Effects of harvesting methods on sustainability of a bay scallop fishery: dredging uproots seagrass and displaces recruits

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Fishing is widely recognized to have profound effects on estuarine and marine ecosystems (Hammer and Jansson, 1993; Dayton et al., 1995). Intense commercial and recreational harvest of valuable species can result in population collapses of target and nontarget species (Botsford et al., 1997; Pauly et al., 1998; Collie et al. 2000; Jackson et al., 2001). Fishing gear, such as trawls and dredges, that are dragged over the seafloor inflict damage to the benthic habitat (Dayton et al., 1995; Engel and Kvitek, 1995; Jennings and Kaiser, 1998; Watling and Norse, 1998). As the growing human population, over-capitalization, and increasing government subsidies of fishing place increasing pressures on marine resources (Myers, 1997), a clear understanding of the mechanisms by which fishing affects coastal systems is required to craft sustainable fisheries management.

Dredging, possibly the most destructive of common fishing methods (Collie et al., 2000), has been the subject of many recent ecological studies (Dayton et al., 1995; Jennings and Kaiser, 1998; Thrush et al., 1998). These studies indicate that dredge extraction and disturbance can have large direct effects on the abundance, biomass, and diversity of resident macrobenthic species (e.g., Caddy, 1973; Eleftheriou and Robert-son, 1992). In addition, dredging can indirectly affect macrobenthic species through disturbance of benthic habitat (Ramsay et al., 1998; Lenihan and Peterson, 1998). Indirect impacts of dredging may be particularly serious where highly structured biogenic habitats, such as oyster reefs or seagrass beds, are affected (Peterson et al., 1987; Lenihan and Peterson, 1998; Collie et al., 2000; Lenihan and Peterson, 2004). These habitats may be considered essential habitat for many species of fish of commercial or recreational value (Thayer et al., 1975), providing refuges from predators (Orth et al., 1984; Castel et al., 1989) and abundant epibiotic food (Virnstein et al., 1984; Sánchez-Jerez et al., 1999).

Among fishery species dependent on biogenic habitat is the commercially and recreationally important bay scallop (*Argopecten irradians*). In the two reproductive seasons, spring and fall, bay scallop recruits settle onto hard substrates (Belding, 1910; Castagna, 1975) where they remain attached for the first few months of their lives. They then complete their 12–24 month life cycle on the estuary floor. In North Carolina, eelgrass is the only hard substrate of any abundance to which bay scallop recruits can attach themselves (Kirby-Smith, 1970).

Commercial harvest of bay scallops in North Carolina is achieved primarily by toothless epibenthic dredge (22.7 kg legal limit; NCFMC[1]). Dredges have the advantage that, unlike rakes, they can be used from boats in deep as well as shallow waters. Their disadvantage is that they decrease the biomass and shoot density of seagrass in scallop beds (Fonseca et al., 1984). Early in the North Carolina scallop season, which extends from December through May (NCMFC[1]), most of the juveniles from the previous fall spawning are still attached to seagrass blades (Spitsbergen[2]). If these juveniles are displaced by habitat destruction, reduced numbers of scallops may be available for harvest in the subsequent year (hypothesized by Thayer and Stuart, 1974). Although seagrasses can recover from small-scale disturbances to shoots by vegetative growth, large-scale disturbances to their subsurface root and rhizome system may permanently reduce the density of submerged aquatic vegetation (SAV) (Peterson et al., 1987) such that it may limit settlement of the following year's recruits or induce greater rates of predation on them (or bring about both). Although, in North Carolina, the bay scallop fishery management plan requires that the scallop season be opened after fall spawning is completed (Peterson, 1990); it fails to consider how methods of harvest may indirectly effect spawning stock biomass in years to come.

