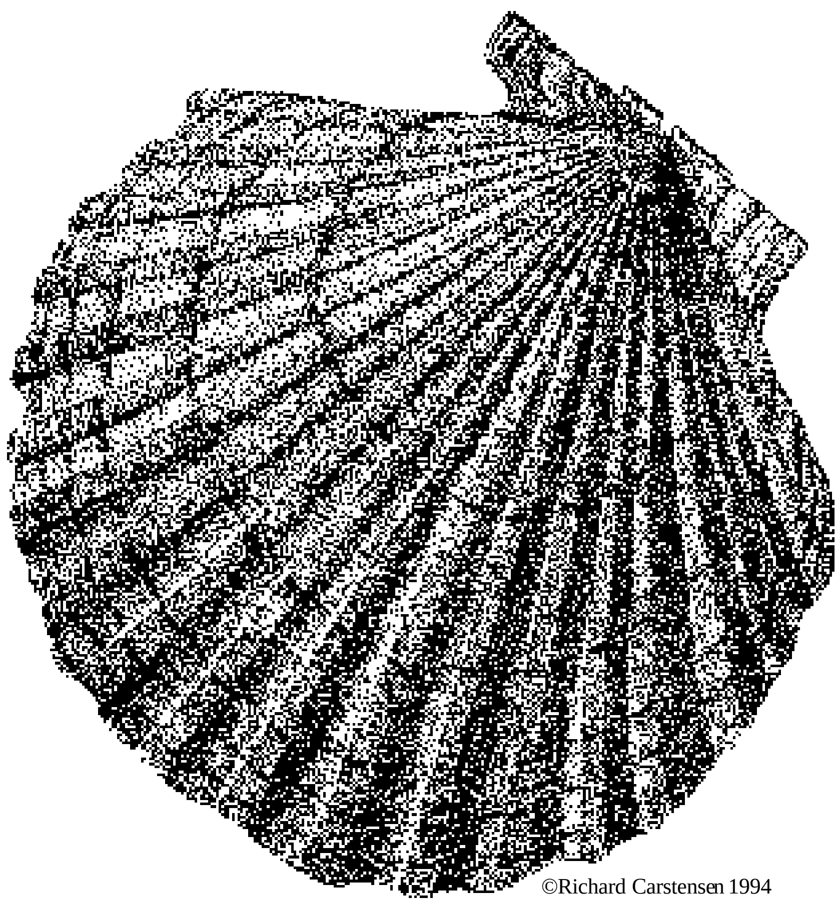
Special Publication 14

# A Workshop Examining Potential Fishing Effects on Population Dynamics and Benthic Community Structure of Scallops with Emphasis on the Weathervane Scallop *Patinopecten caurinus* in Alaskan Waters

June 10–12, 1999
Kodiak, Alaska

**Alaska Department of Fish and Game**
**and**
**University of Alaska Fairbanks**

September 2000





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**ABSTRACT**

This document reviews the results of a workshop on scallop biology and the effects of scallop dredging on benthic communities. The workshop was held in Kodiak, Alaska, during 10–12 June 1999. A review of the history of the Alaskan weathervane scallop fishery was presented. Other speakers presented papers on scallop biology and fisheries in other cold-water areas. Topics of the papers included physical and biological variables influencing distribution, impacts of suspended particles on energetics, modeling approaches to identify dredging impacts, effects of long-term dredging, benthic communities associated with scallops, and the importance of protecting areas from fishing. Following the first day of public presentations, a two-day workshop was convened to develop a viable study program for examining the effects of dredging on the scallop's life history, population dynamics, and associated benthic community. The workshop results were intended to be applied to the Alaskan fishery for weathervane scallops, but they are applicable to many scallop fisheries. The working groups identified ten research topics for which information needs to be gathered. Topics include the importance of spatial distribution on fertilization success, the reproductive output of individuals, the importance of nursery areas, scallop behavior and how it may be altered by dredging, factors that affect growth, fishery induced injury and mortality, causes and rates of natural mortality, long-term factors affecting recruitment, effects of scallop dredging on the benthos, and developing harvest strategies for scallops. Also, the working groups recommended that a monitoring program be established that included short- and long-term data gathering, and they identified methods and tools that might be used for this task.

## ACKNOWLEDGMENTS

The Natural Resources Fund of the University of Alaska Fairbanks, Alaska Sea Grant, and the Alaska Department of Fish and Game provided funding for this workshop. The workshop coordinators were Kevin D. E. Stokesbury, Howard M. Feder, A. J. Paul, Doug Pengilly, and Gordon H. Kruse. We thank the invited speakers: A. Brand, Marine Biological Station, University of Liverpool, Port Erin, Isle of Man, U.K.; J. Grant, Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada; B. MacDonald, Biology Department, University of New Brunswick-Saint John, Canada; E. Kenchington, Department of Fisheries and Oceans, Halifax, Nova Scotia, Canada; P. Dayton, Scripps Institution of Oceanography, California; and session leaders T. Shirley and S. Jewett. We thank A. Tyler, R. Dearborn, and N. Myers for their help and support. We also thank the University of Alaska Anchorage–Kodiak Community College, Kodiak Island Borough, and the National Marine Fisheries Service for providing meeting facilities.

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## INTRODUCTION TO THE WORKSHOP

The weathervane scallop *Patinopecten caurinus* has been commercially fished in Alaska since 1967. This fishery recently reached its highest value, due to increased landings and price. Dredging, the primary harvesting method, may have a severe impact on sustainability of scallop resources and the associated benthic community. We held a three-day international workshop to review world experience on the effects of dredging on scallops, the present state of the Alaskan fishery, and the community of organisms associated with scallop beds. A working group of 23 scientists and agency biologists developed a study program to examine the effects of dredging on scallop life history, population dynamics, and the associated benthic community.

Little is known of weathervane scallop biology in Alaska, including spatial distribution and abundance on large and fine scales, factors influencing fertilization success, the recruitment process and how fishing may affect it, factors affecting growth and reproductive output of individuals, mortality rates and causative factors, the timing of critical periods in the scallop's life history, genetic structure of the populations, and the habitat requirements and associated species of the scallops. Dredging for scallops affects all of these processes in unknown ways. Prudent management of the scallop resource requires resolution of these uncertainties. The workshop focused on topics and scientific approaches that could be useful in creating innovative management strategies that would allow sustainable harvests while preserving the resource and minimizing damage to the habitat.

The University of Alaska Fairbanks (UAF) and the Alaska Department of Fish and Game (ADF&G) invited the public to a day of lectures, on June 10, 1999, reviewing the present state of the scallop fishery in Alaska and effects of dredging in other scallop fisheries throughout the world. This was an opportunity for the public and fishing industry of Kodiak to hear scientists from eastern Canada, the British Isles, and both coasts of the United States to share their knowledge and experience. The extended abstracts from each of these lectures are published in this document. The following two days were working sessions.

We structured these sessions on three biological and two temporal scales. The biological scales and processes guidelines were:

| Individual | Population | Community |
|---|---|---|
| growth | spatial distribution | competition |
| energetics | abundance | predation |
| physiology | growth/age structure | secession/recolonization |
| injury | recruitment | equilibrium shift |
| predation | fertilization success | trophic levels |
| competition | genetics | |

The participants were divided into two working groups:

**Group I**

| Name | Affiliation |
|---|---|
| J. Barnhart | Alaska Department of Fish and Game |
| A. R. Brand | University of Liverpool |
| J. Grant | Dalhousie University |
| A. J. Paul | University of Alaska Fairbanks |
| D. Pengilly | Alaska Department of Fish and Game |
| G. Rosenkranz | Alaska Department of Fish and Game |
| T. Shirley | University of Alaska Fairbanks |
| K. Stokesbury | University of Massachusetts Dartmouth |
| B. Stone | National Marine Fisheries Service |
| C. Trowbridge | Alaska Department of Fish and Game |

**Group II**

| Name | Affiliation |
|---|---|
| B. Bechtol | Alaska Department of Fish and Game |
| P. Dayton | Scripps Institution of Oceanography |
| H. Feder | University of Alaska Fairbanks |
| S. Jewett | University of Alaska Fairbanks |
| E. Kenchington | Department of Fisheries and Oceans |
| G. Kruse | Alaska Department of Fish and Game |
| B. MacDonald | University of New Brunswick Saint John |
| B. McConnaughey | National Marine Fisheries Service |
| D. Woodby | Alaska Department of Fish and Game |

Focus questions of the working groups were:

- What are the dominant species and community structures in undisturbed scallop habitats? Does the community structure change after dredging at different intensities?
- Does dredging influence recruitment, growth, and mortality of scallops left on the grounds?
- What are the main species interactions that influence interannual variation in recruitment of scallops and benthic invertebrates? Which are the predators, the competitors, and the symbionts?
- What are the processes that account for the long-term changes in the assemblages of species?
- What are the main physical oceanographic events that would influence interannual variation in recruitment of scallops and other benthic invertebrates associated with scallop beds?

The temporal scales are short (approximately the life span of a scallop, 13 years) and long term (decades).

**Day 2: Focusing the general questions**

| Time | Topic | | |
|---|---|---|---|
| 0800–1000 | **Short term:** | Group I<br>Individual | Group II<br>Population |
| 1000–1015 | Coffee | | |
| 1015–1200 | General meeting, presentation of two subgroups, and discussion | | |
| 1200–1300 | Lunch | | |
| 1300–1500 | **Long term:** | Group I<br>Population | Group II<br>Community |
| 1500–1515 | Coffee | | |
| 1515–1800 | General meeting, presentation of two subgroups, and discussion | | |

**Day 3: How to experimentally examine the questions identified during Day 2**

| Time | Topic | | |
|---|---|---|---|
| 0800–1000 | **Short term:** | Group I<br>Individual | Group II<br>Population |
| 1000–1015 | Coffee | | |
| 1015–1200 | General meeting, presentation of two subgroups, and discussion | | |
| 1200–1300 | Lunch | | |
| 1300–1500 | **Long term:** | Group I<br>Population | Group II<br>Community |
| 1500–1515 | Coffee | | |
| 1515–1800 | General meeting, presentation of two subgroups, and discussion | | |

## PART I: THE PRESENTATIONS

### Introductory remarks presented by Kevin Stokesbury on June 10, 1999.

I would like to welcome you all to the "Workshop Examining Potential Fishing Effects on Population Dynamics and Benthic Community Structure of Scallops with Emphasis on the Weathervane Scallop *Patinopecten caurinus* in Alaskan Waters." I'm a marine biologist, and a lot of my research deals with spatial distribution of fish and invertebrates. I've worked for several years on the sea scallop and presently I'm working on the Georges Bank fishery. It has been my pleasure to work with Howard Feder of UAF, and Gordon Kruse and Doug Pengilly of the ADF&G to organize this workshop.

The weathervane scallop has been commercially fished in Alaskan coastal waters since 1967, but relatively little is known of its life history. Further dredging, which is the primary harvesting tool for this fishery, may have an impact on the benthic faunal community. The driving idea of this workshop was to review world experience on the effects of dredging on scallops, examine the present state of the Alaskan weathervane scallop fishery and the community of organisms associated with scallop beds, and to develop a viable study program examining the effects of scallop dredging on *P. caurinus* life history, population dynamics, and associated benthic community. We wanted to find out what is being examined, how to examine it, and how to avoid mistakes. To do this we wanted to bring together some of the top researchers working on different aspects of scallop biology such as genetics, physiology, ecology, fishery science, modeling, physical dynamics, and benthic community structure.

When Al Tyler and Howard Feder asked me to help them with this I couldn't believe my luck. I'm originally from the Maritime Provinces of Canada. I completed my Ph.D. at Laval University with John Himmelman, working on a scallop ecology project funded by a program called Ocean Production Enhancement Network (OPEN). OPEN focused on scallops and Atlantic cod and provided a great deal of new information on these species. John encouraged me to read as much about scallops as I could before writing my Ph.D. proposal. One of the first articles I read was a chapter entitled "Scallop Ecology: Distributions and Behaviour" by Andy Brand, in Sandra Shumway's book on scallops. This chapter hooked me on scallops and is an excellent overview of scallop ecology. Dr. Brand has an amazing knowledge of scallops and has come from the Isle of Man to help us with this workshop.

There is a great deal of research on scallops. One of the best studies, which gave me insight into scallop physiology and which I used as a meter stick to try to measure my work, was Bruce MacDonald's work on scallops in Newfoundland. Bruce is now at the University of New Brunswick Saint John campus, and he and his students are working on a number of different benthic marine invertebrates. Bruce was a principal investigator on OPEN and has worked on the weathervane scallop in British Columbia.

Jon Grant was also a principal investigator on OPEN. His work includes carrying capacity of aquaculture sites, sediment work in scallop beds and the effects of the benthic boundary layer, oceanography, and modeling. His insights from an oceanographic perspective will be key.

Before starting my Ph.D. I worked with the Department of Fisheries and Oceans, Canada (DFO), in their invertebrate and marine plant section with Glyn Sharp. When Ellen Kenchington began working at DFO Glyn described her research to me with very high praise. As I read and heard more of Dr. Kenchington's research I saw that the praise was well deserved. Ellen's work on scallop genetics and the difficult task of dealing with the scallop fisheries of Nova Scotia will both be critical to our workshop.

Howard Feder suggested that we invite Paul Dayton. Although I had not previously met Dr. Dayton, his research on marine ecosystems and community structure are world renown, and I look forward to hearing his thoughts.

Further, from Alaska we have Tom Shirley, Steve Jewett, and A. J. Paul. During my two and a half years at UAF I turned to Steve and Tom for advice and input on a number of different topics. Both are top-notch marine scientists and have key local knowledge. I worked with A. J. Paul on the SEA (Sound Ecosystem Enhancement) project; the way A. J. approaches a scientific question is surgical. A. J.'s the most focused researcher I've ever met; he can cut a question to the core.

So we have a dynamic group of researchers to help us with this workshop. We propose to examine the present state of the Alaskan weathervane scallop fishery and to develop a viable study program for examining the effects of dredging on the scallop's life history, population dynamics, and associated benthic community.

My work on Georges Bank has been both intense and political. Scallops are at the center of a growing debate over the effects of mobile fishing on the marine ecosystem, fisheries management, the use of natural resources, and the importance of a way of life. These questions stretch beyond biology or science itself. However, at their core are three questions. These three questions are:

1) What is the abundance of scallops, where are they located, and how does their life history allow them to persist in that location?
2) What species will be collected as bycatch during fishing for these scallops?
3) What effect does the trawl have as it passes over the bottom, and how long does this effect last?

# History and Development of the Scallop Fishery in Alaska

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## ABSTRACT

The weathervane scallop *Patinopecten caurinus* is a large, long-lived pectinid distributed from California to Alaska. A commercial dredge fishery from northern Southeast Alaska to the Bering Sea targets the species. The fishery developed rapidly in the late 1960s, declined sharply in the mid 1970s due to local depletion and availability of other fishing alternatives, and increased quickly in the late 1980s with improved stock conditions and prices. Fishery management evolved accordingly. Passive management regulations were replaced by active fishery management plans in the early 1990s in response to overcapitalization and resource conservation concerns. In recent years, fishery management plans have stabilized harvests at about 0.8 million pounds of shucked meats annually through guideline harvest levels and crab bycatch limits. An onboard observer program is a critical component of the fishery management process, providing important information on the biology, distribution, and relative abundance of Alaska's scallop stocks.

## INTRODUCTION

The purpose of this report is to provide a brief overview of biology, history, and management of the weathervane scallop *Patinopecten caurinus* fishery in Alaska. The fishery is managed with a precautionary approach given a lack of complete information on the species and its productivity. Studies of scallop biology, abundance, productivity, and fishing effects are critically needed to fill information voids so that fishery management can better strive toward sustained optimal yields while minimizing adverse effects on other species and habitats. A high level of observer coverage on a small fleet renders this a very tractable fishery for research.

## THE WEATHERVANE SCALLOP

Weathervane scallops are distributed from Point Reyes, California, to the Pribilof Islands, Alaska (Foster 1991). They are found from intertidal waters to depths of 300 m (Foster 1991), but they tend to be most abundant between depths of 45–130 m on mud, clay, sand, and gravel (Hennick 1973). Scallop beds tend to be elongated in the direction of mean current flow. In Alaska, highest abundances of scallops exist off Yakutat, Kodiak Island, and in the Bering Sea, with smaller aggregations occurring in Prince William Sound and off the Alaska Peninsula and Aleutian Islands (Figure 1).

Most weathervane scallops mature at 76-mm shell height (SH) at about age 3 (Haynes and Powell 1968, Hennick 1973). Funk (unpublished data) fitted Gompertz growth equations to scallop data collected in the late 1960s and early 1970s by Hennick (1973). Scallops off Yakutat grow much more slowly than scallops off Kodiak Island, and scallops off the west side of Kodiak grow more slowly than those from the northeast side of Kodiak. The largest recorded Alaskan specimen measured 250-mm SH and weighed 340 g (Hennick 1973).

