

Abstract—A major cause of the steep declines of American oyster (*Crassostrea virginica*) fisheries is the loss of oyster habitat through the use of dredges that have mined the reef substrata during a century of intense harvest. Experiments comparing the efficiency and habitat impacts of three alternative gears for harvesting oysters revealed differences among gear types that might be used to help improve the sustainability of commercial oyster fisheries. Hand harvesting by divers produced 25–32% more oysters per unit of time of fishing than traditional dredging and tonging, although the dive operation required two fishermen, rather than one. *Per capita* returns for dive operations may nonetheless be competitive with returns for other gears even in the short term if one person culling on deck can serve two or three divers. Dredging reduced the height of reef habitat by 34%, significantly more than the 23% reduction caused by tonging, both of which were greater than the 6% reduction induced by diver hand-harvesting. Thus, conservation of the essential habitat and sustainability of the subtidal oyster fishery can be enhanced by switching to diver hand-harvesting. Management schemes must intervene to drive the change in harvest methods because fishermen will face relatively high costs in making the switch and will not necessarily realize the long-term ecological benefits.

Manuscript approved for publication 25 November 2003 by Scientific Editor. Manuscript received 20 January 2004 at NMFS Scientific Publications office. Fish. Bull. 102:298–305 (2004).

Conserving oyster reef habitat by switching from dredging and tonging to diver-harvesting

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Commercial fishing for demersal fishes and benthic invertebrates, such as mollusks and crabs, is commonly undertaken with bottom-disturbing gear that can inflict damage to seafloor habitats (Dayton et al., 1995; Engel and Kvittek, 1995; Jennings and Kaiser, 1998; Watling and Norse, 1998). Habitat damage from dredges and analogous gear, designed to excavate invertebrates that are partially or completely buried beneath the surface of the seafloor, is generally much more severe than the damage caused by bottom trawls (Collie et al., 2000). Furthermore, impacts on and recovery from bottom-disturbing fishing gear vary with habitat type; generally smaller effects and more rapid rates of recovery are found for infauna in sedimentary habitats and the most severe and long-lasting damage in biogenic habitats that emerge from the seafloor (Peterson et al., 1987; Collie et al., 2000). Such biogenic habitats include seagrass beds, fields of sponges and bryozoans, and invertebrate reefs. Biogenic reefs that provide important ecosystem services such as habitat for other organisms include not only tropical coral reefs but also temperate reefs constructed by oysters (Bahr and Lanier, 1981; Lenihan et al., 2001), polychaetes like *Petaloproctus* (Wilson, 1979; Reise, 1982), and vermetid gastropods (Safriel, 1975). The recovery of such emergent invertebrate reefs is a slow process because of the relative longevity of the

organisms that provide structure for the reef after they die and because of the nature of reefs as accumulations of multiple generations of reef builders.

One widespread temperate reef builder, the American oyster (*Crassostrea virginica*, also known as the “eastern oyster,” Am. Fish. Soc.), has been especially affected by bottom-disturbing fishing gear as the target of fisheries. More than one hundred years of dredging and tonging oysters in the Chesapeake Bay and Pamlico Sound have caused severe degradation of the oyster reef matrix (deAlteris, 1988; Hargis and Haven, 1988), such that reef area and elevation have been dramatically reduced (Rothschild et al., 1994; Lenihan and Peterson, 1998). Reduction in reef height has a serious consequence for the oyster population because one function of naturally tall subtidal oyster reefs is to elevate the oysters up into the mixed surface layer of the estuary; this layer of mixed surface water allows them to avoid mass mortality from persistent exposure to seasonally anoxic and hypoxic bottom water (Lenihan and Peterson, 1998). Reef height and structure also control reef hydrodynamics (e.g., flow speed, turbulent mixing, and particle delivery and deposition), which influence oyster population dynamics and production (Lenihan, 1999). Consequently, harvest-related reef destruction and degradation are considered major factors that have led to declines of American oys-

ters in many estuaries located along the coasts of the Atlantic Ocean and Gulf of Mexico (Lukenbach et al., 1999).

Loss of oysters and the biogenic habitat that they provide appears from archaeological and paleontological evidence to be a worldwide phenomenon in temperate estuaries (Jackson et al., 2001). Oyster loss hurts not only the oyster fishery but, more importantly, imperils the ecosystem services provided by the oysters. These include, especially, the provision of emergent habitat and reef-dependent prey resources for many fish and crustacean populations of commercial and recreational importance (Peterson et al., 2000; Lenihan et al., 2001; Peterson et al., 2003), the filtration of estuarine waters (Newell, 1988), and the promotion of estuarine biodiversity by provision of hard-bottom habitat in fields of mobile sediments (Wells, 1961).

