SPATIOTEMPORAL VARIATION OF BENTHIC COMMUNITIES ON WEATHERVANE SCALLOP (*PATINOPECTEN CAURINUS*) BEDS WITH SOCIOECONOMIC CONSIDERATIONS OF THE COMMERCIAL FISHERY OFF THE COAST OF ALASKA

By

Jessica Rose Glass

RECOMMENDED: Dr. Stephen Jewett

Mr. Scott Miller

Dr. Franz Mueter

Dr. Gordon Kruse
Advisory Committee Chair

Dr. Shannon Atkinson
Chair, Graduate Program in Fisheries Division

APPROVED: Dr. Michael Castellini
Dean, School of Fisheries and Ocean Sciences

Dr. John Eichelberger
Dean of the Graduate School

Date 8/15/14

SPATIOTEMPORAL VARIATION OF BENTHIC COMMUNITIES ON WEATHERVANE SCALLOP (*PATINOPECTEN CAURINUS*) BEDS WITH SOCIOECONOMIC CONSIDERATIONS OF THE COMMERCIAL FISHERY OFF THE COAST OF ALASKA

A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

Jessica Rose Glass, B.S.

Fairbanks, Alaska

August 2014

Abstract

Weathervane scallops (*Patinopecten caurinus* [Gould, 1850]) off Alaska are commercially harvested in areas that contain commercially important groundfish and crabs. Using observer bycatch data collected during 1996-2012, we analyzed spatial and temporal patterns in community composition on weathervane scallop beds and explored whether observed patterns related to environmental variables (sediment, depth, bottom water temperature, and freshwater discharge) and anthropogenic variables (trawling and dredging effort). Significant ($P<0.05$) differences in community structure were observed at the scale of state fishery registration districts, as well as among individual scallop beds. Spatial differences were most strongly correlated with sediment, depth, and dredging effort. Sequential changes over time were also detected, as was a split between 1996-1999 and 2000-2012. Temporal changes were weakly yet significantly correlated with freshwater discharge and dredging effort. We also conducted a socioeconomic assessment of the commercial weathervane scallop fishery, structured within the framework of a SWOT (strengths, weaknesses, opportunities, threats) analysis. Specifically, we focused on five categories: social, technological, economic, environmental, and regulatory. Whereas the data-poor status of the stock appears to be the fishery's biggest weakness, the largest strengths are conservative management, industry self-regulation, and the fishery's small footprint. Impending threats include stock declines, effects of dredging, and changes in the structure of the fishery. These analyses provide a baseline of benthic community composition on weathervane scallop beds, as well as socioeconomic information to contribute to the environmental, economic, and social sustainability of the Alaska scallop fishery.

Table of Contents

Page

Page

List of Figures

Page

List of Tables

Page

Page

List of Appendices

Acknowledgements

I would like to thank my advisor, Gordon Kruse, for his wonderful guidance and support as a mentor. My committee members, Franz Mueter, Stephen Jewett, and Scott Miller, provided extensive help throughout all stages of my research. Gregg Rosenkranz and Ryan Burt, from the Alaska Department of Fish and Game (ADF&G), provided invaluable assistance obtaining and formatting the scallop observer dataset, as well as graciously welcoming me to Kodiak. Ric Shepard, also from ADF&G, assisted with data formatting. Steve Lewis from NOAA fisheries was extremely helpful in providing commercial fishing data from the Catch in Areas Database, and I am very grateful for the amount of time he spent assisting me. Craig Rose from the Alaska Fisheries Science Center (AFSC) also provided helpful advice on incorporating commercial trawl data into my analyses. Jane Reid from the U.S. Geological Survey Pacific Coastal and Marine Science Center, and Bob McConnaughey and Mark Zimmerman from AFSC all graciously provided sediment data. I am also grateful to Jim Stone, Bill Harrington, and the rest of the weathervane scallop fleet for their cooperation and assistance with my research. I would especially like to thank my friends and family, including the staff, faculty and students at the University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, for their ongoing support and encouragement.

Lastly, I would like to acknowledge my funding sources. These include the National Science Foundation (NSF) Graduate Research Fellowship Program, the NSF Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) IGERT, the Northern Gulf of Alaska Applied Research Award, the H. Richard Carlson Fellowship, the North Pacific Research Board, and the University of Alaska Coastal Marine Institute with funding from the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM).