Weathervane scallops are long-lived; the oldest Alaskan specimen was estimated to be 28 years old (Hennick 1973). Kruse (1994) estimated mortality rates for four areas in Alaska using three different methods. Instantaneous natural mortality rates varied from 0.04 to 0.21 with a median of 0.13, corresponding to 12% annually.

## FISHERY HISTORY

The Alaskan scallop fishery provides a classic example of fishery evolution through several developmental stages: discovery and initiation of development, bandwagon growth, fallback, and subsequent evolutionary development (Walters 1986). A fishery for weathervane scallops in Alaska began in 1967 using paired New Bedford-style scallop dredges (Haynes and Powell 1968). Within one year the fishery became fully developed when 19 vessels made 125 landings totaling 1.7 million pounds of shucked meats (Figure 2).[1] Catches peaked in 1969 when 157 landings totaled 1.9 million pounds. Harvests off Kodiak and Yakutat accounted for nearly all of the landings in the early years of the fishery. Whereas catches from the early fishery were dominated by old scallops (≥7 years of age), landings shifted toward younger ages (2–6 year olds) by the early 1970s (Hennick 1973). Landings declined to 0.4 million pounds in 1975 as average landing per trip declined (Kaiser 1986). Less than

[1] Meat recovery rate averages about 10% but varies between 9% and 11% depending on scallop size, season, and area.

three vessels participated in the fishery each year from 1976–1979. No vessels participated in 1978.

In the 1980s the weathervane scallop fishery received renewed interest due to increased exvessel prices and recovering stock conditions. On an annual basis during the 1980s, an average of nine vessels delivered 0.6 million pounds worth $2.15 million. Unlike the 1970s when Kodiak and Yakutat accounted for 93% of the landings, during the 1980s 33% of the landings were taken from Dutch Harbor and other areas such as Southeast Alaska, Cook Inlet, Alaska Peninsula, and the Bering Sea.

In 1990 nine vessels made 144 deliveries that totaled 1.5 million pounds (Figure 2). By late 1992 landings exceeded 1.8 million pounds, the highest harvest since fishing on virgin stocks. The fishing power of the fleet increased substantially in the 1990s. The number of vessels increased from 4 in 1988 to 16 in 1993. Mean vessel length increased from 83 feet in 1981 to 110 feet in 1991, and mean crew size increased from 5.5 in 1984 to 12 in 1993. Some vessels used automatic shucking machines. Concerns about resource conservation and fleet overcapitalization led to new state (1994) and federal (1995) fishery management plans (FMPs). As a result, statewide landings have averaged about 0.8 million pounds since 1996. For more complete descriptions of the history of the Alaskan scallop fishery, see Kaiser (1986), Kruse and Shirley (1994), and Shirley and Kruse (1995).

## FISHERY MANAGEMENT

Prior to 1993 no FMP existed for scallops in Alaska. Rather, the fishery was managed by a set of passive regulations, such as gear restrictions, closed areas to protect crabs, and fishing seasons (ADF&G 1993, Kruse et al. 1992). Owing to increased landings, fishing power, and resource conservation concerns in the early 1990s, the scallop fishery met the conditions of a high-impact emerging fishery (5 AAC 39.210 in ADF&G 1993). Therefore, the Alaska Department of Fish and Game (ADF&G) developed fishery management options (Kruse et al. 1992), solicited public comment, and implemented an interim FMP and associated regulations in 1993 (5 AAC 38.076 in ADF&G 1993). Later, a draft FMP (Kruse 1994) was prepared to fully describe the rationale and strategy for scallop management and fishing regulations. The Alaska Board of Fisheries (BOF) adopted a scallop FMP in March 1994, and a current version appears in state regulations (5AAC 38.076 in ADF&G 1999).

In 1995 the National Marine Fisheries Service (NMFS) became involved in scallop fishery management when the catcher–processor vessel *Mister Big* fished in the Exclusive Economic Zone (EEZ) without a State of Alaska permit. NMFS issued an emergency interim rule in February 1995 to close federal waters to scallop fishing to prevent overfishing. In July 1995 the North Pacific Fishery Management Council (NPFMC) adopted a federal FMP to formally close EEZ waters to scallop fishing. Since then, the federal FMP, including six amendments, delegates most management to the State of Alaska.

Primary management objectives of the scallop FMP are to: (1) ensure long-term viability of scallop populations, (2) minimize adverse effects of gear on habitat and other species, (3) prosecute steady-paced fisheries that provide long-term socioeconomic benefits,

(4) maintain resource availability to subsistence users, and (5) conduct research to increase knowledge for future management decisions. Key management measures to achieve these objectives include establishment of nine registration areas, area closures to protect crab habitat, a limited entry program to prevent overcapitalization, fishing seasons (July 1 through February 15, except for August 15 to October 31 in Kamishak Bay), gear specifications (e.g., no more than two dredges of maximum size, 15 feet with 4-inch minimum ring size), guideline harvest ranges for each area constrained by an overall cap of 1.24 million pounds of shucked meats, crab bycatch limits set at 0.5% to 1% of the crab population, 100% onboard observer coverage requirements, and efficiency controls (e.g., crew size limited to 12 and a ban on automatic shucking machines). Scallop regulatory proposals are reviewed once every three years by the BOF and as needed by the NPFMC.

## DATA COLLECTION AND FISHERY RESEARCH

ADF&G conducts a small research program on weathervane scallops to implement and improve management of the fishery. The most important element is an onboard observer program that was instituted in 1993. All scallop vessels, except those fishing in Kamishak Bay, must carry an onboard observer at their own expense unless ADF&G waives this requirement. The observer collects valuable information on fishing locations, bycatch and scallop catch, size distributions, sex composition, reproductive condition, meat recovery, and injury rates. Annual reports (e.g., Barnhart and Rosenkranz 1999) provide complete descriptions and summaries of the observer data. A vessel operators' logbook program provides additional information on the fishery.

Collection of observer data has facilitated ongoing spatial analyses of scallop stock status and productivity. The geographic distribution of scallop beds has been mapped, and depletion estimators of abundance have been calculated for some beds. Ongoing aging studies are examining reliability of growth rings as a measure of age. Size and age data are providing valuable information for studies of recruitment. Preliminary analysis of biological reference points from data collected in the late 1960s and early 1970s indicated target harvest rates of 12% to 14% and overfishing rates of 16% to 20% (F. Funk, unpublished data). Updated analyses with contemporary observer data are planned. Other research needs include studies of basic biology and life history, genetic stock structure, fishery-independent stock assessments, population dynamics, gear catchability and selectivity, handling mortality, and effects of scallop dredges on the sea floor.

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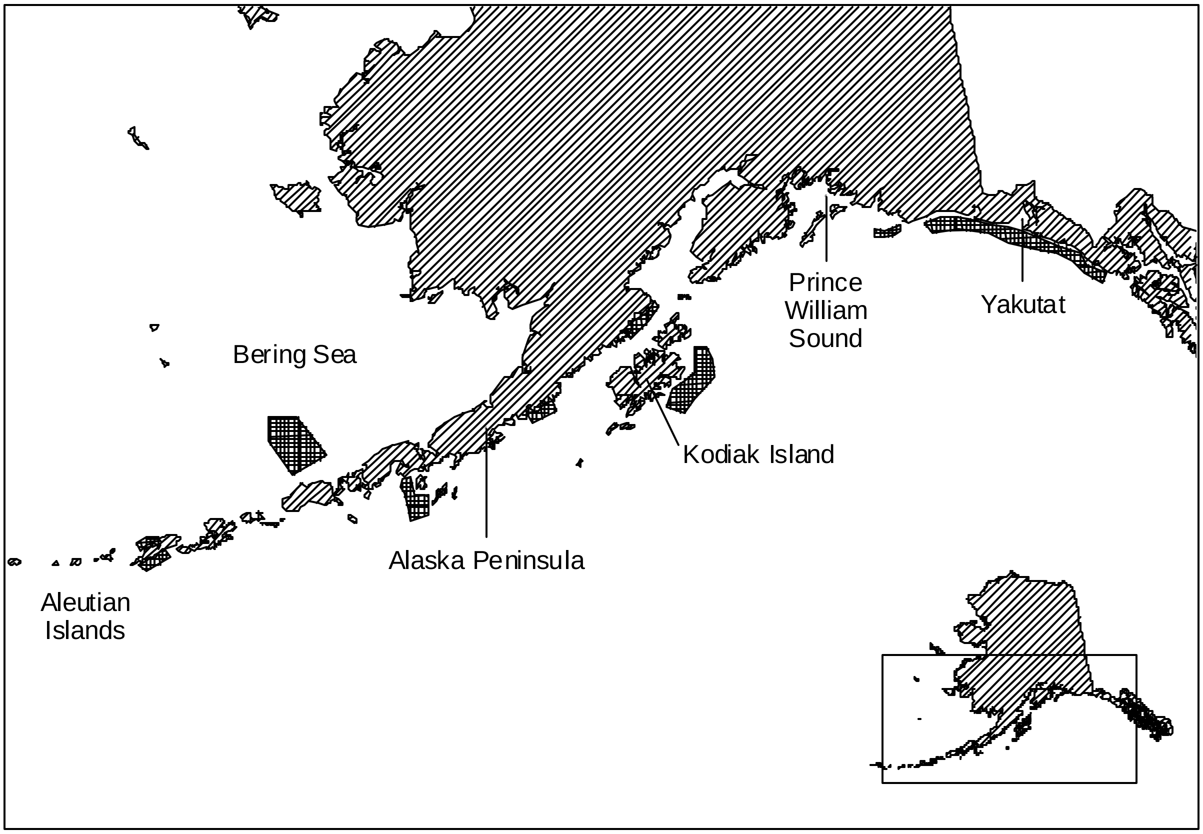


Figure 1. Locations of commercial scallop beds in Alaska.

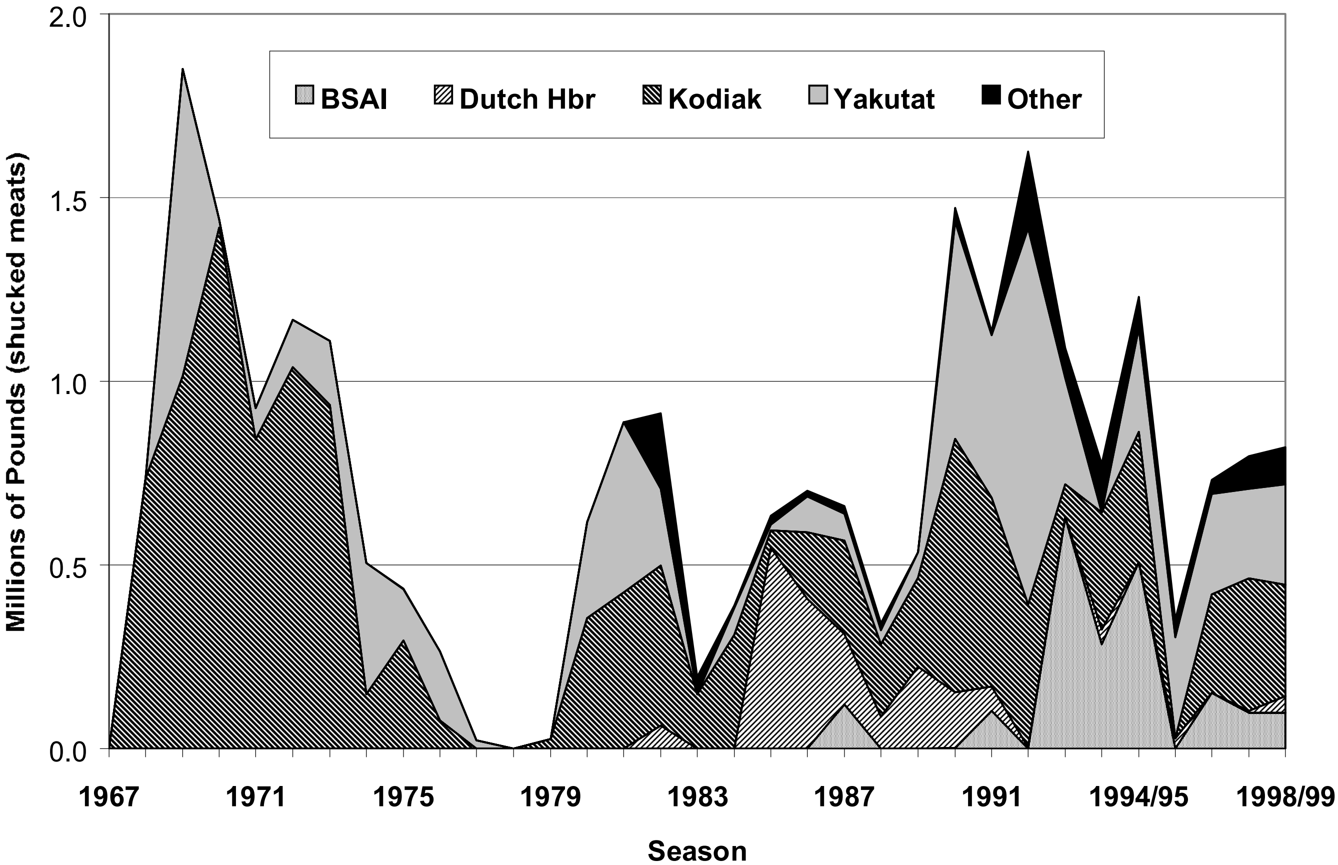


Figure 2. Historic Alaska scallop harvests during 1967–1998 for the Bering Sea–Aleutian Islands (BSAI), Dutch Harbor, Kodiak, and Yakutat Management Areas. Additional harvests occurred in Prince William Sound and Cook Inlet.

# Physical and Biological Variables Influencing the Spatial Distribution of the Giant Scallop *Placopecten magellanicus*

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## ABSTRACT

Sea scallops *Placopecten magellanicus* aggregate on both a large (kilometer) and a small (centimeter) scale. Large-scale aggregations are strongly associated with gravel substrates while small-scale aggregations (clumps) are not. The short distance between scallops within clumps, the high proportion of clumps with both sexes present, and an average of three scallops per clump suggest high fertilization success within clumps. Comparisons of the physical and biological conditions within scallop beds and in adjacent areas with low scallop densities indicate that gravel substrate, low decapod predation, and presence of filamentous flora and fauna are critical factors determining scallop aggregation location. Scallop movement appears to be random, and scallops did not appear to migrate from unsuitable to suitable habitats. However, scallops may move to form clumps resulting in increased fertilization success. Recent surveys of Georges Bank closed areas indicated areas of high scallop densities and highly aggregated distributions. These surveys demonstrate the positive effect of allowing heavily fished scallop grounds a reprieve.

## INTRODUCTION

Scallop distribution, on the scale of both kilometers and centimeters, is a result of a complex mosaic of inter- and intraspecific interactions. We examined some of these interactions in Port Daniel Bay, Quebec, Canada, during the summers of 1991 and 1992. We conducted experiments examining the scallop's spatial distribution on various scales (kilometer, meter, and centimeter), the biological and physical factors influencing these distributions, and the scallop's ability migrate from unsuitable to suitable habitats. Conclusions from these experiments provide information on scallop aggregations and are presented in chronological order from recruitment to the adult reproduction.

Scallops were found on gravel or gravel–sand substrates. However, not all gravel substrates supported high densities of scallops. Temperature, salinity, and current direction and velocity were similar inside and outside scallop aggregations in Port Daniel Bay.

We found that filamentous flora and fauna distributions may influence where scallop spat settles. High *P. magellanicus* spat settlement was not consistently associated with scallop densities, but the filamentous organisms on which scallops settle were more abundant in the scallop beds, possibly enhancing recruitment (Stokesbury and Himmelman 1995, Harvey et al. 1993).

Following settlement, scallop survival is influenced by predation. Tethering experiments indicated that the risk of predation was low within scallop beds compared to adjacent areas (Stokesbury and Himmelman 1995). The intensity of asteroid predation was similar within scallop beds and in surrounding areas with few scallops. The lobster *Homarus americanus* was most abundant on bedrock and the rock crab *Cancer irroratus* on sand. Decapods appeared to inflict considerable mortality on both small and large scallops. Highest mortalities of small tethered scallops (35–45 mm in shell height) were on sandy bottoms where rock crabs were most abundant, and shell remains indicated that most mortalities were from predation by decapods. Mortality of large scallops (>70 mm) was correlated with abundance of lobsters. A high proportion of the dead large scallops had broken shells, similarly indicating decapod predation. It has been suggested that mollusks obtain a refuge from decapod predation after they reach a specific shell height (Juanes 1992). Our field research suggests that *Placopecten magellanicus* is not safe from predation by decapods when it has attained a large size (Stokesbury and Himmelman 1995). This has significant implications because decapod prey-size selection is an important component of molluscan community structure.

