A REVIEW OF THE EFFECTS OF FISH HARVESTING PRACTICES ON THE BENTHOS AND BYCATCH: IMPLICATIONS AND RECOMMENDATIONS FOR NORTH CAROLINA

By

Terry L. West and William G. Ambrose, Jr.[1]
Department of Biology, East Carolina University
Greenville, North Carolina, USA

Gregory A. Skilleter
Institute of Marine Ecology, University of Sydney,
New South Wales, Australia

[1] Current Address: Biology Department, Bates College, Lewiston, Maine, 04240 USA

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EFFECTS OF FISH HARVESTING METHODS ON THE BENTHOS: SUMMARY AND RECOMMENDATIONS:

The objective of this study was to conduct a literature review of the effects of fishing methods on (a) the community of organisms living on or within bottom sediments (= the "benthos", "benthic community"), and (b) the inadvertent capture of non-target species of fish ("bycatch"), with the intent of assessing their potential effects on the complex of estuaries comprising the Albemarle-Pamlico system, and suggesting appropriate management actions. Our choice of literature was therefore biased toward relevance to this estuarine system. Departures from this bias were taken in the event of the lack of any pertinent local studies of a particular aspect of the effects of fishing practices on the benthos or bycatch.

An evaluation of the effects of fish harvesting practices on the benthos requires an understanding of the physical (habitat types, water quality, hydrography) and biological (fish and benthic invertebrate community structure, and seasonal cycles of abundance) features of the ecosystem, as well as a knowledge of those North Carolina fisheries that are most likely to affect the benthos.

The critical physical features of the Albemarle-Pamlico estuarine complex are as follows: (1) it is a lagoonal system created by the presence of barrier islands which permit only a limited exchange with the Atlantic Ocean; (2) salinity ranges from brackish (<0.5 parts per thousand) to polyhaline (>30 parts per thousand; (3) unvegetated, fine sand sediments predominate; (4) water circulation is wind-driven; (5) basin size is large and shallow; and (6) water temperature and dissolved oxygen concentration show large seasonal variation. These features combine to make the Albemarle-Pamlico Lagoonal System (APLS) physically rigorous, and subject to significant levels of natural disturbance in the form of temperature, dissolved oxygen, and turbidity.

The North Carolina commercial fishery consists of six categories: (1) sink net; (2) winter trawl; (3) pound net; (4) long haul; (5) shrimp trawl; and (6) crab fishery. These fisheries represent five different harvesting methods: (a) sink net (b) pound net; (c) long haul; (d) trawling; and (e) "pots". Shrimp trawling is potentially the greatest single source of disturbance for the benthos as a result of the gear design, fishing intensity and areal extent of harvesting activities of this fishery. Fisheries of lesser monetary value but similar gear type (e.g., bay scallop dredging, clam trawling, crab dredging, oyster dredging), will also significantly disturb the benthos.

The fish community of North Carolina's estuarine system consists of approximately 136 species. However, only 10 species account for approximately 95% of the total number of individuals caught in the Albemarle, Croatan, and Pamlico Sounds. This group consists of 8 species of finfish (bay anchovy ,*Anchoa mitchelli*); spot, *Leiostomus xanthurus*; Atlantic menhaden, *Brevoortial tyrannus*; Atlantic croaker, *Micropogonias undulatus*; white perch, *Morone americana*; inland silverside, *Menidia beryllina*; blueback herring, *Alosa aestivalis*; and silver perch, *Bairdiella chrysoura*) and 2 species of shellfish (brown shrimp, *Penaeus aztecus*; and blue crab, *Callinectes sapidus*). A seasonally varying combination of these species numerically dominate the local fish community throughout the year. The majority of the commercially important fish species fall into three categories, based on life cycle and migratory habits: (1) anadromous (e.g., herrings such as *Alosa aestivalis*); and (2) marine migratory [e.g., spot (*Leiostomus xanthurus*), croaker (*Micropogonius undulatus*), shrimp (*Penaeus* spp.)]; and (3) estuarine indigenous (e.g., blue crab (*Callinectes sapidus)*

The fish community has strong trophic links to the benthic invertebrate community because most of the abundant fish species feed on invertebrates for part or all of their life cycle within North Carolina's estuarine system. The benthic community of this estuarine system has not been extensively described or studied. Available information suggests that this is a relatively low diversity community as a result of low average salinity, unstable sediments, high turbidity, and seasonally low dissolved oxygen levels.

The impacts of trawling on the benthos are potentially diverse. Trawling can modify the living structural components of the habitat by damaging submersed beds of aquatic vegetation and reefs of sessile organisms such as oysters. Trawling can also modify the nonliving structural aspects of the habitat through resuspension of sediment and its subsequent redeposition. These effects of trawling are in part related to the type of gear used. Dredges and trawls typically liquify the upper layers of the sediment. The extent of this liquification is dependent upon the depth of penetration of the dredge or trawl. Some otter trawls and scallop dredges penetrate muddy sediments to depths of 10 cm, while hydraulic clam dredges can disturb depths up to 30 cm in sandy sediments. Shrimp trawls penetrate muddy sediments less than any of these gears.

Trawling can potentially stimulate primary productivity if nutrients stored in the sediments are released into the water column as the sediments are resuspended by the action of the trawl. Trawling could also inhibit primary productivity by reducing the depth of the euphotic zone as a result of increasing the turbidity of the water. This aspect of trawling impacts is virtually unstudied.

The effects of trawling on secondary productivity are potentially as diverse as those concerning primary productivity. Secondary productivity could be increased as predators and scavengers feed on epifauna (organisms living on top of the sediments) and infauna (organisms living within the sediments) injured from fishing activity, or in some other way made vulnerable to predation. Secondary productivity could be decreased as a result of inflicting fatal injuries on benthic organisms, or by impairing foraging success of visual predators.

Management Recommendations

Potential management actions concerning the issue of trawling (and similar fishing practices) in estuarine areas are: (1) no action; (2) ban trawling from all estuarine waters; (3) restricted trawling by gear type; (4) restrict trawling purely by habitat type (e.g., submersed grass beds, oyster reefs); (5) permanently ban trawling from selected, multiple habitat types which would then function as spawning and recruitment sanctuaries for surrounding areas subjected to trawling; and (6) restrict trawling by season, by the number of trawling days within a season, or by the duration of trawling per day.

Of these options, all but the first and second require additional research. We encourage management to first implement a research program dedicated to providing information that would enable them to select the best alternative based on a combination of sociological, economic and ecological knowledge and understanding.

We specifically recommend the following lines of research be undertaken:

(1) Quantify trawling practices so that a measure of trawling effort per unit area and time could be determined; in addition, determine turbidity levels generated by the gear type, and the subsequent rate(s) of redeposition.

(2) Determine the depth of penetration of trawling gear into the sediments, and the effect of this trawling on the sediment grain size distribution.

(3) Sample areas normally subjected to trawling in order to describe the local benthic infaunal and epifaunal communities. The benthic community of trawled areas is virtually unknown. An important aspect of this work is to identify the seasonal cycles of species abundance and recruitment. This information is essential in that it enables management to estimate the times of the year during which the benthos would be most sensitive to trawling disturbance (i.e. times at which benthic diversity and abundance is highest).

(4) Measure *in situ* rates of growth, mortality, and recruitment of selected species of benthic invertebrates exposed to trawling.

(5) Measure *in situ* growth and survival of selected demersal predators in trawled and untrawled areas.

(6) Evaluate the effect of trawling on primary productivity.

(7) Evaluate secondary effects of turbidity caused by resuspension of sediments.

(8) Compare the effects of trawling on water quality (temperature, salinity, dissolved oxygen, turbidity) and the sediments (sediment grain size distribution, organic carbon content) with that caused by natural agents of disturbance such as storms. These comparisons are critical in defining the ecological role of trawling, and would aid management by helping to delineate the relative magnitudes of anthropogenic and natural levels of disturbance to the benthos.

BYCATCH IN NORTH CAROLINA MARINE AND ESTUARINE WATERS: SUMMARY AND RECOMMENDATIONS

Bycatch is defined as that part of the catch which is captured incidentally to the species toward which there is a directed effort. Fishing gear using small mesh sizes are particularly prone to the bycatch problems, because escape of smaller finfish diminishes with decreasing mesh size.

Several gear types associated with particular fisheries in North Carolina contribute to the bycatch problem. These gear types include gill nets, crab trawls, pound nets, long haul seines, flynets,, and shrimp trawls.

Areas of concern for gill nets include: (1) incidental catches of fish species reserved for recreational fishermen; (2) mortality of undersized commercial fish species; (3) mortality of other non-target fish species; (4) mortality of aquatic mammals and sea birds; and (5) mortality of all aquatic animals associated with "ghost nets", i.e., nets which have been lost and abandoned.

The blue crab (*Callinectes sapidus*) fishery in North Carolina is largely dependent on crab pots, which do not contribute to the bycatch problem when they are actively being fished. However, pots that are lost or abandoned may continue to fish and become significant sources of mortality for both crabs and fishes. Work carried out by the North Carolina Division of Marine Fisheries in the region of the Pamlico River indicates that crab trawling bycatch consists primarily of undersized southern flounder (*Paralichtyes lethostigma*). The catch of undersized flounder averages about 50% of the total flounder catch (by weight) per fishing excursion (trip). The average total bycatch (all finfish species) per trip is about 60 kg; therefore the crab trawl bycatch is small compared to the that of the North Carolina's major fisheries. Catch limits have recently been imposed on the total weight of legal size flounder caught by crab trawling.

Pound nets are considered nonselective once fish enter the gear; they have historically been blamed for contributing to the decline of important food species such as the weakfish (*Cynoscion regalis*) and the destruction of other undersized species. However, evidence now indicates that pound net bycatch is significantly less than that of the flynet and long haul fisheries, and is minor relative to the shrimp fishery.

Available North Carolina Division of Marine Fisheries data indicate that the flynet and long haul are among the state's most important contributors to bycatch. These two fisheries collectively accounted for about 75% of the approximately 8.8 million pounds of undersized finfish landed annually as scrapfish during 1988-1990. Undersized spot (*Leiostomus xanthurus*), Atlantic croaker (*Micropogonias undulatus*), weakfish are the most common bycatch species in the flynet and long haul catches; the flynet fishery also captures significant amounts of undersized Atlantic menhaden (*Brevoortia tyrannus*).

The shrimp fishery is the most important contributor to bycatch in North Carolina, and in the southeastern Atlantic region in general. The bycatch problem results from the size of the fishery (number of vessels), the areal extent of North Carolina's waters affected by the fishery, and the small, non-selective mesh size of the nets. The estimated shrimp bycatch, based on a 1:4 catch weight ratio of shrimp to fish, is about 10 times larger than the reported landed bycatch of the flynet and long haul fisheries. Approximately 80% of the annual North Carolina shrimp landings is derived from fishing estuarine waters.

There is a great need for information on (age-specific) mortality of fishes caught as bycatch in North Carolina, and considerable effort is now being directed to this aspect of the bycatch problem by North Carolina Sea Grant and North Carolina Division of Marine Fisheries investigators. Much of what is currently known concerning bycatch is derived from studies done on coastal vessels from other southeast states. Results of these studies may not be applicable to North Carolina because its shrimp fishery is estuarine based.

There is a general lack of information concerning the survivorship of species of finfish caught as bycatch in North Carolina. Studies carried out elsewhere indicate that the majority of finfish caught as bycatch die as a result of being caught in trawls, or as a result of stress during sorting and handling. Survival of bycatch is closely related to the length of time the animals spend out of the water, which is in turn determined by the time taken to sort the catch. Experiments holding bycatch in tanks found that nearly 90% died within 12 hours after capture. Considerably lower mortality (36%) has been observed in local blue crabs caught by crab trawls.

Bycatch mortality of juveniles of Atlantic croaker (*Micropogonias undulatus*), red snapper (*Lutjanus campechanus*), summer flounder (*Paralichthys dentatus*), and weakfish (*Cynoscion regalis*) has been attributed as a central cause in the decline in the populations of these species in the Southeast Atlantic. However, there is no study to date which actually demonstrates a direct causal link between bycatch mortality and the population status of a particular species. Nevertheless, it is likely that the ecological consequences of bycatch are profound, pervasive, and complex. Many of the fish species vulnerable to bycatch are predators of other fish, or predators of benthic invertebrates, or are competitors with other fish for various food resources. As a result of the complexity of these trophic relationships, a reduction in the abundance of a single fish species could produce a multitude of trophic consequences, which ripple throughout the ecosystem.

Concern over the potential ecological and economic impacts of shrimp fishing bycatch has fueled research in bycatch reduction devices (BRDs) that act to exclude non-target species from the catch (e.g., Turtle Excluder Device, "TED"; Finfish Excluder Device, "FED"; Finfish Separator Device, "FSD"). These devices work best when the sizes of the bycatch species and the target species are very different. These separators work, and have been recently tested in North Carolina, resulting in a 60% reduction in non-target finfish bycatch. More research is needed in this area, because the effectiveness of the separator varies with habitat and fish species. Other alternatives to reducing bycatch which are currently under investigation are modifications in net mesh size, mesh shape, and alternative net and gear designs (e.g. skimmer trawls).

Management Recommendations

(1) It is important to continue studies on the extent of the bycatch problem in the inshore estuarine waters of North Carolina sounds and inlets, such as that currently underway by NC Sea Grant and NCDMF personnel. Extrapolation of the results taken from offshore fisheries in South Carolina, Georgia and Florida are unlikely to provide an accurate picture of the bycatch problem in North Carolina. Such studies should include more detailed information on the spatial and temporal distribution of species likely to be affected, especially by the shrimp fishery. Age-specific estimates of bycatch for important species are required to allow bycatch related mortality rates to be estimated.

(2) More information is required about the interspecific relationships among the different species occupying the estuaries and inlets of North Carolina. It is essential to understand how losses of one species as a result of bycatch-related mortality will affect the abundance and distribution of other species. For instance, will there be compensatory increases in the abundance of other species due to increased food as a top competitor is removed? Will large pelagic predatory fishes increase

in abundance as a result of less competition for food, or will they decrease in abundance due to a reduction in the availability of prey species?

(3) Another priority for future research is to continue studies of the effectiveness of bycatch reduction devices (BRDs) in North Carolina's inshore estuaries and inlets. Recent NCDMF work on BRDs, have shown that these devices can consistently reduce bycatch by 50-60%. These studies could be extended to include evaluation and refinement of BRD designs using remote cameras.

(4) The role of gill nets in finfish bycatch, and their impact on marine birds and mammals, needs to be assessed in North Carolina's estuaries. Large numbers of dolphins and porpoises frequent these waters and may be impacted by the many gill nets used in these estuarine waters.

(5) Active education and cooperative programs such as the NMFS Regional Observer Program, and NCDMF collaborative work with local fishermen on BRDs, must be continued in order to gain the widespread approval of the use of BRDs (including turtle excluder devices) throughout the fishing industry. Research into better designs for BRD's will help to keep the cost of purchase down for the fishermen further making them acceptable to the industry.

(6) If areal and seasonal closures are to be pursued as a management option, then it is imperative that the socioeconomic impacts on individual fishing communities and groups be examined. Designation of further primary and secondary nursery areas could force many shrimp fishermen to absorb increased costs for fuel and maintenance to enable them to travel from their traditional fishing areas to the newly designated fishing areas. This may in turn throw them into competition with the offshore fleet which generally utilizes larger boats and trawls. The possibility of excluding these larger vessels from estuarine fishing and limiting them to offshore habitats should be considered. An examination of the biological and ecological ramifications of the bycatch question are not the only considerations for the state, especially as it struggles to redefine fiscal policies.

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PART 1:

EFFECTS OF FISH HARVESTING METHODS ON THE BENTHOS

By

T.L. West, and W. G. Ambrose[1]
Department of Biology, East Carolina University,
Greenville, North Carolina 27858

[1] Current Address: Biology Department, Bates College, Lewiston, Maine 04240

Introduction

The impact of fishing activities on non-target species has concerned fishery managers since the 14th century (cf. de Groot, 1984) . Two of the most important concerns are the effects of trawling on benthic communities, and the inadvertent collection of non-target species (i.e., bycatch). These concerns are being addressed by fishery managers throughout the world and are two of the major unresolved issues in fisheries management in North Carolina.

Assessment of the effects of fishing activities on the benthos and on non-target species is subject to three fundamental types of constraints. First, the nature and magnitude of the effects of fishing activities depends heavily upon the physical and biological characteristics of the area in question. As a result, there are strict limitations on the degree to which local effects can be inferred from studies of the effects of fishing practices carried out elsewhere.

Second, the impacts of fishing activities on the benthos, and on fish stocks via bycatch, are complex and may vary qualitatively and quantitatively with time of the year. In addition, little useful information may exist on any number of the potentially important effects of fishing. Hence, a comprehensive review of the effects of fishing activities is difficult--if not impossible--owing to the diversity of relevant issues to be researched on the one hand, and the paucity of good data on the other.

Third, the scales of time and space needed to delineate the effects of fishing are not necessarily the same as those which can be reliably observed or determined by experimentation. For example, the effects of fishing activities can be divided into short term and long term impacts. Short term impacts (e.g. effect of trawling on resuspension of benthic sediments; survival of benthic organisms) are usually directly observable and easily quantified. Long term impacts (e.g., effects of trawling on finfish community structure), however, may be indirect and are more difficult to quantify. In addition, it is often impossible to separate the long term effects of fishing activities on benthic communities and fish stocks from those caused by changes in climate or other environmental factors (Anon., 1991). Fishing activities also impact different spatial scales. Thus while the effect of a trawl on bottom topography can be easily observed and quantified, extrapolating these effects to a regional scale is risky at best due to the uneven spatial distribution of trawling effort.

Given these limitations, the objective of this report is to review the literature concerning the known effects of fishery harvesting methods on benthic communities and on the populations of fish caught as by catch. These effects will then be related to fishery practices and habitats in North Carolina with the goal of determining what effects current fishing practices might have on nontarget species in North Carolina.

Physical Characteristics of the Albemarle-Pamlico Lagoonal System (APLS)

Effects of trawling on the benthos must be evaluated in the context of the physical structure of the local environs. Important physical features in this regard are habitat diversity, water flow regimen and rates of sediment transport, deposition and resuspension.

The Albemarle-Pamlico estuarine complex is a lagoonal system of bays and drowned river valleys (Pritchard, 1967; Kjerfve, 1986; Wells and Kim, 1989), and is the second largest estuarine system in the United States (Giese et al., 1979). Albemarle Sound forms most of the northern portion of the system (Figure 1.1; Table 1.1). It is oligohaline (0-5 ppt) (Roelofs and Bumpus 1953), and receives the bulk of its freshwater inflow from the Roanoke River and its

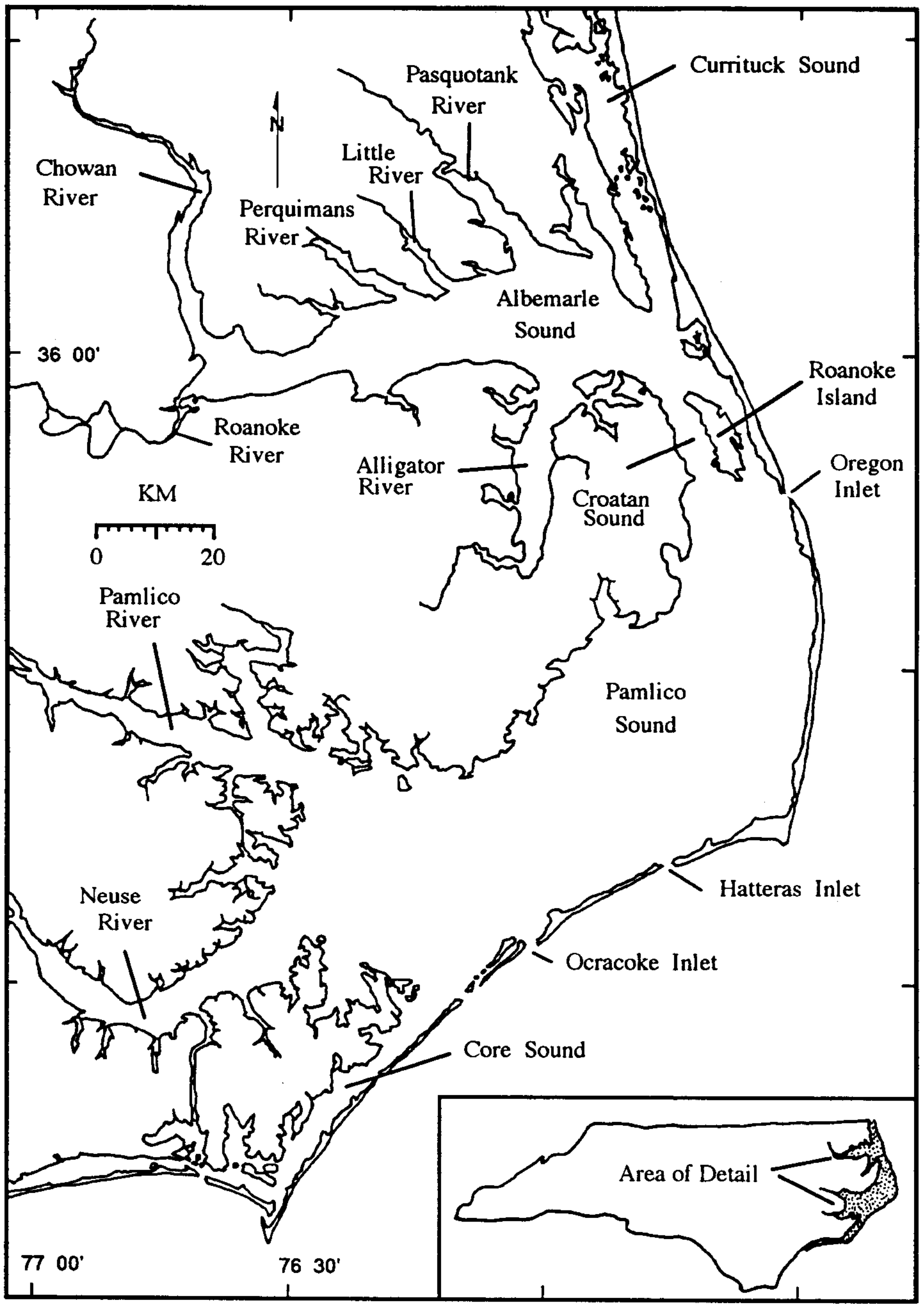


Figure 1.1. The Albemarle-Pamlico Lagoonal System

Table 1.1 . Features of size of the major sounds and rivers of the Albemarle-Pamlico Lagoonal system (adapted from Giese et al., 1979). Albemarle Sound area includes Currituck and Croatan Sounds; Pamlico Sound includes Core and Roanoke Sounds. Drainage areas include all major tributaries of the designated water body.

Feature	**Albemarle S.**	**Pamlico S.**	**Neuse-Trent R.**	**Tar-Pamlico R.**
Surface Area (km^2)	1,243	5,335	----	583
Volume (m^3)	6.55×10^9	2.59×10^{10}	----	----
Average Depth (m)	5.3	4.8	2.4-5.2	3.4
Drainage Area (km^2)	47,550	32,427	14,504	1,137

tributaries (Giese et al., 1979). The eastern part of Albemarle Sound joins Currituck Sound to the north, and Roanoke Sound and Croatan Sound to the south. These latter two sounds interconnect Albemarle Sound and Pamlico Sound. Pamlico Sound is polyhaline (18-30 ppt) and receives most of its freshwater from the Pungo River, Tar-Pamlico River, and the Trent-Neuse River. Pamlico Sound is continuous with Core Sound to the south.

Water Quality

Temperatures vary seasonally from approximately 6 °C (January) to 30 °C (July/August) in the major sounds and rivers comprising the Albemarle Pamlico Lagoonal System (APLS) (Williams et al., 1973). Water temperature is strongly affected by, and closely linked to, air temperature (Giese et al., 1979).

Dissolved oxygen varies inversely with temperature, being highest in the winter and lowest in the summer. Certain regions of the APLS, such as the deeper waters of the Pamlico River, experience hypoxia or anoxia during the warm summer months (Tenore, 1972).

The Albemarle-Pamlico Lagoonal System is bordered by the Outer Banks, a series of barrier islands separated by narrow inlets. The barrier islands dampen exchange between the lagoonal system and the Atlantic Ocean to the extent that the there is only a minor tidal character throughout most of the lagoonal system (Marshall, 1951). Water flow and water level within the sounds are primarily wind-driven (Roelofs and Bumpus, 1953; Giese, et al., 1979; Pietrafesa et al., 1986). The direction of the prevailing winds varies seasonally, blowing from south-southwest between April and August, and from north-northwest between September and February. The wind has a nearly uniform directional distribution during March (Wells and Kim, 1989). Water level may vary by as much as 1 m during periods of persistent unidirectional winds (Copeland and Riggs, 1984).

Current flow in the Pamlico Sound averages 10-26 cm/s, with extremes of 0.5 cm/s to 69 cm/s (storm) (Roelofs and Bumpus, 1953). Wind blowing along a south-southwest axis will generate surface water currents in the same direction at approximately 1/10 of the wind speed. Sustained wind action will cause water to pile up at the outer banks, which in turn will create a bottom current flow proceeding in a direction opposite to that of the surface flow (Pietrafesa et al. 1986).

Salinities vary seasonally within the lagoonal system (Table 1.2). Values are typically lowest in April and highest in December (Epperly and Ross, 1986). The seasonal variation in salinity is a latent response to periods of maximal freshwater inflow and low evaporation during February, and the period of minimal freshwater inflow and high rates of evapotranspiration in June (Wells and Kim, 1989). Salinity also varies with depth. The vertical salinity gradient can attain 5-10 ppt in the lower half of the Pamlico and Neuse rivers, while a gradient of 1 ppt is typical of the Pamlico Sound (Hobbie and Smith, 1975; Giese et al., 1979).

Salinity of the Albemarle Sound ranges from 1-9 ppt (Table 1.2; Williams et al., 1973). Salinity values vary along an west-east axis, with the highest values occurring in the eastern portion of the Sound. The Sound is well mixed owing to its shallow depth and wind-generated water flow; hence bottom salinities are within 2-3 ppt of surface salinities. Lowest salinity values generally occur in April and highest salinity values occur in December or January (Williams et al., 1973). The salinity of the Albemarle Sound is 1/2 to 1/3 of that of the Pamlico Sound owing to the comparatively higher rate of freshwater input per sound volume for the Albemarle, and because the

Table 1.2. Approximate salinity (ppt) ranges for the major parts of the Albemarle-Pamlico Lagoonal system (after Williams et al., 1973). S=surface; B=bottom.

Mon	Albemarle S.		Croatan S.		Pamlico S.		Tar-Pamlico R.		Neuse-Trent R.	
	S	B	S	B	S	B	S	B	S	B
Jan	3-5	1-9	8-14	11-17	11-25	13-26	10-12	12-14	3-11	6-16
Feb	1-4	2-4	4-9	4-10	5-13	7-14	5-12	7-14	1-13	3-14
Mar	1-4	1-4	3-4	4-6	11-20	13-21	3-11	5-13	3-11	2-10
Apr	1-3	1-3	2-3	2-3	11-25	12-29	2-10	2-12	6-11	9-12
May	1-3	1-3	5-11	9-14	11-20	12-30	2-8	3-15	1-11	2-12
Jun	1-4	1-4	12-18	13-20	11-24	12-25	1-9	2-13	2-11	4-12
Jul	1-4	1-4	5-11	6-14	12-26	14-26	5-12	5-14	4-12	9-15
Aug	1-4	2-4	5-10	5-11	14-26	16-26	1-13	9-15	5-13	11-17
Sep	- -	- -	- -	- -	13-30	14-31	3-16	8-19	5-13	7-14
Oct	2-8	6-7	8-13	8-10	13-24	16-26	4-13	12-17	2-15	8-15
Nov	1-6	5-6	8-10	9-11	16-27	15-22	8-17	11-16	3-14	6-15
Dec	1-5	1-5	5-8	6-24	14-20	15-24	7-16	12-16	5-14	7-14

Albemarle Sound lacks any direct connection to the ocean, receiving only sea water previously diluted by the Pamlico Sound (Giese et al., 1979). Dissolved oxygen levels are consistently high throughout Albemarle Sound, seldom falling below 80% saturation.

Salinity of the Pamlico Sound varies from 5-31 ppt (Table 1.2). The lowest values occur along the western edge of the Sound, and the highest values occur along the eastern margin of the Sound. The Sound is well mixed with small differences in surface and bottom salinities. Seasonal variation in salinity follows a pattern similar to that of the Albemarle Sound, with lowest values in March, and highest values in December or January. Temporal variation in salinities in the Pamlico Sound far exceeds that of the Albemarle Sound. Bottom dissolved oxygen levels seldom drop below 50% saturation in Pamlico Sound (Giese et al., 1979).

Salinity of the Pamlico and Neuse rivers ranges from a minimum of <1 ppt to a maximum of about 24 ppt for the Pamlico River (Stanley, 1988). and about 32 ppt for the Neuse River (Garrett, 1992). A west-east gradient of increasing salinity prevails in these rivers, similar to that observed in the Albemarle and Pamlico sounds. Temporal and spatial variations in salinity in these rivers are greater than that seen in any of the major sounds. The annual maximum and minimum downstream locations of the 1-5 ppt isohaline in these rivers spans about 20 km in the Pamlico River, and about 30 Km in the Neuse River (Stanley, 1987, 1988; Wells and Kim, 1989). Inter-annual differences in salinity in the Pamlico River can vary by a factor of 2-3 (Stanley, 1988). Lowest and highest salinities typically occur in the spring (February-March) and early winter (December-January), respectively (Table 1.2).. However, this temporal pattern may be reversed depending upon climatic factors (Stanley, 1988). Short term temporal variation (days) in salinity can be pronounced, equalling the magnitudes observed seasonally within a year, and between years ((Garrett and Bales, 1991; Garret, 1992). These short term variations are apparently caused by storms. Vertical stratification in salinity is more pronounced in these rivers than in the sounds. Differences in surface and bottom salinities in the Pamlico River at a single site can equal the longitudinal gradient of a particular depth for the entire river (Stanley, 1988).

Dissolved oxygen in the Pamlico and Neuse rivers also varies markedly according to depth, season, and location. Bottom dissolved oxygen values less than 10% saturation are common in the warm months of the year in both rivers (Giese et al., 1979; Stanley, 1988). The magnitude of short term variations in dissolved oxygen can equal that of salinity (Garrett and Bales, 1991; Garret, 1992), and is also apparently caused by storm activities.

Habitat Structure

The majority of sediments in the Albemarle-Pamlico Lagoonal System is fine grain sand. Exceptions are the central basin of Pamlico Sound, the central region of the western half of the Albemarle Sound, and the midchannel regions of the Pamlico River and Neuse River, all of which consist primarily of silt, and may contain as much as 15% total organic carbon by weight (Wells and Kim, 1989; Riggs et al., 1989; Riggs et al., 1993). Fine grain sand sediments in APLS are generally derived from shoreline erosion, although a significant additional source of fine grain sand in Pamlico Sound is the Outer Banks. Sharp discontinuities between sandy and fine grained, muddy sediment characterize the shallow near shore, and deeper midchannel regions of the Pamlico and Neuse rivers (Tenore, 1972; Copeland et al., 1984; Wells and Kim, 1989; Riggs et al., 1989). Isolated patches of shelly material derived from relic oyster reefs occur seaward of the mouths of the Neuse River and the Pamlico River. Shelly sediments also occur in the vicinity of the Oregon, Hatteras, and Ocracoke inlets (Wells and Kim, 1989).

Rates of sediment deposition, transport, and resuspension are poorly known for the APLS.

Turbidity of surface waters of the lower region of the Neuse River range from 5-15 mg/L (Khorram and Cheshire, 1983). Greater turbidities (> 15mg/L) occur in the Pamlico Sound, especially in the region of the central basin. The relatively high turbidity of the Pamlico Sound reflects its size, shallow depth, prevailing winds, and abundance of fine grain sediments (Wells and Kim, 1989).

The littoral and shallow subtidal regions of the estuarine side of the Outer Banks south of Oregon Inlet contain extensive beds of submersed aquatic vegetation. Submersed aquatic vegetation has several functions within an ecosystem. The vegetation constitutes a habitat for a host of invertebrates and fishes (Peterson 1979; Heck and Thoman, 1984; Heck et al., 1989). Abundances of infaunal species within the grassbeds may exceed abundances of the same species outside of the beds. The shoots slow the rate of water flow which in turn facilitates the deposition of fine grained sediments, reduces turbidity, and leads to a local increase in the concentration of food particles (Davis and Brinson, 1980; Peterson et al., 1984). The root system also may help to stabilize the sediment.