General Introduction

Exploratory fishing expeditions identified commercially viable weathervane scallop (*Patinopecten caurinus* [Gould, 1850]) beds around Yakutat and Kodiak Island in the early 1950s and mid 1960s. However, a commercial scallop fishery did not develop until 1967, likely because of a lack of specialized scallop gear in Alaska (Hennick 1973). After a single vessel fished in 1967, 11 vessels landed 785 mt in 1968 and 15 vessels landed 855 mt in 1969 (Hennick 1973). A "boom and bust" fishing cycle occurred during 1970 to 1993, as vessel participation varied with the stock status of weathervane scallops and with fluctuations in U.S. and Canadian sea scallop stocks (Kruse et al. 2005). Many weathervane scallop vessels originated from the U.S. east coast, where the New Bedford-style dredge was developed. Other participants converted crab, salmon, halibut, and shrimp vessels to dredge for scallops (Kaiser 1986).

After a record high harvest value of $11.7 million (inflation-adjusted 2013 dollars) in 1992, the fishery management shifted from passive set of regulations to a more active fishery management plan implemented by the State of Alaska in 1993. After a single scallop fishing vessel usurped state management by remitting its state fishing permit and continuing to fish in federal waters after the quota was taken and the season was closed, a federal fishery management plan was put into place in 1995 (NPFMC 2014a). This plan relegated most day-to-day management to the State of Alaska, with some issues reserved for federal management. Interestingly, 80% of the commercial scallop beds occur in federal waters (3-200 miles), while the remaining 20% are located in Alaska state waters (0-3 miles). The state fishery management plan established scallop registration areas and included management measures to regulate the efficiency of the fleet, including establishing observer and reporting requirements, catch limits, fishing seasons, crew sizes, and limiting dredge widths. It also banned the use of automatic shucking machines. Over the past decade, annual harvests have averaged only 210 mt during a season that extends July 1 – February 15 in all but the Cook Inlet registration area, where dredging is allowed from August 15 – October 31.

Weathervane scallops are distributed from central California to the eastern Bering Sea and western Aleutian Islands (Foster 1991), but the only active commercial fishery occurs off Alaska. Currently, prominent scallop beds are located off Yakutat, Kayak Island (southeast of Prince William Sound), Kamishak Bay, Kodiak Island, along the Alaska Peninsula and Aleutian Islands, and in the southeastern Bering Sea. Beds consist of a variety of substrates, including clayey silt, sand, and gravely sand sediments (Turk 2001), and tend to be spatially aligned with bottom currents and bathymetry (Masuda & Stone 2003, Kruse et al. 2005). Weathervane scallops range < 300 m in depth, but are generally commercially fished between 38-182 m in depth (Turk 2001).

The weathervane scallop fishery is considered a "hard-on-bottom" fishery. Alaskan vessels typically tow two New Bedford-style dredges, 4.57 m wide, although smaller versions are also used. This gear is efficient at catching weathervane scallops, which comprised 73.8 - 86.1% of the catch during the 2010-2011 season (Rosenkranz & Spafard 2013). Other species caught as bycatch include benthic invertebrates (e.g., crabs, sea stars, and anemones) and fishes (e.g., skates, Pacific cod [*Gadus macrocephalus*], and flatfishes). Since 1993, 100% observer coverage has been required for vessels fishing in all registration districts except Cook Inlet. Aside from simple summary statistics, bycatch data in the scallop observer dataset have not been analyzed to date, with the exception of the bycatch of commercially important Tanner crab *(Chionoecetes bairdi)* and snow crab *(C. opilio)* mortality (Rosenkranz 2002). In order to mitigate bycatch of commercially important crab, strict limits are established for commercially important species of crab (Tanner and red king crab, *Paralithodes camtschaticus*) in most registration areas. Moreover, throughout the geographic range of the commercial weathervane scallop fishery, many areas are closed to dredging.

Given limited weathervane scallop resources available for commercial harvest, a federal license limitation program (LLP) and a state limited entry permit (LEP) program were initiated in the early 2000s. The LLP restricts the fishery in federal waters to nine vessels, including two vessels exclusively allowed to fish in the Cook Inlet registration area (NPFMC 2014a). In 2000, six out of the nine permit holders formed the North Pacific Scallop Cooperative, which is now incorporated (as of 2011) as the Alaska Scallop Association, an Alaska Cooperative Corporation. The cooperative functions by sharing observer data among vessels to avoid crab and to allocate quota and crab bycatch to individual vessels (Brawn & Scheirer 2008, Rosenkranz & Spafard 2013). In recent years, only four of the nine available permits have been actively fishing, with three out of those four vessels belonging to the cooperative (Rosenkranz & Spafard 2013, NPFMC 2014b). Recently, there have been political tensions concerning the amount of consolidation that has taken place in the fleet, namely that consolidation has hindered economic opportunities for Alaskan residents. As a result, the State of Alaska Legislature did not renew the LEP program in 2013, leading to an open-access fishery in state waters in 2014. Aside from these resource allocation issues, there are other recent concerns about stock status, and whether some areas containing viable scallop beds that were closed in the 1960s should remain closed due to the lack of recovery of king and Tanner crab populations. The long span of onboard observations provides a rich database on the biogeography and biodiversity of benthic communities on scallop beds across the continental shelf off Alaska, and allows for an examination of benthic community structure over time.