The ratio of predation to predator density fluctuates between a linear and a nonlinear relationship, depending on the scallop's swimming ability. Movement did reduce predation rates to 0% to 30% compared to mortalities (28% to 79%) estimated from tethered scallops; however, a positive correlation between predator density and rate of scallop movement was only found for one predator, *C. irroratus*. Therefore, scallops may move for reasons other than to escape predation. Swimming ability is affected by the scallop's size and by environmental conditions such as photoperiod and temperature. Scallops increased their movement in unsuitable habitats, dispersing randomly, and did not appear to migrate to suitable habitats (Stokesbury and Himmelman 1996).

The scallop's distribution may also be influenced by intraspecific interactions, for example, the formation of clumps. I propose that the fertilization success of scallops is greatly enhanced by the degree of clumping and that swimming in *P. magellanicus* may have evolved so that individuals could form clumps, at the scale of centimeters, as well as to escape from predators (Stokesbury and Himmelman 1993, 1996). The concentration of gametes in the water column decreases with distance from the source. This suggests that fertilization success may decrease exponentially with increased clump area, as gametes would have greater distances to travel before they encounter gametes from the opposite sex. Dredging has been found to change scallop distributions from contagious to random, and this may decrease fertilization success (Langton and Robinson 1990). Thus distribution may influence the number of spat initially in the water column and possibly the number available for settlement, although many other variables are also associated with larval survival and dispersion (Sinclair 1988, Tremblay et al. 1994). Finally, the contagious distribution of scallops probably influences the distribution of filamentous flora and fauna as these species often colonize the shells of adult scallops.

## The Georges Bank Scallop Fishery

Georges Bank is the world's largest single natural scallop resource, supporting a fishery since the 1880s. Annual harvests have fluctuated depending on year class strength, which is influenced by environmental and biological factors. Two present management strategies have affected scallop population dynamics on Georges Bank. The first in 1977 was the 200-mile (370-km) fishing zone established by Canada and the United States restricting fishing effort to specific locations, replacing the traditional movement of the fleet from one aggregation to another as densities fluctuated. The second in 1994 was the closure of three large areas of the United States portion of Georges Bank to fishing in an effort to protect depleted groundfish stocks (Figure 1). These closures resulted in a second reduction in the scallop ground available to the fishing fleet, concentrating intense fishing pressure on the remaining open areas. Presently, the actual abundance of scallops within these closed areas is unknown.

Alternative management strategies may allow increased landings of scallops and contribute to the recovery of heavily fished groundfish fisheries. A thorough scientific survey of the scallop resource in Closed Area II was the critical first step in developing these management strategies.

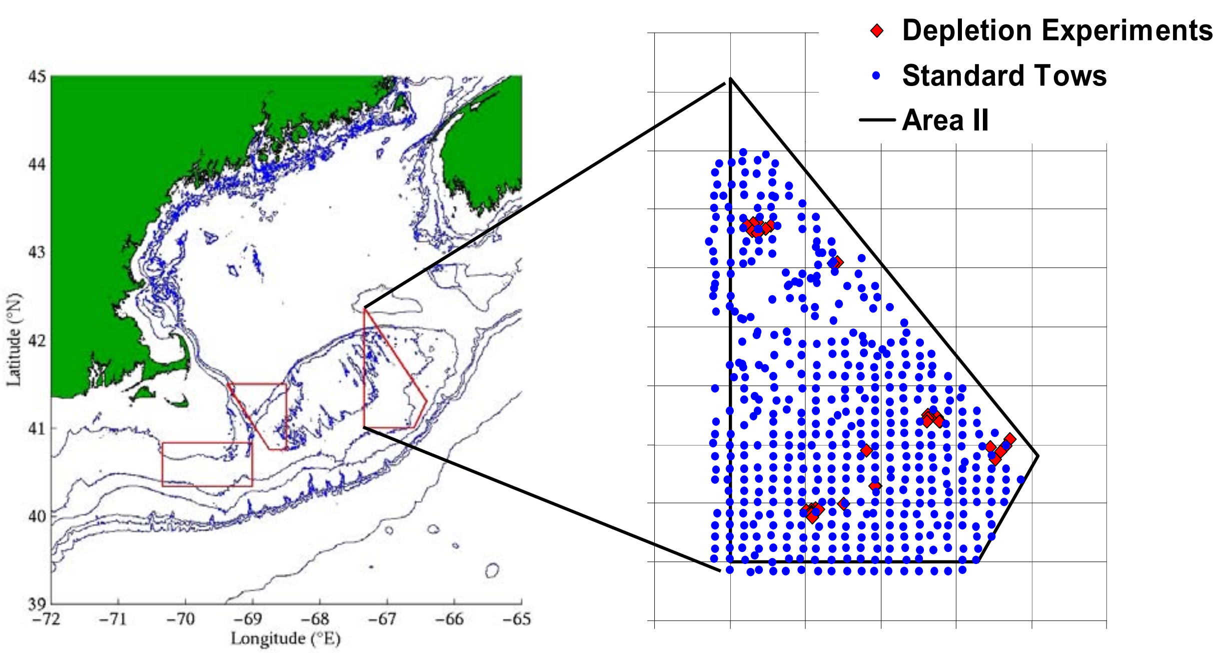


Figure 1. Locations of systematically assigned standard tows and depletion experiments in Georges Bank Closed Area II surveyed from 28 August to 5 October 1998.

We surveyed the scallop resource in Closed Area II of Georges Bank from 28 August to 5 October 1998 with the Fishermen's Survival Fund of New Bedford, Massachusetts, the NMFS at Woods Hole, and the Virginia Institute of Marine Science (VIMS). The objectives of the Closed Area II survey were to determine the absolute abundance and spatial distribution of fishable scallops (number of scallops$\cdot m^{-2}$ >75-mm shell height). To do this we calculated the efficiency of the New Bedford offshore scallop dredge from 39 depletion experiments. We examined the size structure of scallops. We compared results from stations in the Closed Area II to stations sampled adjacent to the south and west boundaries of the Closed Area, where fishing is permitted.

## METHODS

Six commercial fishing vessels were used, and the primary sampling gear was the New Bedford offshore dredge which is 4.5-m wide, weighs approximately 1,870 kg, has three tickler chains, a 20.3-mm diamond-mesh twine top, and a 4.5 x 0.8-m bag knit of 89-mm steel rings.

To estimate the density of scallops in Closed Area II from the standard tow data we first determined the area each tow sampled (about 0.0134 $km^2$, 1.491-km tow distance x 9-m tow width; about 0.0167 $km^2$ including the set and retrieval distances). To calculate the number of individuals sampled within a tow the mean shell height (in millimeters) per tow was determined. The number of scallops within a basket is related to the scallops' size by the equation $\log y = 8.094 - 2.898 \log x$ ($r^2 = 0.823$, df = 525, $P<0.001$), where $x$ is equal to mean shell height per tow and $y$ is equal to the number of individuals within a basket. The number of individuals per basket was multiplied by the number of baskets collected per tow to estimate the number of individuals collected per tow. This estimate agreed with the actual number of scallops counted for shell height measurements and the number of recorded baskets. Biomass was estimated by converting the number of scallops per area ($x$ = scallops$\cdot m^{-2}$) into meat weight ($y$, in grams) from the scallops' shell height ($\log y = -4.416 + 2.819 \log x$; $r^2 = 0.94$, df = 122, $P<0.001$).

The 39 depletion experiments provided an estimate of fishing efficiency. Depletion experiments consisted of a series of 10-min tows repeatedly sampling the same area until the catch was reduced to <25% of the initial tow. Depletion experiment locations were selected based on preliminary scallop density (Figure 1). The Leslie model, which regresses catch per unit effort against accumulative catch, was applied to these data. The slope of this regression is an estimate of the gear's catchability, and the x-intercept provides an estimate of the population within the sample area. Each successive tow removes a fraction of the population, and as a consequence the catch per effort declined proportionately. This decline in catch per effort (baskets of scallops per tow) is called the catchability coefficient ($q$).

The assumption of a closed population, defined as those scallops within the average area covered by the repetitive tows, is often violated in trawl depletion studies as it is difficult to exactly repeat the tow track in open ocean conditions.

In order to estimate trawl efficiency from the depletion experiments, we first removed all extreme geographical outliers where the vessel track markedly veered from the initial track line. We determined the proportion of area that was sampled more than once using the overlap factor $1–A/a'$, where $A$ is the total area fished one or more times and $a'$ is the area that would have been fished if the tows were adjacent to one another ($a' = na$; $n$ = number of tows). If there is no overlap $1–A/a' = 0$, and if there is complete overlap $A/a' = 1/n$. This measure of overlap works well as a correction factor if the amount of overlap within the experiment is high ($1 – A/a' > 0.4$) but is unreliable at lower values.

## RESULTS AND DISCUSSION

Two large areas in the north and south of Closed Area II supported high densities of scallops. The northern aggregation covered approximately 857 $km^2$ and contained 38.0% of the biomass sampled. The most northerly quadrat contained 28.4% of the total biomass sampled. The southern aggregation covered about 2,274 $km^2$ and contained 49.6% of the biomass sampled. These areas were separated by 2,915 $km^2$ containing only 12.4% of the total biomass. An average of 4.00 (SD = 8.6) baskets per tow was sampled within Closed Area II while an average of 0.050 (SD = 0.74) baskets per tow was collected in the adjacent open area (1,132 $km^2$). There was eight times more biomass per area and six times more individuals per square meter in Closed Area II than in adjacent open areas.

Twenty experiments had a high degree of overlap (minimum = 0.4, mean = 0.7, SD = 0.24). These experiments estimated a mean trawl efficiency of 16.0% (SD = 6.49) when the correction factor for each experiment was applied.

The shell height (in millimeters) frequency for all scallops from Closed Area II was symmetrical from 75 to 170 mm with a mean of 115.5 (SD = 18.91), and a second small dome occurred below 75 mm.

Our estimates of the New Bedford offshore scallop dredge efficiency (16.0%, 95% confidence limits = 2.84) agreed with independent estimates of offshore trawl efficiency using scuba and video camera observations (15%, Bourne 1966; 15.4%, Caddy 1971; Stone and Hurley 1987). Experimental modeling using maximum likelihood techniques to estimate trawl efficiency suggests a high dredge efficiency (estimates vary with models with means ranging from 23%, D. Cai, unpublished data, to 40%, P. Rago, personal communication, NMFS, Woods Hole, Massachusetts). Given the critical role efficiency estimates play in survey estimates of density, further experimentation in the field and with different analysis techniques is essential.

Using a trawl efficiency of 16.0%, the relative density calculated from the standard tows, the absolute biomass of fishable scallops within Closed Area II was estimated as about 37,340,000 kg (82 million lb; 60 million lb using set and retrieval distances). The absolute estimate of about 37,000,000 kg meat weight for fishable scallops in Closed Area II is a product of increased density (based on the scallops' spatial distribution) and increased meat weight with size. Scallops in the Closed Area II were larger than in the open area, and the meat weight-to-shell length increases exponentially. For example, to obtain 1,000 kg of scallop meat in the open area, 58,343 scallops would be required. To obtain 58,343 scallops, 8.3 $km^2$ would need to be scraped by the dredge. The mean age of these scallops is about 5 years old (Thouzeau et al. 1991), and they would produce 42.5 million eggs per female at the time of harvest (McGarvey et al. 1992). To obtain 1,000 kg of scallop meat in Closed Area II, 40,469 scallops would be required. To obtain 40,469 scallops, 0.93 $km^2$ would need to be scraped by the dredge. The mean age of these scallops is about 6.5 years old (Thouzeau et al. 1991), and they would produce 77.4 million eggs per female at the time of harvest (McGarvey et al. 1992). Therefore, fishing in the Closed Area increases the mean age and size in the catch by 1.5 years, doubling the meat weight per individual. The area scraped is reduced substantially and so is the fishing mortality, but population fecundity is almost doubled.

The positive effect of giving heavily fished areas of Georges Bank a reprieve from harvesting is clearly demonstrated from this survey. The scallop population within Closed Area II is mature and has a high density. Therefore a productive fishery is possible while at the same time reducing fishing effort on Georges Bank. Further research is required to ensure nursery areas are not disturbed and to identify possible areas for closure to allow presently heavily fished areas a similar reprieve.

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# Potential Impacts of Increased Particle Concentrations on Scallop Feeding and Energetics

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## INTRODUCTION

There have been numerous studies looking at the effects of increasing particle concentration on feeding in bivalves, including the sea scallop *Placopecten magellanicus* (e.g., MacDonald and Thompson 1986, Cranford and Grant 1990, Cranford and Gordon 1992, MacDonald and Ward 1994, Bacon et al. 1998, Cranford et al. 1998). Many of these studies have focused on how the sea scallop will respond to changes in the concentration and quality of the suspended food particles, which are highly variable and dependent on local biological and physical conditions. Fluctuations in the concentration and quality of suspended particles results from many natural processes including phytoplankton blooms, bioturbation, flocculation, erosion of soils, and resuspension of sediments (Grant and Thorpe 1991). The concentration and nutritional characteristics of the suspended particles may also be influenced on a large or localized scale by man's actions through the introduction of particles through construction activity, dredging, offshore drilling, fishing activity, etc. Relatively high concentrations of particles low in quality or organic content may be introduced into the water column thereby "diluting" the naturally occurring nutritional particles and potentially impacting feeding and production in local suspension-feeding bivalves (e.g., Widdows et al. 1979, Vahl 1980).

The objectives of this paper are to look at the possible effects that an increase in particle concentration will have on short-term feeding activity and energy gain, and longer-term consequences for growth and reproduction in scallops. To accomplish this I will use the sea scallop from Newfoundland as the model species because a good database exists for studies on physiological rates and production.

## MATERIALS AND METHODS

The approach in this paper is to use published studies employing techniques of physiological energetics in the field using natural seston with those in the laboratory environment using artificial mixtures of particles to predict short-term energy gain (scope for growth, SFG) under increasing particle concentrations. Predicted impacts of consistent increases in particle concentration on SFG and the long-term consequences on growth and reproduction were projected over a 13-year period.

Seston data for coastal Newfoundland waters were compiled from MacDonald and Thompson (1986), MacDonald and Ward (1994), and unpublished data. Estimates of physiological activity (e.g., clearance, ingestion, absorption efficiency, excretion, respiration, and SFG) for scallops exposed to a controlled range of particle concentrations and organic quality in the laboratory environment and then using natural seston were provided by Bacon et al. (1998), MacDonald et al. (1998), and MacDonald and Thompson (1986), respectively. Production (somatic growth and reproductive output) for various ages of scallops from natural populations in Newfoundland was obtained from MacDonald and Thompson (1985).

## RESULTS AND DISCUSSION

A reduction in clearance rate and production of pseudofaeces was observed in *P. magellanicus*, as also reported for many other species, as a means to regulate ingestion when particle concentration increased (Cranford and Gordon 1992, Bacon et al. 1998). Despite the decline in clearance as concentration increased, ingestion of organic material still increased because it is a product of clearance and organic concentration. In Newfoundland coastal waters an increase in particle concentration from about 2–10 $mg{\cdot}L^{-1}$ resulted in some "dilution" in the particulate organic matter (POM) of the seston from about 60% to approximately 20% (Figure 1). While dilution of seston by particulate inorganic matter (PIM) is quite common, Fegley et al. (1992) reported no such dilution by PIM in Great Sound, New Jersey when concentrations increased three-fold over a tidal cycle. Obviously, whether this "dilution effect" is observed will depend on the location studied and the nature of the particles being added in suspension, and whether it is likely to have any impact on a species will depend on its ability to "compensate" through changes in feeding activity and selection.

Sea scallops have been shown to have the ability to preferentially reject poor-quality particles when exposed to natural assemblages of particles in the field as well as mixtures of algal cells and inorganics in the laboratory (MacDonald and Ward 1994, Bacon et al. 1998). The authors of both of these papers reported that the efficiency with which *P. magellanicus* selected particles decreased as POM decreased. A decrease in selection efficiency as POM decreased was also recently reported for the green mussel *Perna viridis* (Wong and Cheung 1999).

Relationships of SFG for sea scallops exposed to 1, 3, 7, and 14 $mg{\cdot}L^{-1}$ and POM levels of 25%, 50% and 80% derived from MacDonald et al.'s (1998) Figure 4 are presented in Figure 2. Note that a theoretical relationship for 5 $mg{\cdot}L^{-1}$ was added between the 3 and 7 $mg{\cdot}L^{-1}$ values for illustrative purposes. The calculation of these relationships represents the scallop's integrated response (e.g., pseudofaeces production, selection, ingestion and absorption rates, excretion and respiration rates) when exposed to the various experimental conditions. SFG decreases as POM and concentration of the seston decrease. If natural concentrations of seston in Newfoundland increased according to the linear relationship in Figure 1, SFG would follow the solid black line in Figure 2. On the other hand, if concentrations increased according to the power relationship in Figure 1 SFG would follow the dashed black line in Figure 2. While the shape of the SFG relationships may vary slightly, it is predicted that SFG would continue to increase to a maximum of approximately 25 $J{\cdot}h^{-1}{\cdot}g^{-1}$ as concentration increased to 8 $mg{\cdot}L^{-1}$. This would occur despite a drop in POM from about 60% to 20%;

however, further increases in concentration and decreases in POM would result in declining SFG. Note that it is still higher than values recorded at low concentrations and high POM quality.