Implementation of gear restrictions that allow only hand methods of harvesting scallops (i.e., hand, rake, dip nets) may minimize impacts of harvesting on scallop recruits by reducing damage to seagrass and the loss of juvenile bay scallops that comprise the year class that will be fished in the following year. Although such restrictions were introduced to Bogue Sound in 1992 in response to the 1987 red tide that decimated scallop populations in that water basin (Summerson and Peterson, 1990), this conservation-based measure was discontinued in 1998 because of social pressure from fishermen. In the present study, we ascertain the impacts of dredges and hand-harvesting methods on the biomass of seagrass, as compared to undisturbed controls, 1) by measuring the biomass of seagrass directly dislodged by each method, and 2) by ascertaining, through measurements of biomass one month later, whether this removal affects the standing stock of seagrass over a longer temporal scale. We also tested both direct and indirect effects of seagrass removal on bay scallop recruits by measuring their density before and one month after harvesting and by ascertaining whether any documented difference can be explained by the numbers directly removed by uprooting of seagrass during harvesting. Such an assessment of ecological impacts of dredging on bay scallop recruits is urgently required given that North Carolina landings of bay scallops have fallen to an historic low since the relaxation of gear restrictions (Burgess and Bianchi[3]).

Materials and methods

Nine adjacent experimental plots, 25 m × 8 m, were established as a research sanctuary, closed to commercial fishing activity, in western Bogue Sound, North Carolina (34°41.6′N, 76°59.1′W), prior to the opening of the scallop season in winter 2001–2002. Although this section of Bogue Sound has been closed to scallop dredging since at least 1998, its high-tide water depth of 1.5 m is well within the depth range for harvesting with this method. Plots contained continuous seagrass beds dominated by *Zostera marina* on a muddy-sand bottom. Three of the plots were randomly assigned to each of the experimental treatments: hand-harvested, dredge-harvested, and control (undisturbed). In order to ensure that our treatments were representative of harvesting methods and intensities used by the industry, they were performed with participation of an experienced commercial scallop fisherman (Ted Willis of Salter Path). Dredging was achieved with a standard 72-cm wide steel scallop dredge, at an intensity of five parallel tows, each running along the length of the plot within a 10-minute period. This method, which mimicked commercial fishing
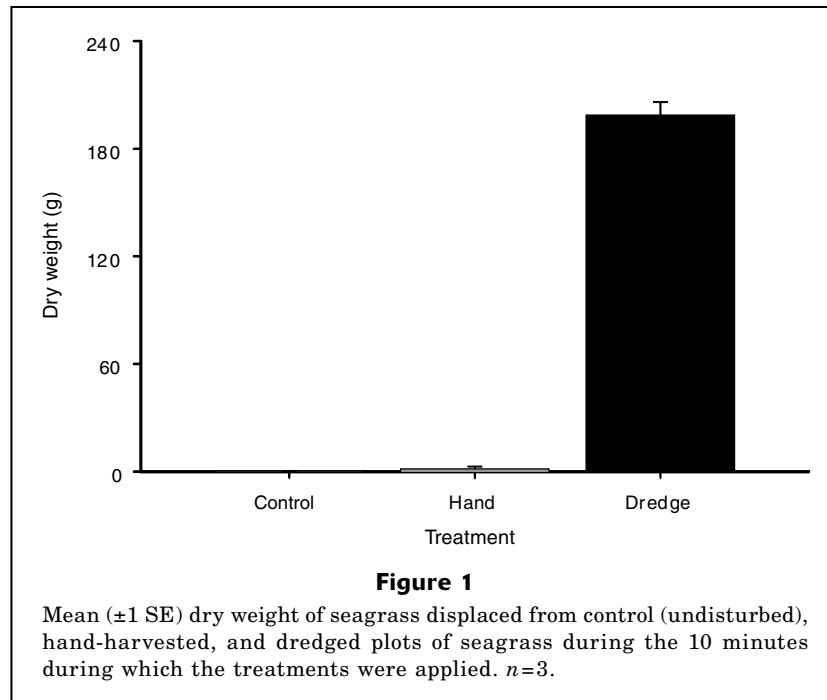
practices, minimized overlap between the dredge paths. Hand scalloping involved a single fisherman collecting scallops from the bottom by hand, also during 10-minute periods. Care was taken to ensure that the treatments were applied evenly over the entire plot to avoid creating large within-plot variance that might preclude detection of differences among plots.