Because of the importance of restoring and sustaining oysters and their reefs to serve both the oyster fishery and the ecosystem, we designed a field test of the habitat impacts of three oyster harvesting methods: dredging, tonging, and hand extraction by divers (diver-harvesting). Our study is a gear comparison, in which we assess not only the traditional response variable of quantitative harvest per unit of effort with each gear but also the degree of reef habitat damage induced by the extraction of the oysters (analogous to Peterson et al., 1983). We additionally examine the quality of the oysters harvested as a function of gear type. The results indicate that diver-harvesting is a more environmentally sound way of harvesting oysters than traditional methods with dredges and tongs and may be more compatible with conserving oyster reef habitat.

Methods

Study site

Gear comparisons were conducted on subtidal oyster reefs in the Neuse River estuary, North Carolina (35°00'20"N, 76°33'50"W). Environmental conditions of this estuary are well described elsewhere (Paerl et al., 1998; Lenihan, 1999). Briefly, the estuary is mesohaline, an optimal habitat for the American oyster, and was once an important oyster fishery ground (Lenihan and Peterson, 1998). The estuary contains remnants of many large, natural subtidal oyster reefs that have been intensely mined by oyster harvesting gear for over a century. Dredging is the most common fishing practice. Mining of the reef matrix has combined with sediment loading and eutrophication-associated hypoxia (Paerl et al., 1998) to degrade the oyster reef habitats and greatly reduce oyster populations (Lenihan and Peterson, 1998). In harvested areas, reefs that were 2–3 m tall in quantitative surveys in the late 1800s ($n=8$ reefs) were all <1 m tall in our survey conducted in 1994—a modification of habitat caused entirely by the removal of oysters and shells during harvesting with dredges and tongs (Lenihan and Peterson, 1998). To help maintain oyster harvests, the North Carolina Division of Marine Fisheries (NCDMF) restores oyster reefs throughout many locations in the estuary by creating piles of oyster shell, or marl, on the seafloor. These

restored oyster reefs are also targeted by oyster fishermen using dredges and, less often, using manual oyster tongs (Marshall¹).

Experimental oyster reefs

Gear comparisons were conducted in March 1996 on 16 subtidal oyster reefs that had previously been created in July 1993 as part of a reef restoration experiment (Lenihan and Peterson, 1998; Lenihan, 1999) in collaboration with NCDMF. The experimentally restored reefs (referred to as “experimental reefs” in this gear-comparison study) were piles of oyster shells 1 m tall, 6–7 m in diameter (28.3–38.5 m² in area), and generally hemispherical in shape. Natural subtidal reefs located elsewhere in the estuary are typically larger, rectangular biogenic structures, ranging from 8–13 m wide and 20–30 m long. Experimental reefs were constructed in 3–4 m of water on a firm and sandy bottom, and were separated by at least 50 m. From the time of their construction until use in our experiments, the restored oyster reefs remained research sanctuaries, protected from commercial and recreational shellfishing.

As oysters settle and undergo metamorphosis on the shells of other (live and dead) oysters, to which they are attracted by chemical cues (Tamburri et al., 1992), they help cement together and add to the shell matrix of the reef over years. Prior to our harvest treatments, the experimentally restored reefs were colonized by at least three generations of oysters, many of which grew to adult size (range of oyster sizes on experimental reefs at the start of our experiment: 2–11 cm in shell height). Consequently, the shell matrices of the reefs had become somewhat cohesive, although probably less so than natural oyster reefs. In February 1996, before initiation of experimental harvests, there was no significant difference in the mean density of adult (>1 cm in shell height) oysters (mean \pm SD 179.1 \pm 18.4/m²) among the four sets of four experimental reefs randomly selected to receive the four harvesting treatments (one-way ANOVA; $F_{3,12}=0.29$; mean square error=285.06; $P=0.83$). Experimental reefs in the Neuse River usually had slightly higher oyster densities nearer their base and larger oysters near the crest (see Lenihan, 1999).