Oregon Inlet represents the northern limit of *Halodule wrightii* (shoalgrass), while sounds and bays in the southern portion of North Carolina represent the southern limit of *Zostera marina* (eelgrass). Shoalgrass and eelgrass are the most abundant grasses south of Oregon inlet. Abundance of these two grasses vary seasonally, with shoalgrass most abundant during periods of warmer water and eelgrass more abundant during the periods of cooler water. *Ruppia maritima* (widgeon grass) is sympatric with shoalgrass and eelgrass, and becomes the dominant vegetation in the more brackish waters of Croatan Sound and Currituck Sound. *Myriophyllum spicatum* (Eurasian water milfoil), *Najas guadalupensis* (bushy pondweed), *Potamogeton pectinatus* (sago pondweed), *P. perfoliatus* (redhead grass), and *Vallisneria americana* (wild celery) are also common vegetation in these low salinity waters (Ferguson et al. 1989).

Shoalgrass and eelgrass are not abundant along the western shore of Pamlico Sound. Causes of the low abundance are not clear, but may be related to the greater level of turbidity of the water along the western edge of Pamlico Sound (Ferguson, et al. 1989).

Little submersed vegetation is found in the Pamlico and Neuse rivers. That which does occur consists primarily of *V. americana,* with occasional patches of *R. maritima*. Populations of submersed vegetation in the Pamlico River have shown dramatic fluctuations during the last 15 years.

Summary

The critical physical features of the APLS are: (1) large spacial differences in salinity, with some areas also showing high temporal variation in salinity; (2) the predominance of unvegetated, fine sand sediments; (3) wind-driven water circulation; (4) large size and shallow depth; and (5) large seasonal range of water temperature and dissolved oxygen.

These features combine to make the APLS ecosystem both physically rigorous, and subject to significant levels of natural disturbance in the form of temperature, dissolved oxygen, and turbidity.

Major North Carolina Fisheries and Corresponding Gear Types

The North Carolina commercial fishery consists of six main categories: (1) sink net ; (2) winter trawl; (3) pound net; (4) long haul; (5) shrimp trawl; and (6) crab fishery (Table 1.3). The

Table 1.3. The primary North Carolina fisheries and their corresponding gear types (from NCDMF, 1993).

Fishery	**Primary Species**	**Target Area**	**Season**	**Gear**
Sink Net	weakfish, bluefish, croaker	Ocean side of outer outer banks from north of Oregon Inlet to Drum Inlet	Dec-- April	weighted monofilament gill net
Winter Trawl	summer flounder	Ocean side of outer banks; shallow water	Sept-- April	Flounder trawl
Winter Trawl	summer flounder scup, black sea bass	Offshore of outer banks; deep water	Nov-- Jan	Flounder trawl; combination trawl
Winter Trawl	croaker, weakfish. blue fish, butterfish	Ocean side of outer banks; Dec shallow and deep water	Sept--	Flynet
Pound Net : sciaenid	weakfish, bluefish, butterfish, harvestfish; spot flounder, spanish mackerel, menhaden	Estuarine side of outer banks	May-- Oct	stationary entrapment
Pound Net : flounder	summer and southern flounder, flounder, red drum, butterfish	Estuarine side of outer banks from SE Albemarle Sound to Cape Lookout	Aug-- Dec	stationary entrapment
Pound Net : river herring	American shad, hickory shad, striped bass, white perch, gizzard shad	Estuarine; Chowan River; Albemarle Sound		stationary entrapment
Long Haul Seine	bluefish, Atlantic croaker, weak-fish, Atlantic menhaden	regions of mainland and outer banks from SE Albemarle to Bogue Sound	Apr-- Nov	monofilament net

Table 1.3. (Cont).

Fishery	Primary Species	Target Area	Season	Gear
Shrimp Trawl	brown shrimp	Estuarine; SE Albemarle Sound to S.C.[1] border	June--Oct	flat trawl; channel net
Shrimp Trawl	pink shrimp	Estuarine; SE Albemarle Sound to Bogue Sound	Oct--Nov; April	flat trawl; channel net
Shrimp Trawl	white shrimp	Newport River; Cape Fear River; Core and Bogue sounds	May--June; Sept--Dec	mongoose trawl; skimmer trawl
Crab Trawl	blue crabs, flounder	Estuarine; SE Albemarle Sound to Bogue Sound	Nov--Jan Mar--June	crab trawl
Crab Pot	blue crabs	Estuarine; statewide	Mar--Nov	crab pot

[1] S.C. = South Carolina

sink net and winter trawl fisheries are limited to the shallow or deep waters on the Atlantic Ocean side of the Outer Banks. The remaining fisheries take place primarily within the Albemarle-Pamlico Lagoonal System.

Sink Net

Sink nets are weighted monofilament gill nets designed to capture fish near the bottom (Figure 1.2). Although considerable numbers of *Cynoscion regalis* (weakfish) and *Pomatomus saltatrix* (bluefish) are harvested annually by this fishery (NCDMF, 1992), there is no evidence that sink net activities contribute importantly to bottom habitat disturbance.

Winter Trawl

The winter trawl fishery employs three types of gear--flynet, flounder trawl, and combination trawl. The fly net is used to catch pelagic schooling fish and hence probably does not measurably contribute to bottom disturbance.

A flounder trawl typically has a 55-65 ft headrope with 5-6" mesh in the wings and 5.5" mesh in the tailbag, and up to 75 ft of chain, which drags over the bottom to force the flounder up into the water column and into the net above. Combination nets are used to fish bottom fish (flounder) and pelagic fish (weakfish; butterfish [*Peprilus triacanthus*] and squid [*Loligo pealei*]). Summer flounder caught by this trawl contributes most to the winter trawl catch. The founder trawl by design would disturb the benthos, but the magnitude of this disturbance has not been investigated.

Pound Net

Pound nets are stationary arrays of netting which lead fish into entrapment areas (Figure 1.2). Hence, they do not contribute to disturbance of the benthos.

Long Haul

A long haul seine consists of a 1000-1800 yd length of netting which is first towed a variable distance between two boats. Eventually the net is brought into a circle and the fish are enclosed. Long haul seining is done in moderately deep to shallow water (<2 meters) where the bottom is firm. At the present time seine length and mesh size are controlled only in Currituck Sound. Long haul seining may disturb the bottom.

Shrimp Trawl

A shrimp trawl is a modified otter trawl with a minimum mesh size of 1 1/2" (Figure 1.3). "Otter boards" or "doors" are rectangular structures attached to each side of the mouth of the net and function to keep the mouth of the net open during towing. Net design, and the number of nets simultaneously towed, are variable. Two commonly used nets in North Carolina are two-seam (flat) nets made from two panels of netting , and four-seam (semiballoon) nets made from four panels of netting. Two flat nets, or four semiballon nets are typically towed at the same time.

The footrope runs along the lower leading edge of each net. Weights or chains are attached to the footrope in order to keep the lower edge of the net near the bottom. As the footrope rides over the bottom, the shrimp attempt to escape from their burrows by swimming vertically, into the overhanging upper leading edge of the net. The doors, and the chains interconnecting the doors

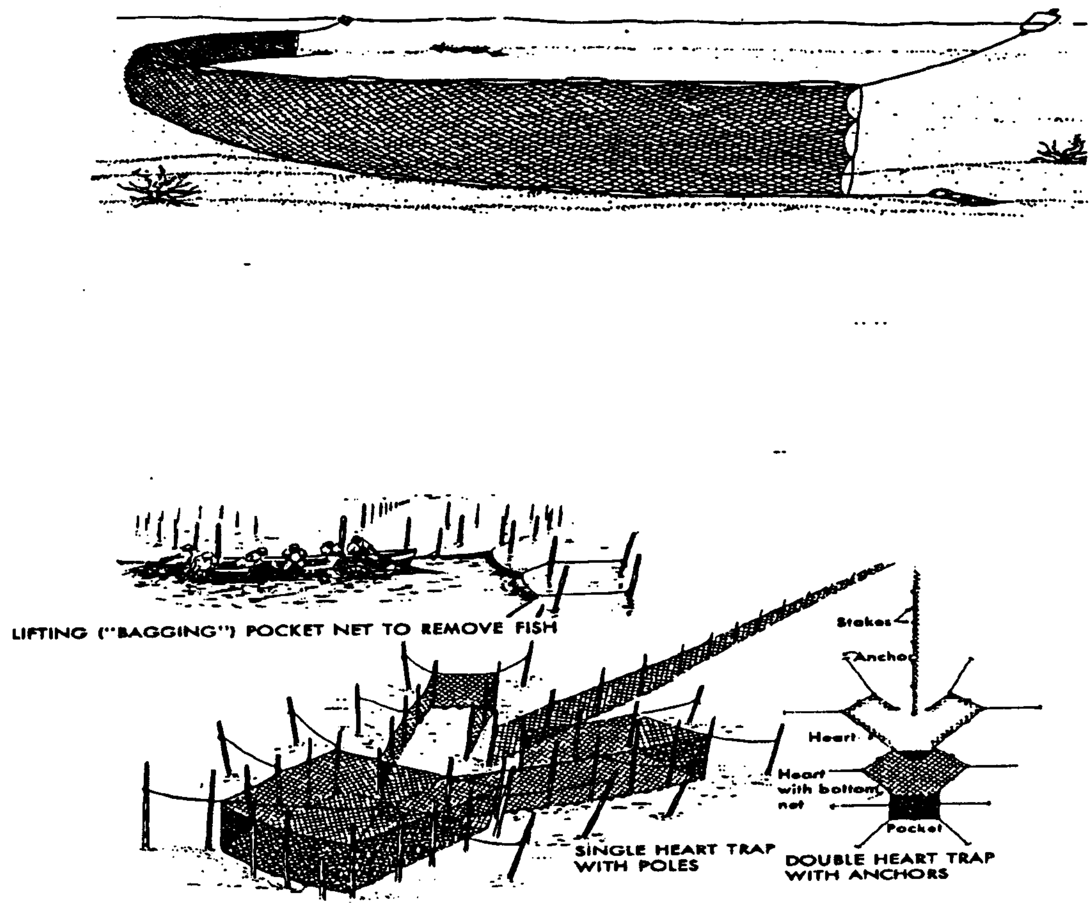


Figure 1.2. A schematic representation of a sink net (above; after Cunningham et al., 1992), and a pound net (below; after Rounsefell, 1975).

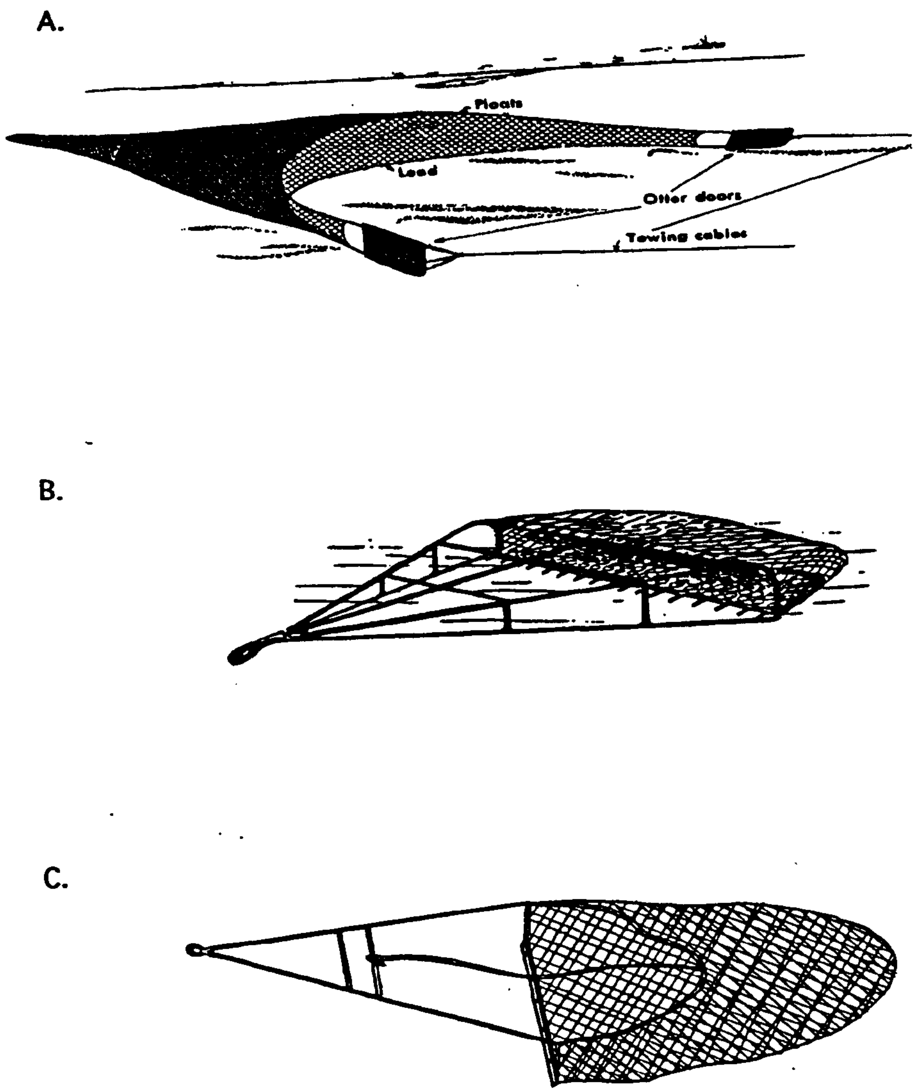


Figure 1.3. Representations of a shrimp trawl (A), crab dredge (B), and scallop dredge (C) (after Cunningham et al., 1992).

and the net ("tickler chains), are rigged to minimize penetration into the sediment, because otherwise the net quickly becomes filled with shell and debris. Nevertheless, the turbidity caused by the doors and tickler chains can be pronounced (G. Judy, NCDMF, personal communication).

Shrimp trawling is permitted throughout most of the APLS, exclusive of Albemarle Sound (Figure 1.4)[1]. Modern trawlers may simultaneously tow as many as four individual trawls, with a total headrope length in excess of 160 feet. A single tow lasts 1-3 hours. Most of the brown shrimp (*Penaeus aztecus*) and pink shrimp (*P. duorarum*) are caught using two-seam or four-seam shrimp trawls. Trawling is carried out during both day and night for brown shrimp , and during the night for pink shrimp . A different type of trawl ("mongoose trawl"), which fishes a greater proportion of the water column, is used to capture white shrimp (*P. setiferous*). White shrimp trawling occurs during the day (NCDMF, 1993).

The brown shrimp fishing season extends from June to October, and brown shrimp landings constitute about 70% of the total shrimp harvest. Pink shrimp are fished during the fall and the spring, and represent about 20% of the total shrimp landings. The majority of brown shrimp and white shrimp are caught in Pamlico Sound and Core Sound. White shrimp are harvested in May and June, and during August to December. White shrimp are fished primarily in the southeastern region of the state (Newport River and Cape Fear River), and make up about 5% of the total landings (NCDMF, 1993).

Shrimp trawling represents the greatest potential disturbance to the benthos given the gear design, and the temporal and spatial extent of this fishery. However, the monetary value of the average annual landings of shrimp during 1980-1991 has far exceeded that of all other commercial species of finfish and shellfish (Table 1.4). Approximately 80% of the value and the weight of shrimp landed were derived from estuarine trawls.

Crab Fishery

Crab trawls are similar in size and construction to shrimp trawls, except that the crab trawl is designed to penetrate more deeply into the bottom sediments. Mesh size limits vary from ≥ 2" (soft crabs) to ≥ 3" (hard crabs). Crab trawling is permitted throughout most of the Pamlico, Croatan, and Roanoke sounds, and in the major tributaries and subtributaries of Pamlico Sound (Figure 4). Functionally however, the crab trawl fishery is divided into an eastern and western fishery. Most of the eastern fishery occurs in the vicinity of the inlets, and consists primarily of mature female crabs. The western fishery catch includes crab and flounder.

[1] Figures 1.4 and 1.6 (taken from Cunningham et al., 1992), which show the areas of the APLS open to various fishing practices, are somewhat misleading because they omit, or fail to clearly delineate, a number of regions permanently closed to all trawling or similar activities. These regions include the seagrass meadows bordering the western shores of the Outer Banks, restricted military training areas, and all primary and secondary nursery areas. Areas permanently closed to trawling (including Albemarle Sound) account for approximately 50% of the 2.2 million acres of North Carolina's estuarine waters.

Table 1.4. Average annual landed value and weight of finfish and shell fish for the gear types used in the Albemarle-Pamlico Lagoonal system during 1983-1992. (from NCDMF, general canvas data).

Gear	Value ($)	Percent Total Value	Lbs Landed
Shrimp Trawl	10,654,167	31.5	6,398,408
Crab Pot	8,237,006	24.4	30,672,209
Pound Nets	2,735,377	8.1	8,886,851
Long Haul Seine	2,439,893	7.2	9,225,153
Anchor Gill Net	2,195,389	6.5	4,877,385
Rakes (Other)	1,937,564	5.7	369,284
Clam Trawl (Kicking)	1,551,159	4.6	311,982
Crab Trawl	1,132,603	3.3	2,676,367
Oyster Dredge	827,050	2.4	414,131
Bay Scallop Dredge	357,216	1.1	144,584
Purse Seine (menhaden)	301,930	0.9	10,637,931
Channel Net (Bag)	301,596	0.9	173,749
Other	267,269	0.8	45,214
Runaround Gill Net	241,313	0.7	458,726
Eel Pot	192,798	0.6	213,612
Oyster Tong	99,784	0.3	43,811
Clam Dredge	73,163	0.2	15,412
Spears	72,753	0.2	53,193
Fish Pot/Trap	44,272	0.1	228,623
Oyster Rake	42,995	0.1	18,328
Common Haul Seine	29,090	0.1	85,548
Tongs (Other) "	24,606	0.1	5,134
Skimmer Trawl	14,689	0.0	8,607
Long Line (Surface)	9,446	0.0	56,007
Common Dip Net	7,925	0.0	4,386
Crab Dredge	7,221	0.0	19,276
Hand Lines	5,023	0.0	6,027
Other Drift Gill Net	2,996	0.0	19,523
Fyke/Hoop Net	2,900	0.0	17,388
Trot Line (Baited)	2,612	0.0	13,267
Fish Trawl	2,094	0.0	3,324
Turtle Trap	714	0.0	2,469
Hand (Oyster)	601	0.0	209
Scallop Trawl	419	0.0	202
Troll Lines	272	0.0	485
Wheels	159	0.0	675
Butterfly Net	62	0.0	50
Total	33,816,127		

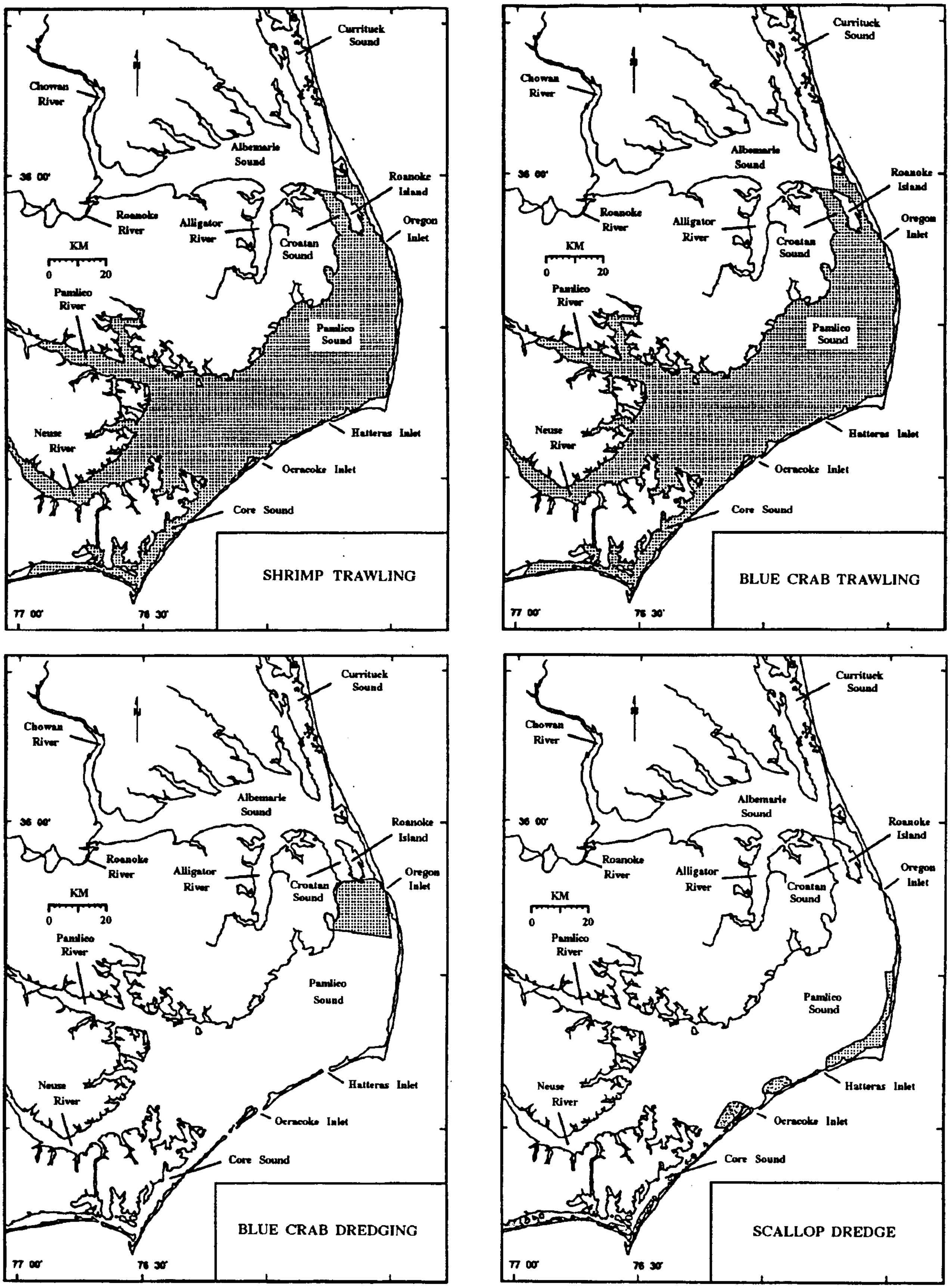


Figure 1.4. Areas of the APLS open to shrimp and blue crab trawling, and blue crab and scallop dredging (after Cunningham et al., 1992).

The proportion of the annual blue crab harvest represented by crab trawling has decreased from about 50% in the 1960s to less than 4% since 1988. This dramatic decline in crab trawl catch is the result of the fishermen converting to the use of crab pots. The crab trawl season is open throughout the year, but fishing activities tend to be most frequent during March to June, and November to April.

Crab pots are stationary gear that do not contribute significantly to disturbance of the benthos.

Other Fisheries

A number of other fisheries are carried out within the estuaries of North Carolina which are smaller than the major fisheries described above in terms of revenue and landings (Table 1.4), but which nevertheless employ trawling or similar gear. These minor fisheries include blue crab dredging, bay scallop dredging, clam trawling, and oyster dredging.

Blue Crab Dredge. The blue crab dredge (Figure 1.3) consists of a metal frame supporting a bag of iron hooks or rings. Teeth are usually present along the leading edge of the frame. The season is from to January to March and the dredging is limited to northeast Pamlico Sound (Figure 1.4).

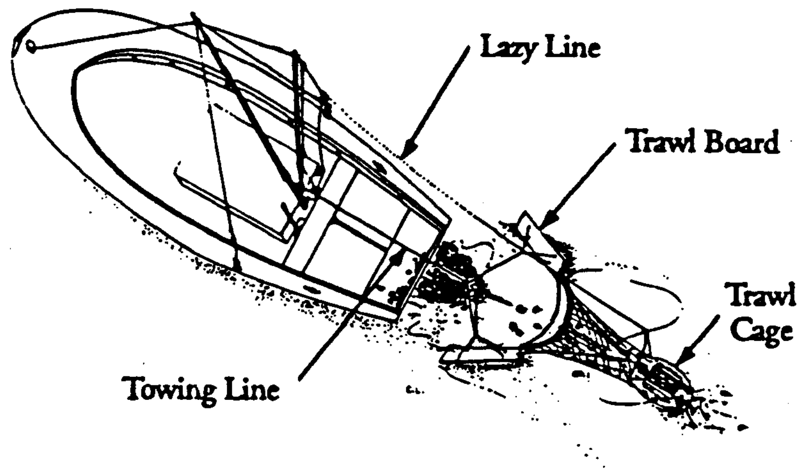
Scallop Dredge. The scallop dredge (Figure 1.3) consists of a metal frame and a wire or nylon bag. The width of the frame at the mouth of the bag is 24"-31"; the length of the dredge is 36"-40". The scallop dredge is designed to ride along the surface of the sediment and scoop up the epifaunal bay scallops (*Argopecten irradians*). Hence the weight of the dredge cannot exceed 50 lbs., and the frame at the mouth cannot bear teeth. The season extends from January to May. Harvesting areas are currently confined to regions of Bogue Sound, east Core Sound along Core Banks, and east Pamlico Sound along Ocracoke and Hatteras Islands (Figure 1.4). The scallop dredging season overlaps with recruitment of blue crab (*Callinectes sapidus*) postlarvae into the grass beds which border the western edge of the Outer Banks.

Clam Trawl.. Clam trawling (=clam kicking) is a mechanical harvesting method in which clams dislodged from the sediment by propeller backwash are caught in an otter trawl net containing a heavily weighted steel cage (Figure 1.5). The spacing of the cage bars serves as a culling device to eliminate small clams and shell debris. The target species is the quahog, *Mercenaria mercenaria*, and the season extends from December to March. Clam kicking is prohibited in primary nursery areas, and in beds of aquatic plants eelgrass, widgeon grass, shoalgrass, and cord grass (*Spartina alterniflora*). Currently clam kicking is carried out in specified regions of the White Oak River, Newport River, New River, and along the western edge of Core Sound south of Cedar Island (Figure 1.6).

Oyster Dredge. The oyster dredge is a metal framed basket with a bottom of iron rings and top of nylon, weighing about 100 lbs (Figure 1.5). The lower leading edge of the metal frame bears teeth which angle downward. The oyster dredging season runs from November to March, and is permitted in large regions of the Croatan, Roanoke and Pamlico Sounds, and the Pamlico and Neuse Rivers (Figure 1.6).

Skimmer Trawl. The net of a skimmer trawl is positioned along the side of the boat, and is "pushed" through the water, as opposed to being pulled through the water like an otter type of trawl (Figure 1.7). Two nets are typically used, one on each side of the boat. Each net is supported by a tubular metal frame and rides ("skims") over the bottom on a weighted metal shoe.

A.



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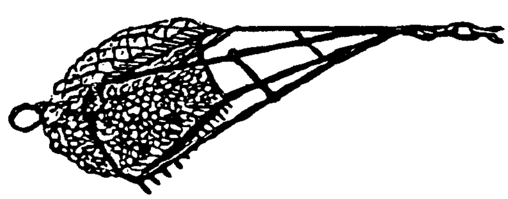

Figure 1.5. Representations of a clam trawl (A), and an oyster dredge (B) (after Cunningham et al., 1992).

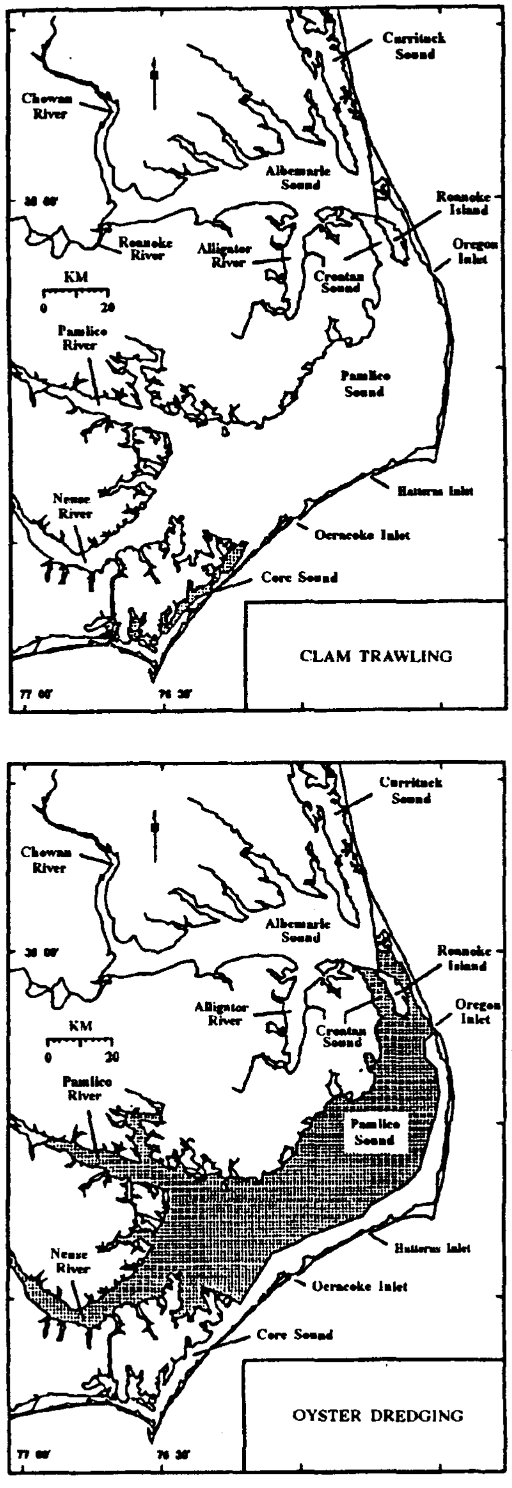

Figure 1.6. Areas of the APLS open to clam trawling and oyster dredging (after Cunningham et al., 1992).

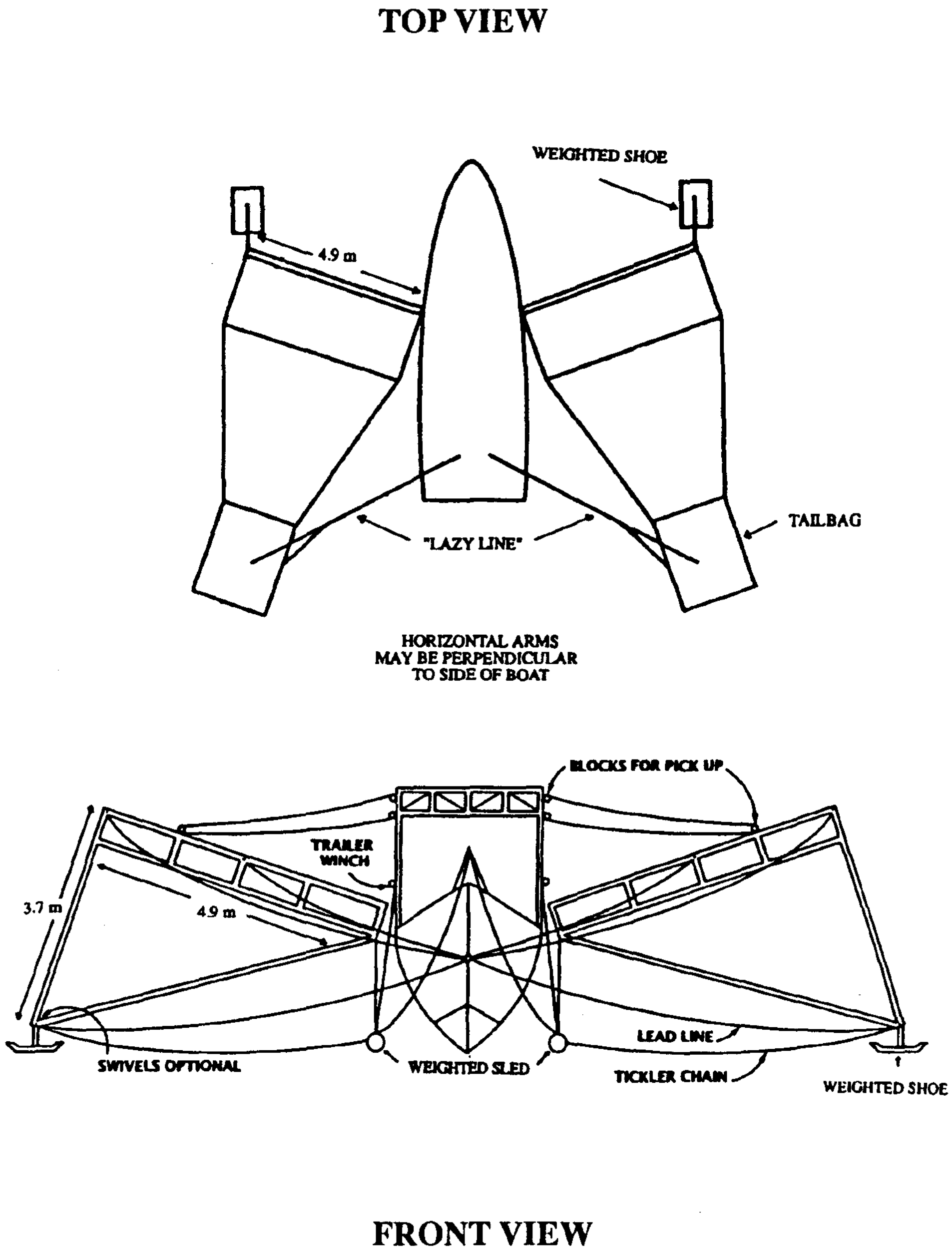

Figure 1.7. Representation of the skimmer trawl used in North Carolina (after Coale et al., 1993).