Seagrass and scallops collected during harvesting were retained for measurements. The number of adult scallops (>40 mm shell height; Peterson et al., 1989) obtained with each of the methods of harvest was enumerated. The size (to the nearest 0.1 mm) and number of juvenile scallops collected as bycatch and the dry weight of seagrass removed during harvesting were quantified separately. Because not all seagrass and juvenile scallops displaced by harvesting are retained in the dredge or by a fisherman collecting scallops by hand methods, an 8-m long net with 5-mm mesh that extended from the bottom to the surface was set downstream from each plot and perpendicular to the flow of the current during harvest. The nets were strung between stakes marking the corners of the experimental plot. Dislodged juvenile scallops and seagrass collected by the nets were added to the amounts extracted from the dredge to compute displacement totals. Nets were also set downstream of controls to determine natural rates of transport of seagrass and juvenile scallops that could not be attributed to harvesting operations.

Each plot was sampled on 14 January 2002, immediately prior to harvesting on that same day to determine: 1) the density of bay scallop recruits (size ≤40 mm; Peterson et al., 1989); 2) the size distribution of the recruits; and 3) biomass per unit of area of seagrass. These variables were resampled on 25 February 2002, over one month later, to ascertain any lasting impact of harvest. Sampling of scallops was conducted with a 0.5-m^2 cylindrical quadrat, haphazardly positioned at nine locations within each plot. A 1.2-cm tall cylinder of 6-mm nylon mesh, attached to the quadrat and suspended by a buoyant plastic hoop that floated on the surface of the water, isolated the volume of water above each quadrat so that it could be sampled by suction with a Venturi suction device (according to Peterson et al., 1989). The suction device forced 600 mL of water per minute through a 3-mm collecting bag. Suction sampling was necessary because scallops, which typically recline on the bottom, can enter the water to swim when threatened by predators or otherwise disturbed (Peterson et al., 1982). The disturbance caused by suction sampling of only nine small areas was minimal compared to the scale of harvesting disturbance. Upon returning to the laboratory, seagrass was removed from samples for measurement of dry weight biomass and live scallops were counted, measured to the nearest 0.1 mm and categorized as adults (>40 mm) or recruits (≤40 mm) in the subsequent year class.

Seagrass was sampled in five replicate 0.25-m^2 areas within each plot by suction dredging inside a 0.56-m diameter circular quadrat to a sediment depth of 12 cm. Previous sampling has shown this method to be success-

[3] Burgess, C. C., and A. J. Bianchi. 2004. An economic profile analysis of the commercial fishing industry of North Carolina including profiles for state-managed species, 243 p. North Carolina Division of Marine Fisheries, 3441 Arendell Street, Morehead City, NC 28557.

Figure 1

Mean (±1 SE) dry weight of seagrass displaced from control (undisturbed), hand-harvested, and dredged plots of seagrass during the 10 minutes during which the treatments were applied. n=3.

ful in removing both roots and shoots in their entirety (Peterson et al., 1983a). Shoots and roots, which were collected in a 3-mm nylon mesh bag, were dried at 60°C to constant weight to calculate total dry weight biomass of seagrass.

ANOVAs allowed us to test for a significant interaction between time (before versus after) and disturbance (dredge versus hand-harvest versus control) in the biomass of seagrass and recruit density of bay scallops (a basic BACI design; Green, 1979), indicative of an impact of harvest. The cause of any significant time×disturbance interactions was explored by using Student-Newman-Keul (SNK) tests. Prior to each analysis, Cochran's (1951) C-test was done to test for heterogeneity of variances. Where variances were heterogeneous, data were ln (x+1) transformed to remove heteroscedasticity at α = 0.05.