Experimental harvests

We compared three types of oyster-harvesting techniques: dredging, hand-tonging, and diver-harvesting. In March 1996, each of 16 reefs was either dredged, tonged, diver-harvested, or left unharvested as a control (four replicates of each treatment). Experimental dredging and hand-tonging were conducted in the manner applied by commercial oyster fishermen. The dredge, 25 kg in weight and 1 m in width, was pulled behind a powerboat operated by NCDMF personnel with commercial oyster-dredging experience. Hand-tonging was also conducted by a professional oyster

¹ Marshall, M. 1999. Personal commun. North Carolina Division of Marine Fisheries, 3431 Arendell St., Morehead City, NC 28557.

fisherman, R. A. Cummings. Oysters and shell material collected by dredges and tongs were separated aboard the boat on a culling board, using the common culling techniques (i.e., breaking apart oysters and shell with hammers, mallets, and chisels). As mandated by law, oyster shell and undersized oysters (<7 cm in height) were thrown overboard above the reef from which they had been collected.

Hand collections of oysters were conducted by scuba divers (J. H. Grabowski and H. S. Lenihan). Unlike professional oyster divers in Chesapeake Bay and other areas, who rake large quantities of shell and attached oysters into baskets that are pulled aboard ship to be culled, the divers in this trial adopted a different method designed to preserve reef habitat. Instead of collecting shell and oysters indiscriminately, the divers chose only those oysters that appeared alive and of market-size. Selected oysters were hand picked from the reef and placed in heavy plastic mesh baskets that, when full, were subsequently pulled aboard the boat with haul lines.

To standardize fishing effort, each of the 12 harvested reefs was harvested for 2 hours, regardless of the number of oysters collected. A 2-h harvest period for each 28.3–38.5 m² reef was considered to be a thorough but not excessive level of harvesting by the professional fishermen. The numbers of oysters collected in the final three or four dredge hauls and oyster tongs were typically lower (by ~10–20%) than the preceding dredge hauls and tongs. This reduction in the catch per unit of effort was great enough that a fisherman foraging optimally would normally cease harvesting at that time and move on to another reef. Similarly, after 2 hours of diver-harvesting, most of the clearly visible market-size oysters had been harvested.

Quantifying reef structure

Measurements of oyster reef height and diameter were conducted on all 16 experimental reefs both before and after application of the three fishing methods. In February 1996, the preharvest height and radius of each oyster reef were measured by scuba divers using a custom-made “square angle,” consisting of two pieces (2 m and 5 m long) of 3-cm wide steel angle-iron, each with an attached 1-m long carpenter’s level. Both pieces of angle iron were marked at 1-cm intervals. The 5-m long (cross) piece was attached to the 2-m long (upright) piece by a roller-joint. The roller-joint allowed the cross piece to move up and down the upright piece, thus providing a measure of reef height, and to move horizontally in relation to the upright piece, thus providing a measurement of reef radius. The 2-m long piece also had a 0.75-m long piece of angle iron attached perpendicularly near its bottom so that it would not sink into the seafloor when placed upright.

One diver held the 2-m long angle iron perpendicular to the seafloor at the edge of a reef, while the other diver placed the 5-m long angle iron parallel to the seafloor, so that one end rested on the highest point of a reef and the other end met the upright angle iron at the reef’s edge. The height and radius of the reef were then measured by recording the height at which the cross piece met the

upright piece, and the distance at which the upright piece met the cross-piece. For each reef, a mean diameter was calculated by measuring three separate radii (oriented at three compass bearings, all 120° apart), multiplying the radii by two to estimate diameters, and then averaging the three diameters. This averaging procedure was undertaken because the reefs were not perfectly circular. Measurements of reef height and radius were repeated in March, two–five days after experimental harvests were completed.

Sampling oyster populations

We sampled live and dead oysters on each treatment and control reef before (late February 1996) and immediately after (late March) experimental harvests to estimate the proportion of oysters incidentally killed but not harvested by each harvesting treatment. Specifically, oyster data was collected within 30 hours of the application of the harvest treatment on each replicate reef. Densities of live and dead oysters were quantified by divers who haphazardly placed eight 0.5-m² weighted PVC quadrats on the reef surface at haphazard locations and recorded the number of live and dead oysters greater >1 cm in height. The density of dead oysters was measured by counting the number of oyster shells that were articulated and appeared relatively fresh (i.e., not black in color or decayed), or oysters with somatic tissue exposed because of cracked, broken, or punctured shells. Oysters with exposed somatic tissue almost certainly die because of predation by fishes and crabs in the Neuse River estuary (Lenihan, 1999; and see Lenihan and Micheli, 2000). Mean proportions of dead oysters were computed (dead oysters/dead+alive oysters), as well as mean densities of live and dead oysters on each reef.