The mouth of the skimmer trawl is held open throughout the time of operation by the combined action of the weighted shoe at one edge of the mouth, and a weighted sled at the opposing edge of the mouth (Figure 1.7). The fixed dimensions of the mouth of the net enables the skimmer trawl to fish the water column to a height approximately equal to the height of the mouth (Coale et al., 1994). The maximum water depth than can be fished efficiently is determined by the length of the vertical metal arm attached to the weighted shoe. Skimmer trawls were developed to fish for shrimp in shallow, flat bottomed areas.

The impact of skimmer trawls on the benthos are not well understood. They have a tickler chain and are designed to capture brown shrimp, so some bottom disturbance must result from their operation. Skimmer trawling occurs primarily in Core and Bogue sounds (Coale et al., 1993).

Summary

The winter trawl flynet fishery, shrimp trawling, and long haul seining account for the great majority of fish bycatch in North Carolina. Shrimp trawling is also a potentially major source of disturbance for benthic invertebrates owing to the nature of the gear, fishing intensity and areal extent of fishing activities. Fisheries of lesser monetary value (e.g., bay scallop dredging, clam trawling, crab dredging, oyster dredging, skimmer trawling) may also impact the benthos, but to a currently unknown degree.

Fish and Invertebrates of the Albemarle-Pamlico Lagoonal System

Fishes of the APLS and Trophic Links to the Benthos

The fish community of the APLS consists of approximately 136 species (Epperly, 1984). This estimate includes four commercially important species of invertebrates: the blue crab, brown shrimp, pink shrimp, and white shrimp.

Analyses of North Carolina survey data up to 1983 indicated that 95% of the total number of fish collected were represented by only 10 of these 132 species (Epperly, 1984; Ross and Epperly, 1986) (cf.Table 1.5). Four of these 10 species, the bay anchovy (*Anchoa mitchelli*), spot (*Leiostomus xanthurus*), Atlantic menhaden (*Brevoortia tyrannus*), and Atlantic croaker (*Micropogonias undulatus*) accounted for slightly more than 75% of this total. Recruitment of larvae and juveniles is greatest in the spring (e.g., spot, Atlantic croaker, blueback herring) and summer (e.g., weakfish, silver perch).

Species comprising the North Carolina fishery can be placed into seven different types of life histories based on upon migratory patterns and spawning habitat (Epperly, 1984). Four of these life history categories are relevant to those species which are abundant in the APLS. Freshwater transients (FT, Table 1.5; e.g., white catfish, *Ictalurus catus*) are typically confined to waters with a salinity less than 18 ppt. These species are relatively more abundant in the Albemarle Sound and are of greater recreational interest than commercial interest. Anadromous species (ANAD, Table 1.5; e.g., blueback herring) mature in areas of high salinity (>30 ppt; euhaline) but migrate to fresh water in order to reproduce. All anadromous species are commercially important. Estuarine indigenous (EI, Table 1.5; e.g., bay anchovy) species tolerate a wide range of salinity, and are widespread throughout the estuaries and coastal regions of the state. Most of the estuarine indigenous species have little commercial value, with the exception of the blue crab and the white perch (*Morone americana*). Marine migratory species (MM, Table 1.5; e.g., spot) spawn offshore, and emigrate to the estuary as larvae or early juveniles. The bulk of juvenile growth in these Table

1.5. Distribution of the 23 most abundant finfish and shellfish according to the major sounds of the Albemarle-Pamlico Lagoonal system (adapted from Epperly, 1984). Rel % = proportion of total number of fish caught represented by a species; cum % = cumulative proportion of the total catch. LH=life history; EI=estuarine indigenous; MM=migratory marine; ANAD=anadromous; FT=freshwater transient

Species	CATCH PER SOUND Albe	Croatan	N. Pam	W.Pam	Total Catch	Rel %	Cum %	LH Type
Anchoa mitchelli	26419	86453	200172	275897	588941	33.1	33.1	E I
Leiostomus xanthurus	5867	1775	75506	331675	414823	24.1	57.1	M M
Brevoortia tyrannus	18004	1787	42812	280940	343543	19.1	76.1	M M
Micropogonias undulatus	9988	4212	57166	69282	140648	8.1	84.1	M M
Penaeus aztecus	14	169	20675	34075	54933	3.1	88.1	M M
Callinectes sapidus	1718	1338	11835	15488	30379	2.1	89.1	E I
Morone americana	25430	40	314	972	26756	2.1	91.1	E I
Menidia beryllina	14579	3277	1013	7441	26310	1.1	92.1	E I
Alosa aestivalis	22405	900	195	279	23779	1.1	94.1	ANAD
Bairdiella chrysoura	816	390	12459	9789	23454	1.1	95.1	M M
Cynoscion regalis	18	85	11726	6040	17869	1.1	96.1	M M
Lagodon rhomboides	20	46	334	5889	6289	0.1	96.1	M M
Alosa pseudoharengas	5319	12	188	488	6007	0.1	97.1	ANAD
Paralichthys lethostigma	169	17	1891	3880	5957	0.1	97.1	M M
Anchoa hepsetus	80	2506	674	1140	4400	0.1	97.1	E I
Trinectes maculatus	1004	102	557	2621	4284	0.1	97.1	E I
Penaeus setiferous	4	63	3446	765	4278	0.1	98.1	M M
Mugil cephalus	771	162	256	2889	4078	0.1	98.1	M M
Penaeus duorarum	1	106	2314	704	3125	0.1	98.1	M M
Ictalurus catus	2249	10	1	166	2426	0.1	98.1	F T
Lepomis gibbosus	733	26	28	1137	1924	0.1	98.1	F T
Perca flavescens	1608	12	27	173	1820	0.1	98.1	F T
Menidia menidia	197	1206	62	86	1551	0.1	99.1	E I

species occurs in mesohaline (5-15 ppt) estuarine nursery areas. Marine migratory species have significant recreational value and represent more than 50% of the commercial catch (Epperly, 1984).

The fish community also can be categorized according to diet (Table 1.6) and whether they are pelagic and forage within the water column, or are demersal and feed on organisms residing near, upon, or within the sediments. Pelagic species that feed on invertebrates include the blueback herring, alewife (*Alosa pseudoharengas*), bay anchovy, and striped anchovy (*Anchoa hepsetus*), and striped mullet (*Mugil cephalus*). These species feed primarily on zooplankton--small animals that spend their entire life cycle in the water column. However, these species also consume some benthic food items, such as polychaetes [(e.g., blueback herrings, inland silversides (Menidia beryllina)], harpacticoid copepods (striped mullet), and detritus (non-living organic matter;, e.g., striped anchovy, bay anchovy, striped mullet). Atlantic menhaden are distinguished from the other planktivorous species of fish by their dependence on microalgae as a primary food source, although they are also known to ingest significant amounts of detrital material (Hildebrand and Schroeder, 1928). This group contains many commercially important species such as Atlantic menhaden, river herring, alewife, and the striped mullet.

A second group of fish share both pelagic and demersal habitats, feeding on other fish and the larger epibenthic invertebrates. This group includes southern flounder (*Paralichthys lethostigma*), weakfish, silver perch, white perch, yellow perch (*Perca flavescens*), and white catfish. Virtually all members of this group are important species to both commercial and recreational fishermen.

The third group consists of demersal predators of epibenthic and infaunal invertebrates. This group is the largest and consists of spot, croaker, pinfish (*Lagodon rhomboides*), hogchoker (*Trinectes maculatus*), mummichog (*Fundulus heteroclitus*), pumpkin seed (*Lepomis gibbosus*), brown shrimp, pink shrimp, white shrimp, and the blue crab. Commercial catches of spot, croaker, shrimp and blue crab account for at least 75% of the annual commercial landings of all finfish and shellfish. Most of the members of this group are also important recreational species.

Benthic Invertebrates of the APLS

The benthic invertebrate community consists of motile, sedentary, and sessile organisms which live on or in the sediment. The APLS benthic invertebrate community consists of at least 275 species (Stearns and Ross, 1989). Knowledge of this community within the Albemarle-Pamlico Lagoonal System is of great ecological and practical value because members of this community serve as food for the majority of commercially important species of finfish and shellfish (Table 1.6). Nevertheless, no systematic, comprehensive description of the benthic invertebrate community of the APLS exists at this time. This general lack of information about this important community is the result of two primary factors: (1) historically, little interest has been generated in describing this community because most members have no direct commercial value; and (2) collection, enumeration, and identification of invertebrates are typically more expensive, time consuming and difficult than for fishes.

The bulk of the available information on the benthic invertebrate community of the Albemarle-Pamlico Lagoonal System resides in a small number of works (Table 1.7) which typically suffer from one of several limitations in the context of the objectives of this report. First, most of the studies have been carried out in areas of the APLS which receive comparatively little or no commercial fishing pressure. These areas include primary nursery areas (Currin et al., 1984; West, 1984; West and Ambrose, 1992), oligohaline habitats (Civils, 1982), or shallow intertidal

Table 1.6. Dietary components of the most abundant species of finfish and shellfish of the Albemarle-Pamlico Lagoonal System. "Season " refers to the months of high abundance of each species.

Species Name	Common Name	Season	Components of Diet	Reference
Alosa aestivalis	blueback herring	Jun-Aug; Oct-Nov	copepods; insect larvae; polychaetes, shrimp, fishes	Manooch, 1984
Alosa pseudoharengas	alewife	Jun-Aug	copepods, cladocerans rotifers	Vigerstad & Cobb, 1978
Anchoa hepsetus	striped anchovy	Jun-Aug	small crustaceans, detritus	Hildebrand Schroeder,1928
Anchoa mitchelli	bay anchovy	Mar; Jul-Aug	crustacean larvae; amphipods, copepods, mysids, detritus	Schwartz, 1980; Johnson et al., 1980
Bairdiella chrysoura	silver perch	Jun-Aug	mysids, decapods, fish	Schwartz, 1980; Hildebrand & Schroeder, 1928
Brevoortia tyrannus	Atlantic menhaden	Feb-May; Jul-Aug	microalgae, copepods, detritus 1972	Hildebrand & Schroeder, 1928
Callinectes sapidus	blue crab	Mar-Aug	amphipods, bivalves, decapods, fish, foraminifera	Stoner & Buchanan, 1990
Cynoscion regalis	weakfish	Jun-Aug	mysids, decapods, fish (esp. Anchoa spp.)	Schwartz, 1980
Fundulus heteroclitus	mummichog	Apr-Aug	grass shrimp, detritus, molluscs, annelids	Service, et al., 1992 Hildebrand & Schroeder,1928
Ictalurus catus	white catfish	Jul-Nov	fish, insect larvae, detritus	Manooch, 1984
Lagodon rhomboides	pinfish	May-Aug	mussels, decapods, mysids, amphipods, polychaetes, detritus	Schwartz, 1980
Leiostomus xanthurus	spot	Mar-Jul	copepods, amphipods, clam siphons, polychaetes, insect larvae	Currin et al., 1984; Service et al., 1992; West & Ambrose, 1992
Lepomis gibbosus	pumpkin seed	Apr-May	isopods, polychaetes, amphipods, insect larvae	Hildebrand & Schroeder 1928; Gilinsky, 1984

Table 1.6. (Cont.)

Species Name	Common Name	Season	Components of Diet	Reference
Menidia beryllina	Atlantic silverside	May-Aug	crustaceans, molluscs, insect larvae, annelids	Hildebrand & Schroeder 1928
Menidia menidia	inland silverside	Aug-Oct	copepods, amphipods, polychaetes	Gilmurray & Daborn 1981
Micropogonias undulatus	croaker	Apr-Jul	polychaetes, amphipods, copepods, decapods, fish	Darnell,1961; Parker, 1971; Diener et al., 1974; Chao & Musick, 1977; Livingston, 1984
Morone americana	white perch	Jun-Oct	fish, amphipods, isopods, polychaetes, insect larvae	Hildebrand & Schroeder, 1928
Mugil cephalus	striped mullet	Mar-Jun	harpacticoid copepods, mosquito larvae, detritus	Harrington & Harrington,1961; De Silva & Wijeyaratue, 1977
Paralichthys lethostigma	southern flounder	Apr-May	fish, molluscs (squid), decapods, mysids	Hildebrand & Schroeder,1928; Powell & Schwartz, 1979
Penaeus aztecus	brown shrimp	Jun-Sep	organic matter, crustaceans, polychaetes	Williams, 1984
Penaeus duorarum	pink shrimp	Apr-Jun	copepods, ostracods ostracods, molluscs, detritus, bacteria, algae	Odum and Heald, 1972
Penaeus setiferous	white shrimp	Aug-Oct	capitellid polychaetes, bryozoa, sponges	Christmas & Etzold, 1977;Mckenzie, 1981; Service, et al., 1992
Perca flavescens	yellow perch	Mar-May fish, decapods	isopods, amphipods,	Hildebrand & Schroeder, 1928
Trinectes maculatus	hogchoker	May-Aug	polychaetes, small crustaceans	Hildebrand & Schroeder, 1928

Table 1.7. Relevant studies of benthic invertebrates of the Albemarle-Pamlico Lagoonal System.

Subject	Sampling Period	Habitat	Location	Investigator
Community structure	Jun-Sep, 1959	intertidal & subtidal	Eastern shore of Pamlico S.	Bishop, 1960
Faunal distribution & sediment type	Jul, Feb, Oct, 1960--1961	subtidal	Bogue S.	Brett, 1963
Distribution of oyster drills	----	intertidal	Outer banks south to South Carolina	Chestnut, 1955
Community structure & distribution	Monthly, Sep 1976--Apr--1977	subtidal	Upper Pamlico R.	Civils, 1982
Distribution & abundance of *Rangia cuneata*; sediment grain size	Aug, 1970	subtidal	Croatan S.	Crump, 1971
Catch per effort and size of blue crab and *Penaeus aztecus*	Mar-Nov, 1979--1984	subtidal	NW Pamlico S. south to Cape Fear R.	DeVries,1986
Distribution of amphipods (crustaceans)	Monthly, Nov 1963-Oct--1964	subtidal	Western shore of outer banks, W. shore of Pamlico S., Neuse R.	Dexter,1967
Distribution of eastern oyster, bay scallop, quahog	----	subtidal	APLS area	Epperly & Ross, 1986
Abundance & distribution of *Rangia*	monthly, Jun-Aug, 1977	subtidal	Pamlico R.	Gray & Winkler, 1977
Abundance of blue cr and *Penaeus spp.*	Monthly, Jun 1972--Aug 1973	subtidal	Albemarle S. & Neuse R.	Hester & Copeland, 1975

Table 1.7 . (Cont.).

Subject	Sampling Period	Habitat	Location	Investigator
Community dynamics	Monthly, 1976	Intertidal to subtidal	East shore of Bogue Banks	Leber 1978
Abundance of *Penaeus spp.*	May -Jun, 1968	Subtidal		McCoy, 1972
Distribution & abundance of bay scallop & abundance of *Penaeus spp.* & blue crabs	Monthly, Apr 1975-- Jun--1978	subtidal	Bogue S.& Core S.	Spitsbergen, 1979
Distribution of Penaeus spp., blue crab, and mysids	Monthly, Apr 1972-- Dec--1973	subtidal	W. Pamlico from Pamlico R. south to Neuse R.	Spitsbergen & Wolff, 1974
Spatial & temporal changes in community structure; sediment grain size and organic carbon content	Oct, Jan, Apr, Jul, 1968 -1969	subtidal	Pamlico R.	Tenore, 1972
Community structure	Monthly, 1955- 1966	intertidal & subtidal	Newport R.	Wells, 1961
Temporal changes in community structure	bimonthly & quarterly, 1984	Subtidal	Subtributaries of the Pamlico R.	West, 1984
Abiotic and biotic effects on abundances	Bimonthly, 1982--1987	Subtidal of the Pamlico R	Subtributaries	West & Ambrose, 1992
Population dynamics & distribution of *Penaeus spp.*	Monthly, 1948--1952 & Bogue S.	subtidal	Tributaries of Core S.	Williams, 1955

Table 1.7. (Cont.)

Subject	**Sampling Period**	**Habitat**	**Location**	**Investigator**
Habitat preferences of *Penaeus spp.*	Experimental	Laboratory		Williams, 1958
Distribution of *Penaeus spp.*	Monthly, Apr -Aug, 1952-1953	subtidal	Western shore of Pamlico S., south to Cape Fear	Williams, 1955
Community structure; gross sediment characteristics	Jul-Aug, 1978	subtidal	Croatan S.	Wright, 1972

areas (Bishop, 1960; Leber, 1978). Second, the studies may have concentrated on a subset of the total local benthic community, e.g., oyster drills (Chestnut, 1956), the clam *Rangia cuneata* (Crump, 1971; Gray and Winkler, 1977), commercial shrimp (Williams, 1955a, b, 1958; McCoy, 1972; Spitsbergen and Wolff, 1974), and crustacean amphipods (Dexter, 1967). Third, the duration of the study was not long enough to provide an adequate description of seasonal variation in community composition and species abundance (e.g., Bishop, 1960; Crump, 1971; Wright, 1972).

Tenore's study (1972) of the Pamlico River benthos provides insight into the structure, and seasonality of an APLS invertebrate community. This community consists of approximately 36 species, 45% of which are molluscs. However, a small number of species constitutes the bulk of the total number of individuals present at any particular time or location. Hence the clam *Rangia cuneata*, the polychaete *Nereis succinea*, and the isopod crustacean *Cyathura polita* are the most abundant species of the oligohaline (salinity =0.5-5 ppt) regions of the Pamlico River; the clam *Macoma balthica*,and the polychaetes *Heteromastus filiformis* and *Nereis succinea* are most abundant in the mesohaline (salinity = 5-18 ppt) region of the river; and the clams *Macoma mitchelli* and *Munidia lateralis* and the polychaete *Glycera dibranchiata* dominate the polyhaline (>18 ppt) portion of the river. The number of species increases as average salinity increases; in fact 8 species of the entire river community of 36 species are found only in the polyhaline area of the river. The diversity of the Pamlico River community is low relative to communities located in high salinity bays such as Bogue Sound (cf. Brett, 1963; Peterson, 1979; Summerson and Peterson, 1984), or in the regions of the inlets that open into Pamlico Sound (cf. Bishop, 1960).

Seasonal changes in number of species, and numbers of individuals per species, are profound in the Pamlico River, with greatest numbers of species and densities of individual species occurring in the winter and early spring (Tenore, 1972). Between spring and summer, the benthic community is reduced to about 20 species, and numbers of individual species may decrease by a factor of a 100 (e.g., *Macoma balthica* and *Heteromastus filiformis*). Total depletion of benthic fauna was observed at depths greater than 2 meters during July 1969. Similar temporal patterns of abundance and diversity prevail in primary nurseries of the APLS (West, 1984; West and Ambrose, 1992); however it is not clear if this is the case for the communities of the sounds of the APLS (e.g., Pamlico, Croatan, Albemarle, Core).

The large seasonal fluctuations in abundance and number of species in the Pamlico River coincide with seasonal changes in water quality, and apparent recruitment patterns of larvae and juveniles. Tenore (1972) suggested that the summer decline in abundance and diversity resulted primarily from high temperatures and low concentrations of dissolved oxygen. These aspects of water quality, plus the low average salinities, high turbidity and unstable sediments, collectively rendered the Pamlico River a low diversity system relative to other local Bays and Sounds. Recruitment activities in the fall and winter restored the abundance and diversity of species to their annual high levels.

It is presently unclear if physical factors play an equally important role in structuring benthic communities in other regions of the APLS. The large size and shallow depths of the sounds of the APLS, and available hydrographic data (Rolefs and Bumpus, 1953; Giese et al., 1979) argue against a pervasive negative effect of anoxia on benthic communities in the APLS. However, these sounds are also naturally turbid (cf. Wells and Kim, 1989), and the effects of this turbidity on the benthic community remain to be quantified. Turbidity is a complex issue, and its ecological effects could be both positive and negative. Thus turbidity could be an agent of disturbance and cause local mortality of benthic organisms. The organisms that replace those which have died may be different species than the original residents. Turbidity in this way could generate a complex array of disturbed areas of varying size and species composition, and when considered at the spatial scale of an entire sound, may be an important agent of maintaining a high level of benthic diversity. Some of the regions of the APLS with the highest benthic diversity are also known for having high levels of turbidity (e.g., the inlets of the Outer Banks; Bishop, 1960).

Abundance and diversity of benthic fauna in oligohaline tributaries of the Pamlico River undergo seasonal variations similar to those of the Pamlico River (West, 1984). However, the spring to summer decline in numbers of organisms and numbers of species in these creeks precedes the occurrence of seasonal low levels of dissolved oxygen (West, 1984). Results of experiments excluding and including predators indicates that predation by recruiting juvenile fishes (e.g. spot, Atlantic croaker) may be an important factor in the seasonal reduction in individual densities of some benthic species (West and Ambrose, 1992). Earlier studies by Peterson (1979), and subsequent work by Summerson and Peterson (1984), indicate that predation is an important factor in the determining community structure of non-vegetated soft-bottom habitats in the southern sounds of North Carolina.

Summary

The finfish community of the APLS consists of approximately 136 species. However, only 10 of these species occur in great abundance, and a seasonally varying combination of these species numerically dominate the local finfish community throughout the year. The majority of the commercially important finfish species fall into three categories, based on life cycle and migratory habits: (1) anadromous (e.g., Alosid clupeids such as the blueback herring); and (2) marine migratory [e.g., spot, croaker, shrimp *(Penaeus* spp.)]; and (3) estuarine indigenous (e.g., blue crab).

The finfish community has strong trophic links to the benthic invertebrate community because most of the abundant fish species feed on invertebrates for part or all of their life within the APLS. The benthic community of the APLS has not been extensively described or studied. Available information suggests that this is a low diversity community as a result of a combination of low average salinity, unstable sediments, high turbidity, and seasonally low dissolved oxygen levels.

Impact of Trawling on the Benthos

All commercial methods of harvesting demersal fish and epibenthic (=on top of the sediment surface) or infaunal (=within the sediments) shellfish alter the physical structure of the seabed, and to varying degrees, the community of resident organisms. These effects may be immediate and direct, such as the death or injury of benthic animals or the removal of vegetation, or indirect such as the biological consequences of habitat modification, or removal of an important predator or competitor. These effects will be addressed below within the categories of physical, and biological effects of trawling, respectively. It will be shown that there are direct and profound linkages between physical perturbation of the benthic habitat and the dynamics of the community of benthic organisms. Separating the physical and biological consequences of trawling is therefore somewhat artificial, and some redundancy in the following discussion is inevitable.

Physical Modification of the Habitat

Trawling and related fishing activities alter both the living and non-living components of a habitat's physical structure. The living component includes reefs composed of sedentary organisms such as tube-dwelling worms and oysters, and submersed meadows of algae and vascular plants.

The non-living component is the nature of the bottom substratum; e.g., hard or soft bottom, smooth or irregular rock, and sandy sediment or muddy sediment.

Living Components of the Habitat. Permanent loss of oyster beds and reefs of the tube-dwelling worm *Sabellaria* in the North Sea have been attributed to the effects of long-term trawling (> 50 years) (de Groot, 1984). The exact mechanism by which trawling would have completely eliminated these animals remains unclear, but it probably involved alteration of the habitat to the extent that larval recruitment was not sufficient to maintain the population. The larvae of both oysters and *Sabellaria* are highly specific in their choice of the substratum they attach to in preparation for metamorphosis to the adult. Oyster larvae require the presence of adult oyster shell (Cole and Knight-Jones, 1949; Crisp, 1967), while *Sabellaria* larvae require the presence of the adult's tubes (Wilson, 1968).

Fishery harvesting practices (e.g., clam kicking, scallop dredge, otter trawl) also reduce algal and seagrass biomass (Fonseca et al., 1984; Bargmann et al., 1985; Peterson et al., 1987). Reduction of seagrass (*Zostera marina*) biomass was linearly related to the number of times a particular area was dredged, and the effects of dredging were proportionately greater in soft bottom (little sediment compaction) than in hard bottom (substantial sediment compaction) habitats (Fonseca et al. 1984). If reduction in seagrass biomass involves uprooting of the plants, the time required for the region to recover from the harvesting disturbance can be substantial (> 2 years) (Homziak et al., 1982).

Loss or partial destruction of the living component of the habitat typically has serious ecological consequences. Reefs and seagrass beds are islands of high species diversity and abundance relative to the surrounding sediment (Wells, 1961; Peterson, 1979). This diversity results from a complex of factors, including the presence and availability of the habitat for occupation by other organisms, the structural complexity provided by the living structures, increased habitat stability, availability of food, and protection from predation (Thayer et al., 1975; Orth, 1979; Peterson, 1979; Heck and Orth, 1980).

Non-living Components of the Habitat. The degree to which bottom trawls disturb the sediment surface depends on the sediment type and the relationship between gear type, gear weight and trawling speed (Anon., 1991). Various parts of gear may contact and disturb the bottom, such as the undersides of doors, tickler chains, ground ropes, trawl shoes, and belly of the trawl (Anon., 1990). With hydraulic dredges, very little of the gear may contact the bottom but the water pressure used to excavate bivalves may cause severe disturbance to the bottom. For non-hydraulic gear, the pressure on the bottom can be easily calculated from the weight of the gear (in water) and the surface area of the gear in contact with the bottom. Margetts and Bridger (1971) provided such a calculation for a beam trawl, but they failed to consider the upward pull by the cables, which is dependent on trawl speed and angle of the tow line. The relationship between resistance of an otter trawl used in the Bearing Sea ground fishery and towing speed, bridle angle and wing spread and head rope height was determined by Goudey and Loverich (1987). Their work demonstrates the large effect net configuration and tow speed can have on the action of trawl gear on the bottom. The number of tickler chains and their weight per unit length are also variables that can affect the degree of disturbance to the bottom. After comparing depth of sediment disturbance by different numbers and weight of tickler chains, Margetts and Bridger (1971) conclude that the cumulative effect of chains is likely to emulsify the sediment to a depth proportional to the number of chains.

The depth of sediment disturbance by different fishing gear is listed in Table 1.8. The depth of sediment disturbance by the same gear often varies greatly among studies due to differences in gear configuration and tow rope angle, Nevertheless, the depth of penetration is

Table 1.8. Sediment penetration depth of various types of fishing gear. References are as follows: 1--Anon., 1973; 2--Medcof & Caddy, 1973; 3--Peterson, et al., 1987.

Gear Type	Effective Parts of Gear	Towing Speed	Penetration Depth (cm) Mud	Sand
otter trawl [1]	Door, ground rope	3-4	8-10	< 5
Beam trawl [1] (ground fish)	Trawl shoes, chains	7	3-4	0.3-1
Beam trawl [1] (shrimp)	Ground rope, shoes	3	5	2
Scallop dredge [1] (offshore)	Tooth bar and belly	3	10	2-3
Scallop dredge [1] (inshore)	Dredge foot, teeth	2	?	< 1
Clam dredge [2] (hydraulic)	Hydraulic jets	1	-	20-30
Clam dredge [1]	Dredge teeth	1-2	10	5-10
Clam kicking [3]	Propeller wash	2	?	?

always greater in muddy compared to sandy substrata and conventional gear can penetrate the sediment as deep as 10 cm in mud while hydraulic clam dredges can disturb the sediment to 30 cm deep in sand. The depth of penetration into the sediment can also vary depending on whether the trawl is pulled parallel or perpendicular to sand ripples. In a study in the English Channel, narrow shoes of a light beam trawl cut 6-12 mm deep groves into muddy-sand when the trawl was pulled parallel to ridges but cut 25 mm deep when pulled across ridges (Bridger, 1972). Interestingly, in the same study wider shoes of heavier gear left indistinct, hard to locate groves, possibly because the weight of the trawl was spread out over a larger area with the larger shoes on the heavier trawl compared to the narrower shoes on the lighter trawl.

When tickler chains are used, their effect, as noted above, is to emulsify the top part of the sediment. In the process they remove all natural ripples and other surface protuberances and leave a smooth surface in the wake of the trawl (Bridger, 1972, Caddy,1973). Belly rings have a similar effect on sediment surface morphology as chains (Caddy, 1968).

Trawling in sandy and muddy areas will cause resuspension of bottom sediments.Resuspension of sediments has potentially complicated biological effects, which are discussed in the following sections (effects on primary, and secondary, productivity). The critical physical consequences of sediment resuspension are an increase in the turbidity of the water, and--through subsequent redeposition--alteration of the grain size composition of the sediments. The effects of trawling on water column turbidity have not been well documented. The dynamics of sediment clouds created by the movement of the trawl doors across the sediment surface are of practical interest to fishermen because the clouds of sediment help to herd fish toward the mouth of the net. The shape of the suspended sediment cloud is dependent upon the geometry of the trawl doors, towing speed, and the length of cable between doors and the net, and the presence and type of chains or cables (e.g. tickler chains, footropes) which span the distance of the mouth of the net (Main and Sangster, 1981). The amount of turbidity is primarily dependent upon the nature of the substratum, towing speed, depth of bottom penetration, door geometry, and length of the footrope or tickler chain (Schubel et al., 1979; Main and Sangster, 1981).

Measurements of suspended sediments taken approximately 100 m astern of shrimp trawlers at depths of 0.6 m and 2.1 m in Corpus Christi Bay, Texas (average water depth = 4 m), ranged from 100-500 mg/L (Schubel et al., 1979). The total amount of sediment annually disturbed as a result of shrimp trawling was estimated to be 25-209 x 10^6 m^3, which is 10-100 times greater than that dredged during the same time interval for maintenance of shipping channels in the same area (Schubel et al., 1979). Corpus Christi Bay is similar to Pamlico Sound with regard to sediment type and average depth.

Bottom disturbance by trawling can cause both short term and long term changes in the grain size distribution of the sediments (Anon., 1973, 1991). Short term changes in grain size distribution result from size dependent differences in the rate of redeposition of sediments suspended by the plowing action of the trawl through the substratum. Coarse grained sediments settle out relatively quickly; fine grained sediments settle out relatively slowly. Bridger (1972) noted that sediment in the wake of a trawl seemed firmer than the surrounding sediment.

Transport of resuspended fine grained sediments away from the site of trawling can produce permanent changes in sediment grain size. The general long term effect of trawling on sediment composition, therefore, is probably an increase in average grain size. This shift will be particularly pronounced in mud and mud/sand habitats typical of many trawling grounds.

The finer sediment particles dispersed by trawling also include organics which along with the organic material attached to fine grained inorganic particles are the food for deposit feeding infauna. Sediment composition (grain size, skewedness) is known to be extremely important in determining the distribution and abundance of infauna (Rhodes and Young, 1970; Wilson, 1991). One effect of a shift in grain size might therefore be a decrease in the dominance of deposit feeders.

It is important to note that long term changes in grain size composition of the sediments resulting from trawling assumes significant lateral transport of resuspended fine-grained sediments. There is presently little known about this aspect of trawling disturbance, and its potential magnitude in a non-tidal system like the APLS. Long term alteration of sediment grain size distribution would be less pronounced in non-tidal areas where current velocities are low and variable, than in areas with strong directional tidal flow.

Trawls will also dislodge rocks and shells and in the process, raise them above the sediment surface (Caddy, 1968, 1973). This would increase the surface area available for occupation by epibenthic organisms, and modify near-bottom current flow, which in turn could influence settlement and subsequent survival of infauna (see Butman 1987 for discussion of hydrodynamics on settlement of soft-bottom invertebrates) . Holes will be formed where large rocks are dislodged (Caddy, 1973), further modifying bottom topography. Potential ecological consequences of increasing the relief of the seabed surface by unearthing shell and rock by trawling actions are discussed in more detail in the following section (effects on secondary productivity).