Results

Of the two methods used to harvest adult scallops, hand harvesting had by far the greater efficiency in these shallow waters (ANOVA, P<0.0001). Over a period of 10 minutes, an average of 156 ±12 (1 SE) scallops within each 25×8 m plot was harvested by hand as compared to 26 ±1 scallops with the dredge.

The two methods of harvesting differed significantly in their impact on seagrass. Hand harvesting of scallops did not increase dislodgement of seagrass above the natural drift rate (Fig.1). Dredging, in contrast, resulted in 127 times the export of seagrass. This extraction did not, however, result in detectable reductions in biomass per unit of area of seagrass within dredged

plots when sampled one month later. There was no significant temporal change in the biomass of seagrass in any of the three treatments from before to one month after harvesting (Table 1, Fig. 2).

Fewer than 2% of the estimated total number of juvenile scallops in a plot were directly removed by dredging and none was removed by hand-harvesting. Nevertheless, sampling one month after harvesting indicated depressed densities of juvenile bay scallops in dredged plots (Table 2; Fig. 3). This difference could not be attributed to natural change; small increases (16–55%) in numbers of juvenile bay scallops in the hand-harvested and control plots were documented over the same period (Fig. 3). A comparison of size-frequency histograms of juvenile bay scallops within each type of plot from before to after harvesting revealed that the decrease in juvenile scallop numbers in the dredged plots was primarily due to losses of scallops in the smallest size classes (<14 mm; Fig. 4). In the dredged plots, mean (±SE) size of juveniles (≤40 mm in shell height) increased from 17.04 ±0.83 in January to 20.43 ±0.76 in February. Over the same time period, mean size changed little in the control (16.09 ±0.85 to 16.75 ±0.75 mm) or in the hand-harvested (18.19 ±0.85 to 17.95 ±0.65 mm) plots.

Discussion

Previous research indicates that the implementation of certain gear restrictions on estuarine bivalve fisheries can minimize habitat destruction without sacrificing harvesting efficiency (Peterson et al., 1983b; Lenihan and Peterson, 2004). In our study, which successfully mimicked the efficiency of commercial dredging and

Table 1

BACI (Green, 1979) analysis of variance that tests for an impact of scallop harvesting on biomass of seagrass. Nine plots of seagrass were randomly assigned to three treatments: undisturbed control, hand-harvested, dredged. Biomass of seagrass was determined immediately before (Jan 2002) and one month after (Feb 2002) application of treatments to plots. $n = 5$.

Source	df	MS	F	P
Before versus after treatment	1	0.14	0.78	0.41
Treatment	2	0.35	0.81	0.49
Plot (treatment)	6	0.43	3.50	0.00
Before vs. after × treatment	2	0.26	1.41	0.31
Before vs. after × plot (treatment)	6	0.18	1.49	0.19
Residual	72	0.12		
Transformation	$\ln(x+1)$			
Cochran's test	$C=0.16$ $(P>0.05)$			

hand-harvesting of bay scallops (see Burgess and Bianchi[3]), hand-harvesting yielded six times the bay scallop harvest obtained per unit of time by dredging, while reducing deleterious environmental effects. Hand-harvestikng did not result in uprooting of seagrass or displacing juvenile bay scallops, whereas dredging caused significant damage to seagrass. Ten minutes of dredging resulted in an average dry weight loss of 200 g of seagrass per plot—9 % of the estimated biomass of seagrass present prior to harvest. Despite this sizable removal of seagrass biomass, a persistent impact of dredging on seagrass biomass was not detected one month later. To the contrary, a 39% increase in seagrass biomass was seen across the dredged plots that was not replicated in the control plots. This result indicated that dredging had only a short-term negative impact on seagrass shoots (the necessary production of new leaves) and instead appeared to stimulate new production during the winter period that was more than sufficient to replace dredging damage.