It appears that in Newfoundland waters the growth of sea scallops is constrained by seston concentration alone. However, we must remember that SFG is a prediction of the energy available to the animal for production based on a series of short-term physiological measurements. In this example these estimates are based on laboratory experiments using mixtures of cultured microalgae and inorganics held at constant concentrations over several days, which may illicit a different type of response than those observed in the field. The maximum SFG value estimated by MacDonald and Thompson (1986) for sea scallops exposed to very low concentrations of natural seston was 6.9 $J \cdot h^{-1} \cdot g^{-1}$. This is comparable to values recorded for the lowest concentration in this study but lower than the maximum

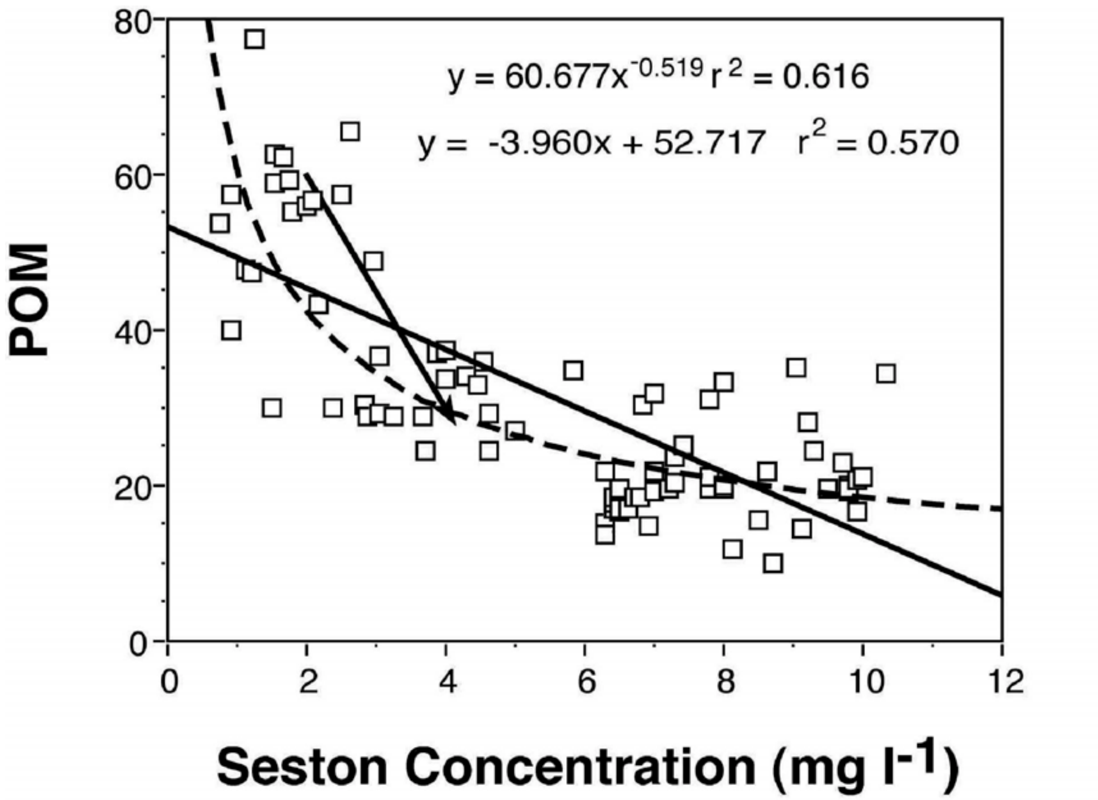


Figure 1. Variation in the percent particulate organic matter (POM) of natural seston collected throughout the year in Newfoundland waters. The solid and the dashed lines represent best fit to the data for the linear and power functions provided on the figure. The arrow represents the decrease in POM (i.e., 60% to 30%) when concentration is increased from 2 to 4 $mg \cdot L^{-1}$ by the addition of 2 mg of inorganic material. See text for details.

predicted. The amount of energy actually spent on the production of gamete and somatic tissue growth measured for these scallops in Newfoundland is approximately 2.5 $J \cdot h^{-1} \cdot g^{-1}$ averaged over the entire year (MacDonald and Thompson 1985). We know that scallops have periods of rapid growth and periods when it is nonexistent or negative (MacDonald and Thompson 1986). Therefore it is not unreasonable to assume sea scallops may have short periods of high SFG (like those predicted in this study) when conditions are more ideal, but they cannot maintain this level of growth over the entire year.

As an example of what impact the addition of low concentrations of PIM could have on the seston concentration in Newfoundland and consequences on SFG, see Figures 1 and 2. For example, the addition of 2 $mg \cdot L^{-1}$ of PIM would change the concentration from 2 $mg \cdot L^{-1}$ at 60% POM to 4 $mg \cdot L^{-1}$ at 30% POM as indicated by the arrow (Figure 1). This change is well

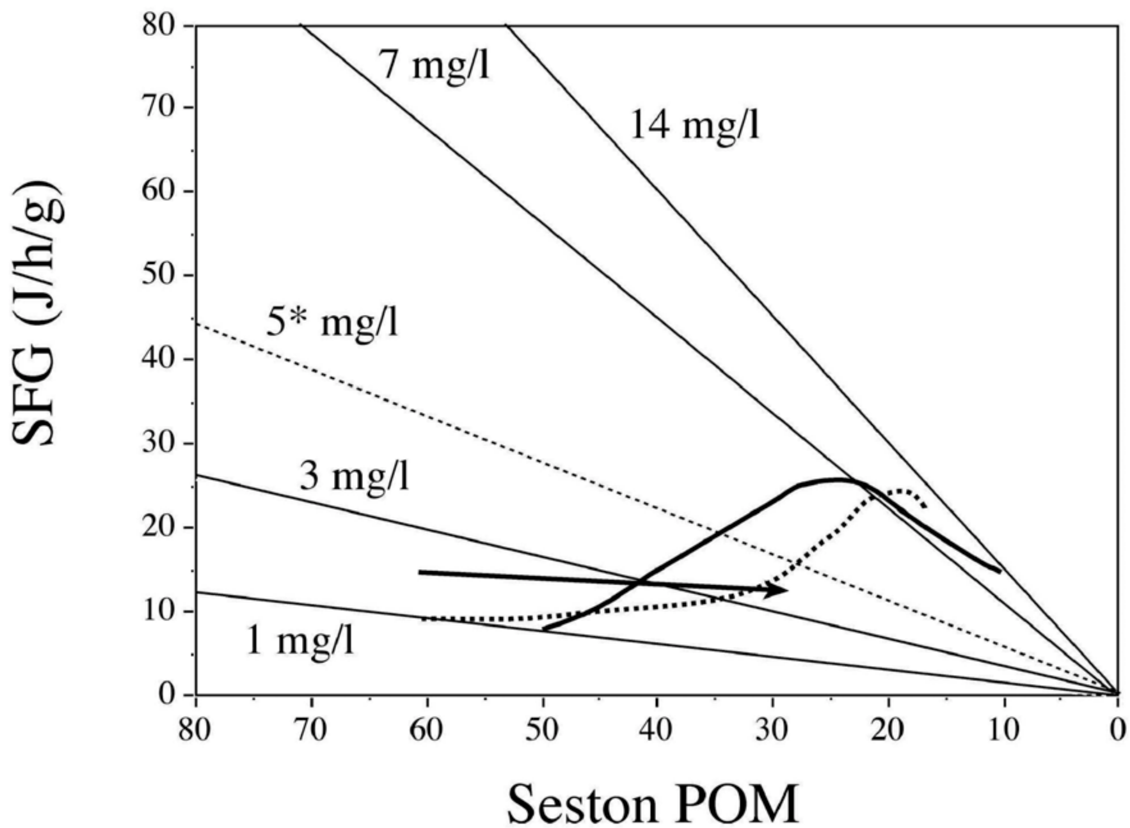


Figure 2. The relationship between scallop predicted scope for growth (SFG), or energy available for production, and the percent particulate organic matter (POM) of various concentrations of seston (from Bacon et al. 1998). Note that a theoretical relationship for 5 $mg \cdot L^{-1}$ was added between the 3 and 7 values for illustrative purposes. If natural concentrations of seston in Newfoundland increased according to the linear equation in Figure 1, SFG would follow the solid line but would follow the dashed line if the seston increased according to the power equation. The arrow represents the predicted change in SFG (about a 5% drop) if seston changes from 2 $mg \cdot L^{-1}$ at 60% POM to 4 $mg \cdot L^{-1}$ at 30% POM.

within the range of conditions the scallops are exposed to and probably happens several times during the year. If we assume it is maintained for a long term then the effect on SFG can be seen by following the arrow in Figure 2. This results in a drop in SFG by approximately 5%, which may not seem like much on the short term, but if it is maintained over a long period it could have a substantial cumulative effect on population production over years (Figure 3a). Total production will continue to drop each year until a 13-year-old scallop will have about 50% less production than it did before the addition of PIM. The addition of even relatively small amounts of PIM could have a major effect on the reproductive output of the scallops (Figure 3). This will have a severe impact on the number of offspring released and negative consequences on recruitment and growth of the population.

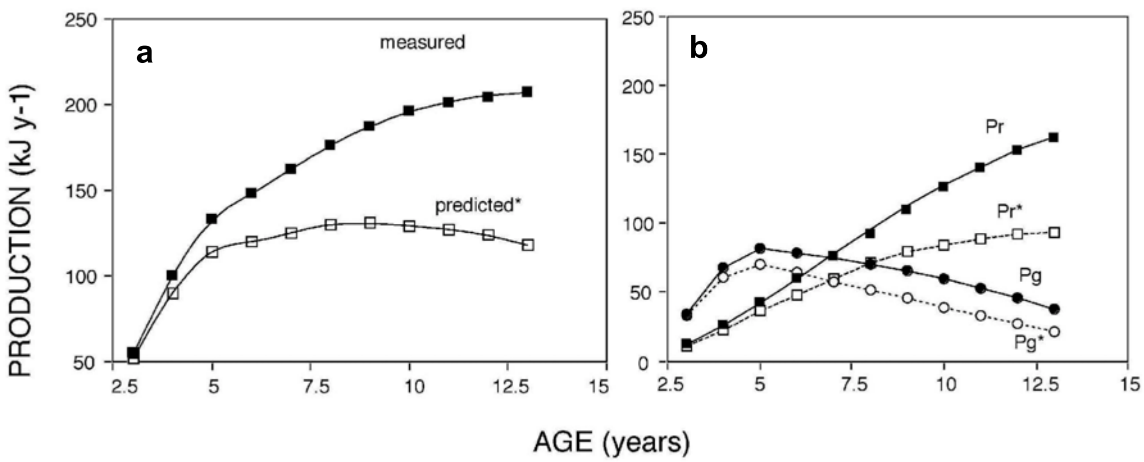


Figure 3. Total production (a), energy spent on growth of somatic tissue (b, Pg) and energy invested in gametes (b, Pr) for scallops from Newfoundland (from MacDonald and Thompson 1985). Predicted* changes in these production estimates if a 5% drop in SFG is cumulative over a period of 13 years.

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# Modelling Approaches to Dredging Impacts and Their Role in Scallop Population Dynamics

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## INTRODUCTION

The dramatic decline in many coastal and shelf fisheries worldwide has focused attention on fishing methods and their potential to impact benthic habitats. These concerns extend to the mortality of target species that do not make up part of the catch but suffer indirect or incidental mortality. There is similar concern about bycatch which may include commercially valuable species. For example, in the context of invertebrate fisheries in Alaskan waters, there are analogous issues that involve dredging for scallops *Patinopecten caurinus* and bycatch of king crabs and Tanner crabs (Shirley and Kruse 1995). The potential habitat alteration caused by mobile fishing gear has been the subject of a variety of recent studies (Hall 1999). It is apparent that the impacts are dependent on sediment type, life history stage, and functional group (infauna, epifauna, etc.; Collie et al. 1997, Thrush et al. 1998). Although some effects, such as the disruption of colonial epifauna, are obvious, questions remain about the implications of fishing practices for the population dynamics of the target species. Despite the goal of optimizing fisheries yields, there are surprisingly few studies which attempt to quantify how gear affects target species. This is a particularly relevant topic for scallop fisheries since the gear is bottom directed (in contrast to some trawls), and the target species is somewhat "delicate" compared to infaunal bivalves, which can burrow or tightly close (Hall 1999). For the scallop example, there are more studies of dredge effects on benthic communities than on scallop populations.

The present paper seeks to quantify some of the impacts of scallop dredging on scallop populations and incorporate them into a yield per recruit model of a scallop cohort for the weathervane scallop *Patinopecten caurinus*. Attempts have been made to utilize life history parameters for this species based on Kruse et al. (2000), but additional information, especially on bioenergetics, has been liberally borrowed from studies of the sea scallop *Placopecten magellanicus*. These models will undoubtedly benefit from the firsthand knowledge of scientists from the Alaska Department of Fish and Game.

The consequences of dredging for scallop populations may be defined in two broad categories: habitat alteration and gear-induced damage and mortality. Habitat alteration involves a broad variety of possible effects, including an array of linkages of scallops to the benthic community, which are poorly known. Gear damage is of more direct consequence to scallop mortality but is difficult to quantify as discussed below.

## HABITAT ALTERATION

There are at least two effects that may be examined in this regard, disruption of settlement substrate for juvenile scallops and resuspension of sediments. The early life history of most scallop species is poorly known, largely due to their small size at settlement. This is more so for the spat of offshore species, which are difficult to sample on coarse bottoms. It appears that byssal attachment is important to most pectinid spat and arborescent structures such as eelgrass and colonial hydroids are known to be significant as settlement substrates. Experiments with Icelandic scallops by Harvey et al. (1993) demonstrated that hydroids collected orders of magnitude more spat than traditionally used monofilament collectors. The implication is that removal of branched epifauna by fishing has a negative feedback to scallop recruitment, but this relationship has not been sufficiently quantified to apply to natural populations.

Sediment resuspension is perhaps the most obvious of bottom-gear habitat impacts and yet the most poorly documented. Despite anecdotal reports of silting in scallops (e.g., Medcof and Bourne 1964), there are no studies for dredges and only a single comprehensive study of trawling impacts on sediment resuspension (Churchill 1989), including a model of erosion/deposition. This work showed that although fishing-induced turbidity was at times significant compared to natural resuspension, the absolute concentrations of suspended sediment were relatively small ($<1\ mg \cdot L^{-1}$). Scallops are generally found in nonturbid waters and the corresponding effects of turbidity on scallops are poorly known. Sea scallops can benefit from organic matter present in resuspended sediment (Grant et al. 1997), although they are sensitive to clay suspensions (Cranford and Gordon 1992). A large variety of bivalve feeding studies demonstrate that excess turbidity decreases clearance rate and increases the production of pseudofaeces. The rate at which clearance falls off with suspended sediment is dependent on species as well as the nature of the suspension. Scallops are likely at the sensitive end of the spectrum.

It should be noted that there are other sedimentary impacts and these are also sparsely studied. Mayer et al. (1991) documented mixing of surface organic matter to sediment depth and the return of reduced solutes to the surface. Yamamoto (1960; in Medcof and Bourne 1964) reports scallop mortality due to anaerobiosis caused by dredge disturbance of anoxic sediment layers. Again, the implications of this sedimentary change for scallops and their niche in the benthic community have barely been explored. As with suspended sediments, scallops are sensitive to oxygen conditions.

The extent and duration of turbidity will depend on sediment type as well as the frequency and depth of disturbance by gear. The most apparent effects will be over mud bottoms where there is abundant fine material available for transport into the water column. On sand bottoms, larger grains will be disturbed by the dredge, but their rapid settling rate ensures that they contribute only briefly to local turbidity. In all cases, scallops ploughed into the sediment by the dredge may have sediment forced into the valves (Medcof and Bourne 1964).

There may be other more subtle gear effects which influence scallop bioenergetics and can be examined in the context of growth rate. Pectinids and a few other taxa are unique in their swimming ability, a response noted frequently in observations of gear performance. Swimming is energetically expensive, although Kleinman et al. (1996) found that adductor condition was enhanced by swimming in juvenile sea scallops. As with feeding inhibition by turbidity, increased swimming has the potential to add deficit to the scallop energy budget and reduce growth, with resultant implications for fisheries yield.

## MORTALITY

Underwater observations of scallop dredges demonstrate a variety of shell damage can occur as a result of noncapture encounters with the gear (Shepard and Auster 1991). Again, considering the potential importance of these encounters to the fishery, there are relatively few directed studies in this area (Table 1). The basic approaches include seeding natural scallop beds with marked (Gruffydd 1972) or unmarked scallops (Shepard and Auster 1991), creating virgin beds (McLoughlin et al. 1991), or monitoring mortality in existing beds (Caddy 1973, Naidu 1988). Depending on the methods used, these studies yield estimates of indirect mortality ($I$) ranging from annual to daily time scales. The extrapolation of a single dredge-contact event to the lifetime of a scallop is difficult since it is dependent on subsequent damage and survival, as well as further fishing effort on the bed.