The goals of this study are to explore patterns in the benthic species associated with weathervane scallop beds across the continental shelf of Alaska, and to identify a comprehensive suite of social and economic factors influencing the current state and future prospects of the commercial weathervane scallop fishery. In chapter 1, we use observer data to analyze benthic community structure across scallop beds. Specific objectives of chapter 1 are to: (1) quantify the spatial distribution and species composition of benthic communities, (2) quantify changes in species composition of benthic communities over 1996-2012, and (3) relate variability in community composition to environmental (sediment type, depth, freshwater input) and anthropogenic variables (commercial trawl and dredge fishing effort). In chapter 2, we examine socioeconomic considerations of the commercial weathervane scallop fishery via a strengths, weaknesses, opportunities and threats (SWOT) analysis, accomplished through conducting interviews with 29 participants identified as having detailed knowledge of the fishery. We present results from the SWOT framework as it relates to five themes: social, technological, economic, environmental, and regulatory. This study serves as a baseline of benthic community composition over a 17-yr timeframe (1996-2012), against which future changes can be compared and used to improve ecosystem-based fishery management in Alaska. This study also shines light on the rich amount of knowledge held by stakeholders on all aspects of the scallop fishery, from biology to policy, and the need to record their input, particularly for such a small fishery experiencing politically driven changes in structure.

References

Brawn T, Scheirer K (2008) The Alaskan weathervane scallop cooperative. FAO Fisheries Technical Paper 504:349–360

Foster NR (1991) A guide to the common marine bivalves of Alaska. University of Alaska Press, Fairbanks, AK

Hennick DP (1973) Sea scallop, *Patinopecten caurinus*, investigations in Alaska. Commercial Fisheries Research and Development Act Completion Report 5-23-R, Alaska Department of Fish & Game, Juneau, AK 99801

Kaiser RJ (1986) Characteristics of the Pacific weathervane scallop (*Pecten* [*Patinopecten*] *caurinus*, Gould 1850) fishery in Alaska, 1967-1981. Alaska Department of Fish and Game, Division of Commercial Fisheries, RUR-4K86-09

Kruse GH, Barnhart JP, Rosenkranz GE (2005) Management of the data limited weathervane scallop fishery in Alaska. In: Kruse GH, Gallucci VF, Hay DE, Perry RI, Peterman RM, Shirley TC, Spencer PD, Wilson B, and Woodby D (eds). Fisheries assessment and management in data limited situations Alaska Sea Grant College Program AK-SG-05-02, University of Alaska Fairbanks, p 51–68

Masuda MM, Stone RP (2003) Biological and spatial characteristics of the weathervane scallop *Patinopecten caurinus* at Chiniak Gully in the central Gulf of Alaska. Alaska Fish Res Bull 10:104–118

NPFMC (North Pacific Fishery Management Council) (2014a) Fishery management plan for the scallop fishery off Alaska. North Pacific Fishery Management Council, 605 West 4th Ave, Suite 306. Anchorage, AK 99587

NPFMC (North Pacific Fishery Management Council) (2014b) Stock assessment and fishery evaluation (SAFE) report for the weathervane scallop fishery off Alaska. North Pacific Fishery Management Council, 605 West 4th Ave, Suite 306 Anchorage, AK 99587

Rosenkranz GE (2002) Mortality of Chionoecetes crabs incidentally caught in Alaska's weathervane scallop fishery. In: Paul AJ, Dawe EG, Elner R, Jamieson GS, Kruse GH, Otto RS, Sainte-Marie B, Shirley TC, Woodby D (eds) Alaska Sea Grant College Program AK-SG-02-01, University of Alaska Fairbanks, p 717–732

Rosenkranz GE, Spafard M (2013) Summary of observer data collected during the 2010/11 Alaska weathervane scallop fishery. Alaska Department of Fish and Game, Fishery Data Series No 13-09, Anchorage, AK 99518

Turk TA (2001) Spatial distribution and selected habitat preferences of weathervane scallops in Alaska. In: Kruse GH, Bez N, Booth A, Dorn MW, Hills S, Lipcious RN, Pelletier D, Royer, Smith SJ, Witherell D (eds) Spatial Processes and Management of Marine Populations, Alaska Sea Grant College Program AK-SG-01-02, University of Alaska Fairbanks, p 1–15

CHAPTER 1:

Spatiotemporal variation of benthic communities associated with weathervane scallop (*Patinopecten caurinus*) beds off Alaska[1]