Despite the rapid recovery of seagrass from dredging injury, a sustained negative impact of dredging on the density of juvenile bay scallops within plots was detected over the one-month period of our study. In contrast to the small increases in juvenile scallop density that occurred in hand-harvested and control plots over the course of the study, mean density of juveniles in dredged plots declined from 1.37 ±0.33 (1 SE) to 0.89 ±0.23 per 0.5 m^2. This 40% reduction in juvenile scallops in dredged plots cannot be explained by the bycatch alone. Whereas total bycatch of juveniles was, on average, two scallops per dredged plot, the average reduction in the density of juvenile bay scallops was 0.5 per 0.5-m^2 quadrat or 200 per 200-m^2 plot.

Instead, the reduction in density of juvenile scallops in dredged plots is best explained by their migration
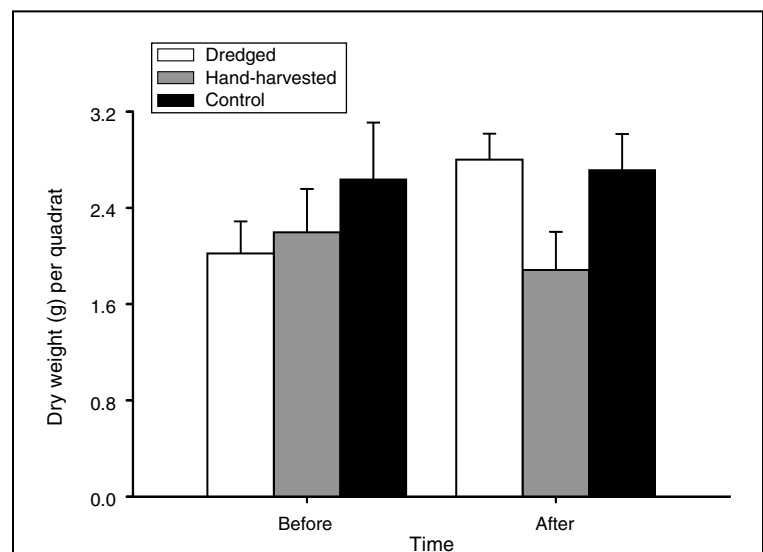
Figure 2

Mean (±1 SE) dry weight of seagrass per 0.25-m^2 quadrat in control (undisturbed), hand-harvested, and dredged plots immediately before and one month after the 10-minute treatments were applied. $n=15$.

after dredging injury to seagrass habitat into adjacent undisturbed control and hand-harvested plots. Abundances of juvenile bay scallops in hand-harvested and control plots increased over the one month of our study by an amount more than sufficient to compensate for losses of juveniles from dredged plots. These increases in abundances in control and hand-harvested plots cannot be attributed to the settlement of new recruits: fall recruitment of juvenile scallops to seagrass beds is typically completed by the end of December (Peterson et al., 1989), spring spawning does not commence until March (Peterson and Summerson, 1992), and scallops spawned during our experiment could not possibly have grown fast enough over one month to reach a size re-

Table 2

BACI analysis of variance testing for an impact of scallop harvesting on density of scallop recruits. Nine plots of seagrass were randomly assigned to three treatments: undisturbed control, hand-harvested, dredged. Density of scallop recruits was determined immediately before (Jan 2002) and one month after (Feb 2002) application of treatments to plots. $n=9$.

| Source	df	MS	F	P
Before vs. after treatment	1	0.89	0.78	0.41
Treatment	2	5.57	2.74	0.14
Plot (treatment)	6	2.03	0.77	0.59
Before vs. after × treatment	2	4.57	4.01	0.08
Before vs. after × plot (treatment)	6	1.14	0.43	0.85
Residual	144			
Cochran's test	$C = 0.13$ ($P>0.05$)			
SNK tests	Before vs. after × treatment			
	Before: control = hand-harvested = dredged			
	After: control = hand-harvested > dredged			

tained by sieves (see Irlandi et al., 1999 for growth rates). Scallops colonizing hand-harvested and control plots were of the right size and of sufficient abundance to be those missing from dredged plots. The migration appears to have included active swimming because tidal currents were perpendicular to the direction of scallop movement.

