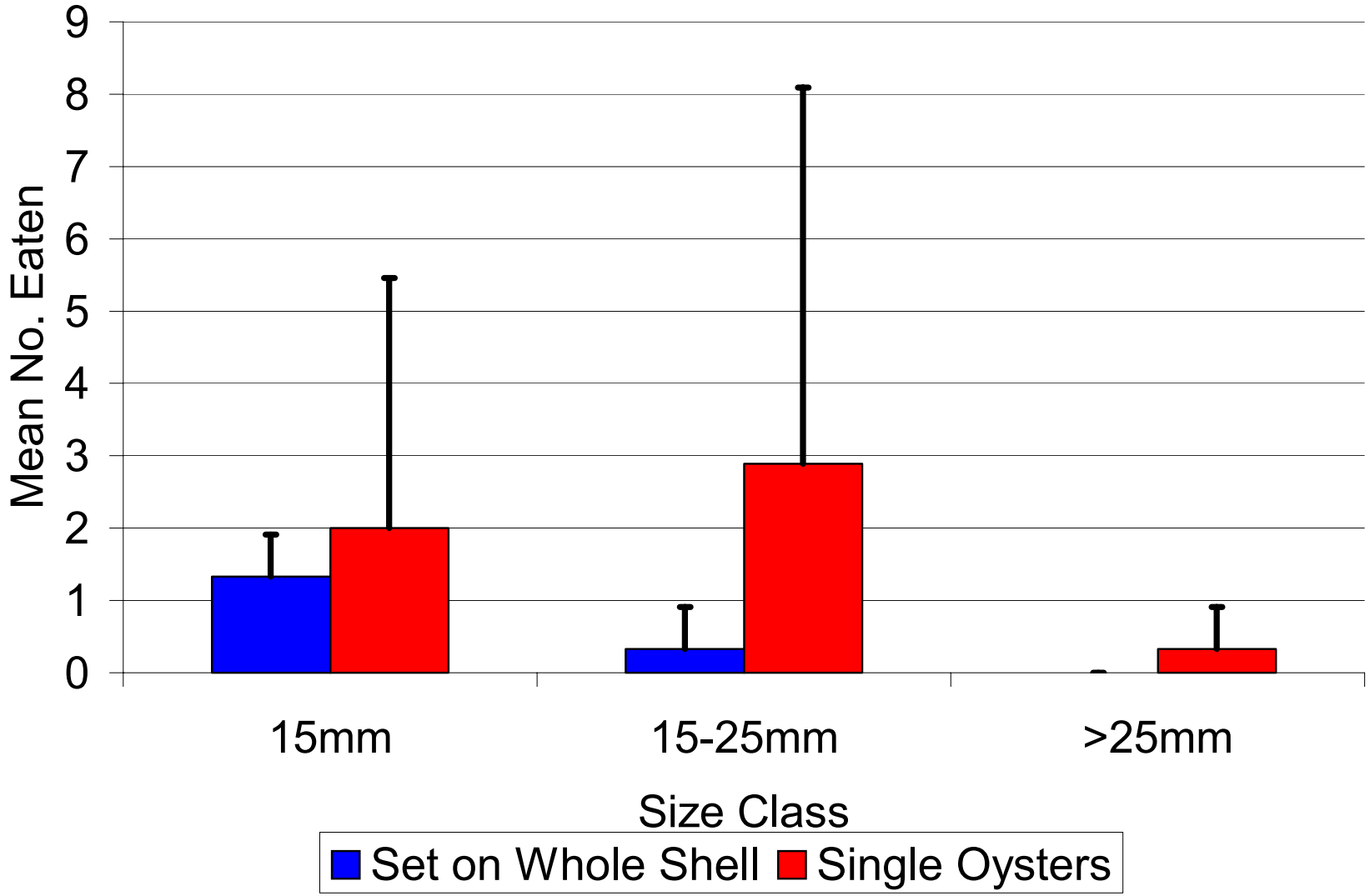
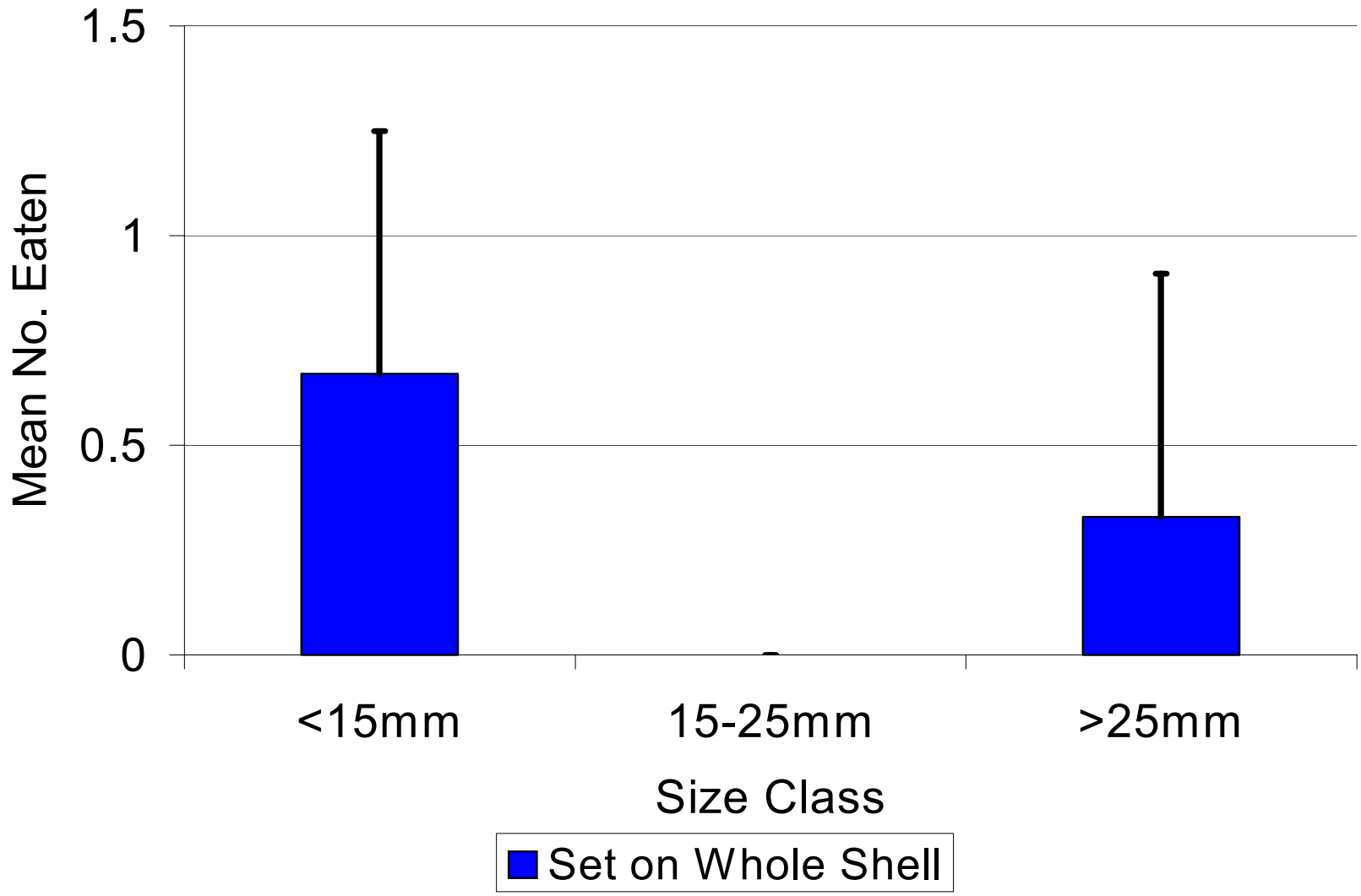
Fig. 26. The mean number of oysters eaten by blue crabs provided oysters set on whole shell.