Catch per unit of effort

The relative efficiency of each harvesting method was determined by comparing the numbers of bushels (1 bushel=36.4 L) of market-size oysters taken per hour of fishing. We quantified numbers of bushels for each harvesting method aboard the boat by placing oysters of legal size in premeasured mesh baskets. After being counted, and upon termination of the harvest trial, many of the oysters were returned to other nearby reefs not involved in the experiment.

Statistics

One-way analysis of variance (ANOVA) was used to compare the following across harvest treatments and controls: 1) changes in mean reef height and diameter; 2) catch per unit of effort; 3) the proportion of oysters found dead on reefs before harvest; 4) the proportion of oysters found dead on reefs after harvest; and 5) the absolute difference in the proportion of oysters found dead before versus after harvesting (*after* minus *before*). Data from all treatment (dredging, tonging, and diver-harvesting; $n=4$ for each treatment) and the control ($n=4$) reefs were used in

Table 1

Results of one-way ANOVAs comparing differences in reef height (cm), reef diameter (cm), and catch per unit of effort (number of oysters collected per hour) among experimental reefs harvested by different methods (dredging, tonging, diver-harvesting, and controls). df = degrees of freedom; ms = mean square; F = F -value; P = P -value; ss = sum of squares. Partial r^2 = treatment ss/total ss.

Source	Reef height					Reef diameter				Catch per unit of effort			
	df	ms	F	P	partial r^2	ms	F	P	partial r^2	ms	F	P	partial r^2
Harvesting treatment	3	0.09	36.90	0.0001	0.90	0.07	15.79	0.0002	0.80	3.21	17.84	0.0001	0.11
Residual	12	0.003				0.005				0.08			
Total	15				Total ss: 0.31								9.64

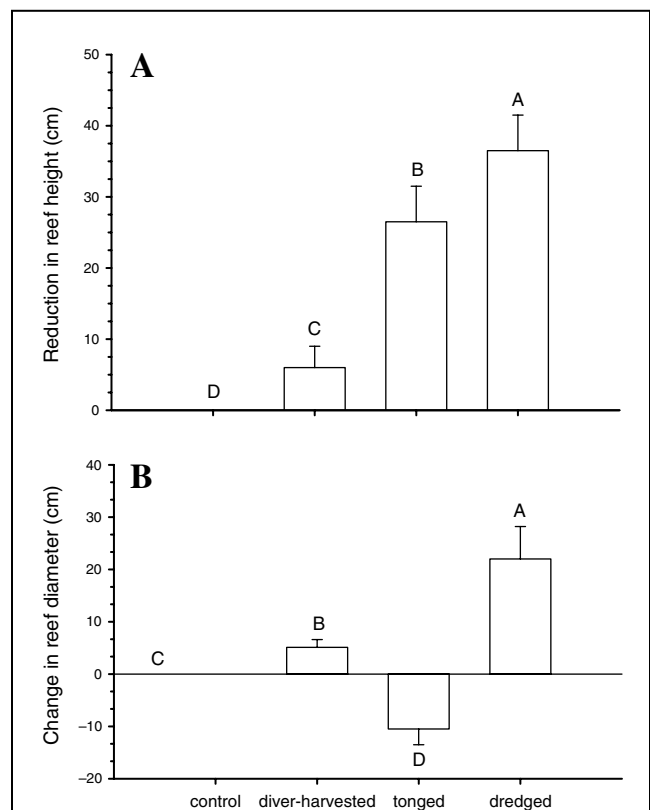
the ANOVA. Before ANOVA, homogeneity of variances was tested by using Cochran's method ($\alpha=0.05$). All data passed this test. After ANOVA, *post hoc* differences among means were compared by using Student-Newman-Keuls (SNK) tests ($\alpha=0.05$).