Although juvenile scallops are largely sessile, our interpretation that juveniles migrate in response to dredging is consistent with field and laboratory observations of juvenile bay scallop behavior. During seasonal sloughing of eelgrass blades, juvenile bay scallops break away

and re-establish byssal attachments to seagrass blades (Thayer et al., 1975). Mesocosm observations confirm that juveniles are capable of swimming distances of at least several meters when displaced (Bishop, personal observ.). Thus, our experimental restriction on dredging to small areas may have facilitated relocation of scallops to adjacent, undisturbed habitat, where they remained one month later even after seagrass had regrown in the dredged plots. In the case of the commercial fishery, however, juvenile scallops emigrating from disturbed habitat over the extensive fished areas would be far less likely to encounter undisturbed seagrass habitat for re-attachment. Indeed, transport to unfavorable unvegetated habitat where predation risk is enhanced would likely inflate mortality.

In our study, juvenile scallops lost from the dredged plots came primarily from the smallest size classes. Small juvenile scallops are more susceptible to benthic predators that forage within seagrass beds than larger juveniles (Pohle et al., 1991). Because the foraging efficiency of some predators increases with decreasing biomass of seagrass (Prescott, 1990), a decrease in seagrass biomass, even for a period of weeks, would likely increase predation on juvenile scallops. Thus, small juveniles probably are increasing their chances of survival by emigrating away from depleted and into denser seagrass. Larger juveniles, in contrast, experience a partial size refuge from predators (e.g., Pohle et al., 1991), and thus have less incentive to emigrate.

This study considered the impact of only a single bay scallop-harvesting event on seagrass biomass and abundance of juvenile bay scallops within small experimental plots. Fishing disturbances are, however, typically chronic, occurring multiple times within a given season, and over large spatial scales.
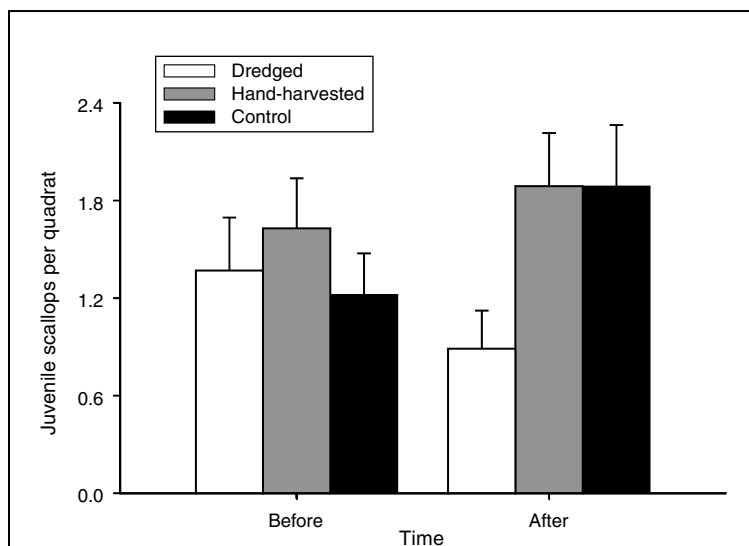
Figure 3

Mean (±1 SE) number of juvenile bay scallops (≤40 mm in shell height) per 0.5-m² quadrat in control (undisturbed), hand-harvested, and dredged plots immediately before and one month after the 10-minute treatments were applied. $n=15$.