The persistence of dredge and trawl tracks on the sediment surface depends on the bottom type, current flow, and the degree to which the sediment is disturbed. On a substrate of muddy-sand with moderate tidal flow, Margetts and Bridger (1971) found that tracks were still visible 3.5 hr after trawling while on bottoms of coarser sand with a strong tide running trawl tracks disappeared “fairly quickly”. On very muddy bottom with limited tidal flow, Caddy (1973) claimed tracks remain recognizable for a "long time" (several days?). Caddy (1973) also recorded that 37% of the bottom in his study areas was covered with tracks made by otter trawls. In other areas with little or no tidal currents, tracks have been noted to persist for days (Anon. 1973) to months (Medcof and Caddy 1971).

More important than how long the tracks remain visible, however, is how long the effects on the benthos persist. This aspect of trawling has not been well studied. Under conditions where the effects of trawls on bottom microtopography persist for longer than a few days, the cumulative effects of even a modest level of trawling on the benthos is likely to be significant. Unless the entire bottom is trawled, however, the effect on the benthic habitat on a large scale will be to increase habitat complexity. Trawled and untrawled areas will differ in bottom roughness, grain size, and possibly the availability of hard substrata. The net result will be a greater variety of microhabitats, and to the extent that diversity is positively correlated with habitat complexity in benthic habitats, a greater diversity of benthic fauna.

As discussed above, one effect of trawling is to increase the roughness of the bottom by raising shells and rocks above the sediment surface. The effect of this modification of bottom topography on the distribution and abundance of epifaunal and infaunal organisms will persist until the rocks and shells are reburied. In areas of low sedimentation, this may require a substantial period of time. In the interim, the new surface area available for epifauna will likely lead to an increase in their abundance. Increased surface roughness will have both positive and negative effects on infaunal abundances depending on the settlement behavior and food and habitat requirements of individual species.

Effects on Primary Productivity

Introduction. Trawling can influence primary productivity in two basic ways: (1) by stimulating chemical exchange between resuspended sediment and the water column; and (2) by altering the maximum depth of light penetration as a result of sediment resuspension. In order to appreciate the consequences of chemical exchange between resuspended sediments and the water column, it is first necessary to understand some of the basic steps in the deposition, burial and chemical transformations of sedimentary materials.

Benthic sediments consist of a mixture of living and non-living animal, plant and algal matter, a large and diverse microbial community, amorphous organic matter, and inorganic minerals of varying particle sizes (e.g. clay, silt, sand). In addition to this particulate phase, a liquid phase is also present, consisting of water and a complex constituency of dissolved ions, which fills the interstices or pores between the particulate materials (Day et al., 1989; Chester, 1990). Particulate matter and dissolved nutrients may originate from outside (allochthonous) sources such as riverine, atmospheric and anthropogenic inputs, or may originate from internal (allochthonous) sources through annual cycles of sediment resuspension, mixing, and blooms phytoplankton (microscopic algae).

Following deposition, a particle of non-living organic matter undergoes a complex series of oxidation-reduction chemical transformations ("diagenesis") which may eventually result in the release of its components in an inorganic (mineralized) form. As the process of sedimentation continues, the particle becomes buried, and over time the particle will occupy successively deeper layers of the sediment. The sediments thereby become stratified. This stratification is manifested as vertical gradients in both the composition of particulate matter and in the chemical nature of the diagenetic process. This chemical stratification is referred to as the diagenetic zone sequence, and represents a vertical structuring of chemical properties of the particulate matter and the ambient pore water (Day et al., 1989; Chester, 1990).

Typically the upper region of the sediments, bounded by the sediment-water interface, is the aerobic or oxic zone, where the interstitial water is oxygenated, oxygen is the primary oxidizing agent, and alteration of sedimentary material proceeds by aerobic respiration. With increasing depth, the amount of oxygen in the pore water diminishes to unmeasurable levels. Within this large anoxic zone, respiration proceeds anaerobically, and the oxidizing agent shifts from oxygen, to nitrate (NO_3), sulfate (SO_4), and ultimately carbon dioxide (CO_2)(Martens, 1978; Froehlich et al., 1979). These diagenetic reactions occur rather slowly, especially within the anaerobic region of the sediments. As a result, large amounts of undegraded or partially degraded organic matter can be sequestered in the anaerobic zone of the sediments if natural rates of sedimentation are high.

All of these diagenetic events are mediated by microorganisms, which participate in diagenesis in order to acquire energy and raw materials for the synthesis of biopolymers. By-products of this microbial breakdown of organic matter include soluble inorganic nutrients (e.g. phosphate, nitrate, ammonia) essential for algal and plant growth (primary production).

These inorganic nutrients become available to the algae and plants via diffusion from the pore water into the overlying water column. The sediments therefore can act as a reservoir of nutrients for primary producers, which at particular times of the year, assume critical importance in fueling local phytoplankton blooms (Bodungen, 1986). As much as 60% of the phosphorous and nitrogen needs of phytoplankton can be supplied by mineralization processes of the sediments (Blackburn, 1986).

The rate of chemical exchange between the sediments and the overlying water column is dependent in part upon the rates of chemical diffusion, rate of deposition of particulate matter, and the magnitude of sediment perturbation. Natural agents of perturbation include sediment mixing and burrow ventilation activities of infaunal organisms, and mass water movement generated via riverine input, wind, or tides. These perturbations facilitate the diffusion-dependent rate of chemical exchange, and stimulate the decomposition of organic phosphorous and nitrogen, resulting in the elevation of nutrient fluxes across the sediment-water interface several times above static conditions (Kristensen and Blackburn, 1987; Day et al., 1989; Chester, 1990).

Chemical Exchanges of Resuspended Sediments. Primary productivity, as manifested by algal and aquatic plant growth, is intimately tied to the diagenetic processes carried out in the sediments. These diagenetic process assume this role because they are critical to the local (and global) geochemical cycling of elements essential for the nutrition of the algae and the plants. The fundamental issue of the effect of trawling on primary productivity is therefore the extent to which the trawling-induced sediment disturbance and resuspension alters the coupling between pelagic and benthic productivity, and geochemical cycling.

To our knowledge, this subject has been virtually unstudied with regard to trawling as the agent of physical disturbance. The single study of Krost (1990; cited in Anon., 1991) indicated that trawling in the Western Baltic resulted in an increase in nutrients, followed by a phytoplankton bloom. The Western Baltic is physically similar to the Albemarle-Pamlico Lagoonal System. Qualitatively similar results were obtained in study involving sediment resuspension generated by dredging (Windom, 1975). In this case, soluble levels of phosphorous and nitrogen increased 50-100 times above ambient levels during dredge spoil dispersal.

The chemical exchanges between resuspended sediments and the water column are not limited to those involving a release of autotrophic nutrients. The sediments also serve as a store for a variety of inorganic (e.g. heavy metals) and organic pollutants, which may be released in soluble form following sediment resuspension (Kinnish, 1986, 1992). Dredging studies (Windom, 1975) revealed that heavy metal concentrations following sediment resuspension varied according to metal and locality. Hence, some metals showed little change in concentration (mercury), a temporary increase in concentration (iron), a sustained increase in concentration (cadmium), and a series of concentration spikes (zinc). Heavy metal ions released from the sediments may be quickly scavenged by insoluble iron hydroxides and clay particles, and become redeposited. The scavenged metal may later be released back into the water column in its ionic form following diagenetic transformation (Windom, 1975). The chemistry involved in pollutant regeneration is highly complex, and cannot be accurately predicted despite a knowledge of metal content of the sediments and sediment type (Windom, 1975; Kinnish, 1992).

Effects of Turbidity on Primary Productivity. Sediment resuspension via trawling can increase water column turbidity, which in turn reduces the maximum depth of light penetration. Hence sediment resuspension can affect primary productivity by compressing the width of the euphotic zone, wherein light energy levels are sufficient to carry out photosynthesis. The magnitude of this effect would depend upon the grain size of the sediments, the size of the trawling area, the duration and periodicity of trawling, gear type, season, and site-specific hydrographic and bathymetric features (Paine, 1979; Kinnish, 1992). Resuspended sediments settle out of the water column at a rate inversely proportional to their size (Margetts and Bridges, 1971).

There have been few attempts to quantify the effect of trawling on turbidity. Shrimp trawling in Corpus Christi Bay, Texas generated total suspended solid levels of 100-500 mg/l, which were significantly higher than ambient suspended solid levels (Schubel et al., 1979;

Churchill, 1989). However turbidity resulting from trawling in the mid-Atlantic Bight was not greater than that generated by natural water currents (Churchill, 1989).

To our knowledge, no studies have been carried out to examine the effect of turbidity produced by trawling on local primary productivity. Dredging studies, however, imply that the effect is strongly dependent upon local conditions. Hence, sediment resuspension caused by dredging operations significantly reduced phytoplankton growth in a naturally clear estuary (South Florida) but not in a naturally turbid estuary (upper Chesapeake) (Windom, 1975).

Effects on Secondary Productivity

Direct Effects: Mortality. Trawling affects secondary productivity directly by causing mortality of fish and invertebrates. Mortality may result from direct capture, smothering, or fatally injuring organisms. The magnitude of trawling mortality reflects features of benthic community structure as much as habitat, gear type, and trawling frequency and periodicity. The effects of trawling on mortality of fish has received far more attention than has the coincident effects on mortality of benthic invertebrates. The effect on fishes is an element of the bycatch issue, and is discussed in the second part of this report.

Several investigators have examined the effect of dredges on scallop mortality. In each case, incidental mortality was significant (Caddy, 1968, 1973; Gruffydd, 1972; Ascham, 1988). The amount of damage to the scallop population was much greater on hard substrata than on sandy substrata (Caddy, 1973). Scallop dredges also cause extensive damage and mortality of other benthic organisms, especially in rocky areas where many of the organisms are epifaunal (Anon., 1991).

Otter and beam trawls appear to inflict much less damage on macrobenthic animals compared to shellfish dredges. This difference is evidently a result of the shallower penetration depth of the trawls compared to shellfish dredges (Margetts and Bridger, 1971).

These limited studies suggest that among the epifauna, large and sedentary or sessile species will be more affected that will small, or motile species (Kinnish, 1992). Infaunal species may not suffer significant mortality, depending upon their resident depth within the sediments. Communities dominated by opportunistic species with short generation times and rapid rates of recolonization may also be less affected by trawling mortality (Kennish, 1992). To our knowledge, the effects of trawling on mortality of benthic epifauna and infauna of the APLS have not been investigated.

Indirect Effects: Trophic Relationships. Large scale harvesting of fish or shellfish species may ripple throughout the community, affecting other organisms and other trophic levels. These indirect consequences of trawling may occur as a result of affecting either the biological components (e.g., abundance of predators and their prey) or physical (e.g., water quality, features of the sediments) components of the ecosystem.

The impact of predation by bottom feeding fishes, crabs, and birds on the structure of soft-sediment communities has received considerable attention in the past 20 years. The exclusion of these epibenthic predators from portions of the soft-sediment community generally results in increased infaunal densities (Peterson, 1979). A reduction in the density of bottom feeding fishes as a result of trawling might be expected, therefore, to lead to an increase in the density of their prey. Not all manipulations of predators in soft-sediment communities lead to changes in prey densities and the strength of trophic links in these communities is being debated (Hall et al., 1990).

Evidence is mounting, however, for the importance of indirect, multi-trophic level effects in soft-sediment communities and the presence of these interactions may confound the results of simple predator manipulations (see Kneib, 1991 for review). The documentation of indirect effects in some benthic communities suggests that a significant reduction in the abundance of a epibenthic predator as a consequence of trawling might affect the abundance of species at several trophic levels.

Observations of trawling tracks and feeding pits indicate that predators (fishes, crabs, amphipods, starfish) are often and quickly attracted to these areas (Caddy, 1968, 1973; Anon., 1973; Oliver and Slattery, 1985). These predators feed on injured or immobilized prey. In some cases prey are lethally injured by trawling and the predators are merely scavenging their remains. In other cases, however, trawling exposes infauna to an increased risk of predation. Given the opportunity, many organisms exposed by fishing activities are able to rebury. The indirect effect of trawling in these cases is to increase predation on infauna. This increased availability of prey will result in a greater effect of fishing on infaunal abundances and may make a significant contribution to the diet of epibenthic predators (Caddy, 1973).

Bycatch may also help sustain the populations of epibenthic predators. Many fisheries do not land their bycatch, but discard it at sea. These discards are often consumed by birds, fishes, crabs, and marine mammals. A study of the fate of discards from the shrimp trawl fishery in the Wadden Sea indicates that the populations of fishes, crabs and birds in the area could easily consume the discards (Berghahn, 1990). In some areas, large populations of birds may be supported by discarded fish (Furness and Hislop, 1981). The effect of discards on other predator/scavenger populations has not been addressed. However, a reduction in trawling or a prohibition of discarding bycatch could have a significant impact on the population sizes of some fishes, crabs, and birds.

Competition in soft-sediment communities, where it exists, does not usually lead to exclusion of inferior competitors (Peterson,1991). Consequently, changes in species, abundance as a result of trawling is not likely to affect the outcome of competitive interactions.

Indirect Effects: Secondary Consequences of Sediment Resuspension. Nutrients released following resuspension of sediments can stimulate phytoplankton growth. This initial stimulus in primary productivity could lead to similar enhancement of secondary productivity in the form of herbivorous zooplankters, and eventually, additional larger organisms which prey upon the zooplankton. As these blooms decline, the remains settle out and add to the food resources of the benthic deposit feeders.

The above scenario of successive pulses of productivity initiated by a trawling disturbance could be mitigated to varying degrees, depending upon the coincident amount of degradable organic matter that is also resuspended in the water column. This organic matter could stimulate heterotrophic microbial production. If the amount of resuspended organic material is large, sustained proliferation of heterotrophic microflora will diminish the oxygen content of the water, and widespread hypoxia or anoxia could ensue to the detriment of benthic and pelagic fauna.

Increasing turbidity can also reduce the foraging success of visual predators. Elevating levels of suspended solids resulted in lower numbers of prey consumed by southern flounder and pinfish (Minello et al., 1987), larval herring (*Clupea harengus harengus;* Johnson and Wildish, 1982), and restricted the volume of water searched per unit time in bluegills (*Lepomis macrochirus*) (Vinyard and O'Brian, 1976).

Resuspended sediment can also contribute to mortality of fish and invertebrates by impeding the normal functioning of feeding and respiratory structures. Sherk et al. (1975) demonstrated the following rank order of sensitivity among seven species of estuarine fishes following a 24 hour exposure to varying concentrations of Fuller's Earth (mean particle size <0.5uM): (cf. Table 1.9).

mummichog	< striped killifish	< spot	< White perch	< Bay anchovy	< Atlantic menhaden	< Atlantic silverside

Least Sensitive — Most Sensitive

This sensitivity hierarchy reflected differences in food capture mechanisms, in which filter feeding species (Atlantic menhaden, Atlantic silversides) were the most sensitive, and demersal (bottom) predators (mummichog, spot) were the least sensitive. Mortality was attributed to clogging of the gill surfaces and concomitant reduction in gas exchange and feeding capabilities. Where tested, larvae were more sensitive to a given level of turbidity than were adult conspecifics.

All of the above results were derived from laboratory studies, and to our knowledge, comparable field studies have not been conducted. These studies bear a number of other important limitations. First, Fuller's Earth assesses relative sensitivity to suspended solids, but does not necessarily provide an accurate estimate of the turbidity level of natural suspended sediments that a species could tolerate and maintain a particular level of mortality. Concentrations of natural silt (from the Pawtuxent River) needed to produce 10% and 50% mortality within 24 hours were 3-4 times higher than the corresponding concentrations of Fuller' Earth (cf. Table 1.10).

Second, the effects of chronic exposure to low turbidity levels remain to be investigated.

Third, sensitivity to suspended sediments varies markedly among species, and reflects natural, habitat-specific differences in water turbidity. Foraging success of the Atlantic croaker, a demersal predator which inhabits turbid estuaries, was not significantly affected by the turbidity level which impaired foraging success in flounder and pinfish (Minello et al., 1987). Other work has shown that mortality of larvae of the American shad (*Alosa sapidissima*), striped bass (*Morone saxatilis*), and yellow perch from the Chesapeake was not significantly increased until they were exposed to concentrations of suspended sediment (500 ug/L) which were 5 times higher than the normal ambient level (Auld and Schubel, 1978). Some species of estuarine bivalves, such as the mussel *Mytilus edulis* (Kiorbe, et al., 1981) and the oyster *Ostrea edulis* (Grant et al., 1990) show enhanced growth rates under turbid conditions. In oysters, turbidity per se does not act to increase mortality; mortality results from burial during large-scale sediment redeposition (Kiorboe and Mohlenberg, 1981).

Lastly, species may show the potential for short term adaptation to local turbidity levels. Suspension feeding bivalves from naturally turbid waters of the Wadden Sea have larger sediment filtering structures (labial palps) than do conspecifics from the clearer waters of the Oresund (Kiorboe and Mohlenberg, 1981).

Recolonization of Trawling-Disturbed Areas

Biological and physical disturbance are widely recognized as important in structuring soft-bottom communities (Peterson 1979, 1991; Thistle, 1981; Wilson, 1991). Disturbances can range from storms affecting kilometer squared areas of the bottom to localized disturbances on the

Table 1.9. Tentative suspended solids classification for estuarine fish based on 24 hour LC 10 values resulting from exposures to fuller's earth suspensions. (Adapted from Sherk et al., 1975). LC 10 = 10% mortality.

Class I. Tolerant Species (>10g/L)	**Class II. Sensitive Species** (>1.0 < 9.9 g/L)	**Class III. Highly Sensitive Species** (< 0.9 g/L)
Common mummichog	White perch (Adult)	Atlantic silverside[1]
Striped killifish[2]	White perch (Larva)	Bluefish (juvenile)
Spot	Striped bass (Adult)[3]	White perch (young of year)
Oyster toadfish[4]	Striped bass (larva)	
Hogchoker	Atlantic croaker	
Cusk eel[5]	Bay anchovy	
Cunner[6]	Atlantic menhaden	
Four-spined stickleback[7]		
Sheepshead minnow[8]		

[1] *Menidia menidia*; [2] *Fundulus majalis*; [3] *Morone saxatilis*; [4] *Opsanus tau*
[5] *Opidium marginatum*; [6] *Tautogolabrus adspersus*; [7] *Apeltes quadracus*
[8] *Cyprinodon variegatus*

Table 10. Concentrations (g/l) of Fuller's Earth which resulted in 10% (LC 10), 50% (LC 50), and 90% (LC 90) mortality after 24 hours of exposure (from Sherk et al., 1975).

Species	LC 10	LC 50	LC 90
Atlantic silverside	0.58	2.50	10.00
Atlantic menhaden	1.54	2.47	3.96
Bay anchovy	2.31	4.71	9.60
White perch	3.05	9.85	36.87
Spot	13.09	20.34	---
Striped killifish	23.77	38.19	61.36
Mummichog	24.47	39.00	62.17

scale of centimeters. Many benthic communities routinely experience natural levels of disturbance which are at least equivalent to trawling in their impact on habitat structure and organisms. Consequently, organisms living in many benthic communities are adapted to disturbance, and trawling, to the extent that it mimics natural disturbances, is not likely to have an effect on these communities which is discernible from natural disturbances. For example, the impact of trawling on communities of highly dynamic, sandy bottoms is hypothesized to be much less than the effect of trawling on deeper, muddy communities where the physical effects of storms is less (Churchill, 1989). Even in these deeper communities, however, biological disturbance may be considerable and the organisms equally well adapted to disturbance as their counterparts in shallower, more physically disturbed environments.

The effects of physical disturbance on a community depend not only on the intensity and spatial and temporal distribution of the disturbance, but also on the modes and rates of recolonization. There have been numerous studies of recolonization following both natural and anthropogenic disturbances in marine soft-bottom communities, but surprisingly few following disturbances by fishing activities. Peterson et al. (1987) found no significant effect on the recruitment of hard clams (*Mercenaria mercenaria*) or the abundance of other benthic invertebrates following experimentally imposed clam kicking in both vegetated (seagrass, *Zostera marina*) and unvegetated (sandy) habitats. Godcharles (1971) found that a hydraulic clam dredge affected the abundance of infauna at only one of three vegetated sites and at no unvegetated site. These harvesting techniques have a much greater impact on the physical structure of benthic communities than trawling (Table 8), so it is perhaps not surprising that Van Dolah et al. (1991) found no effect on soft-bottom community structure of otter trawls used to harvest shrimp in a South Carolina estuary.

All of these studies were conducted in estuaries where physical disturbance of the bottom due to storms, and high rates of sedimentation are common. Consequently, many of the animals that live in these habitats recover rapidly from disturbance and are adapted to colonize disturbed areas. Only one study that we know of has examined recruitment to offshore benthic communities following trawling (Anon., 1990). The results indicated a net increase in the abundance of small bivalves and one polychaete species in the trawled area three weeks after trawling, presumably as a consequence of greater recruitment in trawled versus non-trawled area. There was a decline in the abundances of other bivalve and polychaete species.

Clues to the response of benthic communities to disturbance caused by trawling can be found by examining the response of these communities to other types of biological and physical disturbance. Most experimental work has followed the community development of small (meter squared or less) plots of artificially defaunated sediment. Colonists may arrive in these plots as recruiting larvae (McCall, 1977; Santos and Simon, 1987a; Ambrose 1984) or as postlarvae (Wilson; 1981, Ambrose, 1984; Levin, 1984; Smith and Brumsickle, 1989). Large areas of disturbance (>100 m) appear to be colonized predominately by larvae (Santos and Simon, 1980b; Levin, 1984). Regardless of the area disturbed some species usually become extremely abundant early in the recolonization process (see Thistle, 1981 for review). In all the studies of disturbance of estuarine and nearshore communities, disturbed areas recover to within 90% of background levels of species abundances fairly rapidly. In some habitats and for some species "recovery" occurs within a few weeks (Smith and Brumsickle, 1989). In most cases, disturbed and undisturbed areas are, however, indistinguishable within a year of disturbance (Van Dolah et al., 1984). Recovery of other habitats, such as the deep sea, can take much longer (Grassle, 1977).

It is difficult to relate the results of most recolonization studies to recolonization of areas disturbed by trawling because the scale of trawling disturbance falls in between the two small scale, experimentally manipulated disturbances (0.005 - 1 m) and the large scale natural disturbances such as those caused by red tide (Simon and Dauer, 1977) or sedimentation (Levin, 1984). Even in areas that are heavily trawled, the entire bottom is probably rarely disturbed and trawl tracks are separated by untrawled areas. In addition, most experimental studies of disturbance use defaunated sediment, which is not analogous in physical structure or faunal composition to the benthos in even the most heavily trawling-disturbed areas.

The only natural disturbance of benthic communities that closely approximates the scale and nature of disturbance by bottom trawling is the disturbance caused by bottom feeding mammals. In the process of excavating prey, grey whales, walruses (*Odobenus rosmarus*) and sea otters (*Enhydra lutris*) disturb large areas of the bottom (Oliver and Slattery, 1985; Oliver et al., 1985; Kvitek et al., 1992). Grey whale (*Eschrichtius glacus)* feeding pits can exceed 25 m in diameter and can cover greater than 30% of the seafloor over large geographic areas (Oliver and Slattery, 1985). The pits and furrows in the sediment produced by walruses are not as large as those caused by grey whale feeding, but walruses are the most abundant bottom-feeding marine mammal and their cumulative impact on benthic communities can be large (Oliver et al., 1985). The large feeding excavations of grey whales feeding in the Bering Sea are rapidly colonized by scavenging amphipods (Oliver and Slattery, 1985). The numbers of some colonists remain elevated inside compared to outside pits for longer than two months. Part of the reason for the persistence of high densities of early colonists maybe be due to elevated food resources inside pits because within days the depressions began trapping organic material. A similar pattern of colonization was recorded for ray feeding pits which also trap organic material (Van Blaricom, 1982). Disturbance to the benthos by grey whales may actually enhance the population size of several benthic species (Oliver and Slattery, 1985). In contrast, recovery of walrus feeding pits was not characterized by an influx of opportunistic species and benthic communities in the pits recovered gradually (Oliver et al., 1985). The difference in community response to the disturbance caused by walrus and grey whale feeding is probably due to differences in the abundance of motile crustaceans between the areas where the two mammals feed. Motile crustaceans are rare in walrus feeding grounds and colonization of pits is by larvae of mollusks and bivalves (Oliver et al., 1985). This difference emphasizes the importance of the composition of the ambient, undisturbed community in determining the rate and pattern of recovery of benthic communities following disturbance.

In addition to the dispersal mechanisms of organisms in the undisturbed community, patterns of recolonization and succession in soft-sediment systems also can be influenced by the population biology of these organisms, and the size of the disturbed area and its proximity to a pool of potential recruits. As mentioned above, large areas are recolonized predominately by larvae (Santos and Simon, 1984; Levin, 1984). The timing of disturbance relative to the reproductive state of organisms in the undisturbed community will, therefore, be extremely important in determining patterns of recolonization of large areas (Ambrose, 1984). Distance to spawning populations may also be important for organisms with short larval stages (Peterson and Summerson, 1992).

There are very few estimates of the aerial extent of bottom disturbance caused by trawling, so it is difficult to evaluate the importance of area in determining the pattern of recolonization of these areas. Ascham (1988) estimated that over 50% of the bottom substrate is processed by scallop dredges on the fishing grounds between Spitzbergen and Iceland. Scallop dredges also disturbed an estimated 7,700 km^2, of the 37,000 km^2 scallop grounds on George's Bank (Caddy, 1973). Observations of the effects of otter trawls on the bottom of a bay in the Gulf of St.Lawrence indicated that an estimated 3-7% of the seafloor was covered with tracks. In another part of the Gulf of St. Lawrence, Magdalen Shallows, the entire bottom as been estimated to have been trawled at least once (Messiah et al. , 1991). In the Kieler Bucht of the western Baltic, trawl tracks are so dense in some areas that they almost completely cover the bottom (Anon., 1988). As might be expected, these limited studies reveal a wide range in the portion of the bottom showing evidence of disturbance by trawling. Trawling in estuaries and sounds may disturb a large portion of the bottom because of the restricted area in which fisherman trawl. Regardless, it is unlikely that the entire bottom will be disturbed as occurs following mortality from red tide or episodic sedimentation. Fish and therefore fishing effort tend to be patchily distributed in time and space. Patterns of recolonization following trawling are more likely to resemble those following feeding by bottom feeding mammals described above. While large areas of the bottom may be disturbed, colonists, larvae or adults, probably come from very local populations. Restricting trawling in certain areas in order to preserve breeding populations of infauna is probably not necessary for most species. This of course assumes that infaunal populations are not recruitment limited, a claim which has been found not to hold for some marine fishes (Doherty, 1983, Warner and Chesson, 1985) and hard-substrate invertebrates (Sammarco and Andrews, 1989, Karlson and Levitan, 1990; Hughes, 1990) and is being challenged for invertebrates in soft-sediment systems (Peterson and Summerson, 1992).

Management Recommendations

Potential management actions concerning the issue of trawling (and similar fishing practices) in estuarine areas are: (1) no action; (2) ban trawling from all estuarine waters; (3) restricted trawling by gear type; (4) restrict trawling purely by habitat type (e.g., submersed grass beds, oyster reefs); (5) permanently ban trawling from selected, multiple habitat types which would then function as spawning and recruitment sanctuaries for surrounding areas subjected to trawling; and (6) restrict trawling by season, by the number of trawling days within a season, or by the duration of trawling per day.

Of these options, all but the first and second require additional research. We encourage management to first implement a research program dedicated to providing information that would enable them to select the best alternative based on a combination of sociological, economic and ecological knowledge and understanding.

The essence of the impact of trawling on the benthos is disturbance. The fact that trawling acts as an agent of perturbation does not, however, mean that trawling automatically causes environmental degradation and should therefore be banned from North Carolina's estuaries. Disturbance is a natural phenomenon, with both biological and physical causes. The scale and intensity of the disturbance can vary greatly within either of these natural causes. The fundamental questions raised by the issue of trawling are: (1) "Is the magnitude of the disturbance generated by trawling significantly greater than that resulting from natural sources?"; and (2) "Is the disturbance generated by trawling detrimental to the estuarine ecosystem?".

Answering these questions is vital to rendering a learned and fair resolution to the issue of trawling. However, these questions are not necessarily easy to answer due to: (a) the lack of basic information concerning its effects in our local estuarine system; (b) the general inability to accurately predict local effects of trawling from studies done in other estuaries; and (c) the complex, pervasive nature of its potentially negative impacts on the estuarine ecosystem.

We recommend that management encourage and support a research program designed to provide basic and greatly needed information about the effects of trawling on North Carolina's estuarine ecosystem before developing and implementing a management policy. We realize that the risk in this recommendation is that the research could demonstrate a pernicious effect of trawling, and that precious time would have been lost during the interim. However, we think that taking this risk is justified given the fact that 80% of all fish and shellfish landed in North Carolina is derived from estuarine sources, and that curtailing trawling could have profound cultural, sociological, and economic impacts on the state's fishing community.

We suggest that the following studies be carried out, focusing on the shrimp trawl as the basic gear type, owing to the areal extent of the APLS exposed to shrimp trawling and the economic value of this fishery.

(1) First define the magnitude of the problem. This will require: (a) quantifying trawling practices so that a measure of trawling effort per unit area and time could be determined; and (b) determining turbidity levels generated by the gear type, and the subsequent rate(s) of redeposition. (How turbid does the water become, and how long does it persist?) Large scale effects could be estimated by combining satellite imaging of the APLS with concurrent measurements of suspended solids at predetermined locations within the APLS.

(2) Determine the depth of penetration of trawling gear into the sediments, the effect of trawling on the grain size distribution and organic carbon content of the sediments, and the effect of trawling on water quality (temperature, salinity, and especially dissolved oxygen). This work would provide information complementary to study (1) , and together they would aid in estimating the magnitude of the disturbance generated by trawling.

(3) Sample areas normally subjected to trawling in order to describe the local benthic infaunal and epifaunal communities. The benthic community of trawled areas is virtually unknown. An important aspect of this work is to identify the seasonal cycles of species abundance and recruitment. This information is essential in that it enables management to estimate the times of the year during which the benthos would be most sensitive to trawling disturbance (i.e., times at which benthic diversity and abundance is highest).

(4) Measure *in situ* rates of growth, mortality, and recruitment of selected species of benthic invertebrates exposed to trawling. This work determines the impact of trawling on benthic community structure.

(5) Measure *in situ* growth and survival of selected dermersal predators in trawled and untrawled areas. This work would help to determine if predatory fish and shellfish benefit from trawling disturbance.

(6) Evaluate the effect of trawling on primary productivity. This is an important issue, with several component problems. For example: Does sediment resuspended by trawling result in a release of nutrients for uptake by algae and plants? If yes, how do primary producers respond to these nutrients? Does a stimulus in primary production lead to a stimulus in secondary production? Alternatively, does turbidity resulting from trawling limit photosynthetic production by primary producers by diminishing light penetration?

(7) Evaluate secondary effects of turbidity caused by resuspension of sediments. Turbidity is a pervasive consequence of trawling disturbance. Does this turbidity impede foraging activities of predatory fishes? Is it beneficial to deposit feeding benthic organisms? What is its affect on larval recruitment?

(8) Compare the effects of trawling on water quality (temperature, salinity, dissolved oxygen, turbidity) and the sediments (sediment grain size distribution, organic carbon content) with

that caused by natural agents of disturbance such as storms. These comparisons are critical in defining the ecological role of trawling, and would aid management by helping to delineate the relative magnitudes of anthropogenic and natural levels of disturbance. This would require the additional studies to obtain the data describing the effects of storms on the sediments. However, a similar effort may not be necessary for water quality, because time intensive water quality data for parts of the APLS already exist (Garrett and Bales, 1991; Garrett, 1992), and could be analyzed for correlations to the timing and magnitude of storm activity.

Selected Bibliography

Ambrose, W.G., Jr. 1984. Influence of residents on the development of a marine soft-bottom community. Journal of Marine Research 42:633-654.

Anon. 1971. Underwater observations on performance of clam dredges of three types. International Council for the Exploration of the Sea C.M. 1971/B:10.

Anon. 1973. Effect of trawls and dredges on the sea-bed. International Council for the Exploration of the Sea C.M. 1973/B:2

Anon. 1988. Report of the study group on the effects of bottom trawling. International Council for the Exploration of the Sea C.M./B:56

Anon. 1989. Report of the Benthos Ecology Working group. International Council for the Exploration of the Sea. L:19, pg.1-84.