The general overview that can be gleaned from these studies is that: (1) damage is species-dependent due to variation in swimming, byssal attachment and recessing, (2) damage is substrate-dependent due to differing dredge behaviour on hard and soft bottoms; hard

Table 1. Incidental mortality studies for scallop populations

| Study | Location and species | Gear | Experiments | Results |
|---|---|---|---|---|
| Gruffydd 1972 | Isle of Man *Pecten maximus* | Manx 4-foot dredge | mark–recapture | 10–56%; $(M+I)$ =0.1–0.8 |
| Caddy 1973 | New Brunswick *Placopecten magellanicus* | inshore and offshore dredges | submersible observation | 13–17%; if annual, $I$ = 0.14–0.19 |
| Naidu 1988 | Newfoundland *Chlamys islandica* | inshore and offshore dredges | compare $M$ fished and unfished; cluckers | $I$ = 0.05 (max > 0.3) |
| McLoughlin et al. 1991 | Australia *Pecten fumatus* | Mud dredge, 4.8 m | seed scallops in “new” habitat | 78%–88% indirect mortality $I$ = 1.5–2.1 |
| Shepard and Auster 1991 | Maine *Placopecten magellanicus* | rock rake (inshore dredge) | seed scallops in closed area | 5–25% indirect mortality $I$ = 0.05–0.29 |

substrates cause higher mortality due to lack of refugia (recesses, etc.), (3) size selectivity of the dredge capture is poorly constrained and dependent on gear type and duration of fishing; the exclusion of prerecruits cannot be guaranteed, and (4) incidental mortality ($I$) ranges from values similar to natural mortality ($M$) to several times $M$ and may be the chief source of removal for some fisheries.

## QUANTIFYING IMPACTS THROUGH MODELLING

A simple population model of a cohort's production through its lifetime provides a means to quantify some of the potential impacts arising from fishing. Yield per recruit modelling (see Caddy 1989) uses an overall mortality term to follow cohort numbers through time

$$N_t = N_{t-1} \exp(-Zt), \qquad (1)$$

where $N_t$ and $N_{t-1}$ are population numbers at times $t$ and $t-1$, respectively, and $Z$ is the total mortality coefficient. For annual time periods where $t = 1$, the time term may be neglected. $Z$ may be partitioned as follows

$$Z = F + M + I, \qquad (2)$$

where $F$ = fishing mortality, $M$ = natural mortality and $I$ = incidental mortality. The individual contribution of these terms to temporal decline in cohort numbers proceeds via the catch equation

$$C_a = N_a \exp(-Z)\,(F_a/Z_a), \qquad (3)$$

where $C_a$ = catch at age $a$ and $F_a$ is age-specific fishing mortality. $F_a$ (partial recruitment) is usually considered to be a "knife-edge" function in that recruitment into the fishery at young ages (pre-commercial sizes) is low, increasing to 100% abruptly at the commercial size. $F_a/Z_a$ is the proportion of total mortality due to fishing and $Z$ is age specific when $F_a$ is applied in Eq. 2. There are corresponding terms for other sources of mortality, similar to Eq. 3, using ($M/Z$) and ($I/Z$), although the latter terms are not age specific. $C_a$ multiplied by age-specific biomass (e.g., von Bertalanffy growth) is the yield for a given age; the sum of this yield over the cohort life span normalized to the number of recruits at age $t_0$ is the yield per recruit (YPR). YPR can be plotted versus $F$ to determine a maximum yield as well as other biological reference points (BRP). Because it includes fishing mortality, a single YPR vs. $F$ curve has important management information in it. Rather than focusing on BRPs, I will compare the response of the curve to variation in bioenergetics and noncapture mortality as detailed below.

While it is simple to produce the YPR model in a spreadsheet, use of a graphically based simulation model readily allows interactive changes in model parameters, with immediate graphical results. STELLA software (High Performance Systems Inc., www.hps-inc.com) provides a highly interactive interface in which to examine the response of YPR to various parameters and has been used in the present work. General information on ecological application of STELLA is in Costanza et al. (1998). Grant and Bacher (1998) used STELLA in models of mussel bioenergetics.

Despite the utility of YPR models in regard to partitioning mortality (Mohn 1986), there are few examples of its application to indirect mortality (Kruse et al. 2000). However, coupled with ecophysiological modelling which allows incorporation of nonlethal effects, several impacts can be examined. Among the impacts that can be quantified are decreased growth due to both gear-induced turbidity and increased swimming for avoidance, and increased mortality due to dredge contact for nonlanded animals.

In order to incorporate growth reduction due to turbidity, a STELLA model of scallop bioenergetics developed for *Placopecten magellanicus* was run with a 10% daily increase in turbidity (annual mean = 2.5 $mg{\cdot}L^{-1}$, Grant and MacDonald, unpublished). During scallop dredging, the duration of elevated turbidity is not known, but a 10% increase is a reasonable starting point. The effects of turbidity on feeding in the bioenergetics model are, of course, dependent on parameterization, and in this model the decline in filtration rate with turbidity is fairly steep, as observed for scallops exposed to clay (Cranford and Gordon 1992). Other types of substrates such as phytoplankton and phytodetritus do not display such steep fall-offs (Cranford and Gordon 1992, Grant et al. 1997). The results of tissue growth trajectories (Figure 1) indicate that the 10% increase in turbidity results in a weight decrease of 8% on day 290 (annual peak weight) compared to the default seston level.

The incorporation of increased respiration in the model due to swimming also has uncertainties in that the frequency of swimming to avoid the dredge is not known. Assuming a consistent suspension, turbidity and swimming have a substantial effect on scallop growth with a 23% reduction in peak annual weight (Figure 1).

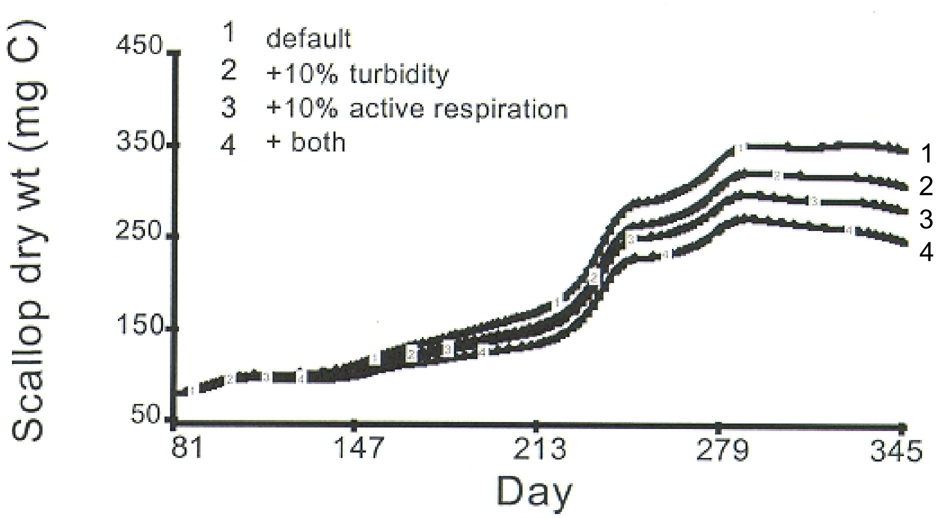


Figure 1. Scallop growth trajectories for different dredging impacts.

These energy budget effects of fishing are now defined in terms of growth, albeit for a different scallop species. They can be incorporated into a yield per recruit model, assuming that growth reduction in Figure 1 can be translated into proportional reduction in the von Bertalanffy *k* parameter. This YPR model uses full recruitment to the fishery at age 3 with partial recruitment of 0.2 and 0.7 for ages 1 and 2, respectively. Natural mortality is set at 0.13 as determined by Kruse et al. (2000). Von Bertalanffy growth is assumed using parameters for *P. caurinus* from Haynes and Hitz (1971). The resulting YPR vs. *F* curves all display a somewhat similar shape with $F_{max}$ around 0.2 (Figure 2). At these fishing levels, yield at $F=0.2$ is reduced by 12% due to turbidity and by 30% due to the combined effects of stress due to both turbidity and swimming. These results indicate that even a relatively small change in scallop bioenergetics can have a major influence on fisheries yield because biomass is negatively affected by dredging impacts on the habitat.

Incidental mortality due to fishing also has a strong effect on the YPR curves (Figure 3) using a low range of values based on the studies in Table 1. Again, increased fishing impact (higher incidental mortality) results in substantial reduction in yield (up to 34% at $F=0.2$ for $I=0.10$). In addition, the curves are less steep with increasing *I*, which reduces the value of $F_{0.1}$. Higher values of *I* cause the curve to become asymptotic rather than descending at greater values of *F*. Incidental mortality removes a significant number of animals at early ages so that yield is maximized with no further consequence of increased fishing pressure.

These examples provide some indication of the usefulness of applying graphical STELLA models to yield per recruit calculations. A STELLA "control panel" allows immediate manipulation of model parameters and their effects on YPR vs. *F* curves. This paper demonstrates that it is feasible to quantitatively include several of the potential impacts on nonyield fishing mortality in the model, including nonlethal effects. Other sources of indirect

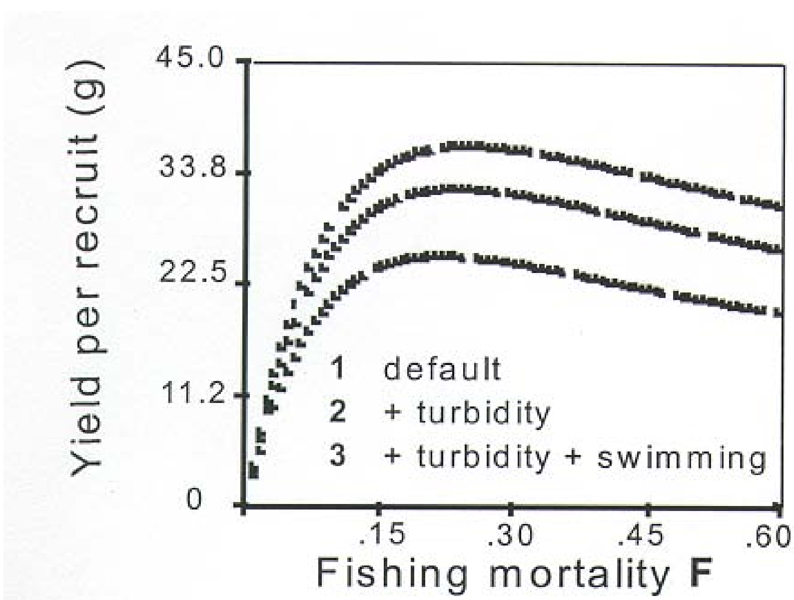


Figure 2. Yield per recruit curves for different dredging impacts.

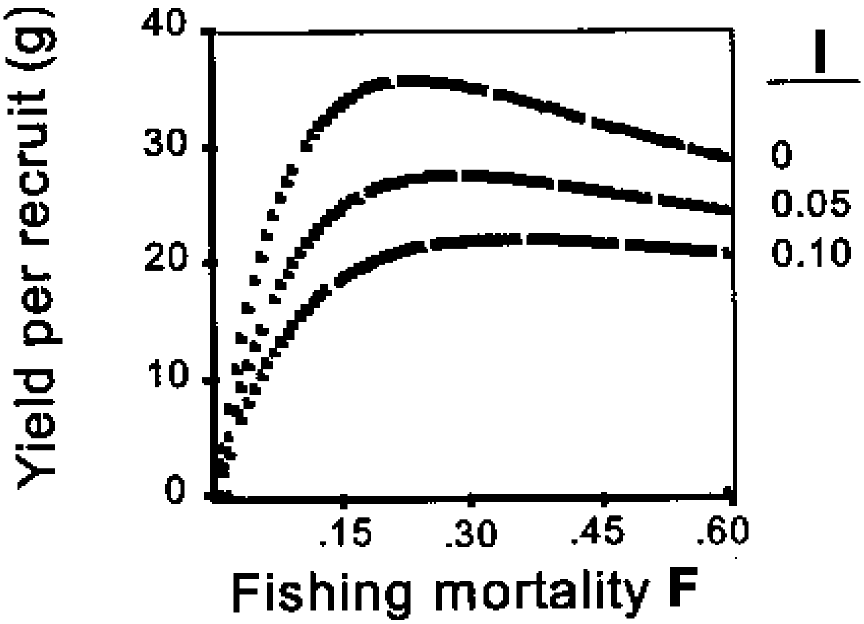


Figure 3. Yield per recruit curves for various levels of incidental mortality.

mortality such as handling mortality of undersize discards (Kruse et al. 2000) can also be examined further. As more insight is gained into the ranges of these effects, the model can readily be modified. The observed regional differences in growth rate for Alaskan populations of *P. caurinus* can be included via changes in von Bertalanffy parameters.

Some specific suggestions for future work relevant to this approach include:

a) assessment of catches, size distribution and growth rate as a function of sediment type to determine whether substrate effects can be detected in yield,
b) examination of regional differences in growth rate in relation to potential environ-mental differences,
c) assessment of shell damage and incidental mortality relative to dredging duration and frequency,
d) further studies of swimming behaviour and feeding ecology to gauge dredge impact, and
e) incorporation of recruitment effects relative to benthic habitat impact using VPA or other stock projection.

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# North Irish Sea Scallop Fisheries: Effects of 60 Years Dredging on Scallop Populations and the Environment

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## ABSTRACT

Over the last 60 years very intensive dredge fisheries have developed in the north Irish Sea around the Isle of Man for the scallop *Pecten maximus* and the queen scallop *Aequipecten opercularis*. Through this period there have been changes in gear type and areas fished, so the modern fishery is based on a series of fishing grounds that differ in the duration and intensity of exploitation, as well as in environmental conditions. Since the scallop populations and benthic communities are both well documented, this provides an excellent opportunity to assess the effects of scallop dredging on both scallop stocks and the environment. Changes in scallop abundance, density, and age structure are discussed, together with bycatch mortalities and benthic community changes in areas of known long-term fishing effort and an area closed to commercial fishing.

## INTRODUCTION

Scallops have been commercially fished in the north Irish Sea, around the Isle of Man, for more than 60 years. Two species are exploited: the scallop *Pecten maximus* (L.) and the queen scallop or queen *Aequipecten opercularis* (L.). *Pecten maximus* is a large species that grows to a shell height of 150 mm or more and has a life span of up to 20 years. It is a relatively poor swimmer and recesses in the seabed, so it is fished with toothed dredges. *Aequipecten opercularis* is smaller, up to about 90-mm shell height, with a maximum life span of 8–10 years. It lives more epifaunally than *P. maximus*, remains a good swimmer through life, and can be fished with dredges or trawls. Together, these two species have dominated the Isle of Man fish catching and processing industry, usually accounting for 80%–95% of the annual first sale value of all fish landings. The proximity of a long-established marine biological station to these commercially important fisheries has ensured that they are amongst the most thoroughly studied and best-documented scallop fisheries in the world (Brand et al. 1991). This paper describes the development of the scallop and queen fisheries, and reviews some of the effects of 60 years of intensive dredging on the scallop populations and on benthic communities.

## DEVELOPMENT OF THE SCALLOP AND QUEEN FISHERIES

The scallop fishery started in 1937 with a few small boats fishing grounds close inshore off the west coast of the Isle of Man. After the war the fishery developed rapidly, more and larger boats joined in each year and new grounds further offshore were exploited. In the early years the individual dredges were comparatively large (3.5–6.0-foot wide) with a fixed tooth-bar, and these were grouped together in “gangs” on a heavy steel towing bar. “Newhaven” spring-tooth dredges were introduced in 1972 (Mason 1983) and rapidly replaced fixed tooth-bar dredges as the normal gear. Then in the early 1980s, individual dredge size was reduced and 2.0- or 2.5-foot spring-tooth dredges have since become more-or-less universal throughout the British Isles. The number of dredges varies with the power of the boat and 4–12 per side is normal, but very big vessels sometimes use larger spreads. These gear developments enabled the boats to efficiently exploit rougher areas of seabed. The start of the queen fishery in 1969 was also a major influence on the exploitation of new scallop grounds. The two species coexist in many areas, so scallops have subsequently been fished in many areas where they occur in densities that would not be viable were it not for the additional queen bycatch. Since the mid 1980s scallop fishing has been taking place on a number of more-or-less distinct fishing grounds all around the Isle of Man (Figure 1a), while queen fishing grounds are mostly to the north, east, and south of the island (Figure 1b).

In the early years of the queen fishery various types of dredges without teeth were tried but Newhaven spring-tooth dredges rigged with shorter, more closely set teeth and smaller ring-diameter bellies were found to be most efficient and have now been generally adopted. Because of the large amount of bottom debris retained by the small-mesh bellies, boats dredging for queens use mechanical riddles on deck to sort the catch. On some grounds bottom trawls are also very efficient at catching queens in the summer months, when the queens actively swim to avoid capture, and some boats trawl for queens for a few months each year (Brand et al. 1991).