Figure 4

Size-frequency distribution of juvenile bay scallops (≤40 mm in shell height) collected from control, hand-harvested, and dredged plots immediately before and one month after the 10-minute treatments were applied.
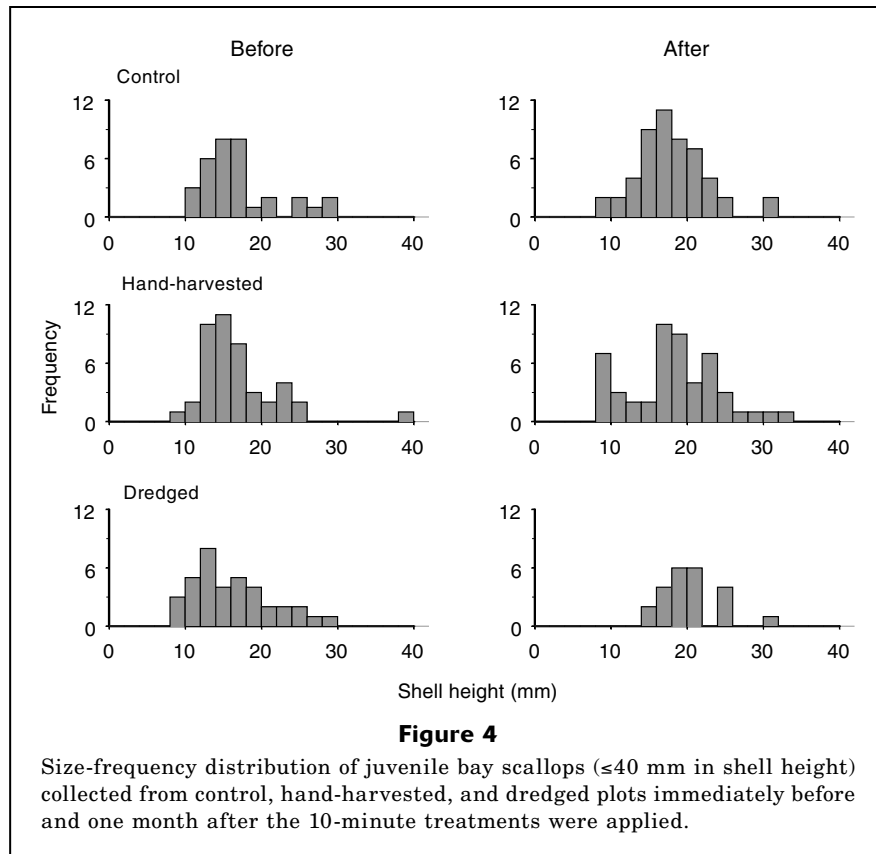
In our study, just 10 minutes of dredging resulted in the removal of approximately 9% of the total biomass of seagrass in the experimental plot. Repeating this fishing disturbance over large spatial scales could, therefore, have substantial detrimental effects on seagrass habitat and, as an indirect result, the abundance of bay scallops that comprise the next generation. In addition, other habitat functions of seagrass are likely compromised until regrowth occurs. Peterson et al. (1987) demonstrated in this same system that a one-time reduction of 65% in seagrass biomass from gear disturbance during clam harvesting was not replaced over a subsequent 2-year period free of additional fishing.

The results of our study raise doubt about the sustainability of a bay scallop fishery in which the harvest method is dredging. Because this species, which lives only 12–24 months, is recruitment-limited (Peterson and Summerson, 1992; Peterson et al., 1996), reductions in densities of juvenile bay scallops by dredging will not only diminish that year's harvest but also presumably result in less spawning-stock biomass. Without restrictions on scallop dredging, impacts of dredging disturbance compounded across years may lead to the gradual collapse of the fishery. Re-imposing gear restrictions in shallow areas where hand harvest is practical may, therefore, pay big dividends. When use of the less destructive hand method carries little or no penalty of reduced fishing success, restricting scallop dredging from shallow SAV represents an appropriate ecosystem-based management choice (Botsford et al., 1997) that may sustain SAV habitat and restore a bay scallop fishery now in serious decline (Burgess and Bianchi[3]).

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