Anon. 1990. Report of the ICES working group on the effect of marine aggregate extraction on fisheries. International Council for the Exploration of the Sea C.M. 1990/E: 35

Anon. 1991. Report of the study group on ecosystem effects of fishing activities. International Council for the Exploration of the Sea C.M. 1991/G:7.

Ascham, M. 1988. The effects of Iceland scallop (*Chlamys islandica*) dredging at Jan Mayen and in the Spitzbergen area. International Council for the Exploration of the Sea C.M./K:16

Auld, A. and J. Schubel. 1978. Effects of suspended sediment on fish eggs and larvae: A laboratory assessment. Estuarine and Coastal Marine Science 6: 153-164.

Bargmann, G., M. Pedersen, and R.J. Trumble. 1985. Final environmental impact statement for the continued harvest of bottomfish in Puget Sound by commercial otter trawl gears. Washington State Dept. of Fisheries. 198 pp.

Bearden, C., R. Low, R. Rhodes, R. Van Dolah, C. Wenner, E. Wenner, and D. Whitaker. 1985. A review and analysis of commercial shrimp trawling in the sounds and bays of South Carolina. South Carolina Marine Resources Center Technical Report No. 62, 51pp.

Bell, S., and B. Coull 1978. Field Evidence that shrimp predation regulates meiofauna. Oecologia 35: 141-148.

Beninger, P., M. LePennec, and A. Donval. 1991. Mode of particle ingestion in five species of suspension-feeding bivalve molluscs. Mar. Biol. 108: 255-261.

Beninger, P., M. lePennec, and M. Auffret. 1990. Peribuccal organs of *Placopecten magellanicus* and *Chlamys varia* (Mollusca: Bivalvia): structure, ultrastructure and implications for feeding. Marine Biology. 107: 225-233.

Berghahn, R. 1990. On the potential impact of shrimping on trophic relationships in the Wadden Sea. Pages 130-140 IN: M. Barnes and R.N. Gibson, eds. Trophic Relationships in the Marine Environment. Proceedings of the 24th European Marine Biology Symposium. Aberdeen University Press, Aberdeen, Scotland.

Bishop, S. 1960. Outer Bank Fauna of the Tidal Flats in Pamlico Sound, North Carolina. Ph. D. Thesis, Duke University. 103 pp.

Blackburn, H. 1986. Nitrogen cycle in marine sediments. Ophelia 26: 65-76.

Bodungen, B. 1986. Annual cycles of nutrients in a shallow inshore area: Kiel Bight.-Variability and trends. Ophelia 26: 91-107.

Boynton, W., W. Kemp, and C. Osborne. 1980. Nutrient fluxes across the sediment-water interface in the turbid zone of a coastal plain estuary pp. 93-109. IN: V. Kennedy, ed. Estuarine Perspectives. Academic Press, Inc..

Brett, C. 1963. Relationships between Marine Invertebrate Infauna Distribution and Sediment Type Distribution in Bogue Sound, North Carolina. Ph. D. Thesis, Univ. of North Carolina, Chapel Hill. 183 pp.

Bricelj, V., R. Malouf, and C. de Quillfeldt. 1984. Growth of juvenile *Mercenaria mercenaria* and the effect of resuspended bottom sediments. Marine Biology 84: 167-173.

Bridger, J.P. 1970. Some effects of the passage of a trawl over the seabed. International Council for the Exploration of the Sea, Gear and Behavior Committee. International Council for the Exploration of the Sea C.M. 1970/B: 10

Bridger, J.P. 1972. Some observations on the penetration into the seabed of tickler chains on a beam trawl. International Council for the Exploration of the Sea, Gear and Behavior Committee. International Council for the Exploration of the Sea C.M./B:7

Butman, C.A. 1987. Larval settlement of soft-sediment invertebrates: the spatial scales of patterns explained by active habitat selection and the emerging role of hydrodynamic processes. Oceanography and Marine Biology Annual Review 25:113-165.

Caddy, J.F. 1968. Underwater observations on scallop (*Placopecten magellanicus*) behavior and drag efficiency. Journal of the Fisheries Research Board of Canada 25:2123-2141.

Caddy, J.F. 1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. Journal of the Fisheries Research Board of Canada. 30:173-180.

Chandler G., and J. Fleeger. 1983. Meiofaunal colonization of azoic estuarine sediment in Louisiana: Mechanisms of dispersal. Journal of Experimental Marine Biology and Ecology. 69: 175-188.

Chestnut, A. 1956. The distribution of oyster drills in North Carolina. Proceedings of the National Shellfisheries Association 46: 134-139.

Chao, K., and J. Musick. 1977. Life history, feeding habits, and functional morphology of juvenile sciaenid fishes in the York River Estuary, VA. U.S. National Marine Fisheries Service Bulletin 75: 657-702.

Chester, R. 1990. Marine Geochemistry. Unwin Hyman Ltd., London. pp. 468-528.

Christian, R., J. Boyer, and D. Stanley. 1991. Multi-year distribution patterns of nutrients within the Neuse River Estuary, North Carolina. Marine Ecology Progress Series 71: 259-274.

Christmas, S, and D. Etzold. 1977. The shrimp fishery of the Gulf of Mexico U.S.; a regional management plan. Gulf Coast Research Laboratory Technical Report Series No. 2. 125 pp.

Churchill, J.J. 1989. The effect of commercial trawling on sediment resuspension and transport over the middle of the Atlantic Bight continental shelf. Continental Shelf Research 9:841864.

Civils, M. 1982. A Distributional Study of Estuarine Macrobenthos in the Sandy Littoral of the Pamlico River, North Carolina. MS Thesis, Dept. of Biology, East Carolina University, 102 pp.

Collins, M. 1985. Species Profiles: Life Histories and Environmental Requirements of Coastal fishes and Invertebrates (South Florida)--striped mullet. U. S. Fish and Wildlife Service. Biological Report 82 (11.34).

Cole, H. A., and E. W. Knight-Jones. 1949. The setting behavior of larvae of the European oyster *Ostrea edulis* L. and its influence on methods of cultivation and spat collection. Fishery Investigations (London) Series II 17: 39 pp.

Copeland, B. , and S. Riggs. 1984. The ecology of the Pamlico River, North Carolina: An estuarine profile. U.S. Department of the Interior, Fish and Wildlife Service FWS/OBS-82/06. 83 pp.

Crisp, D.J. 1967. Chemical factors inducing settlement in Crassostrea virginica Gmelin. Journal of Animal Ecology 36: 329-335.

Crosby, M., R. Newell, and C. Langdon. 1990. Bacterial mediation in the utilization of carbon and nitrogen from detrital complexes by *Crassostrea virginica.* Limnology and Oceanography 35(3): 625-639.

Crump, R. 1971. Population density and distribution of the estuarine clam *Rangia cuneata* in Croatan Sound, North Carolina. MS Thesis, East Carolina University. 68 pp.

Cunningham, P., R. Curry, R. Pratt, S. Stichter, K. West, L. Mercer, P. Phalen, S. Sherman, B. Burns, and S. Winslow. 1992. Watershed planning in the Albemarle-Pamlico Estuarine System. Report 5--Fishing Practices. Albemarle-Pamlico Estuarine Study, Raleigh, N.C., U.S. Environmental Protection Agency and North Carolina Department of Environment, Health and Natural Resources, Report No. 92-05. 227 pp.

Currin, B., J. Reed, and J. Miller. 1984. Growth production, food consumption, and mortality of juvenile spot and croaker: a comparison of tidal and nontidal nursery areas. Estuaries 7: 451-459.

Darnell, R. 1961. Trophic spectrum of an estuarine community, based on studies on Lake Pontchartrain, LA. Ecology 42: 553-568.

Dauer, D., and J. Simon. 1976. Repopulation of the polychaete fauna of an intertidal habitat following natural defaunation: Species equilibrium. Oecologia 22: 99-117.

Davis, G., and M. Brinson 1976. The submersed macrophytes of the Pamlico River estuary, North Carolina. Water Resources Research Institute of the University of North Carolina Report No. 112. 202 pp.

Davis, G., and M. Brinson. 1980. Responses of submersed vascular plant communities to environmental change. United States Fish and Wildlife Service FWS/OBS-79. 69 pp

Davis, G., and M. Brinson 1990. A survey of submerged aquatic vegetation of the Currituck Sound and the western Albemarle-Pamlico estuarine system: Albemarle-Pamlico Estuarine Study. A/P Study Project No. 89-10. 137 pp.

Davis, G., M. Brinson, and W. Burke. 1978. Organic carbon and deoxygenation in the Pamlico River Estuary. Water Resources Research Institute of the University of North Carolina. Report No. 131. 123 pp.

Davis, H. 1960. Effects of turbidity-producing materials in sea water on eggs and larvae of the clam *Venus* (*Mercenaria*) *mercenaria*. Biol. Bull. 118: 48-54.

Day, J., C. Hall, W. Kemp, A. Yanez-Arancibia. 1989. Estuarine Ecology. John Wiley and Sons, New York. 558 pp.

de Groot, S.J. 1984. The impact of bottom trawling on benthic fauna of the North Sea. Ocean Management 9:177-190.

de Silva, S., and M. Wijeyaratue. 1977. Studies on the biology of young grey mullet, *Mugil cephalus* L. II. Food and feeding. Aquaculture 12: 157-167.

Dexter, D. 1967. Distribution and niche diversity of haustoriid amphipods in North Carolina. Chesapeake Science. 8:.187-192.

DeVries, D. 1986. Description and preliminary evaluation of a statewide estuarine trawl survey in North Carolina. EHNR, Division of Marine Fisheries. 33 pp.

Diaz, R., and C. Onuf. 1985. Habitat suitability index models: juvenile Atlantic croaker. U.S. Fish and Wildlife Service Biological Report 82 (10.98).

Diener, R., A. Inglis, and A. Adams. 1974. Stomach content of the fishes from clear lakes and tributary waters, a Texas estuarine area. Contributions to Marine Science 18: 7-17.

Doherty, P.J. 1983. Tropical territorial damselfish: is density limited by aggression or recruitment? Ecology 64:176-190.

Epperly, S. 1984. Fishes of the Pamlico Albemarle Peninsula, N.C. Area Utilization and Potential Impacts. N.C. Department of Environment, Health and Natural Resources, N.C. Division of Marine Fisheries. Special Scientific Report No. 42; CEIP Report No. 23.129 pp.

Epperly, S., and S. Ross. 1986. Characterization of the North Carolina Pamlico-Albemarle Estuarine Complex. NOAA Technical Memorandum NMFS-SEFC-175.

Fegley, S. 1988. A comparison of meiofaunal settlement onto the sediment surface and recolonization of defaunated sandy sediment. Journal of Experimental Marine Biology and Ecology 123: 97-113.

Ferguson, R., J. Rivera, and L. Wood. 1989. Submerged aquatic vegetation in the Albemarle-Pamlico estuarine system. Albemarle-Pamlico Estuarine Study, Raleigh, N.C., Project No. 88-10. 68 pp.

Fonseca, M., G. Thayer, A. Chester, and C. Foltz. 1984. Impact of scallop harvesting on eelgrass *(Zostera marina)* meadows: Implications for management. Transactions of the American Fisheries Society 4: 286-293.

Furness, R.W., and J.R.G. Hislop. 1981. Diets and feeding ecology of great skuas Catharacta *skua* during breeding season in Shetland. Journal of Zoology, London. 195: 1-23.

Fox, R., and K. Bynum. 1975. The amphipod crustaceans of North Carolina in estuarine waters. Chesapeake Science 16: 223-237.

Friedland, K. 1985. Functional morphology of the branchial basket structures associated with feeding in the Atlantic menhaden, *Brevoortia tyrannus* (Pisces: Clupeidae). Copeia 4: 1018-1027.

Froelich, P., G. Klinkhammer, M. Bender, N. Luedtke, G. Heath, D. Cullen, PL. Dauphin, D. Hammond, B. Hartman, and V. Maynard. 1979. Early oxidation of organic matter in pelagic sediments of the easter equatorial Atlantic: suboxic diagenesis. Geochimica Cosmochimica Acta 43: 1075-1090.

Garrett, J. and J. Bales. 1991. Water-quality data from continuously monitored sites in the Pamlico and Neuse River estuaries, North Carolina, 1989-90: U.S. Geological Survey Open-File Report 91-465, 151 pp.

Garrett, J. 1992. Water-quality data from continuously monitored sites in the Pamlico and Neuse River estuaries, North Carolina, 1990-91: U.S. Geological Survey Open-File Report 92-110, 196 pp.

Giese, G., H. Wilder, and G. Parker, Jr. 1979. Hydrology of major estuaries and sounds of North Carolina. U.S. Geological Survey Water Resources Investigations 79-46. 175 pp.

Gilinsky, E. 1984. The role of fish predation and spatial heterogeneity in determining benthic community structure. Ecology 65: 455-468.

Gilmurray, M., and G. Daborn. 1981. Feeding relations of the Atlantic silverside, *Menidia menidia,* in the Minas Basin, Bay of Fundy. Marine Ecology Progress Series. 6: 231-235.

Godcharles, M.F. 1971. A study of the effects of a commercial hydraulic clam dredge on benthic communities in estuarine areas. State of Florida Department of Natural Resources, Technical Series No. 64., 50 pp.

Goudey, C.A. and G. Loverich 1987. Reducing the bottom impact of Alaskan groundfish trawls. Proceedings, Oceans 1987. The ocean-an international workspace. Vol. 2. Marine Engineering; Policy, education and technology transfer. pp. 632-637.

Graham, J., and R. Vrijenhoek. 1988. Detrended correspondence analysis of dietary data. Transactions of the American Fisheries Society 117: 29-36.

Grant, J., C. Enright, and A. Griswold. 1990. Resuspension and growth of *Ostrea edulis*: a field experiment. Marine Biology. 104: 51-59.

Grassle, J.F. 1977. Slow recolonization of deep sea sediment. Nature 265: 618-619.

Gray, S.,and C. Winkler. 1977. Population density and distribution of *Rangia cuneata* in the Pamlico River, North Carolina. Unpublished Report to Dept. of Biology, ECU. 33pp.

Gremare, A.. 1990. Consumption of diatoms and diatom filtrates by the tentaculate deposit-feeder *Eupolymnia nebulosa* (Annelida:Polychaeta). Marine Biology 106:139-143.

Gruffydd, LL. 1972. Mortality of scallops on a manx scallop bed due to fishing. Journal of the Marine Biological Association of the United Kingdom 52: 449-455.

Hall, S.J. , D. Raffaelli, and W.R. Turrell 1990. Predator-caging experiments in marine systems: a reexamination of their value. American Naturalist 136:657-672.

Hall, S., D. Basford, M. Robertson, D. Raffaelli, and I. Tuck. 1991. Patterns of recolonisation and the importance of pit-digging by the crab , *Cancer pagurus* in a subtidal sand habitat. Marine Ecology Progress Series. 72: 93-102.

Hanson, R., and K. Tenore. 1981. Microbial metabolism and incorporation by the polychaete *Capitella capitata* of aerobically and anaerobically decomposed detritus. Marine Ecology-Progress Series.6: 299-307.

Happ,G., J. Gosselink, and J. Day, Jr. 1977. The seasonal distribution of organic carbon in a Louisiana estuary. Estuary and Coastal Marine Science. 5: 695-705.

Happ,G., J. Gosselink, and J. Day, Jr. 1990. Food limitation, spination, and reproduction in *Brachionus calyciflorus*. Limnology and Oceanography. 35 (1): 33-44.

Harned, D., and M. Davenport. 1990. Water-quality trends and basin activities and characteristics for the Albemarle-Pamlico estuarine system, North Carolina and Virginia. Albemarle-Pamlico Estuarine Study, Raleigh, N. C., Rep. No.89-11. 64 pp.

Harrington, R., and E. Harrington. 1961. Food selection among fishes invading a high subtropical salt marsh: from onset of flooding through the progress of a mosquito brood. Ecology 42: 646-666.

Heck, K. L., Jr., and R. J. Orth. 1980. Seagrass habitats: The roles of habitat complexity, competition and predation in structuring associated fish and motile macroinvertebrate assemblages. pp 449-464. IN: V.S. Kennedy, ed. Estuarine Perspectives. Academic Press, New York, New York.

Heck, K., and T. Thoman. 1984. The nursery role of seagrass meadows in the upper and lower reaches of Chesapeake Bay. Estuaries 7: 70-92.

Heck, K., K. Able, M. Fahay, and C. Roman. 1989. Fishes and decapod crustaceans of Cape Cod eelgrass meadows: Species composition, seasonal abundance patterns and comparison with unvegetated substrates. Estuaries 7: 59-65.

Hester, J., and B. Copeland. 1975. Nekton population dynamics in the Albemarle Sound and Neuse River estuaries. University of North Carolina Sea Grant Program Publication. UNC-SG-75-02. 131 pp.

Hildebrand, S., and W. Schroeder. 1928. Fishes of Chesapeake Bay. Bulletin of the U.S. Bureau of fisheries Vol 58 (1927) Part I, 388 pp.

Hirota, J., and J. Szyper. 1975. Separation of total particulate carbon into inorganic and organic components. Limnology and Oceanography 20: 896-899.

Hobbie, J., and N. Smith. 1975. Nutrients in the Neuse River estuary. University of North Carolina Sea Grant, Publ. No. UNC-SG-75-21.

Holland, A., and J. Dean.1977. The biology of the stout razor clam *Tagelus plebeius*:1. Animal-sediment relationships, feeding mechanism, and community biology. Chesapeake Science. 18: 58-66.

Homziak, J.M., M. S. Fonseca, and W.J. Kenworthy. 1982. Macrobenthic community structure in a transplanted eelgrass (Zostera marina L.) meadow. Marine Ecology Progress Series 9: 211-221.

Hsiao, Y., J. Easley, Jr., and T. Johnson. 1987. Testing for harmful effects of clam and scallop harvesting techniques in the North Carolina bay scallop Fishery. North American Journal of Fisheries Management. 7: 187-193.

Hughes, T.P. 1990. Recruitment limitation, mortality, and population regulation in open systems: a case study. Ecology 71:12-20.

Hutchings, P. 1990. Review of the effects of trawling on macrobenthic epifaunal communities. Australian Journal of Marine and Freshwater Resources. 41: 111-120.

Johnson, W. , D. Allen, M. Ogburn, and S. Stancyk. 1981. Feeding relations of the Atlantic silverside *Menidia menida* in the Minas Basin, Bay of Fundy. Marine Ecology Progress Series 6: 231-235.

Johnson, W. , D. Allen, M. Ogburn, and S. Stancyk. 1990. Short-term predation responses of adult bay anchovies *Anchoa mitchelli* to estuarine zooplankton availability. Marine Ecology Progress Series 64: 55-68.

Johnston, D., and D. Wildish. 1982. Effect of suspended sediment on feeding by larval herring (*Clupea harengus harengus* L.). Bulletin of Environmental Contamination and Toxicology 29: 261-267.

Jones, R. and G. Lee. 1981. The significance of dredging and dredged material disposal as a source of nutrient and phosphorus for estuarine waters. pp. 517-529 IN: B. Neilson and L. Cronin, eds. Estuaries and Nutrients. Humana Press, Clinton, New Jersey.

Karlson, R.H., and D.R. Levitan. 1990. Recruitment limitation in open populations of Diadems antillarum: an evaluation. Oecologia 82:40-44.

Kelley, C., C. Martens, and J. Chanton. 1990. Variations in sedimentary carbon remineralization rates in the White Oak River estuary, North Carolina. Limnology and Oceanography 35: 372-383.

Khorram, S., and H. Cheshire. 1983. The use of Landsat MSS digital data in water quality mapping of the Neuse River Estuary, North Carolina. University of North Carolina Water Resources Research Institute Report 193, 29 pp

Kinnish, M. 1986. Ecology of Estuaries. Vol. I: Physical and Chemical Aspects. CRC Press, Boca Raton, Florida. pp. 9-36; pp. 205-239.

Kinnish, M. 1992. Ecology of Estuaries: Anthropogenic Effects. CRC Press, Boca Raton. pp. 357-398.

Kiorboe, T., and F. Mohlenberg. 1981a. Particle selection in suspension-feeding bivalves. Marine Ecology Progress Series. 5: 291-296.

Kiorboe, T., F. Mohlenberg, and O. Nohr. 1981b. Effect of suspended bottom material on growth energetics in *Mytilus edulis*. Marine Biology 61: 283-288.

Kjerfve, B. 1986. Comparative oceanography of coastal lagoons. pp. 63-62 IN: D. Wolfe, ed. Estuarine Variability. Academic Press, Inc. New York, New York.

Kneib, R.T. 1991. Indirect effect in experimental studies of marine soft-bottom communities. American Zoologist 31:874-885.

Kvitek, R., J. Oliver, A. DeGrange, and B. Anderson. 1992. Changes in Alaslan soft-bottom prey communities along a gradient in sea otter predation. Ecology 73:413-428.

Laughlin, R. 1982. Feeding habits of the blue crab, *Callinectes sapidus* Rathbun, in the Appalachicola Estuary, Florida. Bulletin of Marine Science. 32: 807-822.

Leber, K. 1978. Seasonal community dynamics of macrobenthos on a high energy sandy beach in North Carolina. M.S. Thesis, East Carolina University. 89 pp.

Levin, L.A. 1984. Life history and dispersal patterns in a dense infaunal polychaete assemblage: community structure and response to disturbance. Ecology 65:1185-1200.

Livingston, R. 1984. The ecology of the Applachicola Bay system: an estuarine profile. U.S. Fish and Wildlife Service FWS/OBS-82/05. 148 pp.

Main,J., and G. Sangster. 1981. A study of the sand clouds produced by trawl boards and their possible effect on fish capture. Dept. of Agriculture and Fisheries for Scotland, Scottish Fisheries Res. Report No. 20. (ISSN 0308-8022): 21 pp.

Main, J., and G. Sangster. 1983. Fish reactions to trawl gear--A study comparing light and heavy ground gear. Dept. of Agriculture and Fisheries for Scotland, Scottish Fisheries Res. Report No. 27 (ISSN 0308 8022): 18 pp.

Manooch, C. 1984. Fishermen's Guide. Fishes of the Southeastern United States. North Carolina State Museum of Natural History, Raleigh, NC.362 pp.

Margetts, A.R., and J.F. Bridger 1971. The effect of a beam trawl on the seabed. International Council for the Exploration of the Sea Gear and Behavior C.M. 1971/B:8

Marsh, A., and K. Tenore. 1990. The role of nutrition in regulating the population dynamics of opportunistic, surface deposit feeders in a mesohaline community. Limnology and Oceanography 35: 710-724.

Marshall, N. 1951. Hydrography of North Carolina marine waters. pp. 1-76 IN: H.F. Taylor ed. Survey of Marine Fisheries of North Carolina. University of North Carolina Press, Chapel Hill, NC.

Martens, C. 1978. Some of the chemical consequences of microbially mediated degradation of organic materials in estuarine sediments. Biogeochemistry of Estuarine Sediments. UNESCO Paris, pp. 266-278.

McCall, P.L. 1977. Community patterns and adaptive strategies of the infaunal benthos of Long Island Sound. Journal of Marine Research 35: 221-226.

McCoy, E. 1972. Dynamics of North Carolina commercial shrimp populations. Division of Commercial and Sports Fisheries, N.C. Dept. Natural and Economic Resources, Special Scientific Rep. No. 21, 53 pp.

McKenzie, M. 1981. Profile of the penaeid shrimp fishery in the south Atlantic. Southeast Atlantic Fisheries Council, Charleston, S.C. 321 pp

Medcof, J.C. and J.F. Caddy. 1971. Underwater observations on performance of clam dredges of three types. International Council for the Exploration of the Sea Gear and Behavior Comm. C.M. 1971/B:10

Medcof, J., and J. Caddy. 1973. Effects of trawls and dredges on the sea-bed. International Council for the Exploration of the Sea. pg. 345, 346.

Messiah, S.N., T.W. Rowell, D.L. Peer, and P.J. Cranford 1991. The effects of trawling, dredging, and ocean dumping on the eastern Canadian continental shelf seabed. Continental Shelf Research 11:1237-1263.

Minello, T., R. Zimmerman, and E. Martinez. 1987. Fish predation on juvenile brown shrimp, *Penaeus aztecus* Ives: Effects of turbidity and substratum on predation rates. National Marine Fisheries Service Fishery Bulletin 85: 59-70.

Miner, J. and R. Stein. 1992. Interactive influence of turbidity and light on larval bluegill (*Lepomis macrochirus*) foraging. Canadian Journal of Fisheries and Aquatic Science 50: 781-788.

Miron, G., and G. Desrosiers. 1990. Distributions and population structures of two intertidal estuarine polychaetes in the lower St. Lawrence Estuary, with special reference to environmental factors. Marine Biology 105: 297-306.

Muncy, R. 1984. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (South Atlantic)--white shrimp. U.S. Fish and Wildlife Service. FWS/OBS-82/11.27.

Munz, F. 1958. The photosensitive retinal pigments of fishes from relatively turbid coastal waters. Journal of General Physiology 42: 457-459.

North Carolina Division of Marine Fisheries. 1993. Description of North Carolina's coastal fishery resources, 1972-1991. North Carolina Department of Environment, Health, and Natural Resources, Division of Marine Fisheries, Morehead City, N.C. 213 pp.

Odum, W., and E. Heald. 1972. Trophic analysis of an estuarine mangrove community. Bulletin of Marine Science 22: 671-738.

Odum, W., T. Smith, J. Hoover, and C. McIvor. 1984. The ecology of tidal freshwater marshes of the United States east coast: A community profile. Fish and Wildlife Service. U. S. Department of the Interior. FWS/OBS-83/17. 178 pp.

Oliver, J.S., R.G. Kvitek, and P.N. Slattery 1985. Walrus feeding disturbance: scavenging habits and recolonization of the bering sea benthos. Journal of Experimental Marine Biology and Ecology 91: 233-246.

Oliver, J. S., and P.N. Slattery 1985. Destruction and opportunity on the sea floor: effects of gray whale feeding. Ecology 66: 1965-1975.

Orth, R. 1979. The importance of sediment stability in seagrass communities. pp. 281-300 IN: R. Livingston, ed. Ecological processes in coastal and marine systems. Plenum Press, New York.

Paine, R. 1979. Disaster, catastrophe, and local persistence of the sea palm *Postelsia palmiformis*. Science 205: 685-687.

Palmer, M. 1988. Epibenthic predators and marine meiofauna: Separating predation, disturbance, and hydrodynamic effects. Ecology 69: 1251-1259.

Parker, J. 1971. The biology of the spot, *Leiostomus xanthurus* Lacepede, and Atlantic croaker, *Micropogonias undulatus* Linnaeus, in two Gulf of Mexico nursery areas.Texas A&M Univ. Sea Grant Coll. TAMU-SG 71-210. 180 pp.

Peters, D. and M. Kjelson. 1975. Consumption and utilization of food by various postlarval and juvenile fishes of North Carolina estuaries. pp.448-472 IN: L. Cronin, ed. Estuarine Research. Vol. 1. Chemistry, Biology, and the Estuarine System. Academic Press, New York, New York.

Peterson, C. H. 1979. Predation, competitive exclusion, and diversity in the soft-sediment benthic communities of estuaries and lagoons. pp. 233-264 IN: Ecological Processes in Coastal and Marine Systems. R. Livingston, ed. Plenum Press, New York.

Peterson, C.H. 1991. Intertidal zonation of marine invertebrates in sand and mud. American Scientist 79: 236-249.

Peterson, C.H., H. C. Summerson, and S. R. Fegley. 1987. Ecological consequences of mechanical harvesting of clams. National Marine Fisheries Service Fishery Bulletin 85: 281-298.

Peterson, C.H. and H.C. Summerson 1992. Basin-scale coherence of population dynamics of an exploited marine invertebrate, the bay scallop: implications of recruitment. Marine Ecology Progress Series 90: 257-292.

Peterson, C. H., H. C. Summerson, and P. B. Duncan. 1984. The influence of seagrass cover on population structure and individual growth rate of a suspension-feeding bivalve, *Mercenaria mercenaria.* Journal of Marine Research 42: 123-138.

Pietrafesa, L., G. Janowitz, T. Chao, R. Weisberg, F. Askari, and E. Noble. 1986. The physical oceanography of Pamlico Sound. Univ. North Carolina Sea Grant Working Paper Publ. No. 86-5. Raleigh, NC. 125 pp.

Pomeroy, L., E. Smith, and C. Grant. 1965. The exchange of phosphate between estuarine water and sediments. Limnology and Oceanography 10: 167-172.

Powell, A., and F. Schwartz. 1979. Food of *Paralichthys dentatus* and *P. lethostigma.* (Pisces: Bothidae) in North Carolina estuaries. Estuaries 2: 276-279.

Probert, P. 1984. Disturbance, sediment stability, and trophic structure of soft-bottom communities. Journal of Marine Research. 42:893-921.

Pritchard, D. 1967. What is an estuary: Physical viewpoint. pp. 3-5. IN: G. Lauff, ed. Estuaries. Publication No. 83 American Association for the Advancement of Science, Washington, D.C.

Rachlin, J., A. Pappantoniou, and B. Warkentine. 1987. A bias estimator of the environmental resources base in diet preference studies with fish. Journal of Freshwater Ecology 4: 23-31.

Reed, J., J. Miller, D. Pence, and B. Schaich. 1983. The effects of low level turbidity of fish and their habitat. N.C. Water Resources Research Institute Rep. No. 190, 40 pp.

Rhoads D.C., and D.K. Young. 1970. The influence of deposit feeding organisms on sediment stability and community trophic structure. Journal of Marine Research 28:150-178.

Riemann, B., and E. Hoffmann. 1991. Ecological consequences of dredging and bottom trawling in the Limfjord, Denmark. Marine Ecology Progress Series. 69: 171-178.

Riggs, S., E. Powers, J. Bray, P. Stout, C. Hamilton, D. Ames, R. Moore, J. Watson, S. Lucas, and M. Williamson. 1989. Heavy metal pollutants in organic-rich mujds of the Pamlico River estuarine system: Their concentration, distribution, and effects upon benthic environments and water quality. Albemarle-Pamlico Estuarine Study, Raleigh, N.C., U.S. Environmental Protection Agency and N. C. Department of Health, Environment and Natural Resources, Report No. 89-06 108 pp.

Riggs, S., J. Bray, R. Wyrick, C. Klingman, D. Ames, J. Hamilton, K. Lueck, and J. Watson. 1993. Heavy metals in organic-rich muds of the Albemarle Sound estuarine system. Albemarle-Pamlico Estuarine Study, Raleigh, N.C., U.S. Environmental Protection Agency and N. C. Department of Health, Environment and Natural Resources, Report No. 93-02 173 pp.

Roelofs, E. and D. Bumpus. 1953. The hydrography of Pamlico Sound. Bulletin of Marine Science of the Gulf and Caribbean 3: 181-205.

Rogers, S., and M. Van Den Avyle. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic)--Atlantic Menhaden. U. S. Fish and Wildlife Service. Biological Report 82(11.108) 23 pp.

Ross, S., and S. Epperly. 1986. Utilization of shallow estuarine nursery area by fishes in Pamlico Sound, North Carolina, and adjacent tributaries. pp. 207-232 IN: A. Yanez-Arancibia, ed. Fish community ecology in estuarine and coastal lagoons: toward an ecosystem integration . Universidad Nacional Autonoma de Mexico, Mexico.

Rounsefell, G. 1975. Ecology, Utilization and Management of Marine Fisheries. C.V. Mosby Co., St. Louis. 516 pp.

Sammarco, P.W., and J.C. Andrews. 1989. The HELIX experiment: differential localized dispersal and recruitment patterns in Great Barrier Reef corals. Limnology and Oceanography 34: 896-912.

Santos, S.L., and J.L. Simon. 1980a. Marine soft-bottom community establishment following annual defaunation: larval or adult recruitment? Mar. Ecol. Prog. Ser. 2:235-241.

Santos, S., and J. Simon. 1980b. Response of soft-bottom benthos to annual catastrophic disturbance in a south Florida estuary. Marine Ecology Progress Series. 3: 347-355.

Schubel, J., H. Carter, and W. Wise. 1979. Shrimping as a source of suspended sediment in Corpus Christi Bay (Texas). Estuaries 2: 201-203.

Schwartz, F. 1980. Food analyses of selected fishes captured in Cape Fear Estuary and adjacent Atlantic Ocean, North Carolina, 1973-1978. Part A , 254 pp. Report to Carolina Power and Light Co.