Results

Reef height and diameter

Dredge harvesting on experimental reefs removed the largest amount of shell material from the reefs, based on the reduction of reef height (Fig. 1A) and on the qualitative assessment of increases in numbers of oyster shells found on the seafloor around the reefs. Hand-tonging removed an intermediate amount of reef materials, and diver-harvesting removed far less shell matrix than either dredging or tonging. All harvesting methods reduced the height of restored oyster reefs (Fig. 1A), but dredging (34% of reef height) and tonging (23%) had greater impacts than did diver-harvesting (6%). ANOVA demonstrated significant differences among harvest treatments in mean change in reef height (Table 1); all harvest treatments induced a loss in reef height as compared with unharvested control reefs (SNK; $P<0.05$). Dredging reduced reef height more than any other treatment (SNK, $P<0.05$), and tonging reduced reef height more than diver-harvesting (SNK, $P<0.05$). The reduction in reef height caused by diver-harvesting was small (mean \pm SD: 6 ± 3 cm). However, diver-harvesting nearly eliminated the veneer of live market-size oysters on reefs, which provides substantial structure on reef surfaces.

Oyster harvesting either slightly increased or slightly decreased reef diameter, depending upon method (Fig. 1B). Reef material was apparently removed from edges of reefs by tonging, thereby reducing reef diameter. Shell was spread around the reefs by dredging, thereby increasing reef diameter after application of that harvesting method. The effects of oyster harvesting on reef diameter proved significant (Table 1). Tonging significantly reduced reef size compared with controls and the other two harvesting treatments (SNK; $P<0.05$), whereas dredging

**Figure 1**

Modification of reef size and structure caused by various harvesting techniques. (A) Mean (+SE) reduction in the height of experimentally restored oyster reefs caused by three types of oyster harvesting: hand-harvesting by divers, hand tonging, and dredging. Dredges are pulled behind power boats. Reefs were located in the Neuse River estuary, North Carolina. Letters represent results of SNK *post hoc* tests: dredged>tonged>diver-harvested>control at $P<0.05$. (B) Mean (+SE) change in the diameter of experimental oyster reefs caused by different oyster-harvesting techniques. Letters represent results of SNK *post hoc* tests: dredged>diver-harvested>control>tonged at $P<0.05$.

Table 2

Results of one-way ANOVAs comparing differences in the proportion of oysters found dead ("mortality") on reefs before and after harvesting by different methods (dredging, tonging, diver-harvesting, and controls), and the absolute difference (*after-before*) in the proportion of dead oyster found before versus after harvesting. df = degrees of freedom; ms = mean square; *F* = *F*-value; *P* = *P*-value; ss = sum of squares. Partial r^2 = treatment ss/total ss.

Source	Before mortality					After mortality				Difference in mortality			
	df	ms	<i>F</i>	<i>P</i>	partial r^2	ms	<i>F</i>	<i>P</i>	partial r^2	ms	<i>F</i>	<i>P</i>	partial r^2
Harvesting treatment	3	0.001	0.49	0.69	0.11	0.02	7.90	0.004	0.58	0.01	7.56	0.004	0.57
Residual	12	0.001				0.002				0.08			
Total	15	Total ss: 0.01								0.08			

increased reef diameter compared to the other treatments (SNK; $P < 0.05$). The increase in diameter of diver-harvested reefs was also greater than that for controls (SNK; $P < 0.05$). The substantial increase in shell material (with oysters of all sizes) spread out on the seafloor on dredged reefs indicates that the collection efficiency of dredges is less than 100%.

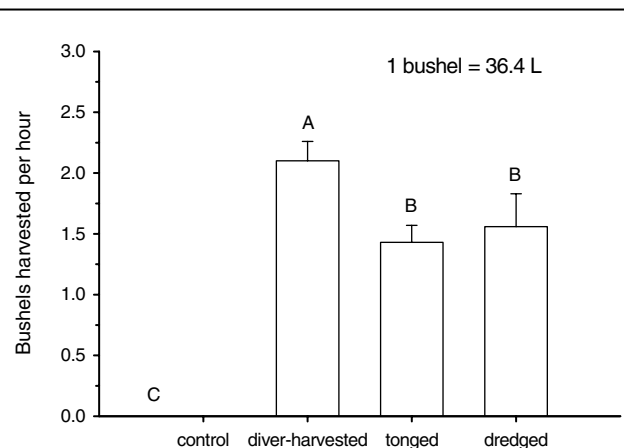
Catch per unit of effort

Catch per unit of effort of oysters included the time required to collect oysters from the reef and the time needed to separate (i.e., cull) them from undersized oysters and shell material. Two of the harvesting methods, hand-tonging and oyster dredging, are one-man operations in which one fisherman can operate the harvesting gear, cull oysters, and drive the boat. Therefore, measurements of catch per unit of effort for dredging and tonging represent the numbers of bushels of oysters one fisherman can collect per hour. In contrast, scuba diving is rarely attempted alone and it is usually necessary for someone else to tend the diver (e.g., helping him or her in and out of the water) and to haul oysters up to the boat when given a signal by the diver on the reef. Divers should preferably work as a team using the "buddy" system for safety reasons. Data for diver-collections are given in bushels per hour collected by one diver but hauled up to the boat and culled by a second person.