Since 1943 there has been a summer closed season for scallop fishing (June–October inclusive) and a minimum legal landing size (110-mm shell length) has been enforced. There are no specific regulations restricting queen fishing, but catches with a high proportion of queens below 55-mm shell height are not usually commercially acceptable. For all boats, there are certain boat and gear size restrictions within the Isle of Man 3-mile territorial zone.

The various scallop and queen fishing grounds around the Isle of Man therefore differ in the historical duration, intensity, and annual pattern of exploitation, as well as in environmental factors such as depth and bottom type. This provides an unusual opportunity to study the long-term effects of scallop dredging on both the scallop populations and the environment.

## EFFECTS OF FISHING ON SCALLOP POPULATIONS

For many fishing grounds a discontinuous series of catch per unit effort data (CPUE, expressed here as numbers of scallops per metre dredge width per hour’s fishing) are available and provide estimates of scallop abundance covering the historical duration of exploitation. Early estimates of scallop abundance on many grounds show initial CPUEs of >150 scallops$\cdot$m$^{-1}\cdot$h$^{-1}$. These fell rapidly on all grounds within a few years after fishing commenced. Since 1981, when detailed CPUE data started to be collected on an unusually small spatial scale (5 x 5-nautical mile grid), scallop abundances have been uniformly low at around 20 scallops$\cdot$m$^{-1}\cdot$h$^{-1}$ on all grounds, but with a general downward trend. CPUE can vary considerably from year to year (usually within the range of 10–40 scallops$\cdot$m$^{-1}\cdot$h$^{-1}$), reflecting differences in both recruitment and exploitation. However, while these variations are of commercial significance, they represent small changes in scallop abundance in relation to the huge changes that followed exploitation of the virgin fisheries.

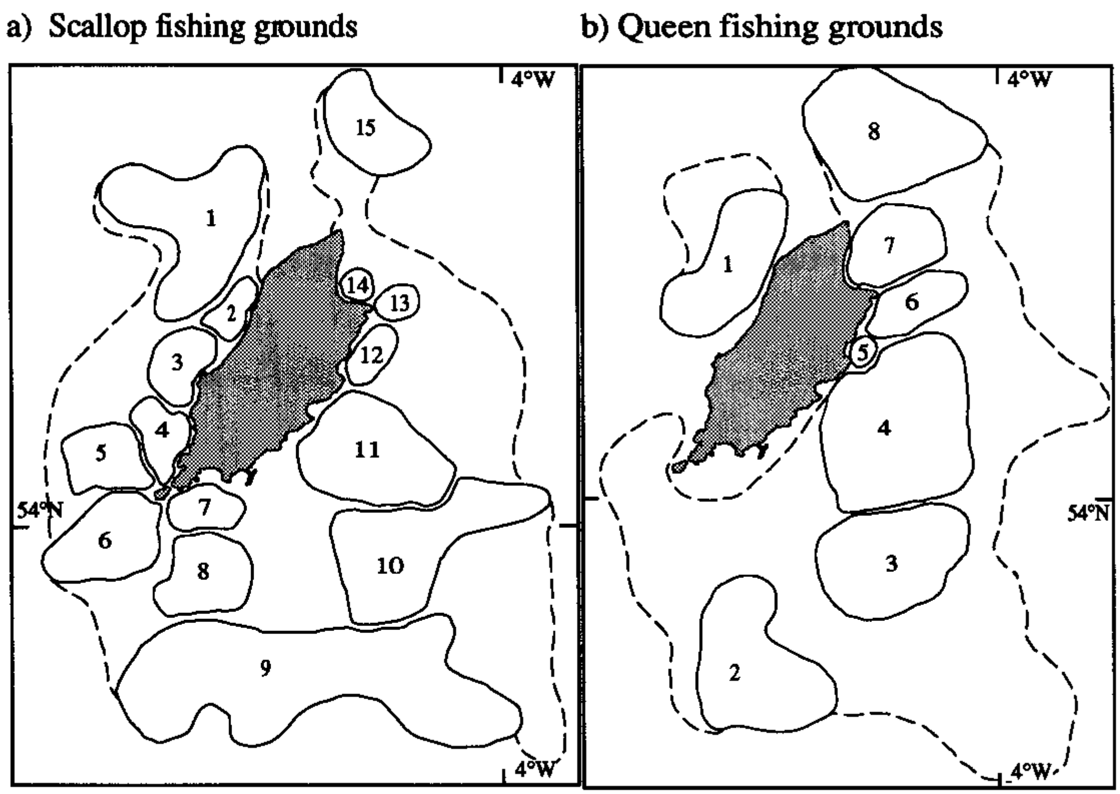


Figure 1. Scallop *Pecten maximus* and queen *Aequipecten opercularis* fishing grounds currently fished around the Isle of Man. Major fishing grounds are bounded by solid lines; a dotted outline indicates areas where scallops occur and are occasionally fished. All boundaries are approximate and many fishing grounds are contiguous. a) Scallop fishing grounds: 1–The Targets, 2–Kirkmichael Bank, 3–Peel Head, 4–Bradda Inshore, 5–Offshore Bradda/West Calf, 6–The Chickens, 7–Port St. Mary, 8–Port St. Mary Offshore, 9–H/I Sector and Offshore South, 10–Southeast Douglas, 11–East Douglas, 12–Laxey, 13–Maughold Head, 14–Ramsey, 15–Point of Ayre. b) Queen fishing grounds: 1–The Targets, 2–H/I Sector, 3–Southeast Douglas, 4–East Douglas, 5–Laxey Bay, 6–Maughold Head, 7–Ramsey Bay, 8–Point of Ayre.

Typical estimates of scallop densities for the Bradda Inshore fishing ground show a long-term decline from 9–20 scallops·100 $m^{-2}$ in the 1950s and 1960s to <7 scallops·100 $m^{-2}$ between 1981 and 1984, <4 scallops·100 $m^{-2}$ in 1986–1990, and <3 scallops·100 $m^{-2}$ in all surveys since then. Low densities of <3 scallops·100 $m^{-2}$ are now typical of most of the inshore fishing areas around the Isle of Man and many of the offshore grounds. For the most heavily exploited fishing grounds, where young scallops dominate the populations, there are large seasonal fluctuations in density. Preseason (October) densities on all the heavily fished grounds are now around 3 scallops·100 $m^{-2}$, depending on the strength of summer recruitment, but fall to about 1.5 scallops·100 $m^{-2}$ by the end of the fishing season. This latter value probably approximates the density that the fishermen currently consider uneconomic; when density falls to this level they move off to fish elsewhere.

For the scallop populations on most fishing grounds, long series of age composition data are available. These show the progressive reliance of the fishery on young scallops as the older age classes become depleted. This characteristic pattern of change is shown as a series of cumulative age frequency curves (Figure 2a) for the Bradda Inshore fishing ground, the longest and most intensively exploited ground in the north Irish Sea. For the last 15–20 years up to 70% of the catch has been 4 years old or less, and mainly below the minimum legal landing size (110 mm). Similar patterns of change have occurred on all the other fishing grounds and scallops of 6 years or older are only present in any quantity on some of the less heavily fished offshore grounds (Figure 2b). Continuous heavy exploitation has therefore lead to stocks dominated by young scallops, high rates of discarding, and fisheries that are highly dependent on the strength of annual recruitment. Fortunately, recruitment in the north Irish Sea has been remarkably consistent from year to year, as indicated by the smooth form of the cumulative frequency curves. Where annual recruitment is less regular, heavy exploitation typically leads to “boom and bust” scallop fisheries (Young and Martin 1989).

## ENVIRONMENTAL EFFECTS OF SCALLOP DREDGING

For the last 6 years a large research programme has studied the environmental impact of scallop dredging around the Isle of Man, including both short-term (hours, days) and long-term (weeks, months) effects (Hill et al. 1997). Three aspects of this work will be considered briefly here: studies of scallop and queen dredge bycatch, comparisons of present benthic communities with a historical dataset, and studies carried out in a closed area.

Detailed studies of the bycatch of scallop and queen dredges have been made on 15 fishing grounds that differ in environmental conditions (depth, bottom substrate, etc.) as well as the historical duration and annual intensity of fishing (both of which are known with some accuracy). Visual assessments of damage, supported by laboratory survival experiments, show that some invertebrate groups are more vulnerable to capture than others. Brittle or fragile animals such as the urchins *Spatangus purpuratus* and *Echinus esculentus*, the brittlestar *Ophiocomina nigra*, starfish *Anseropoda placenta*, and edible crab *Cancer pagurus* all suffer badly in the dredges, while animals with more robust bodies, like the cushion star *Porania pulvillus*, or those with thick shells, such as the gastropod *Colus gracilis* and hermit crabs, have a much lower sensitivity. Queen dredges, by virtue of their more closely set teeth and smaller belly rings, catch and kill a greater number of individuals, species, and biomass of bycatch animals than scallop dredges. Both univariate and multivariate analyses have shown statistically significant relationships between the bycatch assemblage structure and long-term (15-year mean) fishing effort, while associations with other variables such as depth and substrate type are not so strong (Bradshaw et al. *in press*). Prolonged commercial scallop

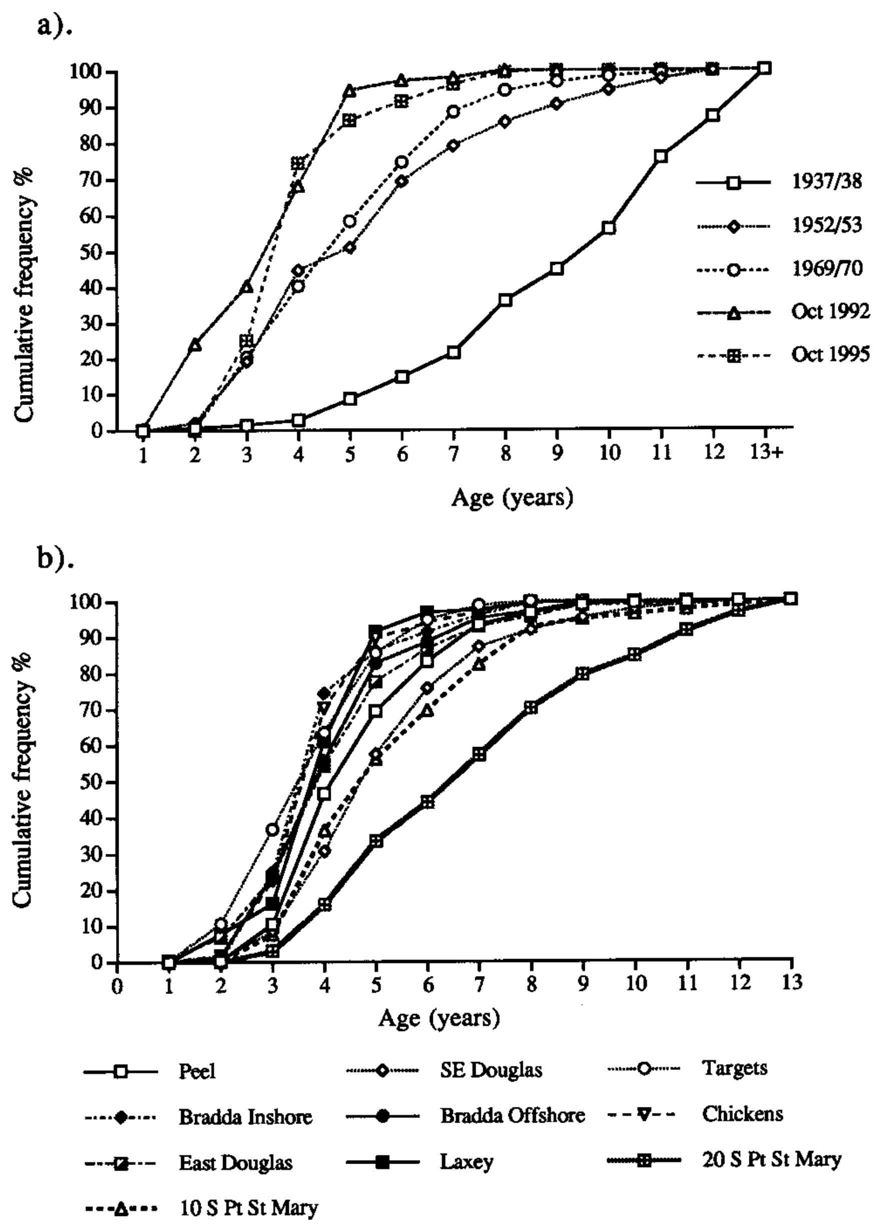


Figure 2. Cumulative age frequency curves for scallops from the Bradda Inshore ground in various years during the development of the fishery (a) and for various fishing grounds in 1995 (b).

dredging has therefore permanently affected community composition.
Detailed studies of the benthic communities around the south of the Isle of Man were carried out during the period 1935–1955, before the scallop dredge fishery started on some grounds (Jones 1940, 1951). Since the original notebooks for these studies are still available it has been possible to reanalyze Jones' original data using modern techniques and to resample some of his sites using similar gear. The differences in benthic community composition between the historical and current samples are remarkable and show comparatively little overlap (Hill et al. 1999). It is not possible, of course, to establish cause and effect since factors other than fishing may have changed over the last 40 years. However, such studies allow us at least to predict the likely effects of fishing on benthic communities and to determine what species or groups may be sensitive to fishing disturbance.

More precisely controlled studies of the effects of scallop dredging have been carried out in a closed area. This fishing exclusion zone of nearly 2 $km^2$ has been closed to commercial fishing with towed gear since 1989; prior to that it was heavily dredged for 50 years, and the surrounding area continues to be one of the most intensively fished grounds in the British Isles (Brand and Prudden 1997). This is a most valuable experimental facility for it has enabled us to study the recovery of benthic communities after the cessation of fishing, as well as to carry out comparative studies of dredged and undredged plots, inside and outside the closed area.

In the natural recovery of the closed area many epifaunal species have increased in abundance including *Pecten maximus*, *Luidia ciliaris*, hermit crabs, spider crabs, brittlestars and upright sessile species such as *Pectinaria koreni*, *Cellaria* spp. and *Polycarpa* spp. Conversely, the predatory starfish *Asterias rubens* has decreased in abundance.

Benthic communities have been compared from experimentally dredged and undisturbed plots within the closed area, and with adjacent plots subjected to high levels of commercial dredging outside the closed area. Multivariate cluster analysis has shown that the benthic communities in the closed area (not dredged for 5 years) were initially more diverse than in the fished areas outside. However, since experimental dredging began in the closed area, the infaunal communities of the dredged plots have become more similar to those of the commercially dredged grounds than to the undisturbed closed area plots. This is some of the strongest evidence in this study showing the effects of dredge disturbance on benthic community structure.

In conclusion, these studies have shown that scallop dredging does affect the benthos in many ways. In general, there is a loss of biodiversity, with more polychaetes and fewer molluscs and other long-lived species, fewer fragile animals like echinoids and certain starfish, and at least a short-term loss of erect filter feeders such as hydroids and bryozoans (which may be important settlement sites for scallop spat). Finally, we have no evidence to support the popular hypothesis that populations of benthic scavengers benefit greatly from bycatch carrion. This is probably because the annual pattern of scallop dredging does not provide a regular food supply for benthic scavengers with limited mobility.

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# Benthic Faunal Species Associated with Scallop Grounds in the Bay of Fundy, Canada

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## INTRODUCTION

Human activities are affecting marine benthic communities that have yet to be fully understood or examined in a pre-disturbance state. As fishing activity is intensive, fairly continuous, and often disturbs a given area more than once in a season, there is likely very little of the sea floor in existence that is representative of an "old growth" benthic community (Auster et al. 1996). Collecting information on species present in scallop drags will identify those affected directly by the fishing process. This information is important in understanding the benthic ecosystem and in making management decisions that support sustainability of marine resources.

The Lower Bay of Fundy is one of the prime fishing areas for the sea scallop *Placopecten magellanicus* and home of the "Digby scallop." It is also an area that supports a wide variety of bottom types within a relatively small area. Caddy (1973) examined both dragging and trawling on scallop grounds in the Bay of Fundy and observed effects on both surficial geology and on the scallop populations. The geological component of the benthos in the Lower Bay of Fundy is comprised mainly of Scotian Shelf Drift, which as described by Fader et al. (1977) is made up of a poorly sorted mixture of sand, clay, pebbles, boulders, and cobbles. Recent work with side-scan sonar, multibeam imaging and seismic techniques has provided insight into the surface topography and stratigraphy of the Bay of Fundy (G. Fader, Atlantic GeoScience Center, BIO, Dartmouth, Canada). Features identified in these images include mussel reefs (referred to as bioherms), shell deposits, sand dunes, ripples of various sizes, fault lines, iceberg troughs, scouring and erosion fields, and inevitably, trawling impacts. The resolution is such that the characteristic paired otter-trawl door tracks can easily be distinguished from those of the multiple "buckets" of the scallop gear. These tracks are locally persistent for over 12 months. Their contribution to the dynamics of the surficial geology within the bay are as yet unknown and is likely to depend upon whether the area impacted is one of erosion or deposition.