Service, S., R. Feller, B. Coull, and R. Woods. 1992. Predation effect of three fish species and a shrimp on macrobenthos and meiobenthos in microcosms. Estuarine and Coastal Shelf Science 34: 277-293.

Servizi, J., and D. Martens. 1992. Sublethal responses of coho salmon (*Oncorhynchus kisutch*) to suspended sediments. Canadian Journal of Fisheries and Aquatic Science 49: 1389-1395.

Sherk, J., J. O'Connor, and D. Neumann. 1975. Effects of suspended and deposited sediments on estuarine environments. pp. 541-558 IN: L. Cronin, ed. Estuarine Research. Vol II: Geology and Engineering. Academic Press, New York.

Sherman, K., J. Reidenauer, D. Thistle, and D.Meeter. 1976. Effects of tropical storm Agnes on soft-bottom macrobenthic communities of the James and York estuaries and the lower Chesapeake Bay. Chesapeake Science. 17: 246-259.

Sherman, K., J. Reidenauer, D. Thistle, and D.Meeter. 1983. Role of a natural disturbance in an assemblage of marine free-living nematodes. Marine Ecology Progress Series. 11:23-30.

Simon, J.L., and D.M.Dauer 1977. Reestablishment of a benthic community following natural defaunation. pp. 139-189 IN: B. Coull, ed. Ecology of Marine Benthos. Univ. South Carolina Press, Columbia.

Smith, C.R., and S.J. Brumsickle. 1989. The effects of patch size and substrate isolation on colonization modes and rates in an intertidal sediment. Limnology and Oceanography 34:1263-1277.

South Atlantic Fishery Management Council. Annonymous public hearing draft; shrimp fishery management plan. pg. 44, 66-70.

Spitsbergen, D. 1979. A study of the bay scallop (*Argopecten irradians*) in North Carolina Waters. N. C. Dept. of Environment, Health, and Natural Resources, Division of Marine Fisheries, Completion Report No. 2-256-R. 44 pp.

Spitsbergen, D., and M. Wolff. 1974. Survey of nursery areas in western Pamlico Sound, North Carolina. EHNR, NC Division of Marine Fisheries Report 2-175-R. 80 pp.

Stanley, D. 1987. Water quality in the Pamlico River estuary 1986. Institute for Coastal and Marine Resources, East Carolina University, Technical Report 87-01. 77 pp.

Stanley, D. 1988. Water quality in the Pamlico River estuary, 1967-1986. Institute for Coastal and Marine Resources, East Carolina University, Technical Report 88-01. 199 pp.

Stanley, D. 1989. Historical trends in land use, nutrient production, water quality and fisheries in the Albemarle-Pamlico estuarine system. Institute of Coastal and Marine Resources, East Carolina University, Technical Report 89-01.

Stickney, R. 1984. Estuarine Ecology of the Southeastern United States and Gulf of Mexico. Texas A&M Univ. Press, College Station, Tx. pp. 247-290.

Stickney, R., G. Taylor, and D. White. 1975. Food habits of five young southeastern United States estuarine Sciaenidae. Chesapeake Science 16: 104-114.

Stoecker, D., and J. Govoni. 1984. Food selection by young larval gulf menhaden (*Brevoortia patronus*). Marine Biology 80: 299-306.

Stearns, D., and S. Ross. 1989. Noncommercial invertebrate species and associated environmental factors within the estuarine complex of Western Pamlico Sound, North Carolina: An information guide. University of North Carolina Sea Grant College Program Publication UNC-WP-89-2. 90 pp.

Stoner, A. , and B. Buchanan. 1990. Ontogeny and overlap in diets of four tropical *Callinectes species.* Bulletin of Marine Science 46: 3-12.

Summerson, H., and C. Peterson. 1984. Role of predation in organizing benthic communities of a temperate-zone seagrass bed. Marine Ecology Progress Series 15: 63-77.

Taghon, G. 1982. Optimal foraging by deposit-feeding invertebrates: roles of particle size and organic coating. Occologia 52: 295-304.

Tenore, K. 1972. Macrobenthos of the Pamlico River estuary. Ecological Monographs 42: 51-69.

Thayer, G., T. Price, R. Sechler, and M. Le Croix. 1975. Invertebrates and sediments of the Newport River Estuary: a status report. Annual Report, Ecology Division of the Atlantic Estuarine Fisheries Center. pp. 202-207.

Thistle, D. 1981. Natural physical disturbances and communities of marine soft bottoms. Marine Ecology Progress Series 6: 223-228.

Thrush, S. R. Pridmore, J. Gewitt, and V. Cummings. 1991. Impact of ray feeding disturbances on sandflat macrobenthos: do communities dominated by polychaetes or shellfish respond differently? Marine Ecology Progress Series 69: 245-252.

Van Blarisom, G.R. 1982. Experimental analyses of structural regulation in a marine sand community exposed to oceanic swell. Ecological Monographs 52: 283-305.

Van Dolah, R., D. Calder, and D. Knott. 1984. Effects of dredging and open water disposal on benthic macroinvertebrates in a South Carolina estuary. Estuaries 7: 28-37

Van Dolah, R., P. Wendt, and M. Levisen. 1991. A study of the effects of shrimp trawling on benthic communities in two South Carolina sounds. Fisheries Research, 12: 139-156.

Vigerstad, T. , and J. Cobb. 1978. Effects of predation by sea-run juvenile alewives (*Alosa pseudoharenges*) of the zooplankton community at Hamilton Reservoir, Rhode Island. Estuaries 1: 36-45.

Vinyard, G., and W. O'Brien. 1976. Effects of light and turbidity on the reactive distance of Bluegill (*Lepomis macrochirus*) Journal of the Fisheries Research Board of Canada 33: 2845-2849.

Warner, R.R. and P.L. Chesson. 1985. Coexistence mediated by recruitment fluctuations: a field guide to the storage effect. American Naturalist 125: 769-787.

Webb, D., and T. Parsons. 1991. Impact of predation-disturbance by large epifauna on sediment-dwelling harpacticoid copepods: field experiments in a subtidal seagrass bed. Marine Biology 109: 485-491.

Wells, H. 1961. The fauna of oyster beds, with special reference to the salinity factor. Ecological Monographs 31: 239-266.

Wells, J., and S. Kim. 1989. Sedimentation in the Albemarle-Pamlico lagoonal system: synthesis and hypotheses. Marine Geology. 88: 263-284.

West, T. 1984. Abundance and diversity of benthic macrofauna in subtributaries of the Pamlico River estuary. Journal of the Elisha Mitchell Scientific Society 101: 142-159.

West, T., and W. Ambrose, Jr. 1992. Abiotic and biotic effects on population dynamics of oligohaline benthic invertebrates. pp. 189-194 IN: G. Colombo, I. Reffari, V. Ceccherelli, and R. Rossi, eds. Marine Eutrophication and Population Dynamics. 25th European Marine Biology Symposium (1990).

Wilber,C. 1983. Turbidity in the aquatic environment: an environmental factor in fresh and oceanic waters. C.C. Thomas. Springfield, Ill. 133 pp.

Wilcox, J., and H. Jeffries. 1974. Feeding habits of the sand shrimp *Crangon septemspinosa.* Biological Bulletin of Woods Hole Oceanographic Institution 146: 424-434.

Williams, A. 1955a. A survey of North Carolina shrimp nursery grounds. Journal of the Elisha Mitchell Society 71:200-207.

Williams, A. 1955b. A contribution to the life histories of commercial shrimps (Penaeidae) in North Carolina. Bulletin of Marine Science of the Gulf and Caribbean 5: 116-146.

Williams, A. 1958. Substrates as a factor in shrimp distribution. Limnology and Oceanography 3: 283-290.

Williams, A. 1984. Shrimp, Crabs, and Lobsters of the Atlantic Coast of the Eastern U.S., Maine to Florida. Smithsonian University Press. Washington, D.C. 550 pp.

Williams, A., G. Posner, W. Woods, and E. Deubler. 1973. A hydrographic atlas of larger North Carolina sounds. University of North Carolina Sea Grant College Program Publication UNC-SG-73-02.

Wilson, D. P. 1968. The settlement behavior of the larvae of *Sabellaria alveolata*. Journal of the Marine Biological Association of the United Kingdom 48: 387-435.

Wilson, W.H. 1981. Sediment-mediated interactions in a densely populated infauna assemblage: the effects of the polychaete *Abarenicola pacifica*. Journal of Marine Research 39: 735-748.

Wilson, W.H. 1991. Competition and predation in marine soft-sediment communities. Annual Review of Ecology and Systematics 21: 221-241.

Windom, H. 1975. Water-quality aspects of dredging and dredge-spoil disposal in estuarine environments. pp 559-571 IN: L. Cronin, ed. Estuarine Research. Vol II: Geology and Engineering.. Academic Press, New York.

Wright, S. 1972. A Preliminary Survey of Benthic Macroinvertebrates in Croatan Sound, North Carolina. MS Thesis, East Carolina University. 85 pp.

PART 2:

BYCATCH IN NORTH CAROLINA MARINE AND ESTUARINE WATERS

By

Gregory A. Skilleter
Institute of Marine Ecology, Zoology Building
University of Sydney, New South Wales, Australia

Terry L. West and William G. Ambrose,[1]
Department of Biology, East Carolina University
Greenville, North Carolina
27858

[1] Biology Department
Bates College
Lewiston, Maine
04240

BYCATCH IN NORTH CAROLINA MARINE AND ESTUARINE WATERS

Introduction

Fishing gears that use small mesh sizes are particularly prone to the problems of being non-selective in their catch. Large numbers of juvenile fishes, fishes smaller than the legal size limit for the target species, and non-targeted species are captured and killed as bycatch in many marine fisheries (Sheridan et al., 1984). Bycatch is defined as that part of the overall catch which is captured incidentally to the species toward which there is a directed effort (Saila, 1983). This includes whole fish, invertebrates (such as crabs, lobsters, mollusks), reptiles (sea turtles), birds and mammals.

Much of this bycatch is neither marketed nor used, resulting in a considerable amount of wastage. Slavin (1982) estimated that the bycatch from the world's shrimp fishery alone is about 3-5 million tons per year. If the discards from the major demersal trawl fisheries and other marine fisheries are added to this, the annual quantity of fish discarded at sea is a substantial loss of available animal protein to mankind. Significant mortalities of juvenile finfish can decrease the spawning stock potential and subsequent yields to the fisheries (Howell and Langan, 1987; Perra, 1992), and also have other potential unknown ecological impacts on fish stocks (Saila, 1983).

Fisheries in North Carolina Marine and Estuarine Waters

The shrimp industry is one of the most important fisheries in the United States in overall value and in 1976 ranked third in overall volume (Juhl and Drummond, 1976) but, because of the small-mesh nets that are used and the non-selective nature of the gear in general, is an area of particular concern with respect to bycatch problems. Shrimp are almost exclusively caught using otter trawls, a very unselective fishery because of the small mesh size of the nets (1.9 cm [0.75 inches]). The most important component of this fishery is the genus *Penaeus* from the Gulf of Mexico and the southeastern United States. The bycatch problem of penaeid fisheries is a worldwide problem, probably as a result of the similarity of the fauna existing in areas where the penaeids live and the similarity in the gear used to catch them (Juhl and Drummond, 1976). Similar problems are also experienced by other fisheries in the Atlantic region, for example the fisheries for *Nephrops* and *Geryon* in the northeastern Atlantic catch large numbers of juvenile hake (*Urophycis spp.*) and whiting (*Menticirrhus spp.*) (Juhl and Drummond, 1976).

For the southeast region of the United States, the penaeid shrimp fishery is the most important fishery; in North Carolina alone, 7.8 million pounds of shrimp (value $15.9 million) were landed in 1990 (Murray et al., 1992). Combined, the Gulf and South Atlantic regions landed over 277 million pounds of shrimp worth $454 million in 1990. As a consequence, the landings of bycatch were also extremely high and caused considerable mortality to finfish (Rothschild & Guiland, 1982). The Gulf of Mexico shrimp fishery was estimated to have caught as bycatch some 300 - 400 million pounds of finfish per year from 1985 to 1989 (Nichols et al., 1990) with most of the bycatch consisting of demersal fish such as Atlantic croaker, spot, seatrout (*Cynoscion spp.*) and porgies (*Stenotomus caprinus*) (NMFS, 1991).

As the shrimp fishery is the most valuable and extensive fishery in the southeastern Atlantic region (and second to blue crabs in value in North Carolina waters) and is, therefore, likely to be the most important contributor to the bycatch. Other fisheries, however, also contribute to the bycatch problem. These fisheries include: (a) the purse seine fishery for menhaden; (b) the gill net fishery; (c) pound net fishery; (d) long haul seine fishery; (e)winter flynet fishery; and (f) the blue crab fishery.

The menhaden fishery is an important industry in the United States, ranking first in tonnage and third in finfish value in 1984 (Rulifson and Cooper, 1986). In the offshore waters of North Carolina, the species of interest is the Atlantic menhaden, *Brevoortia tyrannus*. Approximately 98% of all menhaden tonnage landed is by purse seines. Purse seines exploit the natural tendency of menhaden to feed in large schools, thereby allowing easy capture. Some of the most commonly encountered species caught as bycatch in purse seines include blue runner (*Caranx crysos*), crevalle jack (*Caranx hippos*), red drum (*Sciaenops ocellatus*), Atlantic bumper (*Chloroscombrus chrysurus*) and black drum (*Pogonias cromis*) (NMFS, 1991). Nevertheless, menhaden typically account for 99% of the catch. Therefore, contributions of purse seines to bycatch are low relative to the that of the shrimp fishery (NMFS, 1991).

Gill nets are basically non-selective gear in the sense that they will catch whatever swims into them if the species is of a size that can be gilled. Under some circumstances gill nets are fished to predominantly target a particular species; other species (bycatch) may also be caught depending on their abundance, habits, and susceptibility to the mesh size (Speir, 1985, 1987). Gill nets are usually set as anchor nets, staked nets, drift nets or circle nets. Areas of concern for the use gill nets, include: (1) incidental catches of fishes reserved for recreational fishermen; (2) mortality of small fishes, below the minimal size limit; (3) wastes of fishes taken incidentally by the gill nets; and (4), mortality of fishes that become disentangled and lost from the gill nets before they are harvested and are not documented by landing record (Vojkovish et al., 1990). To this should be added the potentially large impact from so-called "ghost-nets", nets which have been lost to the fishermen but continue to fish for some time afterwards (Carr & Cooper, 1987; Carr, 1988).

Gill nets have also been implicated as a cause of significant mortality of seabirds and marine mammals (e.g., the extensive gill net fishery off California). The entanglement and drowning of diving birds can be substantial and can have further effects on the bird populations if the drowned birds have nestlings, which depend upon the adults for food and protection (California Department of Fish and Game, 1987). Larger meshes can apparently also cause entanglement of the head and/or flippers of porpoises and dolphins. The larger mesh gill nets are typically constructed of stronger material making it harder for the animals to break free (California Department of Fish and Game, 1987).

Pound nets, like gill nets, for the most part are operated close to the shore or in internal marine and estuarine waters such as the sounds of North Carolina. Pound nets, gill nets and haul seines have traditionally been the main commercial gear used to capture fishes in the estuarine bay fisheries of the Chesapeake Bay and elsewhere along the mid-Atlantic and south Atlantic coasts (Chittenden, 1989). Pound nets capture a wide size range of many different species and are usually considered to be a nonselective fishing method once the fish encounter the net. Pound nets have been historically cited as a cause of declines in the catch of important food species such as the weakfish, Atlantic croaker (NCDMF, 1993) (cf. Figure 2.1), and the destruction of other undersized or immature fishes including Atlantic menhaden, butterfish (*Peprilus triacanthus*), spot and thread herring (*Opisthonema oglinum*) (Higgins and Pearson, 1928 cited in Meyer and Merriner, 1976). The shrimp trawl industry, however, has also been blamed for the decline in the weakfish populations (Vaughan et al., 1991) indicating the multiple fishery impacts on some populations.

The long haul seine is used in moderately deep to shallow estuarine waters (<2 meters) where the bottom is firm, and consists of a 1000-1800 yd length of netting which is towed

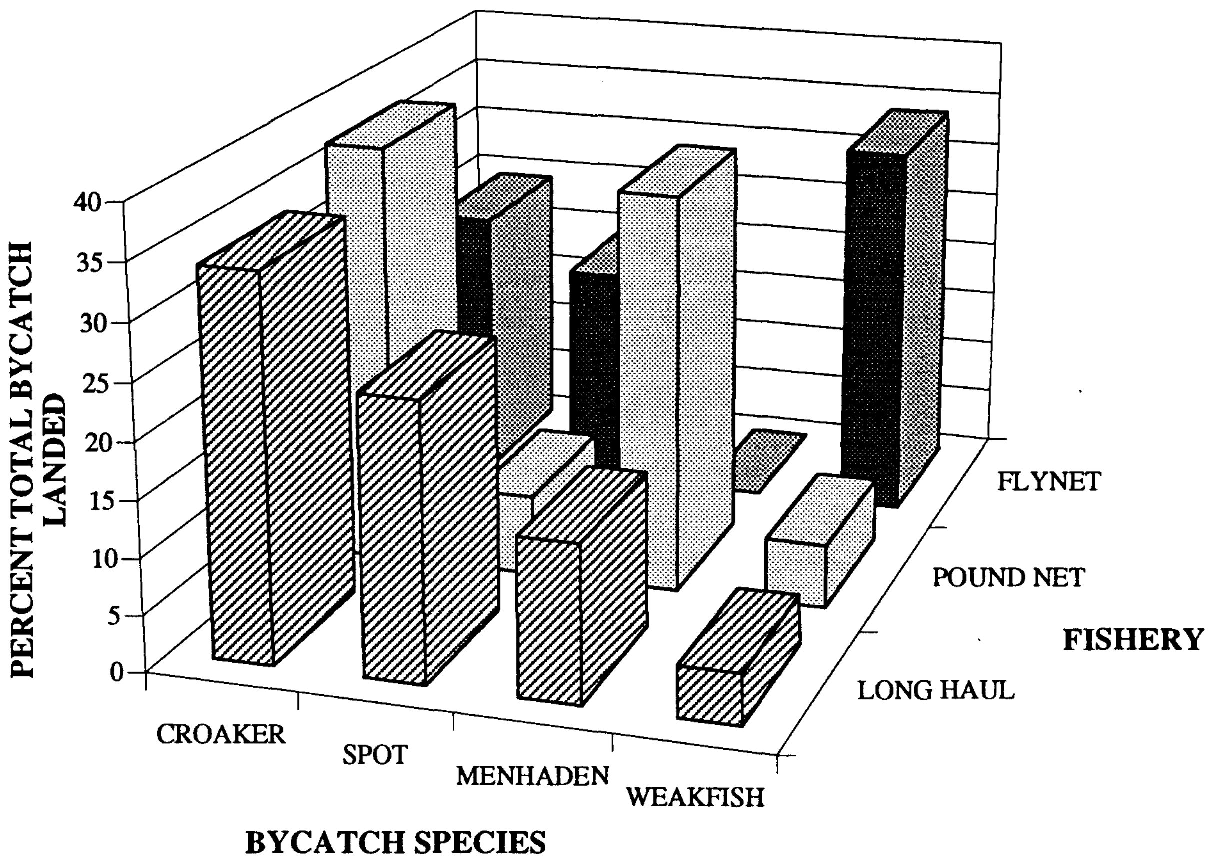

Figure 2.1 . Comparison of predominant bycatch species among three North Carolina Fisheries. Percent values are based on annual mean weight of undersized individuals landed as scrap fish during 1985-1990. Data were obtained from West (1991), and K. West (personal communication).

between two boats. Eventually the net is brought into a circle by the boats and the enclosed fish are removed. Net length and mesh size are currently controlled only in Currituck Sound. Undersized spot, Atlantic croaker, Atlantic menhaden, and weakfish captured by long haul seines collectively account for 30-40% of North Carolina's landed bycatch (scrapfish; NCDMF, 1993) (Figure 2.1). These percentages translate into an average annual landed bycatch of 2.6-3.5 million pounds out a average total annual landed bycatch of 8.8 million pounds (cf. West, 1991).

Flynets are modified trawls that fish the water column. Flynet fishing occurs offshore and is one of three gear types constituting the North Carolina's winter trawl fishery (NCDMF, 1993). Flynets catch a greater proportion of undersized weakfish than either long haul seines or pound nets, as well as substantial amounts of undersized spot and croaker (Figure 2.1). Landed bycatch from the flynet fishery is similar to that of the long haul fishery (West, 1991).

The fishery for blue crabs utilizes "pots" which are baited with fish (usually Atlantic menhaden and/or Atlantic thread herring), and crab trawls. Actively fished pots do not contribute to the bycatch problem, but lost or abandoned pots may continue to fish and become a significant cause of mortality not only for crabs (McKenna and Camp, 1992) but for fishes (Casey & Wesche, 1981). Derelict pots collected from the tidewaters of Maryland have yielded large catches of seabass, white perch, tautog (*Tautoga onitis*), spot and flounder. The extensive nature of the blue crab fishery throughout the estuarine waters of North Carolina warrant that this problem be addressed.

The crab trawl fishery is divided into an eastern and western fishery. The eastern fishery occurs in the vicinity of the inlets, and the catch includes primarily mature female blue crabs (NCDMF, 1993). The western fishery occurs in the Pamlico, Croatan, and Roanoke sounds and their respective tributaries. Most of the crab trawling is concentrated in the winter and early spring months when crab pots are either ineffective or prohibited. Studies of crab trawling in the Pamlico and Pungo rivers have shown that finfish constitute approximately 60% of the catch (by weight) per trip during November to March. A trip refers to the total fishing activity of a boat per day or night, during which an average of 3 tows are taken. The finfish catch includes about 26 species. Over 95% of this catch (by weight) consists of southern flounder; the most common species in the remaining 5% of the finfish catch are spot, Atlantic croaker, and menhaden (McKenna and Camp, 1992).

Crab trawl bycatch in the Pamlico and Pungo rivers consists primarily of undersized flounder and blue crabs. Approximately 50% (by weight) of all flounder , and 33% (by weight) of all blue crabs, caught are undersized (McKenna and Camp, 1992). This bycatch is highly seasonal; nearly 80% of the flounder bycatch was caught during November and December. The greatest amount of undersized blue crabs were also caught during November and December, but the highest percentage (73%) of undersized crabs were caught in June (McKenna and Camp, 1992).

Existing N.C. regulations prohibit the use of inshore trawling for the direct purpose of capturing finfish. However, crab (and shrimp) trawling currently enjoy a unique position within the N.C. fisheries, because the legal sized flounder caught in the pursuit of the "primary" target species can be kept and marketed (NCDMF regulation 15A NCAC 3J .0104 A). Historically there was no limit on the amount of undersized flounder caught; however, a recent ruling has placed a 500-1000 lb limit on the total finfish bycatch for crab trawling. The actual limits varies with the month of the year.

The Problem of North Carolina

The Shrimp Fishery

The southeastern Atlantic shrimp fishery is aimed at shrimp from the Family Penaeidae which are found in the warm temperate waters on the U.S. continental shelf and in the estuaries, sounds and bays. The species which dominate the catch are the white shrimp ***Penaeus setiferus***, the pink shrimp ***Penaeus duorarum***, and the brown shrimp ***Penaeus aztecus***. The fishery can be broken into two parts, an offshore commercial fleet which operates over wide geographic areas, and the inshore fleet. The inshore fleet uses mainly otter trawls but, in certain locations, also uses butterfly nets, beam trawls, traps and cast nets (NMFS, 1991). In addition to the inshore commercial fleet, approximately 45,000 recreational shrimpers harvest shrimp in inshore waters during the summer and fall months (NMFS, 1991).

Bycatch in the Southeastern Atlantic region

Keiser (1976) provided an extensive examination of the problems of bycatch in the waters off South Carolina. He found that 105 species of fish representing 45 families and 15 orders were caught in shrimp trawls in this region. Eleven of these families comprised 97.5% of the yearly catch (see Table I). The Sciaenidae, Engraulidae and Clupeidae contributed to the total catch throughout the year while the other families represented a sizable portion of the catch only in certain months. Fourteen of the species caught in the trawls were considered to be sports fishes including the southern kingfish (*Menticirrhus americanus*), the Atlantic croaker, the weakfish or gray trout, and spot. Most of these fish were of small size (less than legal limit) but some spot, Spanish mackerel (*Scomberomorus maculatus*) and summer flounder were occasionally of marketable size and were culled from the catch for sale (Keiser, 1976).

Knowlton (1972) provided a similar account of the species composition of shrimp bycatch from Georgian waters. He found that 4 families of fish each represented greater than 3% or more of the yearly average catch for all districts in Georgia. These were the Sciaenidae (73.8 %), Clupeidae (8.5 %), Dasyatidae (3.6 %) and the Ariidae (3.3 %). Note that while the Sciaenidae, Clupeidae and Ariidae all occurred in the top 11 for Deiser's study in South Carolina (Table 2.1), the Dasyatidae (stingrays) were not recorded as being very abundant in trawls taken in Georgia. Apart from this difference the results closely mirror those presented by Keiser for South Carolina. The most common species from Knowlton's (1972) study were spot, Atlantic croaker, whiting and kingfish (*Menticirrhus* spp.), menhaden, and gray seatrout, star drum (*Stellifer lanceolatus*), stingrays (*Dasyatis* spp.), sea catfish (*Arius felis*) and banded drum (*Larimus fasciatus*). The fisheries in South Carolina and Georgia are primarily based in offshore waters although some sounds and bays have been open to shrimping in late summer and fall.

In contrast to the fisheries in Georgia and South Carolina, the majority of shrimping in North Carolina is concentrated in the sounds and inlets with little fishing being conducted in offshore water (Keiser, 1977). Pamlico Sound provides up to 50% of the state's shrimp catch. Other areas frequently fished for shrimp include Core Sound, Bogue Sound, Beaufort Inlet, Ocracoke Inlet, and the mouths of the Neuse, Newport, New and Cape Fear Rivers (Keiser, 1977). The Pamlico Sound shrimp fishery began in 1937, and has increased in size since then. In 1985, the combined landings of brown shrimp and pink shrimp accounted for 66% of the North Carolina total shrimp landings (8,328,390 lb / 3,777,733 kg), with an ex-vessel value of $13,921,809 (Pearce et al., 1989).

Table 2.1. Most common families of fish occurring as bycatch in trawls collected in 1974 from the coastal waters of South Carolina. % contr.=the percent contribution by number for 11 families of fish commonly occurring in trawls, averaged over 12 months (adapted from Keiser, 1976).

Family	**Species Commonly Occurring as Bycatch**	**% Contr.**
Sciaenidae	spot (*Leiostomus xanthurus*); Atlantic croaker (*Micropogonias undulatus*); sea trouts (*Cynoscion* spp.)	60.46
Engraulidae	*Anchoa mitchelli, A. hepsetus*	9.16
Clupeidae	Atlantic menhaden (*Brevoortia tyrannus*); Atlantic thread herring (*Opisthonema oglinum*);	8.26
Gadidae	spotted hake (*Urophycis regius*);	7.30
Carangidae	Atlantic bumper (*Chloroscombrus chrysursus*);	2.56
Bothidae	flounder (*Paralichthys dentatus, P. lethostigma*);	2.37
Stromateidae	Southern harvestfish (*Peprilus alepidotus*), butterfish (*Peprilus triacanthus*)	2.26
Cynoglossidae	blackcheek tonguefish (*Symphurus plagiusa*)	2.05
Soleidae	hogchoker (*Trinectes maculatus*)	1.18
Ariidae	sea catfish (*Arius felis*), gaff-topsail catfish (*Bagre marinus*)	0.94
Scombridae	spanish mackerel (*Scomberomorus maculatus*), king mackerel (*Scomberomorus cavalla*)	1.00

Table 2.2. Species composition and percent contribution (% Contr.) by weight of bycatch taken in shrimp catches in North Carolina (after Keiser, 1977).

Species	Common name	% Contr.
Leiostomus xanthurus	spot	38.7
Micropogonias undulatus	Atlantic croaker	24.2
Orthopristes chrysoptera	pigfish	8.4
Paralichthys sp.	edible flounders	4.0
Cynoscion regalis	weakfish	3.9
*	inedible flounder	3.1
Lagodon rhomboides	pinfish	2.8
Synodus foetens	inshore lizardfish	2.0
Calamus sp., Stenotomus sp.	porgies	1.7
Menticirrhus sp.	kingfish and whiting	1.4

* = blackcheek tonguefish (*Symphurus plagiusa*), fringed flounder (*Etropus crossotus*), windowpane (*Scophthalmus aquosa*), spotted whiff (*Citharichthys macrops*), hogchoker (*Trinectes maculatus*), oscellated flounder (*Ancylopsetta quadrocellata*), and naked sole (*Gymnachirus melas*).

Ten species or species assemblages of fishes comprise approximately 90% of the bycatch from North Carolina (Table 2.2; Keiser, 1977). During the mid-1970's, spot, Atlantic croaker, pigfish and edible flounders made up 75.3% of the total catch. Keiser estimated that between 1973 and 1975 shrimp trawlers from North Carolina caught an estimated 73.2 million pounds of fish, of which some 95% was discarded despite the fact that at the time North Carolina was the only southeastern Atlantic state engaged in shrimp fishing which had industrial facilities for processing bycatch into pet food.

More recent work has indicated that the catches of undersized Atlantic croaker, spot, and weakfish averaged 2.5, 1.7, and 1.5 million pounds/year, respectively, during 1987-1990 in the combined flynet, long haul, and sciaenid pound net fisheries (cf. West, 1991). These values refer to the landings of these species as components of the scrapfish catch. Scrapfish is undersized fish which cannot be legally sold (General Statute 113-185). Scrapfish caught by the shrimp fishery is normally discarded at sea, and therefore is not represented in these values. However, the amount of undersized fishes caught by shrimp fishing could be estimated assuming a 1:4 catch ratio of shrimp weight to fish weight. Shrimp to fish catch ratios are known to be highly variable within North Carolina (Keiser, 1977), and have been criticized as poor estimators of shrimp bycatch. Nevertheless, the 1:4 ratio is a highly conservative value which has been corroborated as part of the NMFS Regional Observer Program aboard commercial shrimp vessels. If this catch ratio is accurate, shrimp trawling may account for more than 75% of North Carolina's total bycatch (Figure 2.2); i.e., approximately 29 million pounds per year (West, 1991) .

Impacts at the Population Level

The National Marine Fisheries Service (1991) provides examples of how overfishing of an incidentally caught species (bycatch) may affect the status of the population. Atlantic croaker were once very abundant in the northern Gulf of Mexico but have declined significantly since the 1950s. Also, the size of individuals and number of year classes in the catch is markedly reduced compared with stocks in the 1950s. The fish appear to be reaching a spawning state at a smaller size, a response which is common to populations with reduced adult spawning stock (NMFS, 1991). The trouble with assessments such as this is that there is no direct evidence that the decline in Atlantic croaker populations is a result of the shrimp industry catching and discarding them as bycatch. Declines in habitat quality or changes in some other factor affecting the demography of the fish may be the cause of the population declines for the Atlantic croaker; the correlation between increased fishing activity and the decline in Atlantic croaker stocks is not an indication of a causal relationship.

A more topical example is the red snapper (*Lutjanus campechanus*). Although the adult red snapper occur around rocky reefs and other topographic discontinuities, and are unlikely to be affected by shrimp trawling, the juveniles are found on the shrimping grounds and are vulnerable to incidental capture. Removal by the shrimp fleet of a significant percentage of juvenile red snapper by shrimp trawlers is blamed for severe reductions in the populations levels, although the actual extent of the problem is disputed by the shrimp fishermen themselves. Many shrimpers argue that the extent of the apparent decline in red snapper population size is actually a result of flawed National Marine Service statistics (Fee, 1991). Is the amount of error in the estimate of 12.5 million red snapper killed per year by shrimp trawls plus or minus 6 million? If so there can be reasonable doubt about the size of the problem and what can be done to correct it.