There was a significant difference in the numbers of bushels collected per hour by the different harvesting techniques (Table 1). Diver-harvesting had a higher catch efficiency than all other treatments (SNK; $P < 0.05$; Fig. 2). Diver-harvesting was about 25% more time efficient than dredge harvesting and 32% more efficient than tonging. There was no statistically significant difference in efficiency between dredging and tonging (SNK; $P > 0.05$).

Incidental oyster mortality

The proportion of oysters found dead on experimental reefs in February 1996 (~20%), prior to experimental

**Figure 2**

Mean (+SE) number of bushels collected per hour on experimental reefs by different oyster-harvesting techniques. Letters represent results of SNK *post hoc* tests: diver-harvested > dredged and tonged > control at $P < 0.05$.

harvesting, was similar to that found on other nearby experimental and natural reefs in the Neuse River estuary in preceding years (e.g., Lenihan and Peterson, 1998; Lenihan 1999). In February, the proportions of dead oysters did not differ among the four sets of reefs destined to be experimentally harvested (Table 2, Fig. 3A). In contrast, there was a large and statistically significant difference in the proportions of dead oysters on the reefs after harvesting (Table 2, Fig. 3A). The proportions of dead oysters on reefs that had been tonged and dredged were significantly greater than on diver-harvested and control reefs (SNK; $P < 0.05$).

Before-after-control-impact (BACI) comparison of the change in proportions of dead oysters from before to after harvesting (*after-before*), a direct estimate of incidental mortality caused by harvesting gear, showed a similar pattern to mortality inferred from *in situ* proportions of dead oysters in March after harvesting (Table 2, Fig. 3B).

A significant treatment effect in the *after* period (Table 2) indicated that the change over time in proportion of dead oysters varied among harvest treatments. Tonging and dredging increased the fraction of dead among *in situ* oysters on reefs (SNK; $P < 0.05$; Fig. 3B), but diver-harvesting did not. Immediately after harvesting, divers found that many oysters on tonged and dredged reefs had been broken open, severely cracked, or punctured.

Discussion

Our comparisons of gear revealed relatively unambiguous differences in their harvesting efficiency for oyster dredges, tongs, and hands of divers. Dredging and tonging had similar and statistically indistinguishable catch efficiencies, which seems reasonable given that both techniques are commonly employed in the same locations and times in the oyster fishery. Presumably, fishermen choose between these two gears on the basis of personal preference, history, and skill, as well as on the basis of water depth, bottom type, and other factors that did not vary in our study. Diver-harvesting of oysters resulted in higher rates of harvest per hour, but this enhancement in catch efficiency required the presence of two people, one diver beneath the surface and another person on deck involved in hauling baskets of oysters onto the deck and culling out marketable oysters. Because the increase in efficiency was only 25–32%, this enhancement falls short of the 100% required to compensate each fisherman to the same degree that dredging and tonging provide. Nevertheless, the immediate economics of diver-harvesting could prove competitive or even superior if the single deckhand could serve two or more divers, which seems likely from our experience with the workload on deck, and if the oysters taken are priced more favorably because of larger size or less damage, which seems possible. A complete short-term economic comparison would need to include higher costs for fuel in dredging and costs of filling air tanks for diving, as well as depreciation of gear.

This discussion of the basic efficiencies and economics of the methods of commercial oyster fishing is based upon short-term considerations only. That short-term time perspective is the cause of failures to achieve sustainability in fisheries quite generally (Ludwig et al., 1993; Botsford et al., 1997). We show that adoption of hand-harvesting by divers would result in substantially less fishery-induced reduction in reef height by a factor of four to six, implying greater preservation of the habitat and thus a more sustainable fishing practice. Our data on the changes in area covered by reefs as a function of harvest treatment revealed only small differences among treatments. The height of a reef