Previous studies of the associated species inhabiting scallop grounds in the northwest Atlantic include work in the Lower Bay of Fundy (Caddy 1970, Caddy and Carter 1984), the Gulf of Maine (Langton and Uzmann 1989, Langton and Robinson 1990) and Georges Bank (Thouzeau et al. 1991). Because of the unique physical characteristics of the Bay of Fundy, it is not yet clear whether or not faunal associations and their response to anthropogenic disturbance are the same as in other areas in the Fundy–Maine–Georges larger ecosystem

(Percy et al. 1996). Communities in the sublittoral benthos of the Lower Bay of Fundy have been studied by Logan and Noble (1971), MacKay (1975), Wildish and Peer (1983), Wildish (1984), and Logan et al. (1986).

Benthic species associated with commercial scallop grounds in the Lower Bay of Fundy were inventoried by sorting faunal bycatch during the 1997 Department of Fisheries and Oceans inshore scallop population surveys. Details of this study are reported in Fuller et al. (1998). All tows were made with four-gang gear consisting of drags with an inside width of 76 cm. Known scallop grounds off of Digby, Yarmouth/Brier Island, Nova Scotia, and Grand Manan, New Brunswick were included in the survey. These areas differ in geography and tidal and current influence with respect to their proximity to the entrance of the Bay of Fundy. Exact tow locations can be found in Fuller et al. (1998). Depth ranged from 12 to 152 m (mean = 76 m, standard deviation = 31 m). The contents of 234 tows were assessed and species were recorded on a presence/absence basis providing data both on the frequency of occurrence and distribution. Epifaunal species occurring on the sea scallop *Placopecten magellanicus* were recorded, as well as the level of epifaunal encrustation. A total of 261 taxa were identified to at least family level and often to species level. Thirteen phyla and 131 families were present.

## MAJOR GROUPS OF ORGANISMS FOUND ASSOCIATED WITH SCALLOP BEDS

**Porifera**: A total of 23 species of sponges (Porifera) were identified. Sponges are integral members of the benthic community and provide habitat for hundreds of other species (Klitgaard 1995). Observations from this study and by Caddy (1970) indicate that the area above Digby Gut has high densities of branching sponges. Species included in this assemblage are *Haliclona oculata*, *H. urceolus*, *Isodictya deichmannae, I. palmata,* and *Esperiopsis normani*. Sponges are suspension feeders and thrive in areas of high current velocity. In some areas both diversity and abundance of sponges was high. Two taxa, *Iophon* sp. and *Pseudosuberites sulphureus,* were observed to be growing almost exclusively on the brachiopod *Terebratulina septentrionalis*.

**Coelenterata**: Hydroids comprised a significant part of the benthic community, especially on shell-debris substrates in the area above Digby Gut. Like the sponges, hydroids are frequently overlooked in studies of the benthos. *Hydrallmania falcata, Sertularia pumila*, and *Sertularella polyzonias* were often observed in dense quantities and were also ubiquitous in distribution. Presence of these species provides a niche for other organisms and high abundances of *Ophiopholis aculeata*, *Nymphon* spp., and *Hyas* spp. were found in association with dense hydroid cover. Anemones prefer hard substrates and were generally present in all areas, with the exception of very muddy or sandy tows. They were not the most frequently encountered faunal unit inhabiting the benthic community of scallop grounds off Digby as reported by Caddy and Carter in 1984. Soft corals were also collected.

**Bryozoa**: The most conspicuous bryozoan was the leafy species *Flustra foliacea*, commonly referred to as lemon weed, which was recorded very frequently and in high densities in the Digby area, but rarely encountered in the other study sites. This species appears to be increasing in distribution and fishers acknowledge that trawling impacts its range. The increase in range is associated with a reduction of effort in the area. *Eucratea loricata* was described to be the most abundant branching bryozoan in the Digby area by Caddy (1970). Although this species was often present, it was not abundant in any particular area. The effects of this apparent change in epifaunal distribution on the rest of the benthic community have yet to be studied and may reflect fishing activities or cycles in abundance. Encrusting bryozoans were generally always present in areas with rock and shell debris as substrates. Evidence from Collie et al. (1996) indicates that these organisms were some of the few that were not affected by trawling activity.

**Brachiopoda**: The brachiopod community in the Lower Bay of Fundy has been extensively studied by Logan and Noble (1971), Logan et al. (1975), Noble et al. (1976), and Logan et al. (1986). *Terebratulina septentrionalis* is the only species occurring in the area. Very dense populations of *T. septentrionalis* tended to occur in deeper water, and this species was present most frequently in tows off of Yarmouth.

**Polychaeta**: Drag sampling does not adequately sample infaunal species, and those collected tend to be filtered out as the drag is brought to the surface. Forty-two species of polychaetes were identified at least to genus. The tube building worms *Spirorbis borealis* and *Filograna implexa* were the most frequently observed polychaetes in this study. Both species build calcareous tubes and are found encrusting on both shells and rocks. *Filograna implexa* tends to grow in dense mats inside empty *Modiolus* shells when they are present (this study, Collie et al. 1996). *Potamilla reniformis* and *Thelepus cinncinatus* were associated with *Placopecten magellanicus* in all areas. *Spirorbis spirorbis* was observed to be associated with hydroids, and abundance was directly proportional to hydroid abundance.

**Molluscs**: The most frequently observed mollusc was the sea scallop *Placopecten magellanicus*. Population and demographic survey results for the scallop grounds discussed in this report are available (Kenchington and Smith 1997, Kenchington et al. 1997). Fifty other species including mussels, chitons, moonsnails, and whelks were also present. The waved whelk *Buccinum undatum* and the wrinkle whelk *Neptunea lyrata decemcostata* were by far the most abundant and frequently occurring gastropods in all study sites. In all study sites gastropod diversity was highest in sand/gravel substrates.

**Cephalopoda**: The most common cephalopod was the small spoonarm octopus *Bathypolypus arcticus* found in deep water areas in both Digby and Grand Manan. Recent research efforts have investigated the biology of this species in this area (Wood et al. 1996, 1998).

**Crustacea**: Although the sampling method was far from optimal for assessing the amphipod component of the benthos, several species were collected and identified in this study; fewer isopods were recorded. The most commonly occurring species were *Leptocherius pingius* and *Erichthonius* spp. All belong to the Aoridae family, which are tube and nest dwelling (Bousfield 1960) and therefore tend to reside in the sediments as opposed to inhabiting the hyperbenthos. This makes it more likely to catch such specimens in drag and grab samples. The corophid *Unciola irroratus* was also collected often, and is tube dwelling as well. Several species of Caprellidae were collected; *Aeginina longicornis* and *Caprella* *septentrionalis* were most commonly observed. High densities of both species were observed in association with branching sponges *Halichondria panacea* hydroids, and in the interstices of sandy substrate. Caprellids tended to be attached to emergent epifaunal species like sponges and hydroids. Both *Cancer borealis* and *C. irroratus* were recorded from all sites and all substrate types, and presence did not appear to be affected by depth. *Hyas araneus* and *H. coarctatus* were most abundant in association with hydroid and sponge epifaunal communities. Specimens often had sponges, hydroids, and barnacles colonizing the carapace. The hermit crabs *Pagurus acadianus* and *P. pubescens* were ubiquitous and particularly abundant in the area of highest gastropod density (an abundance of shells for houses). Lobsters were also captured.

**Echinodermata**: The echinoderm distribution found in this study is very close to that illustrated by Caddy (1970). *Solaster papposus, Henricia* spp., *Ophiura sarsi, Cucumaria frondosa*, and *Strongylocentrotus* have all been described as having the ability to survive strong flow and abrasion (Ursin 1960). All require hard substrate to attach to as movement of tube feet over soft substrate is difficult. The most frequently observed sea cucumber was *Cucumaria frondosa*, the orange-footed sea cucumber. This species was associated with rocky substrates in all three study sites and is being commercially harvested in New England. Other species of holothuroidians were collected.

**Chordata**: Many more species of ascidians, commonly referred to as tunicates or sea squirts, were observed in the Grand Manan site than in any other site. The stalked ascidian *Boltenia ovifera* was locally abundant, clogging the gear during one tow. Several specimens were observed to have sponges, hydroids, and other epifaunal species encrusting the stalk. *Cliona intestinalis* was observed colonizing the insides of dead *P. magellanicus* shells.

## EPIFAUNAL OCCURRENCES ON SCALLOP SHELLS

Caddy (1970) suggests that the distribution of epifaunal species occurring on *P. magellanicus* shells is directly proportional to the distribution of the scallop. No epifaunal species recorded in this study occurred exclusively on the sea scallop. The larger scallops tended to have a greater number of species growing or occurring on their shells. A total of 49 species were recorded drawn from the Porifera, Hydroida, Nemertea, Brachiopoda, Bryozoa, Polyplacophora, Pelecypoda, Polychaeta, Crustacea, Echinodermata, and Chordata.

## COMMUNITY ASSOCIATIONS AND SURFICIAL SEDIMENT

It is important to consider substrate when discussing community structure, and substrate alteration has a marked effect on community composition (Caddy 1973, Schneider et al. 1987, Thouzeau et al. 1991, Auster et al. 1996, Collie et al. 1996, 1997). The process of dragging often covers large areas of the benthic habitat and tends to reduce topographical complexity and niche diversity (Auster et al. 1995, Anonymous 1996, Auster et al. 1996). Although substrate type does not fully account for variability in benthic community composition in this study, there is evidence that certain functional groupings can be made based on surficial sediment type (Peer et al. 1980, Schneider et al. 1987).

## EMERGENT EPIFAUNA

Studies in other areas have investigated the role of epifauna in providing biogenic habitat structure and shelter for other benthic species (Witman and Sebens 1990, Auster et al. 1996). A recent study in the Faroe Islands found 242 epi- and infaunal species associated with 11 species of sponges (Klitgaard 1995). Similar studies in the Bay of Fundy may yield increased species data as well as assess the ecological importance of epifaunal species that are susceptible to disturbance. It was noted in the Bay of Fundy that toad crabs (*Hyas* spp.), brittle stars (*Ophiopholis aculeata*), and blood stars (*Henricia* spp.) were more abundant when sponges and hydroids occurred in large amounts. Caprellids and several species of amphipods were most abundant when associated with branching sponges, and *Spirorbis spirorbis* and sea spiders were specifically associated with hydroids (Fuller et al. 1998).

Collie et al. (1996) found a significant decrease in emergent epifauna in dredged areas in the Gulf of Maine and also state that emergent colonial epifauna provide important habitat for several benthic species (Collie et al. 1996). The role of emergent epifauna as a significant part of the benthic habitat has yet to be fully understood in the Bay of Fundy.

## CONCLUSIONS

Comparison to past studies of this area shows little apparent change in benthic macrofaunal species composition over a period of 30 years despite an increase in fishing effort. Why is this? The area has been actively fished for scallops for almost 50 years, thus it is possible that both studies examined fauna representative of a disturbed community. The Lower Bay of Fundy is also a high-energy environment and the benthos is subject to extreme tides and currents. The extant fauna in the area may already be adapted to high levels of disturbance caused by the tidal regime against which the impacts imposed by trawling are reduced in significance. This is not to say that the 30 intervening years of trawling, trapping, and dragging has had no impact on the marine benthos in this area. Many species were encountered only rarely, including one previously unidentified species of sponge. The data were insufficient to describe quantitative declines in abundance over this time period, although some obvious changes as noted above for the bryozoans and anemones were observed. And of course, trawling has had a tremendous impact on the scallop beds themselves, many of which are at the lowest levels of abundance since the 1970s.

The preservation of marine biodiversity is now viewed as one of the major aims of conservation. Today, the integrity of entire coastal ecosystems is threatened as a result of human activities (e.g., Beatley 1991), and public concern has prompted governments to adopt new policies to protect natural resources for humanity. The economic value of "non-commercial" species has recently been focused on the tremendous potential associated with new products for medical, pharmaceutical, and biotechnological applications. The economic success associated with relatively recent discoveries such as *Taq* polymerase, an enzyme discovered from hyperthermophilic bacteria living in deep-sea vents (estimated annual sales of US$100 million), and new cancer-fighting drugs derived from molluscs and bryozoans that are currently in preclinical and clinical trials, have been invaluable in directing public attention to the importance of protecting marine diversity for the future (de Fontaubert et al. 1996). Most of our fishing activities are affecting species other than the target species. While measures have been taken to restrict or eliminate the bycatch of other commercial species (e.g., the Nordmore grate to eliminate redfish bycatch in the shrimp fishery), little attention is paid to the bycatch of species which have no immediate commercial potential. The 261 taxa that were collected from the scallop drags in this study are all directly influenced by scalloping.

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# Problems in the Coastal Zone: A Generic Case for Marine Protected Areas

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**ABSTRACT**

Coastal zones are usually managed with two main objectives: (1) conservation/maintenance of biodiversity and intrinsic ecosystem services and (2) maintenance of sustainable fisheries. The management needs that can be met with marine protected areas fall into corresponding categories. First, fully protected (that is, no-take) reserves—parks—offer benchmarks and protect ecosystem integrity while encouraging research, education, and aesthetic appreciation of nature. Second, by allowing focused local control of human impacts, marine protected areas can be used to focus more intense local management designed to increase yield and allow research to help define sustainability and protect against uncertainty by using carefully managed fisheries as a research tool. We have been gambling with the future by establishing a poor balance between short-term profit and long-term risks. The absence of meaningful, fully protected reserves has produced a situation in which there are virtually no areas north of the Antarctic in the world's oceans that have exploitable resources where scientists can study natural marine systems. In most areas the higher-order predators and many other important species have been virtually eliminated; many benthic habitats have been much changed by fishing activities. Without solid data documenting changes through time, the relative merits of various causes and effects that operate in complex ecological systems can always be argued. Without natural systems important questions cannot be studied—for example, how the ecosystem roles of various species can be assessed, how they can be managed in a sustainable manner, and how we can evaluate resilience or relative rates of recovery. Networks of fully protected reserves could facilitate research into such questions, contribute to the recovery of many coastal systems, and enable society to enrich its existence by observing species that should be part of its heritage (Murray et al. 1999). The use of marine protected areas as fishing refugia has met strong resistance by fishers and many managers, and it is misunderstood by many conservation biologists because different proponents have different, usually simplistic, visions. It is important to spell out the objectives of each proposed example. Our essential habitat perspective emphasizes that each situation depends on specific life-history parameters and emphasizes critical thresholds in population dynamics, including density and behavior for fertilization, transport processes, settlement, survivorship, and growth to maturity. These are extremely difficult problems, and we cannot expect simplistic solutions to be effective. The only basis for optimism is that most of the seriously affected species are not yet extinct, and we still have a little time to establish permanent fully protected reserves to allow mankind to appreciate its rich but much depleted biological heritage. At least in some systems recovery can be measured over short time scales

(<10 yrs), whereas others are much slower. Society as a whole is the ultimate stakeholder, not only the commercial and sports fishing industries that so dominate the public arena. Society will have to play a more active role if these species and habitats are to be saved.

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The abstract from that paper is reprinted here with permission from the *Bulletin of Marine Science*.

# PART II: THE WORKSHOP

## Research Needs for Preserving Scallop Stocks and Scallop Habitat

At the conclusion of the keynote lectures, a two-day workshop took place. The focus was to identify research needs for preserving scallop stocks, habitat, and fisheries. Participants were divided into working groups, after which they presented and discussed their recommendations. The program committee integrated the findings of the two working groups into the following document. Ten key questions were identified. For each question we present the rationale, research studies suggested to address the questions and comments, and considerations relative to those studies.

### Question 1. How does spatial distribution (distance of its nearest neighbor) affect fertilization success?

Rationale

A key factor in successful scallop recruitment is having a high egg-fertilization rate. Scallop gametes are broadcast into the water and rely on currents to mix sperm and eggs. Because of the dilution of the sperm, males and females need to be close to one another for successful fertilization. Therefore spatial distribution is critical.

Suggested Research Studies

- Laboratory fertilization trials to determine the effects of distance, dilution, and time to fertilization
- Measure fertilization success in the field
- Measure synchronization of spawning in the field
- Model fertilization probabilities and the effects of fisheries on them

Comments and Considerations

- Distribution is patchy: develop tools for measuring micro- and macro-scale distributions
- Compare spatial distribution of adults on fished and unfished beds during spawning
- Determine if there is interannual variation in the spatial distribution of adults
- Measure local current and temperature profiles over several years
- Determine the stimuli that trigger spawning (e.g., temperature, phytoplankton metabolites, sperm as an egg-release trigger)
- Critical density: Allee effect. Is there a critical density for successful spawning?