The North Carolina Division of Marine Fisheries has been concerned about the steady decline in landings of summer flounder and weakfish in recent years. Both species are listed in the NMFS list for special attention (Table 2.3; Murray et al,. 1991). Research by Miller et al. (1990)

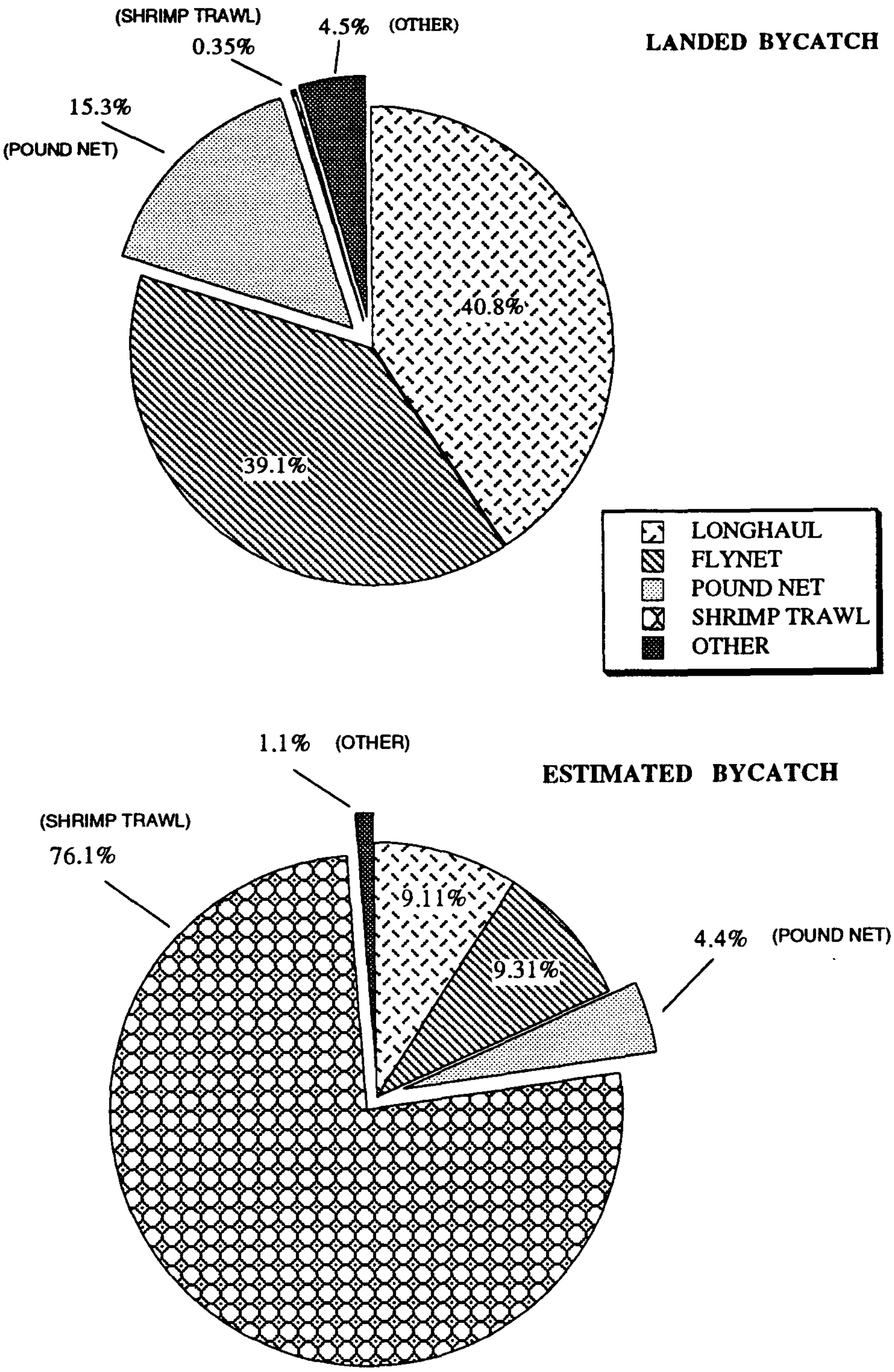

Figure 2.2. Comparisons of fishery-specific bycatch in North Carolina according to reported landings (upper graph), and estimates based on a 1:4 shrimp to fish ratio for shrimp trawls (lower graph) (after West, 1991).

indicates that the limiting factor for populations of sciaenids and other fishes in the North Carolina lagoonal estuarine systems (such as Pamlico Sound) is colonization of the available habitat. The lagoons are poorly connected to the ocean which is the source of larvae and juveniles and increases in juvenile mortality caused by shrimp trawling may result in declines in adult populations. They used caging studies to show that the system can support five-fold increases in the density of spot without decreasing rates of growth or increasing rates of mortality. Species such as summer flounder which have relatively slow rates of growth (i.e. spend longer periods in the "juvenile" stage), are likely to be more affected through bycatch mortality than other species. Miller et al. (1990) believed that there is strong evidence linking bycatch mortality of juveniles to reduced adult stocks. Recent work by NCDMF has shown that bycatch landed as scrapfish accounts for 25-45% of the total commercial landings of weakfish, spot and Atlantic croaker. These values are nearly doubled for spot and Atlantic croaker if estimates of shrimp bycatch are included (Figure 2.3).

The Lack of Current Information

Under current National Marine Fisheries Service research guide-lines (NMFS, 1991), 34 species of fish commonly caught as bycatch in the Gulf of Mexico and southeastern Atlantic regions have been identified as being of special importance, based on their numerical dominance within trawls, their commercial and/or recreational value, or because they are already managed under a current Fishery Management Plan (Table 2.3). Of the fish which were found to occur most frequently in North Carolina bycatch (Keiser, 1977) only pigfish (*Orthopristes chrysoptera*), pinfish (*Lagodon rhomboides*) and the inedible flounders are not included in this "priority" list (compare Table 2.2 with Table 2.3).

The Fisheries Service has indicated that the current database on the spatial and temporal patterns of distribution for these 34 species is insufficient to allow precise estimates of current shrimp bycatch, and they recommend that up-to-date information be obtained on age-specific estimates of bycatch for each species during normal shrimp trawling activity to allow bycatch related mortality rates to be estimated (NMFS, 1991). It is again important to note that North Carolina, with most of its shrimp fishery concentrated in the estuarine areas, cannot rely on estimates from the offshore fisheries based in other states in the southeastern region.

The appropriate departments in North Carolina, mandated to manage the state's fisheries and fishery habitats, must obtain these necessary data for those species impacted by the inshore and offshore fishing fleets, in the appropriate estuarine waters, especially Pamlico Sound, in order to make management decisions appropriate to the state's special fishing status.

There are many questions that need to be addressed by biologists and ecologists to aid fisheries managers in making decisions concerning the bycatch problem. These may include: (1) How are interspecies relationships affected when one species is reduced below optimal levels? For example, does the loss of juvenile fishes of one species (say a dominant competitor) through bycatch mortality result in compensatory increases in the standing stocks of other species, through reductions in competition for available resources? (2) By introducing bycatch mortality, does the shrimping industry actually boost production and population sizes of other fish or scavengers such as blue crabs? Wassenberg and Hill (1987) suggested that stocks of the commercially fished blue swimmer crab (*Portunus pelagicus*) in Moreton Bay, Australia were enhanced by the increased availability of food from discarded bycatch by the prawn trawling industry in the bay. (3) Are pelagic fish populations (such as bluefish, king and spanish mackerel) higher because adults have less competition for food, or conversely are they lower because the densities of prey species are reduced?

Table 2.3. List of potentially important species taken as bycatch during shrimp fishing. Abundant = species frequently caught in trawls; F.M.P. = species contained within a Fishery Management Plan; Valuable = species with important commercial and / or recreational value (from: NMFS Report, 1991).

Common Name	Scientific Name	Index
Atlantic Croaker	*Micropogonias undulatus*	abundant
longspine porgy	*Stenotomus caprinus*	abundant
sand/silver sea trout	*Cynoscion arenarius/nothus*	abundant
sea robins	*Prionotus sp.*	abundant
blue swimmer crabs	*Portunus sp.*	abundant
blue crabs	*Callinectes sapidus*	abundant
weakfish	*Cynoscion regalis*	abundant
inshore lizard fish	*Synodus foetens*	abundant
rock sea bass	*Cantropristus philadelphia*	abundant
southern kingfish	*Menticirrhus americanus*	abundant
harvestfish	*Peprilus paru*	abundant
Atlantic spadefish	*Chaetodipterus faber*	abundant
fringed flounder	*Etropus crossotus*	abundant
spot	*Leiostomus xanthurus*	abundant
Gulf butterfish	*Peprilus burti*	abundant
Atlantic cutlassfish	*Trichiurus lepturus*	abundant
hardhead catfish	*Arius felis*	abundant
Atlantic Bumper	*Chloroscombrus chrysurus*	abundant
whiting	*Menticirrhus sp.*	abundant
red snapper	*Lutjanus campechanus*	F.M.P.
vermillion snapper	*Rhomboplites aurorubens*	F.M.P.
lane snapper	*Lutganus synagris*	F.M.P.
king mackerel	*Scomberoumorus cavalla*	F.M.P.
Spanish mackerel	*Scomberomorus maculatus*	F.M.P.
cobia	*Rachycentron canadum*	F.M.P.
red drum	*Sciaenops ocellatus*	F.M.P.
sharks	*Chondrichthyes*	F.M.P.
sheepshead	*Archosargus probatocephalus*	valuable
bluefish	*Pomatomus saltatrix*	valuable
Summer flounder	*Paralichthys dentatus*	valuable
speckled seatrout	*Cynoscion nebulosus*	valuable
black drum	*Pogonias cromis*	valuable
southern flounder	*Paralichthys lethostigma*	valuable

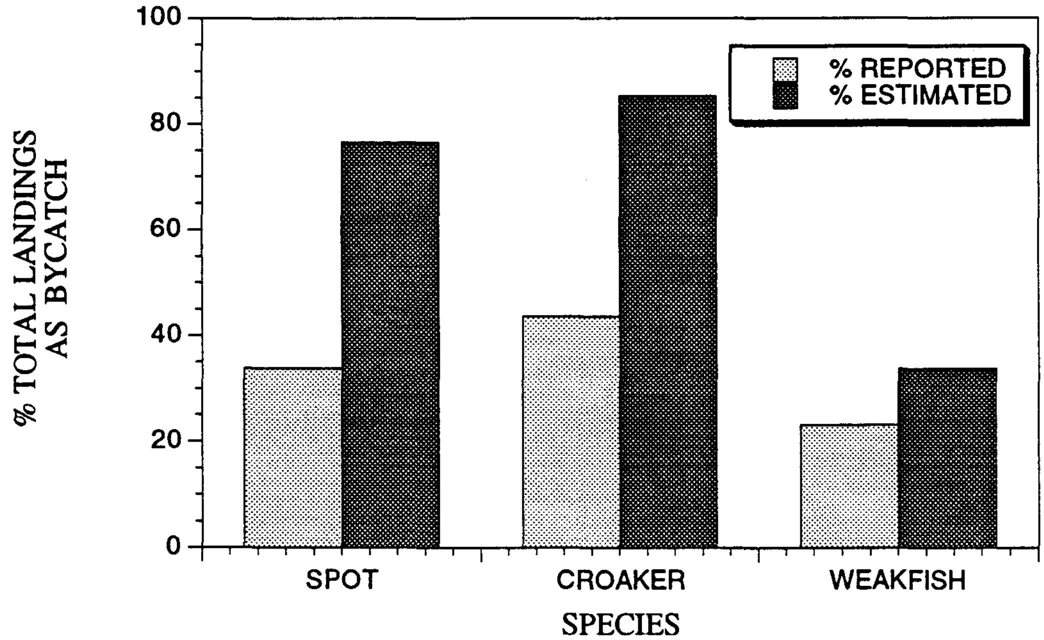

Figure 2.3. Comparison of reported bycatch landings (scrapfish) and estimated bycatch of spot, Atlantic Croaker, and weakfish as a proportion of the total average landings (weight) of each species during 1988-1990. Both sets of values are calculated values. Reported landings values are derived from a knowledge of the annual species composition of landed bycatch and the average total annual bycatch landings. The estimated bycatch is a combination of the reported bycatch landings and the estimated shrimp bycatch, based on a 1:4 ratio of fish bycatch to shrimp (modified from West, 1991).

Research into bycatch problems

Does Bycatch Survive?

There seems to be little doubt that the majority of the finfish caught as bycatch die as a result of being caught in trawl nets, and the subsequent period when they are exposed out of water during sorting and handling of the catch. Mortality of bycatch must also take into consideration those fish which enter the trawl net but ultimately manage to escape through the cod end. These fish may have suffered substantial abrasion from the net itself or from other objects in the net, such as debris (woody branches in estuaries), spiny crustaceans such as the blue crab, and rough skinned fishes (Main & Sangster, 1988).

Several studies have examined survivorship of different groups found occurring as bycatch in the Australian penaeid fishery. Wassenberg and Hill (1990) found that the fate of discarded bycatch is initially a function of whether the animals float or sink when they are dumped, and secondly by whether those that sink are alive or dead when they reach the substratum (see also Harris and Poiner, 1990). Animals that float when discarded have a high probability of being eaten by surface scavengers (e.g. piscivorous birds - Blaber and Wassenberg, 1989), whereas those that sink may be eaten by midwater or benthic scavengers.

Hill and Wassenberg (1990) found that one of the most important factors affecting the survival of discards was the length of time the animals spend out of the water, which was in turn determined by the time taken to sort the catch. They placed animals from trawls into seawater tanks to determine the proportion which survived after realistic periods of exposure on the deck, and found that nearly 90% of the fish tested died within 12 hours of being trawled. They did find that invertebrates such as sponges, echinoderms and bivalves were frequently alive and sank to the bottom when returned to the water, probably suffering little damage. Also, about 50% of the crustaceans survived. These results were fairly consistent in two geographically distant areas: Torres Strait in the north, and Moreton Bay on the east coast of Australia (see Wassenberg and Hill, 1990 for a comparison). The main difference in the results from these two studies was in the final fate of animals which reached the bottom. In Moreton Bay, the main scavenger was a portunid crab, *Portunus pelagicus*, whereas in Torres Strait, benthic fishes were utilizing the bycatch when it reached the bottom. They found no evidence that the prawns themselves benefitted from the extra food source. In an earlier study, Wassenberg and Hill (1989) had found that *Portunus pelagicus* was the scavenger which most rapidly and frequently arrived at the site of dumped bycatch, and suggested that the crab populations in Moreton Bay may be sustained at levels which are greater than if there were no prawn trawl industry.

Most of the other studies which have examined mortality of fishes caught in trawls have not been specifically related to shrimp trawling, but the results are relevant because many other directed fisheries utilize otter and beam trawls. Houghton et al. (1971), De Clerk and Hovart (1972) and van Beek et al. (1989) all examined the survival of fishes in otter and beam trawls fitted with different numbers of tickler chains, and also under different condition of fishing (trawling) speed and total catch in the cod end. The damage to these fishes included damage caused by tickler chains hitting and crushing the fish, being crushed and scraped within the cod end of the net, depressurization as the fish are brought are brought to the surface, and on deck there is damage during sorting. There is a distinct lack of information concerning the survivorship of species of finfish which are captured as bycatch in North Carolina, such as spot, Atlantic croaker and weakfish.

Hill and Wassenberg (1990) found that about 50% of crustaceans survived capture in trawls, while Stevens (1990) found that only 21% of king and Tanner crabs survived after being caught in trawls, with exposure time being an important factor in rates of mortality. The latter study involved exposing crabs to freezing sub-Arctic conditions, and may therefore help account for the differences in mortality among these two studies. Heat may play a similar role in reducing survivorship of blue crabs; crabs caught by crab trawling during summer in North Carolina showed a significantly higher mortality than crabs caught in any other season of the year (McKenna and Camp, 1992). Blue crab mortality is also related to the fishing gear used to capture them. North Carolina crabs held for 14 days after being caught in crab trawls showed a mortality level about 4 times greater than that of crabs caught in crab pots (36% vs. 8% mortality, respectively) (McKenna and Camp, 1992).

Some of the potential ecological effects of discarding bycatch have been resolved. Browder (1981) developed an energetic model for the Gulf of Mexico and in this work addressed several issues pertinent to the fate of discarded bycatch. Browder found that the rates of nitrogen regeneration from discards was inconsequential compared with other forms of organic matter and input due to animal excretion and river input, and was unlikely to serve any role in increasing the phytoplankton-based detritus which could be used as a food for shrimp. It was also evident from this study that the overall biomass of the discarded bycatch was unlikely to provide a significant increase in the overall availability of food for shrimp unless they were to strongly favor the discards as food, which seems unlikely (see also Hill and Wassenberg, 1990).

Research Into Bycatch Reduction Devices (BRDs) for the Shrimp Fishery

The need for a selective fishing gear to be incorporated in shrimp trawls in the United States was first discussed by Seidel (1975). A separator trawl that would efficiently reduce finfish bycatch mortality would be of enormous benefit to both the demersal fish industry, by providing greater resource abundance, and the shrimp fishery, by reducing trawl drag, fuel consumption, and time and labor costs for sorting the catch (Watson et al., 1986).

Selective shrimp trawls were developed in Belgium, Norway and Iceland in the 1960s. Further development of these trawls has continued in Canada, Norway and Great Britain, using panels of webbing placed in the mouth, throat, or along the wings of the trawl. The panels were designed to lead the fish toward openings through which they could escape, while allowing the shrimp to pass through large panel meshes into the cod end of the trawl. These separator designs were successful in fisheries where the difference in sizes of fish and shrimp is great. In the European crangonid and pandalid fisheries the shrimp are small relative to the size of the finfish bycatch and may represent up to 90% of the total catch (Watson and McVea, 1977). In contrast, shrimp caught in the southeastern Atlantic fishery are larger and may only make up 10% of the catch (that is, the fish to shrimp ratio is very high; see section Bycatch in the Southeastern Atlantic Region, above). Another major difficulty with these separator designs for the southeastern Atlantic shrimp fishery was the diversity of sizes and types of fish associated with the shrimp. The simple mesh panels became clogged with fish and other debris affecting separation and leading to unacceptable (greater than 10%) losses in shrimp production (Watson and McVea, 1977; Watson et al., 1986).

In response to the call for reducing mortality of endangered sea turtles in shrimps trawls in the southeastern Atlantic and Gulf of Mexico fisheries, the National Marine Fisheries Service (NMFS) introduced the Turtle Excluder Device (TED). The TED was designed to allow turtles to escape from the shrimp trawls before they were drowned. The standard TED is a flat oval or square-metal grate positioned just ahead of the cod end of the trawl. The basic idea is that the turtle enters the net, moves through the trawl until it encounters the grate, and then escapes through a flap (trap door) located either directly above or below the TED. Shrimp pass through the grate and go into the cod end of the trawl.

When the TED was being developed, SCUBA divers observed that fish and shrimp entering the trawl had marked differences in their behavior. Fish appeared to show escape reactions in the vicinity of the TED, as evidenced by the number of fish gilled there in a standard shrimp trawl. Modifications to the original TED led to the development of the current generation of Bycatch Reduction Devices (BRDs) or finfish separator devices (FSDs). These BRDs utilize the differences in the behavioral responses of the finfish and the shrimp, and the superior swimming ability of the fish to separate and exclude them from the catch in the cod end. When the original TEDs were observed to have a dual role in excluding both turtles and finfish, their name was changed to Trawling Efficiency Devices, but to avoid confusion we will continue to refer to them as BRDs. The equipment was considered to be an efficiency device because it could increase the catch of shrimp by removing the large debris which often clogs the cod end and requires the trawl to be pulled up and cleared. This enabled the trawl to be fished for longer periods of time. In addition, it could improve water flow through the trawl, thereby reducing drag and probably leading to fuel savings for the fishermen.

The following description of the TED-modified Bycatch Reduction Device is from Watson et al. (1986). A funnel of webbing in the BRD unit accelerates water flow entering the cod end (see Figure 2.4). The water accelerated by this funnel carries the shrimp, which are weak swimmers, past the TED deflector grid into the cod end. Finfish swimming in the trawl also travel through the funnel, which stimulates them to try and escape the trawl. As they pass through the funnel, fish either strike a finfish deflector or enter an area of reduced water flow to the side of the main flow coming out of the funnel. The fish are guided by webbing panels to exits on the side of the trawl. The shrimp do not have the swimming ability, or the behavioral responses, to reach the exits and are carried through to the cod end. Larger objects and/or organisms (such as sea turtles) cannot pass through the openings on the main deflector grid and are ejected through the trap door on the top of the TED. Even those fish that were carried past the main deflector grid into the cod end tend to swim forward along the bottom and sides of the cod end until they reached the walls of webbing at the front frame of the TED.

The effectiveness of these BRDs in separating finfish bycatch from the shrimp varies with individual species and appears to be related to the swimming ability of the fish and their individual behavioral responses. There are also differences in separation rates between night and day (Watson et al., 1986). Further trials and research at the Pascagoula NMFS labs, led to the development of a second, smaller deflector grid, placed behind the main deflector frame of the BRD. The smaller deflector grid acts as a mechanical stimulus and a generator of sound vibrations, which scare the fish out of the escape holes, resulting in much improved nocturnal separation rates. In early trials, Watson et al. (1986) report separation rates of 78% during the day and 48% in the night.

Gibbs (1991) reported on trials of a variety of arrays of lights and noise makers aimed at attempting to either scare or lure fish away from the trawls. These devices will be used in conjunction with the excluder equipment and may further reduce the biomass of bycatch caught in trawls.

Do BRDs Work?

In Maine, shrimp fishermen were catching large numbers of juvenile flatfish and codfish as

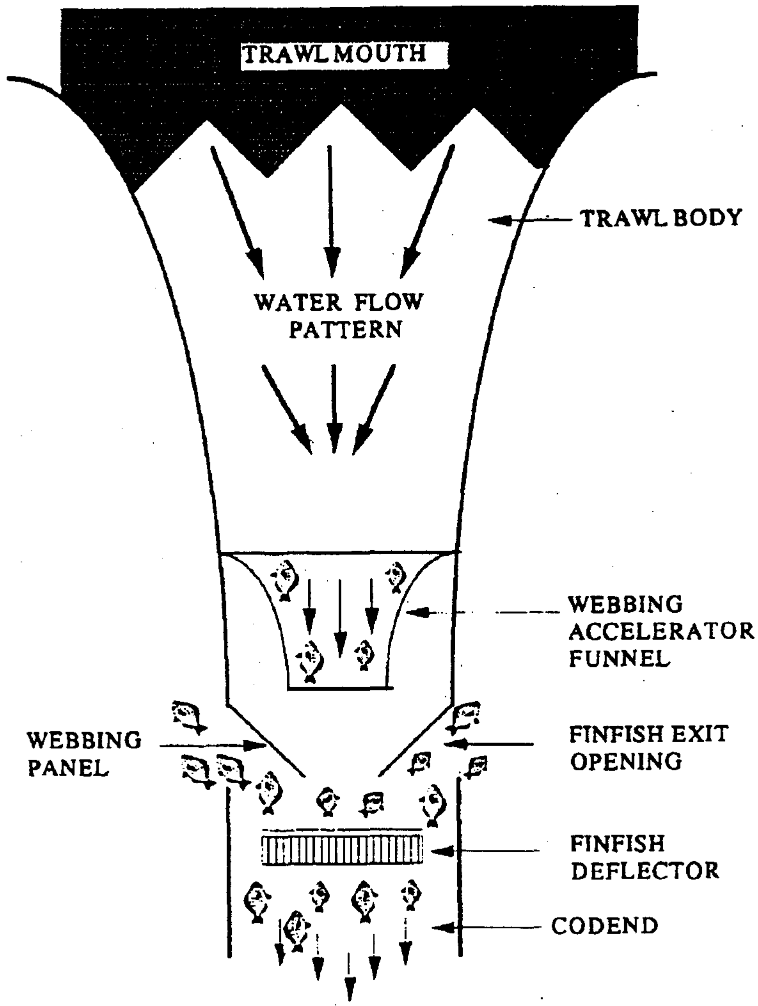

Figure 2.4. TED finfish separation techniques. The basic design shown here has been incorporated and modified to provide a number of different Bycatch Reduction Devices (BRDs) (from Watson et al., 1986).

bycatch, so they were interested in a trawl which would save the shrimp but also allow them to keep any large codfish which were often more valuable than the targeted shrimp. The trawl had to release the juvenile codfish and flatfish and all the trash fish (Averill, 1986). The Fisheries Technology Service (a division of the Department of Marine Resources in Maine) eventually developed a net incorporating a separator panel which retained fish that were of marketable size. The fishermen are not losing a large proportion of their catch; they have the additional benefit of being able to sell the large cod they catch, and the stocks of small fishes are allowed to grow and be caught at a later date.

The NMFS lab in Pascagoula has been testing numerous BRDs to determine how effective they are in reducing the bycatch problem (Workman, 1990). The incorporation of the TED designs in Bycatch Reduction Devices is a necessity because by law, any finfish excluder device must include a federally approved Turtle Excluder Device, unless the trawl is retrieved by a non-mechanical method. Workman (1990) gives a detailed breakdown of the results of the testing done to date on a number of these devices, indicating how far the research at the Pascagoula laboratories has advanced. They are achieving high reduction rates of up to 67.7% (combined day and night testing) for some devices, but there was considerable variability in the rates of reduction among different devices (down to a low of 9% reduction). Unfortunately, the device that gave the highest bycatch reduction was the one device that also produced statistically significant shrimp loss compared to control trawls (Workman, 1990). Notably, the other devices did not reduce the shrimp catch by a significant amount, an absolute requirement if the BRDs are to gain widespread acceptance by the fishing industry.

Reduction rates for two commercially important demersal fish species, Atlantic croaker and spot (species important as bycatch in North Carolina), were substantial with some of the devices being tested. Reductions from 38.9 - 65.9% for Atlantic croaker and 50.2 - 92.4% for spot have been achieved. They have also obtained reduction of 56.9% - 98.9% for king mackerel (*Scomberomorus cavalla*) (Workman, 1990) although these same devices were not as effective for Spanish mackerel or red snapper. Seidel (1991a) however, reported that a modified Florida Fish excluder did obtain up to a 50% reduction in catch rates for red snapper indicating that several different devices may need to be carried by shrimping boats, and changed depending on the abundance of different species of bycatch.

Testing of TEDs and BRDs under identical, and therefore comparable, conditions in a single area serves the purpose of allowing comparisons to be made between the different devices but it is important to note that conclusions cannot and should not be extrapolated from such tests to all possible conditions. A TED/BRD that works in one area and under one set of circumstances may not necessarily work elsewhere (Rulifson et al., 1992).

Many of these BRDs and TEDs are being developed and tested in the Gulf of Mexico and they may not be as useful in the estuaries and sounds of North Carolina which are more turbid than the offshore coastal waters. In waters with abundant debris, it should be expected that the TED/BRD device will collect this debris and may have its performance altered. As plant (seagrasses) debris collects on the diagonal bars, the shrimp that are supposed to pass through the screen unhindered may be deflected towards the exit doors. The shrimp will likely remain there due to their poor swimming abilities, and will be ejected whenever a large object activates the door. As a result, the fishing fleet may incur significant reductions in shrimp catch and an attendant loss of money.

Preliminary testing of four devices in the Pamlico Sound shrimp fishery (Pearce et al., 1989) showed that the effectiveness of the BRDs varied with the type of fish, and the placement of the device within the trawl. Three of the gears showed a significant overall catch reduction when compared with a control trawl: (1) the Georgia TED; (2) the Florida Fish excluder; and (3) the Parrish TED (Rulifson et al., 1992). The first two gears did not show a significant loss of shrimp. A fourth gear type, the Scottish Separator Trawl, lost a significant amount of shrimp. Descriptions of the gears can be found in Pearce et al. (1989) and Workman (1990).

The North Carolina Division of Marine Fisheries has several ongoing research programs investigating ways of reducing the bycatch in the shrimp fishery and assessing the success of various bycatch reduction devices. North Carolina is to date the **only** state requiring BRDs in all shrimp trawls. The main types of BRD being tested are the Florida Fish Excluders (FFE), and a TED/FED combination consisting of paired accelerator panels within a modified Super Shooter TED. The two most effective FFEs were a pyramidal array of metal tubing with a 9" by 9" diamond-shaped opening (Figure 2.5), and a rectangular ("tunnel) array of metal tubing with a 6.5" by 7.5" opening (Figure 2.6). These designs were tested during the spring and summer of 1991. The FFEs reduced total finfish bycatch by 49-63% with a 1-4% loss of shrimp relative to control nets lacking any bycatch reduction devices (McKenna and Monaghan, 1993). The effectiveness of the gear in reducing bycatch varied according to gear design, size and shape of the escapement opening, the number of devices installed, and the location of the devices relative to the tailbag. Effectiveness of the FEE diminished with increasing distance from the beginning of the tailbag. This distance effect could be overcome to some extent by increasing the size of the escapement opening (McKenna and Monaghan, 1993). It is apparent that an individual would have to do some initial experimentation with the location of the FEEs in the net in order to maximize the performance of a particular FEE design.

FEE performance is also affected by the nature of the bycatch species. Large numbers of captured jellyfish resulted in a greater retention of fish bycatch and a greater loss of shrimp from the net (McKenna and Monaghan, 1993).

The FEEs performed slightly better than the TED/FED, which reduced overall bycatch by 39% with a 7% reduction in shrimp catch. There were also some apparent species-specific differences in the bycatch reduction capabilities of the FEEs and the TED/FED. Weakfish and southern flounder bycatch was substantially lower in the FEEs than in the TED/FED. However, both the FEEs and the TED/FED were similarly effective in reducing spot and Atlantic croaker bycatch. These two species accounted for a larger percentage of the total fish bycatch than did any other pair of species in all of the experimental trials (McKenna and Monaghan, 1993).

The results of these studies are extremely promising for future reduction of the bycatch from the shrimp industry in North Carolina. Given the rapid increase in available technology, and the fact that groups such as the NMFS Pascagoula laboratories are working closely with the industry, it seems likely that a device will soon be available, and this device will already have run the gauntlet of industry approval.