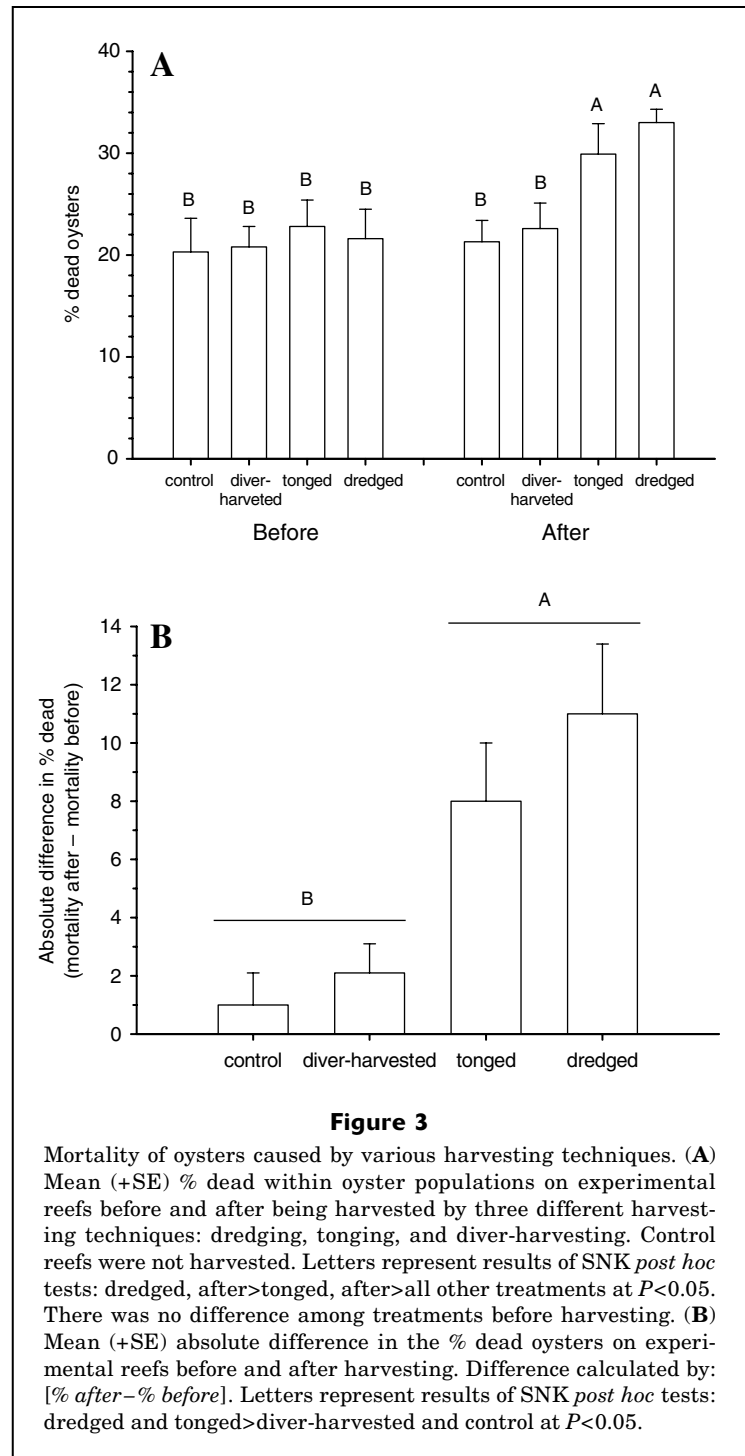


Figure 3

Mortality of oysters caused by various harvesting techniques. (A) Mean (+SE) % dead within oyster populations on experimental reefs before and after being harvested by three different harvesting techniques: dredging, tonging, and diver-harvesting. Control reefs were not harvested. Letters represent results of SNK *post hoc* tests: dredged, after>tonged, after>all other treatments at $P < 0.05$. There was no difference among treatments before harvesting. (B) Mean (+SE) absolute difference in the % dead oysters on experimental reefs before and after harvesting. Difference calculated by: [% after - % before]. Letters represent results of SNK *post hoc* tests: dredged and tonged>diver-harvested and control at $P < 0.05$.

is a critical variable in sustaining the reef as an engine of oyster production because short reefs can be easily covered by sediment (Lenihan, 1999), can be abraded by sediment transport (Lenihan, 1999), and can fail to extend above hypoxic bottom waters (Lenihan and Peterson, 1998). Tall reefs (i.e., reefs not degraded by harvesting) produce faster flow speeds and more turbulence for oyster populations, which in turn increase oyster growth rate, increase

physiological condition, reduce disease incidence and intensity, and decrease mortality (Lenihan, 1999). Consequently, assessment of economics of the oyster fishery over longer time frames would likely demonstrate higher returns from practicing diver-harvesting, assuming that this technique conserved reef structure. Diver-harvesting also killed fewer of the oysters that remained on the bottom, thereby sustaining future harvests better through reduced wastage and by retention of more live oysters that would produce more reef material.