**Question 2. What is the reproductive output of individuals relative to weight, size, and age?**

Rationale

The reproductive output of large females is considerably higher than that of recently matured females. Females curtail reproduction when they get to be very old. Thus, size and age structure of the population is important for determining reproductive success. The current harvest strategy removes the most fecund females by selecting for larger individuals. The consequence of harvesting these large females is not understood.

Suggested Research Studies

- Conduct laboratory studies that measure reproductive output relative to weight, size, and age
- Conduct field studies of reproductive cycle with size, age, and location components
- Construct models linking reproductive output with fertilization success in different areas
- Construct models linking reproductive output with fishing activity

Comments and Considerations

- Consider both the number and quality of gametes produced by size and age
- Seasonal cycles: gonads, meat weight, lipids, water content
- Gonad reabsorption and factors responsible for it
- Collect monthly samples of GSI (gonad–somatic tissue index) to develop seasonal cycle. Quantify using stereology (quantify cells by type over time), a technique that would also demonstrate reabsorption
- Are there years when no spawning occurs? If so, what are the conditions that lead to it?
- Does fractional spawning occur? If so, is it a function of size?

**Question 3. Where and when do spat settle, and what constitutes nursery areas?**

Rationale

Protecting juveniles is critical to the survival of any harvested species. The spatial relationship between adult and juvenile distributions is unknown. Identifying and protecting nursery areas are commonly used management tools to preserve a resource.

Suggested Research Studies

- Collect information from population surveys and fishery observer programs including benthic and epibenthic species present, and geologic and biogenic structures where juveniles occur
- Identify habitat preferences through laboratory experiments (e.g., temperature, salinity, and food).

- Examine stomachs of potential scallop predators to identify mortality sources and relate to the timing of settlement
- Identify food type and size for larval survival
- Estimate larval duration and growth to determine when spat settle
- Identify oceanographic features that may retain larvae (e.g., fronts, gyres, eddies, currents)
- Develop a larval drift model

Comments and Considerations

- Develop methods to define where settlement occurs. Laboratory component: use alternative substrates (e.g., filamentous algae, hydroids) for settlement. Field component: add substrates to field sites to compare settlement success; use scuba dive depths for in situ settlement experiments (easier to recover substrates)
- Consider metapopulation structure such as areas with consistent settlement versus areas of chance settlement
- Identify positive and negative effects of coexisting species on survival of scallop recruits
- Is there a density-dependent effect on settlement and survival of juvenile scallops?
- What species are optimal prey? What prey size and abundance are optimal as food for juveniles?
- Determine if different parental stocks contribute to settlement in a given bed in a particular year using genetic techniques
- Can we develop a habitat suitability model for juvenile scallops?

**Question 4. After settling, what movement behaviors are critical for survival of juvenile and adult scallops, and are these behaviors altered by dredging?**

Rationale

The distribution of scallops is critical to reproductive success. Dredge fishing alters the distribution of juvenile and adult scallops. The consequences of this redistribution are unknown, but in adults it may reduce fertilization success. Anecdotal evidence indicates large movements of scallop aggregations sometimes occur.

Suggested Research Studies

- Investigate the scallop's capacity for movement
- Measure the distance a scallop can swim per unit time as a function of size and season
- Is the scallop's capacity for movement altered by the effects of dredging?
- What are the effects of handling, aerial exposure, being discarded (e.g., righting response)?
- If juvenile and adult distributions differ, how and when do juveniles migrate into the adult areas?

- Observe movements relative to sediment type, predators, currents (velocities, direction, eddies, gyres), and fishing gear
- Determine if scallops move to reaggregate after disruption

Comments and Considerations

- Determine the timing for byssal detachment
- Investigate natural movements during spawning and after dredging using tools like video, sonic tags, and ID tags
- Do scallops increase nearest neighbor distances when densities are high to avoid competition?
- Do scallops decrease nearest neighbor distances when densities are low to improve fertilization success?

**Question 5. What factors determine growth rates of scallops?**

Rationale

Growth rates determine age of recruitment and potential yield to the fishery. There are geographical differences in growth rates that may be related to physical conditions, primary production levels, scallop densities, or genetic characteristics.

Suggested Research Studies

- Determine physical factors that affect growth: temperature/salinity, turbidity, seasonality, storm activity
- Determine biological factors that affect growth: metabolism, food, maturation, genetic (stock) effects on physiology, injury, age, and population density
- Develop a bioenergetic model for growth rates of weathervane scallops

Comments and Considerations

- Why are there differences in growth rates between populations, areas and years (e.g., genetic and/or environmental factors–Yakutat versus Kodiak weathervane scallops)?
- Quantify energy allocated to metabolic rate, shell, meat, and gonads over time
- What is the nutritional value of the water column versus resuspended carbon?
- Measure available carbon using sediment traps
- What is the effect of Alaska’s short spring bloom on food availability?
- In field studies consider the effects of shell damage on growth (e.g., monitor during surveys and by observers)

**Question 6. What are the effects of fishery-induced injuries and handling on mortality?**

Rationale

Dredging can damage scallops, some of which are not brought to the surface. Management strategies need to incorporate this mortality but currently do not for lack of data.

Suggested Research Studies

- Fishery discards
- Injured or disturbed but uncaptured scallops (e.g., lethal versus sublethal, acute versus chronic)

Comments and Considerations

- Contrast live scallops with the fouled shells of dead scallops in catch versus independent survey to evaluate vulnerability to gear
- How reliable are harvest records?
- What are the effects of other fisheries and their gear (e.g., pots, otter trawls) on scallop stocks?
- What are the age- or size-specific rates of mortality related to fishery-damaged scallops recently recruited into the population?

**Question 7. What is the natural mortality rate of scallops from recruitment into the fishery onward?**

Rationale

Management plans predict natural mortality so sustainable harvest quotas can be set. For scallops natural mortality rates are poorly understood. Mortality rates probably differ with locality, age structure, local physical conditions, and benthic community structure.

Suggested Research Studies

- Specific locations at several fishery and closed areas
- Annual variability at several fishery and closed areas
- What are the factors influencing natural mortality?

Comments and Considerations

Information needed to determine natural mortality rate:

- Physical conditions of habitat
- Age structure
- Predator prevalence and their abundance
- Food
- Disease
- Parasites
- Boring animals and epifauna

- Evidence of mass die-offs based on abundance of "clappers" (dead scallops that are still joined by the hinge ligament)
- The length of time clapper hinges stay intact in specific areas

**Question 8. What factors affect recruitment of scallops?**

Rationale

Viable fisheries depend on populations with abundance levels that allow harvest. Population abundance trends are dictated by recruitment. Interannual variability and recruitment depend on environmental processes, which are modified by fishing. In scallops, recruitment is periodic.

Suggested Research Studies

- Compare differences in recruitment between fished and unfished beds
- Identify sources and sinks, at the bed level, of recruiting scallops
- Consider indirect effects of fishing through enhanced settlement, predation, disease, and other factors
- Examine the member–vagrant theory and the ocean factors influencing it
- Develop age-structured models of the populations to estimate recruitment
- Develop methods to estimate juvenile scallop abundance using bottom-sampling devices, surveys of predator stomachs, submersibles
- How does the timing of dredging affect recruitment success (pre- and post-settlement)?
- Contrast recruitment indices from different areas using age data

Comments and Considerations

Information needed to quantify recruitment:

- The role of stock density and spatial distribution on recruitment
- The effects of environmental factors (e.g., food availability, predation, and advection) on the larval stage of scallops
- The effects of habitat quality, predation, and disease on juvenile survival
- Optimal habitat quality for recruitment
- Develop a recruitment model to identify critical life stages and causes of mortality

**Question 9. What is the effect of scallop dredging on the benthos?**

Rationale

Dredges alter the structure of the sediment and topography, kill some species, and displace others. Many species affected are commercially important or important prey of other commercially important species (e.g., shrimp, crabs, groundfishes). Dredging may lead to both short- and long-term detrimental consequences for scallops and associated species.

Suggested Research Studies

Geochemical studies need to be performed to:

- Determine how dredging affects geochemical (including organic content) and physical attributes (e.g., topography) of the bottom
- Determine how dredging affects water-column or interface turbidity
- Compare the effects of dredging to natural disturbance (e.g., tidal currents, storm events, runoff from land)

Ecological studies need to be performed to determine:

- Dominant infaunal and epifaunal benthic species and their relationships by bottom type
- How dredging affects benthic mobile epifauna and groundfish (e.g., crabs, flatfishes)
- How dredging affects sessile epifauna (e.g., hydroids, bryozoans, and long-lived species)
- How dredging affects the infauna community structure and successional events
- How dredging affects faunal patchiness within these communities
- What are the consequences of the frequency of dredging on benthic communities?
- What are the consequences of the amount of area dredged on benthic communities?
- Which species settle first into a disturbed area?
- Which predators benefit from dredging?

Comments and Considerations

- How do you separate anthropogenic from natural change?
- Does dredging affect physical, chemical, and biological parameters in the same direction as natural disturbances?
- Monitor boring sponges and other species that damage shells via surveys and fishery observers; examine archives of old shells for evidence of boring damage
- Monitor parasites and diseases of scallops before and after dredging
- Develop a food web for open and closed areas
- Develop photographic documentation of benthos for open and closed areas
- Examine “unobserved” gear damage and mortality by counting numbers of damaged scallops and other benthic fauna after pass of gear and compare closed areas
- Determine which parameters should be measured to assess changes after dredging (e.g., choose indicator species representative of different temporal scales of change: short-term = opportunistic polychaetes; long-term = sponges, anemones, hydroids, bryozoans, bivalves). Assess how these species respond to change
- Should marine protected areas be chosen for closure to distinguish natural and man-made change?
- What are the characteristics of the benthic environment that support a long-term scallop fishing bed?

- How do you evaluate habitat and associated faunal changes (e.g., what is “good” and “bad” from a societal standpoint)?
- What are the effects of discarded shells on faunal structure and recruitment of the benthos?

**Question 10. What are the considerations for developing harvest strategies of scallops?**

Rationale

In several scallop fisheries around the world overfishing and significant alterations of the benthic community have been demonstrated. The following suggestions may serve to avoid the mistakes in other fisheries and capitalize on successful harvest strategies. It is important to learn from the worldwide experiences associated with various scallop species and the fisheries for these species.

Suggested Research Studies

Beyond the ecological considerations mentioned in this document the following should be addressed and understood in the development of harvest strategies for scallops:

- Stock size relative to the unfished population
- The scallop distribution and proportion of their habitats fished
- How many year classes support the fishery?
- What is the applicability of traditional harvest models for scallops?
- What harvest level or rate is sustainable?
- Is MSY (maximum sustainable yield) appropriate?
- Determine if there are several scallop beds with different abundances in a management area
- What is the appropriate unit for a management area? Is it at the level of a bed or larger?
- Need to consider the effect of scallop removals on spatial distribution relative to critical density
- Size versus age limit: What is optimum age or size of harvest given meat yield and reproduction?
- What are the effects of area closures and rotation on scallop recruitment?
- What is the unit stock, and where do the recruits come from?
- Should areas with persistent recruitment be set aside as nurseries?
- Can we set aside areas of broodstock for fishery enhancement?
- Do different year classes come from different parental sources?
- What is the heritability of growth, and does the fishery affect growth?
- What is the best season for fishing?
- Consider dredge efficiency and estimates of population size, removals, and unobserved mortality
- Develop model of stock–recruitment, growth, survival

Comments and Considerations

- What is the appropriate size and placement of marine protection areas?
- Select self-sustaining productive scallop beds for marine protected areas
- Are fishing seasons related to seasonality in growth, reproduction, and larval recruitment?
- For the weathervane scallop consider using the Kamishak Bay (Cook Inlet, Alaska) stock to model natural and anthropogenic effects

The current management strategy for Alaskan scallops and many other scallop fisheries uses registration areas, annual harvest guidelines, seasonal closures roughly based on spawning cycle, and bycatch limits. The management strategy should consider patchy or nonrandom distribution of scallops on varying spatial scales. Scallop experts throughout the world consider this to be an important feature in conserving the resource because broadcast spawning is the mode of reproduction. For example, white abalone, another broadcast spawner, is nearly extinct because spatial distribution was not considered in its harvest strategy. Some potential tools to set harvest guidelines would be harvest site rotation or closures, "no fishing" reserves, and harvest based on abundance and the degree to which individuals need to aggregate for successful reproduction. The size and age structure of populations in a harvest area and the seasonal biological events key to the recruitment process have to be considered in the management strategy. Guideline harvest ranges must be set using fishery-independent data on abundance and spatial distribution. They also must incorporate losses due to discards, mortality, and mortality of those injured or disturbed, but uncaptured, on the bottom.

In addition, the management strategy should consider the habitat for coexisting species, some of which are not economically important. To do this a value system has to be created to judge the consequences of habitat disruption. Examples of potential currencies to accomplish this task are biodiversity, genetic diversity, or economic values.

## Recommendations Identified by the Working Group

### 1. Long-term environmental and biological monitoring programs

Rationale

Changes in marine ecosystems may occur over decadal time scales, and monitoring studies should be designed accordingly. It is difficult to assess the implications of a disturbance to marine ecosystems. For example, it may take a long period of time for a community to stabilize if the dominant species has been artificially removed and another species inhabits its niche. This may be occurring in the areas of scallop populations in the Gulf of Alaska and the Bering Sea.

Suggested Environmental Monitoring Programs

- Assess long-term sediment structure via acoustic-based profiles and chemical properties of sediment
- Establish long-term oceanographic monitoring at standard stations. Data collected at stations should identify currents, gyres, eddies, fronts, turbidity, phytoplankton composition and dynamics, carbon flux to bottom, food supply, boundary layer flow, temperature, and benthic faunal structure

Comments and Considerations

- Measure oceanographic features that could explain larval retention, advection to explain bed shape, and distribution of juvenile and adult scallops
- Look at physical and biological features needed for larval survival
- Look at physical and biological features at shallower and deeper depths on each side of scallop beds to help explain scallop distribution
- Juvenile redistribution: compare settlement sites to adult distribution (mindful of differential survival)
- Oceanographic study: ocean stability and advection on phytoplankton concentrations and larval dispersal and retention mechanisms
- Retrospective analysis: consider index of storm intensities, other measures to correlate to year class success; use Kamishak Bay as a model site for analysis (age data available since 1983); use old and new observer data

Suggested Biological Monitoring Programs

- Start a long-term archive of shells and soft tissues from identified beds
- Spatial distribution and abundance of scallops beds
- Are there “reserves” in unfished areas or margins of fished areas?
- Monitor long-term changes in age and size structure
- Need to monitor and document changes in fishing gear efficiency, selectivity, and catchability (e.g., ring size, bag size, etc.), and their effects on habitat

Comments and Considerations

- Long-term sampling does not have to be carried out continuously, it may have several year gaps in data collection cycles.

- Need to sample in areas other than the fishing grounds
- Need to use gear other than those used in the fishery (e.g., video and laser-line scanning)
- Need for genetics studies
- Need to monitor oceanographic features

## 2. Document the present state of gear technology used to prosecute this fishery

Rationale

Scallop dredge design has changed over time as technology has advanced. The fishing parameters of this gear are not clearly understood. To determine the effects of fishing gear it is vital to know the gear efficiency over different substrates, how the gear is deployed and retrieved, what speeds the gear is towed, and how these vary with sea state and tidal current. Gear bias is critical when comparing historic data. Changing the gear may alter the effects of dredging on the environment.

Gear Technology

- Continually document gear attributes such as ring size, bag size, configuration, etc.
- Estimate efficiency, selectivity, and catchability and variability associated with different gear, deployment, and substrates
- Design new gear to be bycatch and habitat friendly

Comments and Considerations

- Contrast video and dredge transects (keep patchiness and precise positioning in mind)
- Estimate the rate at which a dredge fills throughout a haul

## 3. Methodology and tools

During the meeting the groups listed these methods and tools for consideration in developing studies. This list only includes methods and tools mentioned during the meeting and is not intended to be all-inclusive.

The group was unanimous in suggesting that a baseline of scallop abundance and community structure be established before fishing a new scallop stock.

Reconnaissance

Do a preliminary survey before the final study design to pick sites, identify species, select potential species for particular emphasis, choose appropriate sampling gear, and identify spatial distribution that affects survey design. Age distribution can indicate sites of consistent recruitment.

Design

- Contrast heavily fished versus unfished (long-term)
- Conduct Before–After–Control–Impact (BACI) manipulative experiments (short-term)
- Experimentally vary fishing intensity and contrast degree of effects
- Conduct experiments to consider the best fishing season based on seasonal impacts on scallops and other species
- Consider that there may be no undisturbed areas. For example, are the 30-year closures in south end of Kodiak providing an "undisturbed" site?

Tools

- Grabs
- Cores
- Video/photographic surveys, photographic documentation
- Side-scan surveys: verify that area is covered as designed
- Dredges: use acoustic tracking to verify exact location
- Spat collectors
- Measure turbidity
- Use permanent moorings to measure biological and oceanographic parameters
- Sediment traps
- Tethering: use cameras to see which organisms prey on scallops
- Genetic stock structure (use microsatellites)

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