The most important aspect of any gear development program--after the development of a specific gear--is adoption of this gear by the people who will be required to use it. Hence the task the North Carolina Division of Marine Fisheries faces is one of obtaining widespread approval of the equipment by the local shrimp fishermen. In order to accomplish this task, information on successful gear development must be disseminated to the fishermen. In addition, adoption of the developments by the industry should be as affordable as possible. Otherwise it is unlikely that the fishing industry would be willing to adopt the new equipment and/or use it correctly. Under these circumstances, active policing of the new practices would be costly and probably unsuccessful. If there is a successful education program for the use of TEDs--which are already mandated--the

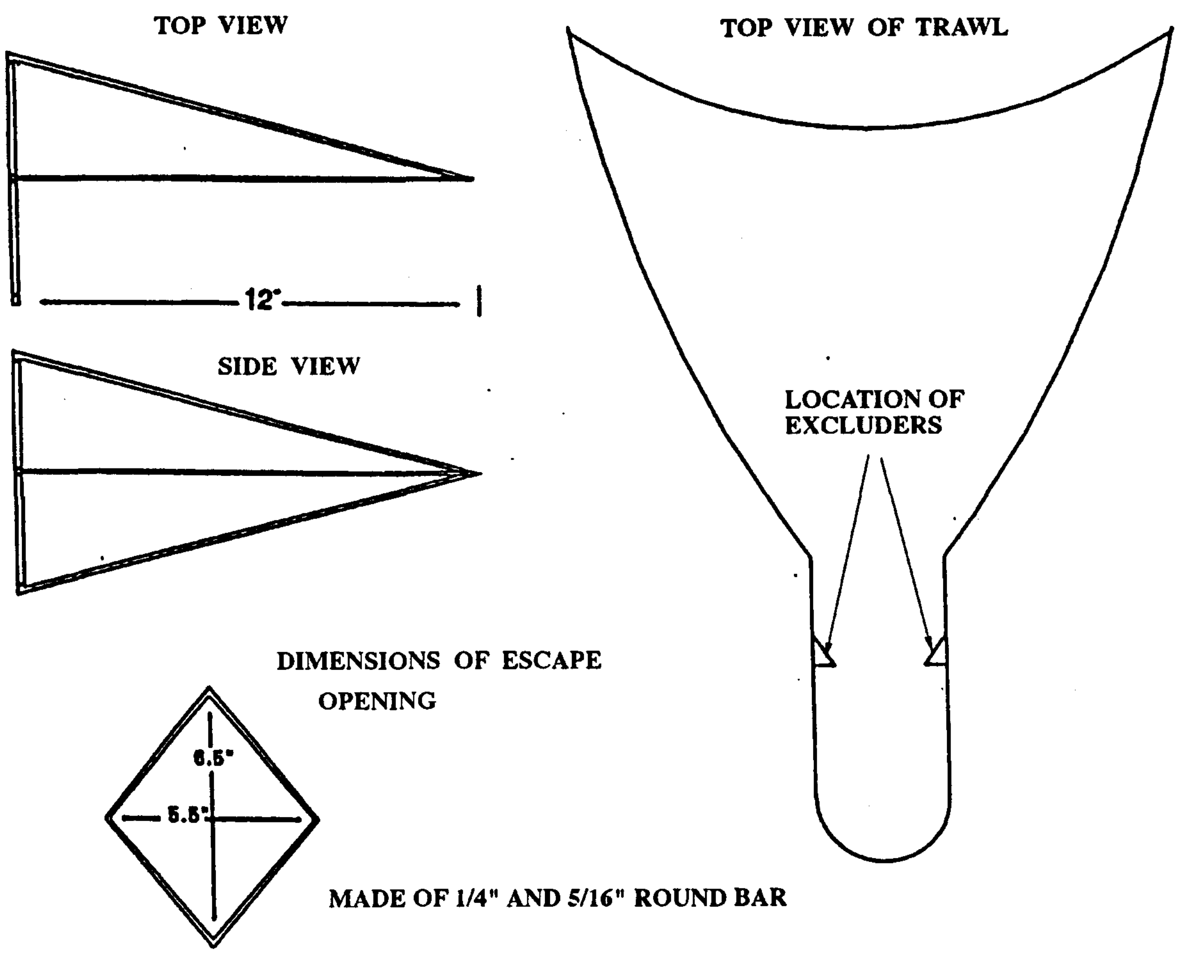

Figure 2.5. Design and placement of a Florida Fish Excluder (FFE 6) tested in Pamlico Sound, North Carolina, during June 1991 (modified from McKenna and Monaghan, 1993),

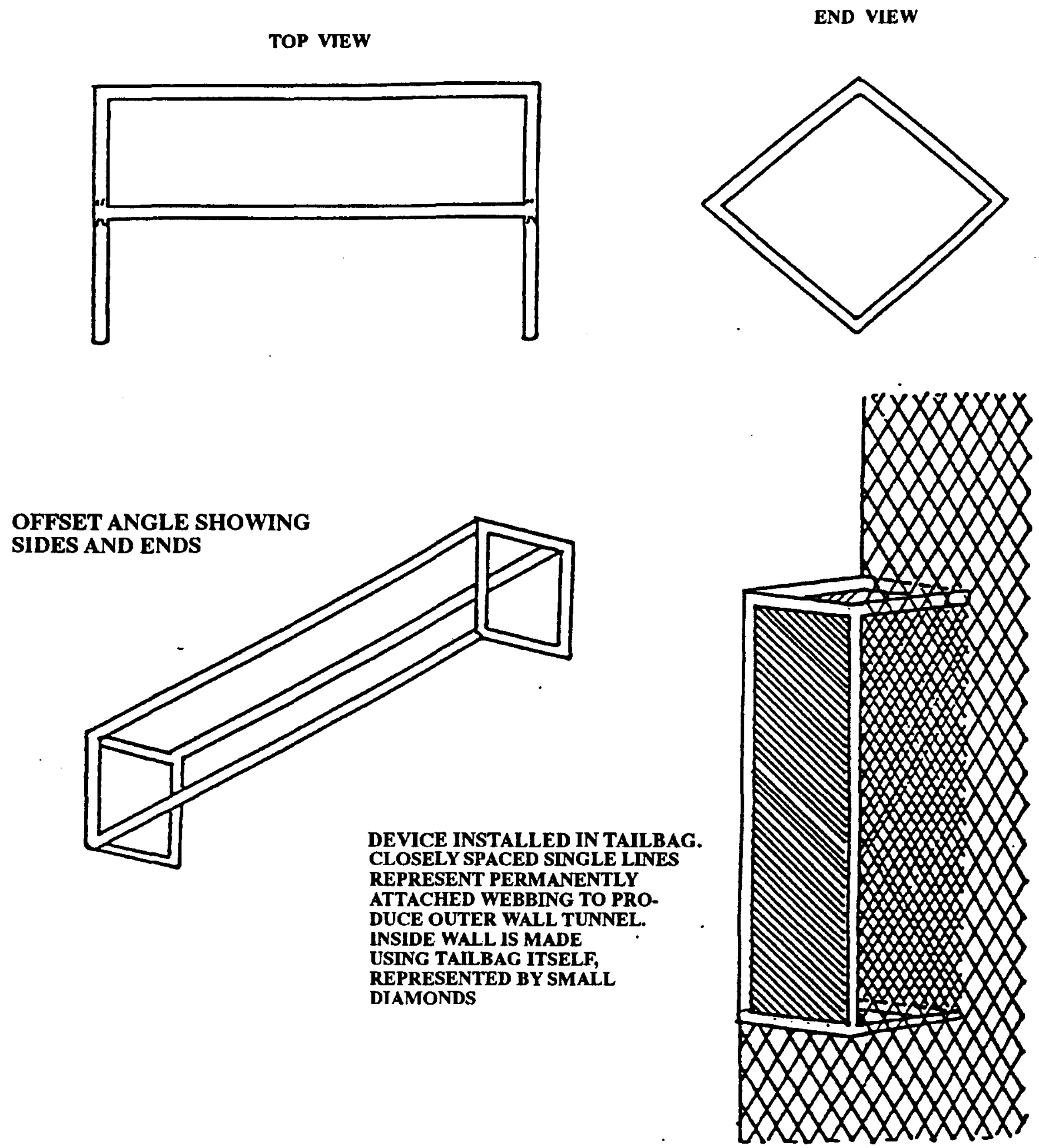

Figure 2.6. Design of a Florida Fish Excluder (FFE 19) tested in Pamlico Sound, North Carolina, during July and October 1991 (modified from McKenna and Monaghan, 1993).

versus similarly sized diamond mesh, and weakfish length increased with increasing size of the square mesh (McKenna and Monaghan, 1993). As a result of these findings, NCDMF has required the codend mesh of ocean flynets to be changed from 51 mm to either 76 mm (3") square mesh, or 89 mm (3.5") diamond shaped mesh, in order to reduce the bycatch of weakfish smaller than 254 mm (10").

Similar work by NCDMF has shown that increasing mesh size reduces finfish bycatch of crab trawling. Approximately 50% of the undersized southern flounder, and virtually all of the remaining finfish species, were eliminated from the catch when the mesh size of the tailbag was increased from 3" to 4". However, increasing the mesh size of the tailbag also resulted in a 3-4 fold reduction in the catch of legal sized blue crabs (McKenna and Camp, 1992). Restrictions on crab trawling mesh size have not been changed.

Meyer and Merriner (1976) suggested that panels of different sized mesh in pound nets may help to reduce capture of undersized fish in that industry. The differences in the behavior between sciaenids (spot, croaker and weakfish) and clupeids (Atlantic menhaden and Atlantic thread herring) could be exploited by having a larger mesh panel on the bottom of the pound net, where the sciaenids congregate after capture, allowing them to escape. The clupeids remain near the surface and would be concentrated in the pound-head by the smaller mesh on the sides of the pound net. NCDMF has since implemented the use of larger mesh escape panels in pound nets in selected areas (NCDMF, 1993).

Alternative types of trawl gear also show some promise in reducing bycatch. The skimmer trawl was developed in Louisiana for commercial shrimp fishing (Murray et al., 1992) in flat-bottomed shallow water habitats (Coale et al., 1993). The skimmer trawl nets are positioned along each side of the boat, rather than behind the boat (cf. Figure 1.6, Major North Carolina Fisheries and Corresponding Gear Types; Chapter 1). This location of the nets permits easy and frequent retrieval of the codends without having to cease fishing activities. The codends are typically emptied at 30 minute intervals; consequently, skimmer trawls are not required to be equipped with a TED (cf. Coale et al., 1993).

A comparison of skimmer trawl and otter trawl performance near Harkers Island, North Carolina, demonstrated gear-specific differences in shrimp species capture, and in the amount and composition of the bycatch. The skimmer trawl was more effective in catching white shrimp, but less effective in catching brown shrimp (Coale et al., 1993). The greater catch of the pelagic white shrimp may reflect the capability of the skimmer trawl to fish a larger proportion of the water column than the otter trawl. Conversely, a greater degree of sediment penetration and disturbance of the otter trawl may make it more effective in capturing brown shrimp. The skimmer trawl caught approximately 25% less bycatch (weight) per unit time than did the otter trawl. Shrimp, spot and crabs (*Callinectes spp.*) constituted about 45% of the total bycatch biomass for both types of gear, but skimmer trawl caught less undersized Atlantic croaker and southern flounder.

Management Alternatives

The two extremes for management of the bycatch problem in North Carolina are simply ignoring the issue completely, or banning commercial fishing altogether (Murray et al., 1992). Less extreme options are available, however, including the traditional alternatives of seasonal and/or area closures. For example, in South Carolina Keiser (1976) showed that the fish-to-shrimp ratio was greater in May than the subsequent three months after May. These data suggest that closure of areas during May could reduce the overall take of finfish bycatch while at the same time maintain profits because the average shrimp size and weight will increase until they are caught later in June (Murray et al., 1992).

Similar data are needed for the inshore waters of North Carolina, especially Pamlico Sound, to determine whether there is a time period when closures may help to reduce the mortality of juvenile sciaenids caught as bycatch. A nighttime restriction on crab trawling in certain rivers during the winter was recently enacted by the North Carolina Marine Fisheries Commission (MFC) to reduce flounder bycatch. The MFC also lengthened the weekend prohibition on inside trawling to occur between one hour after sunset on Friday until one hour before sunset on Sunday.

In North Carolina, trawling is currently prohibited in approximately 50% of the 2.2 million acres of inshore waters. Prohibited areas include virtually all of Albemarle Sound, the seagrass meadows bordering the western shores of the Outer Banks, restricted military training sites, primary and secondary nursery areas, and special secondary nursery areas during part of the year, due to their supplemental role as nursery areas for juveniles of commercially important species (personal communication - NC Division of Marine Fisheries). Area closures should be further investigated to determine whether some sections of the inshore sounds have greater incidences of bycatch. Murray et al. (1992) suggested that more areas should be designated as nursery areas, and the closure period for special secondary nursery areas should be extended. (Special secondary nursery areas are currently closed from 15 May - 15 August; these areas may be opened by NCDMF proclamation during other times of the year.) The result of this action will be that the shrimp will ultimately be caught at a later date (when they are larger), as they move out into the ocean.

Although the overall biomass of shrimp-catch for the state may not change, and may even increase (the shrimp are larger by the time they are caught), this suggestion ignores the potential impacts on fishermen who operate in a localized region (e.g. sections of the Neuse River and southern Pamlico Sound). They would be required to travel increased distances, with greater costs for fuel and maintenance, and would be competing with other fishermen who are local to the area. Such changes to the Fisheries Regulations would need to be carefully assessed before they were implemented. An examination of the biological and ecological ramifications of the bycatch question are not the only considerations for the state, especially as it faces potentially reduced revenues as a consequence of the development of a new fiscal policy.

The continued advances in the development of the TED/BRD equipment may prove the most acceptable answer to the question. If these devices work, without a significant decline in the catch of shrimp, then the fishermen are likely to endorse their use because of the improved quality of the shrimp, reduced fuel costs, and reduced labor involved in sorting the catch. Further seasonal and/or areal closures are likely to have striking impacts on some sections of the inshore fishing fleet.

The Utilization of Bycatch

Some attention has been paid to the possibility of making effective use of the finfish caught as bycatch (cf. Juhl and Drummond, 1976). However, North Carolina prohibits marketing bycatch for use as bait, or for any other manner of sale or commercial use (General Statute 113-185). Furthermore, promoting economic and technological development of bycatch utilization would run the risk of directly or indirectly counteracting the diverse efforts to reduce bycatch.

Management Recommendations

(1) It is important to continue studies on the extent of the bycatch problem in the inshore

estuarine waters of North Carolina sounds and inlets, such as that currently underway by NC Sea Grant and NCDMF personnel. Extrapolation of the results taken from offshore fisheries in South Carolina, Georgia and Florida are unlikely to provide an accurate picture of the bycatch problem in North Carolina. Such studies should include more detailed information on the spatial and temporal distribution of species likely to be affected, especially by the shrimp fishery. Age-specific estimates of bycatch for important species are required to allow bycatch related mortality rates to be estimated.

(2) More information is required about the interspecific relationships among the different species inhabiting the estuaries and inlets of North Carolina. It is essential to understand how losses of one species as a result of bycatch-related mortality will affect the abundance and distribution of other species. For instance, will there be compensatory increases in the abundance of other species due to increased food as a top competitor is removed? Will large pelagic predatory fishes increase in abundance as a result of less competition for food, or will they decrease in abundance due to a reduction in the availability of prey species?

(3) Another priority for future research is to continue studies of the effectiveness of bycatch reduction devices (BRDs) in North Carolina's inshore estuaries and inlets. Recent NCDMF work on BRDs have shown that these devices can consistently reduce bycatch by 50-60%. These studies could be extended to include evaluation and refinement of BRD designs using remote cameras.

(4) The role of gill nets in finfish bycatch, and their impact on marine birds and mammals, needs to be assessed in Pamlico Sound. Large numbers of dolphins and porpoises frequent these waters and may be impacted by the many gill nets used in these estuarine waters.

(5) Active education and cooperative programs such as the NMFS Regional Observer Program, and NCDMF collaborative work with local fishermen on BRDs, must be continued in order to gain the widespread approval of the use of BRDs (including turtle excluder devices) throughout the fishing industry. Research into better designs for BRD's will help to keep the cost of purchase down for the fishermen further making them acceptable to the industry.

(6) If areal and seasonal closures are to be pursued as a management option, then it is imperative that the socioeconomic impacts on individual fishing communities and groups be examined. Designation of further primary and secondary nursery areas could force many shrimp fishermen to absorb increased costs for fuel and maintenance to enable them to travel from their traditional fishing areas to the newly designated fishing areas. This may in turn throw them into competition with the offshore fleet which generally utilizes larger boats and trawls. The possibility of excluding these larger vessels from estuarine fishing and limiting them to offshore habitats should be considered. An examination of the biological and ecological ramifications of the bycatch question are not the only considerations for the state, especially as it struggles to redefine fiscal policies.

Selected Bibliography

Anderson, E. D.,. J. M. Mason, A. M. T. Lange and C. J. Byrne. 1983. Cod end mesh selectivity in the Long Island spring trawl fishery for summer flounder and associated species. National Marine Fisheries Service. Northeast Fisheries Center, Woods Hole Laboratory, Woods, Hole Laboratory Reference Document No. 83-33.

Averill, P. 1986. DMR Separator Trawl. pp. 15-16. IN: Goudey, C. A-. Paterson, C. E., Ree. T. J. eds. Gear Selectivity as a Management Tool. Massachusetts Institute of Technology, October 14-15, 1986. Cambridge, MA. Center for Fisheries Engineering Research, MIT Sea Grant Program

Baxter, K. N. 1973. Shrimp- discarding bv the commercial fishery in the western Gulf of Mexico. Marine Fisheries Review 35(9): 26.

Blaber, S. J. M. and T. J. Wassenberg, 1989. The feeding ecology of the piscivorous birds *Phalacrocorax varius*, *P. metanoteucos* and *Stema bergir* in Moreton Bay, Australia: diet and dependence on trawler discards. Marine Biology 101: 1- 10.

Briggs, R- P. 1992. An assessment of nets with a square mesh panel as a whiting conservation tool in the Irish Sea *Nephrops* fishery. Fisheries Research 13(2): 133-152.

Browder, J. 1981. Use of an energy flow model to evaluate alternative harvesting strategies in a multispecies fisheries. IN: International Symposium on Energy and Ecological Modelling. Louisville, Kentucky, April 20-23, 1981. International Society for Ecological Modelling.

Caddy, J. F. 1982. Management of shrimp fisheries. pp. 120-123 IN: Fish bycatch ... bonus from the sea. Georgetown, Guyana, 27-30 October, 1981. Ottawa. IDRC (IDRC - 1981).

California Department of Fish and Game. 1987. Impacts of gill and trammel net fisheries in central California. pp. 1-24 In: Report to the Legislature and Legislative Analyst. State of California, The Resources Agency, Department of Fish and Game.

Carr, H. A. 1988. Long term assessment of a derelict gillnet found in the Gulf of Maine. IN: pp. 984-986 Oceans '88 Conference Proceedings: A Partnership of Marine Interests. Baltimore, Maryland, USA, October 31 - November 2., 1988.

Carr, H. A, and R. A. Cooper. 1987. Manned submersible and ROV assessment of ghost gillnets in the Gulf of Maine. pp. 622-624 IN: Oceans '87 Conference Proceedings: The Ocean - An International Workplace. Halifax, Nova Scotia, Canada, September 28 October, 1987.

Casey J. F., and A. E. Wesche. 1981. Effect of derelict crab pots on future commercial Tidewater harvest investigated by tidewater administration. Fisheries News. 14: 1-2.

Chittenden Jr., M. E. 1989. Sources of variation in Chesapeake Bay pound-net and haul catch compositions. North American Journal Fisheries Management. 9: 367-371.

Clark, J., and R. Condrey. 1991. Enhancing the benefits derived from shrimp management in the Gulf of Mexico by optimizing shrimp management in Louisiana. In: Fourth Annual MARFIN Conference (abstract). San Antonio, Texas, September 10 - I 1, 1991.

Coale, J., R. Rulifson, J. Murray, and R. Hines. 1994. Comparisons of shrimp catch and bycatch between a skimmer trawl and an otter trawl in the North Carolina shrimp fishery. North American Journal of Fisheries Management 14: 751-768.

Cooper, C. 1991. Shrimpers search for inexpensive and simple fish excluder. National Fisherman, January Issue:

Cooper, C. G., and W. M. Hickey. 1987. Selectivity experiments with square mesh cod on haddock and cod. pp. 608-613 In: Oceans'87 Conference Proceedings: The Ocean--An International Workplace. Halifax, Nova Scotia, Canada, September 28 October 1, 1987.

Crean, K. 1982. Handling and storage of shrimp bycatch at sea. pp. 65-67 In: Fish bycatch ...bonus from the sea. Georgetown, Guyana, 27-30 October, 1981. Ottawa. IDRC (IDRC - 1981).

De Clerck, R., and P. Hovart. 1972. On the effects of tickler chains. In: International Council for the Exploration of the Sea. Gear and Behaviour Committee B. 15 pp.

Fee. R. 1991. Shrimpers take aim at bycatch. National Fisherman, November,Issue:

Ferguson, R- G., and H. A. Regier. 1963. Selectivity of four trawl cod ends towards smelt. Transactions of the American Fisheries Society 92: 125-131.

Garcia, S., and L Le Reste. Life cycles, dynamics, exploitation and management of coastal penaeid shrimp stocks. pp. 1-215 In: FAO Fisheries Technical Paper 203.

Gibbs, L. 1991. Feasibility study: finfish excluding gear in shrimp trawls in the western Gulf of Mexico. In: Fourth Annual MARFIN Conference (abstract). San Antonio, Texas, September 10 - 111, 1991.

Gitschlag, G. R., M. L. Renaud, and E. F. Klima. 1991. Evaluation of the impacts of bycatch reduction devices (BRDS) on finish and shrimp catch rates in the Gulf of Mexico. In: Fourth Annual MARFIN Conference (abstract). San Antonio, Texas, September 10 - 11, 1991.

Gray, C. A., V. C. McDonall and D. D. Reid. 1990. Bycatch from prawn trawling in the Hawkesbury River, New South Wales: Species composition, distribution and abundance. Australian Journal of Marine and Freshwater Research 41: 13-26.

Gutherz, E. J., G. M. Russell, A. F. Serra and B. A. Rohr. 1975. Synopsis of the northern Gulf of Mexico industrial and foodfish industries. Marine Fisheries Review 37: 1-6.

Harris, A. N., and 1. R. Poiner. 1990. Bycatch of the prawn fishery of Torres Strait, Composition and partitioning of the discards into components that float or sink. Australian Journal of Marine and Freshwater Research 41: 37-52.

Hennemuth, R. C., and F. E. Lux 1970. The effects of large meshes in the yellowtail flounder fishery. International Commission for the Northwest Atlantic Fisheries. Redbook, Part 111. pp. 111- 115.

Higgins, E., and J. C. Pearson. 1928. Examination of the summer fisheries of Pamlico and Core Sounds, N.C., with special reference to the destruction of undersized fish and the protection of the gray trout, *Cynoscion regalis* (Bloch & Schneider). pp. 29-65 IN: Report to U.S. Commission of Fisheries for 1927.

Hill, B. J., and T. J. Wassenberg. 1990. Fate of discards from prawn trawlers in Torres Strait. Australian Journal of Marine and Freshwater Research 41: 53-64.

Hoar, P., J. Hoey, J. Nance, and C. Nelson. 1992. A research plan addressing finfish bycatch in the Gulf of Mexico and South Atlantic shrimp Fisheries. Gulf and South Atlantic Fisheries Development Foundation, Inc. 4 pp.

Houghton, R. G., T. Williams, and R. W. Blacker. 1971. Some effects of double beam trawling. pp. 1- 18 In: International Council for the Exploration of the Sea. Gear and Behaviour Committee B: 5.

Howell, W. H., and R. Langan. 1987. Commercial trawler discards of four flounder species in the Gulf of Maine. North American Journal of Fisheries Management 7: 6-17.

Hudson, A. V., and R. W. Furness. 1988. Utilization of discarded fish by scavenging seabirds behind whitefish trawlers in Shetland. Journal of the Zoological Society of London 215: 151-166.

Jean, Y. 1963. Discards of fish at sea by northern New Brunswick draggers. Journal of the Fisheries Research Board of Canada 20: 497-524.

Jensen, A. C., and R. C. Hennemuth. 1966. Size selection and retainment of silver and red hake in nylon cod ends of trawl nets. ICNAF Research Bulletin Number 3: 86-101.

Juhl. R. 1974. Economics of the Gulf of Mexico industrial and food fish trawlers. Marine Fisheries Review 36: 39-42.

Juhl. R., and S. B. Drummond. 1976. Shrimp bycatch investigation in the United States of America; Status Report. pp. 213-220 IN: Stewart, H. B. Jr. ed. Cooperative Investigations of the Caribbean and Adjacent Regions - II Symposium on Progress in Marine Research in the Caribbean and Adjacent Regions. Caracas, Venezuela, 12 - 16 July 1976. Papers on fisheries, aquaculture and marine biology. FAO Fisheries Report No. 200, FIR / R200.

Keiser, R. K. 1976. Species composition,, magnitude and utilization of the incidental catch of the South Carolina shrimp fishery. Marine Resources Research Institute, South Carolina Wildlife and Marine Resources Department Charleston, South Carolina. Technical Report Number 16.

Keiser. R. K. 1977. The incidental catch from commercial shrimp trawlers of the South Atlantic States. Marine Resources Research Institute, South Carolina Wildlife and Marine Resources Department. Charleston. South Carolina. Technical Report Number 26.

Knowlton, C. J. 1972. Fishes taken during commercial shrimp fishing in Georgia's close inshore ocean waters. Georgia Game and Fish Commission Coastal Fisheries Office. Georgia.

Kulbicki, M. and L. Wantiez. 1990. Comparison between fish bycatch from shrimp trawl net and visual censuses in SL Vincent Bay, New Caledonia. Fishery Bull. U.S. 88: 667-675.

Main, J., and G. 1. Sangster. 1986. Are separator trawls effective? Scottish Fisheries Bulletin 49: 3-6.

Main, J., and G. 1. Sangster. 1988. Scale damage and survival of young gadoid fish escaping from the cod-end of a demersal trawl. In: Proceedings of a workshop on "Trawl Net Selectivity and the Survival of Fish escaping from cod-ends." University of Rhode Island Graduate School of Oceanography, May 16-17, 1988. Narragansett, Rhode Island. National Sea Grant Depository Publication #RIUW-88-002 pp. 17-33.

Margetts, A. R. 1963. Escapes of fish through the component parts of trawls. ICNAF Special Publication No. 5: 158-165.

McCracken, F. D. 1963. Selection by codend meshes and hooks on cod, haddock, flatfish and redfish. ICNAF Special Publication No. 5: 131-155.

McKenna, S., and J. Camp. 1992. An examination of the blue crab fisher in the Pamlico River estuary. Albemarle-Pamlico Estuarine Study, Raleigh, N.C., U. S. Environmental Protection Agency Report No. 92-08 92 pp.

McKenna, S., and J. Monaghan, Jr. 1993. Gear development to reduce bycatch in the North Carolina trawl fisheries. Completion Report for Cooperative Agreement Number NA90AA-H-SKO52 (Gulf and South Atlantic Fisheries Development Foundation). 59 pp.

Meyer, H. L., and J. V. Meniner. 1976. Retention and escapement characteristics of pound nets as a function of pound-head mesh size. Transactions of the American Fisheries Society 105: 370-379.

Miller, J. M., L. J. Pietrafesa and N. P. Smith. 1990. Principles of hydraulic management of coastal lagoons for aquaculture and fisheries. FAO Fisheries Biology Technical Paper, 314.

Murray, J. D., J. J. Bahen, and R. A. Rulifson. 1992. Management considerations for bycatch in the North Carolina and southeast shrimp fishery. Fisheries 17: 21-26.

National Marine Fisheries Service (NMFS). 1991. Shrimp Trawl Bycatch Research Requirements. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, and National Marine Fisheries Service. pp. 1-66.

Nichols, S., A. Shah, G. J. Pellegrin Jr., and K Mullin. 1990. Updated estimates of shrimp fleet bycatch in the offshore waters of the U.S. Gulf of Mexico, 1972 - 1989. NMFS, Pascagoula. pp. 1-22.

North Carolina Division of Marine Fisheries. 1993. Description of North Carolina's coastal fishery resources, 1972-1991. North Carolina Department of Environment, Health, and Natural Resources, Division of Marine Fisheries, Morehead City, N.C.213 pp.

Pearce, K. B., D. W. Moye, and S. K Strasser. 1989. Evaluation of trawl excluder devices in the Pamlico Sound shrimp fishery. Albemarle-Pamlico Estuarine Study, Raleigh, N.C. Project No. 88-07.

Perra, P. 1992. Bycatch reduction devices as a conservation measure. Fisheries 17: 28-29.

Robertson, J. H. B. 1988. Square and diamond mesh in trawl and seine net cod end selectivity. pp. 7-15 IN:Proceedings of a workshop on "Trawl Net Selectivity and the Survival of Fish escaping from cod-ends" University of Rhode Island Graduate School of Oceanography, May 16-17, 1988 Narragansett, Rhode Island. National Sea Grant Depository Publication #RIU-W-88-002.

Robertson, J. H. B., and P. A. M. Stewart .1988. A comparison of size selection of haddock and whiting by square and diamond mesh cod ends. Journal du Conseil International Exploration de Mere 44:148-161.

Robin, J. P. 1992. The brown shrimp fishery of the Loire estuary - production and bycatch of juvenile fish. Fisheries Research 13: 153-172.

Ross, J. L 1990. Winter Trawl Fishery. In: North Carolina Division of Marine Fisheries. Assessment of North Carolina Commercial Finfisheries, 1988-1989 Fishing Season. NC Department of Natural Resources and Community Development Division of Marine Fisheries Annual Report, Proj. 2-IJ-16-1.

Rothschild, B. and J. A. Gulland. 1982. Interim report on the workshop on the scientific basis for the management of penaeid shrimp, Key West, Florida, November 1981. pp. 1-66 IN: National Oceanographic and Atmospheric Administration Technical Memorandum NMFS /SEFC 98.

Rulifson, R. A., and J. E. Cooper. 1986. A method to determine mesh-size selectivity in commercial menhaden purse seines. North American Journal of Fisheries Management 6: 359-366.

Rulifson, R. A., J. D. Murray, and J. J. Bahen. 1992. Finfish catch reduction in South Atlantic shrimp trawls using three designs of bycatch reduction devices. Fisheries 17: 9-20.

Saila, S. B. 1983. Importance of discards in commercial fisheries. FAO Fisheries Circular No. 765. pp. 1-62.

Seidel, W. R. 1975. A shrimp separator trawl for southwest fisheries. Proceedings of the Gulf and Caribbean Fisheries Institute 27: 66-76.

Seidel, W. R. 1991a. Shrimp trawl bycatch reduction. In: Fourth Annual MARFIN Conference (abstract). San Antonio, Texas, September 10 - 11, 1991.

Seidel, W. R. 1991b. TED technology transfer. In: Fourth Annual MARFIN Conference (abstract). San Antonio, Texas, September 10 - 11, 1991.

Sheridan P. F., J. A. Browder and J. E. Powers. 1984. Ecological interactions between penaeid shrimps and bottom fish assemblages. pp. 235-254 IN: Penaeid Shrimps - their Biology and Management. J. A. Gulland and B. J. Rothschild eds. Fishing New Books, Farnham, Surrey.

Slavin, J. W. 1982. The utilization of the shrimp bycatch. In: Fish bycatch ... bonus from the sea. Georgetown, Guyana, 27-30 October, 1981. Ottawa. IDRC (IDRC - 1981) pp. 21-28

Somers, L. F. 1990. Manipulation of fishing effort in Australia's penaeid prawn fisheries. Australian Journal of Marine and Freshwater Res. 41: 1-12.

Speir, H. 1985. Investigation of the potential for a directed white perch fishery with anchor and stake gill nets in selected areas of the Chesapeake Bay. Maryland Department of Natural Resources, Tidewater Administration. Estuarine Fisheries Program, Special Analysis # 4.

Speir, H. 1987. Analysis of catch of white perch and striped bass in two types of gill net in Chesapeake Bay, Maryland. Maryland Department of Natural Resources, Tidewater Administration. Estuarine Fisheries Program, Special Analysis 5.

Stevens, B. G. 1990. Survival of King and Tanner crabs captured by commercial sole trawls. Fishery Bulletin U.S. 88: 731-744.

Tiews, K. P., P. Sucondharmarm and A. Isarankura. 1967. On the changes in the abundance of demersal fish stocks in the Gulf of Thailand from 1963 / 1964 to 1966 as a consequence of the trawl fisheries developments. Marine Fisheries Laboratory Bangkok 8: 1-39.

van Beek, F. A., P. 1. Van Leeuwen, and A- D. Rijnsdorp. 1989. On the survival of plaice and sole discards in the otter trawl and beam trawl fisheries in the North Sea. International Council for the Exploration of the Sea. Demersal Fish Committee G: 46. pp. 1- 17.

Vaughan, D. S., R. J. Seagraves, and K. West. 1991. An assessment of the status of the Atlantic weakfish, 1982-1988. In: Atlantic States Marine Fisheries Commission, Special Report 21, Washington, DC.

Vojkovich, M., K. Miller, and D. Aseltine. 1990. A summary of 1983-1989 Southern Califomia gill net observation data with an overview on the effects of gill nets on recreational catches. In: Technical Report from Califomia Department of Fish and Game. pp. 1-52.

B. J. Hill. 1987. Feeding by the sand crab *Portunus pelagicus* on material discarded from prawn trawlers in Moreton Bay, Australia. Marine Biology 95: 387-393.

Wassenberg, T. J., and B. J. Hill. 1989. The effect of trawling and subsequent handling on the survival of bycatch discarded from prawn trawlers in Moreton Bay. Fisheries Res. 7: 99-110.

Wassenberg, T. J. and B. J. Hill. 1990. Partitioning of material discarded from prawn trawlers in Moreton Bay. Australian Journal of Marine and Freshwater Res. 41: 27-36.

Watson, J. W. 1986. Southeast TED experience. pp. 16-17 In: C. A.Goudey, K E.Paterson, and T. J Ree, eds. Gear Selectivity as a Management Tool. Massachusetts Institute of Technology, October 14-15, 1986. Cambridge, MA- Center for Fisheries Engineering Research, MIT Sea Grant Program.

Watson, J. W., and C. McVea Jr. 1977. Development of a selective shrimp trawl for the southeastern United States penaeid shrimp fisheries. Marine Fisheries Review 39: 18-24.

Watson. J. W., J. F. Mitchell and A. K. Shah. 1986. Trawling efficiency device: a new concept for selective shrimp trawling gear. Marine Fisheries Review 48: 1-9.

Watson, J. W., and W. R. Seidel. 1980. Evaluation of techniques to decrease sea turtle mortalities in the southeastern United States shrimp fishery. In: International Council for the Exploration of the Sea. ICES C. M. 1976 / B:28.

West, K. 1991. Scrapfish information paper. Unpublished Summary submitted to the North Carolina Marine Fisheries Council.

Whitaker, D. R. 1973. The U.S. shrimp industry: past trends and prospects for the 1970's. Marine Fisheries Review 35(1): 23-30.

Workman I. K. 1990. Shrimp trawl bycatch reduction. Unpublished Annual Report. National Fisheries Service, Southeast Fisheries Center. Pascagoula, Mississippi.