Although the relative advantage of diver-harvesting for conserving reef structure is evident, the absolute conservation of reef habitat under the various oyster harvesting methods is not clear from our study. Our data on impacts of diver-harvesting revealed slight declines in reef height, but whether these same declines would apply to an older reef, as opposed to a recently restored reef, is open to question. The level of cementation that binds the shells of the reef is not as great on recently restored reefs, making them more susceptible to degradation with physical disturbance. Our study measured only the immediate drop in reef elevation after fishing at a level that removed a large fraction of legally marketable oysters. In a well-managed fishery, this drop in reef elevation would represent virtually an entire season's decline, after which substantial reef growth would occur through recruitment and growth of smaller oysters before a new harvesting season. Thus, a healthy oyster reef may well be able to compensate for the modest reduction in elevation caused by diver-harvesting. If so, oyster reef sanctuaries now being created throughout the Chesapeake Bay (Luckenbach et al., 1999) could conceivably be opened to diver-harvesting (without implements) and still preserve the reef services to the ecosystem. This possibility deserves to be evaluated in order to minimize conflicts between the goals of restoring oyster reef habitat for conservation purposes and restoring oyster reefs for the restoration of lost fisheries.

Application of the results of our gear comparisons to management of oyster fisheries will likely encounter some impediments. Although various artisanal fisheries worldwide have employed free diving as a fishing technique and some modern fisheries, including the American oyster fishery, involve the use of scuba, diving is not a skill possessed by most oyster fishermen and probably is not a method under consideration for oyster fishing in general. In addition, the peak of oyster harvesting season on the Atlantic and Gulf coasts is usually during winter months (e.g., November–March) when water temperatures in estuaries are quite low (0–10°C). Such conditions require cold-water diving equipment (e.g., dry-suits), which will further increase the cost of this new harvesting technique. Thus acceptance of diver-harvesting by the industry would require training in diving skills and safety, education and demonstration of the advantages of this gear, and perhaps even investment of public funds to defray costs of the transition from traditional dredges and tongs to scuba or hookah. Because the gains of switching to diver-harvesting accrue to the industry over the long term, while individual fishermen who switch may suffer economically in the short-term, gear choice represents a

modified example of the tragedy of the commons (Ludwig et al., 1993). Only when armed with some form of ownership rights and an attendant long-term perspective would an individual oyster fisherman choose to switch to diver-harvesting. The precipitous declines of over 99% in oyster landings in mid-Atlantic estuaries (Rothschild et al., 1994; Lenihan and Peterson, 1998) mean that oyster fishermen can hardly be expected to bear the costs of switching fishing methods. Therefore, government intervention would be required to convert subtidal oyster dredge and tong fisheries into diver-harvesting operations for two reasons; the need for compensation of start-up costs and the need to overcome the tragedy of the commons. Given the dire state of oyster fisheries today (Rothschild et al., 1994), the habitat destruction in these declines (deAlteris, 1988; Hargis and Haven, 1998; Rothschild et al., 1994; Lenihan and Peterson, 1998), the broad ecosystem services provided by healthy oyster reefs (Jackson et al., 2001; Lenihan et al. 2001), and the very real potential for restoring oysters and their reefs (Luckenbach et al., 1999; Lenihan, 1999), a mandate to switch fishing methods for subtidal oyster fisheries could pay large dividends.

Acknowledgments

We thank Mike Marshall, Jeff French, and those many NCDMF people working on deck for initially creating experimental reefs to our specifications and for later applying the experimental dredge harvesting treatment. We thank Robert A. Cummings for applying the hand-tonging treatment, and Jonathan H. Grabowski for helping with diver-harvesting of reefs. This work was funded by the North Carolina General Assembly through the Cooperative Institute of Fisheries Oceanography (to C. H. Peterson), and NOAA-Chesapeake Bay Program Oyster Disease Program (to H. S. Lenihan, C. H. Peterson, and F. Micheli)

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