ABSTRACT

We conducted an analysis of benthic communities in areas targeted by a commercial weathervane scallop (*Patinopecten caurinus*) fishery on the continental shelf off Alaska, USA. Some bycatch species taken in this fishery are commercially valuable, including Tanner crab (*Chionoecetes bairdi*). Using bycatch data collected by onboard observers during 1996-2012, we analyzed spatial patterns in community composition on weathervane scallop beds, as well as changes in community composition over time. We also explored whether spatiotemporal differences in benthic communities could be related to environmental variables (sediment type, depth, bottom temperature, and freshwater discharge) and anthropogenic variables (trawling and dredging effort). Using non-parametric statistics, statistically significant ($P < 0.05$) differences in community structure were observed at the scale of state fishery registration districts, as well as among individual scallop beds. Certain species displayed a longitudinal gradient across the continental shelf. Spatial differences were most strongly correlated with sediment, depth and dredging effort. Changes over time were also detected, with significant differences between 1996-1999 and 2000-2012. However, these changes could be due to changes in the observer program after start-up years or altered fishing behavior associated with the formation of a fishery cooperative. Subtle changes during 2000-2012 were also present. Temporal changes were weakly yet significantly correlated with freshwater discharge and dredging effort. Results from

[1] Glass, J. R. and G. H. Kruse. 2014. Prepared for submission to Marine Ecology Progress Series.

this study provide a quantitative baseline of benthic community composition on weathervane scallop beds against which future changes can be assessed. Findings also contribute to our understanding of essential fish habitat for weathervane scallops and associated species.

Keywords: Benthic communities, weathervane scallops, bycatch, essential fish habitat, fishing effects, dredging

INTRODUCTION

Benthic community ecology is gaining scientific interest worldwide with increasing appreciation for benthic species' roles in marine ecosystem function and health (Gili & Coma 1998, Orejas et al. 2000, Austen et al. 2002), as well as for the development of indicators of ecosystem change, including climate change (Kennedy & Jacoby 1999, Lenihan et al. 2003, Piepenburg et al. 2011). In Alaska, benthic community structure has been studied in the context of oil and gas development (Atlas et al. 1978, Blanchard et al. 2003), effects of commercial fishing (McConnaughey et al. 2000, Brown et al. 2005a, Stone et al. 2005, Rooper et al. 2011), and coastal development (Feder & Jewett 1986, Jewett et al. 2009). Over the past two decades, research focus has shifted towards ecosystem-scale properties, including habitat characteristics, multispecies interactions, and long-term environmental change (Hare & Mantua 2000, Mueter & Megrey 2005). These efforts have paralleled regional and national efforts to implement ecosystem-based management of marine resources (Witherell et al. 2000, Latour et al. 2003). For example, the U.S. Sustainable Fisheries Act of 1996 mandated the identification of habitats essential to federally managed species, as well as measures to conserve and enhance this habitat.

The Sustainable Fisheries Act defined essential fish habitat (EFH) as, "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." Sparse information on benthic communities and habitats was originally available to define EFH for federally managed fisheries in Alaska for groundfish, crabs, scallops and salmon. As a default, EFH was primarily described based on the distribution of commercial catches of the federally managed species. Benthic epifauna are among the most poorly studied species in Alaskan marine ecosystems. Bottom trawl surveys conducted in the Gulf of Alaska and Bering Sea are designed to assess the abundance and distribution of commercially important groundfish, king crab (*Lithodes* sp., *Paralithodes* sp.), Tanner crab (*Chionoecetes bairdi*), and snow crab (*C. opilio*). The focus of benthic invertebrate research on crab species stems from their commercial importance, although some investigations have characterized marine benthic fauna more generally in Alaska (Feder & Jewett 1986, Feder et al. 2005, Piepenburg et al. 2011).

The weathervane scallop (*Patinopecten caurinus*) is another invertebrate that has been the focus of some research owing to its commercial importance, although the fishery for this species remains data-limited (Kruse et al. 2005). Prominent scallop beds are located off Yakutat, Kayak Island (southeast of Prince William Sound), Kodiak Island, in lower Cook Inlet, along the Alaska Peninsula and Aleutian Islands, and in the southeastern Bering Sea (Fig. 1). Beds consist of a variety of substrates, including clayey silt, sand, and gravely sand sediments (Turk 2001), and tend to be spatially aligned with bottom currents and bathymetry (Masuda & Stone 2003, Kruse et al. 2005). Weathervane scallops are found at < 300 m in depth, but are generally commercially fished between 38-182 m (Turk 2001).

The commercial weathervane scallop fishery in Alaska began in 1967, and the current season runs from July 1st - February 15th for most registration districts. Alaskan vessels typically tow two New Bedford-style dredges, 4.57 m wide, although smaller versions are also used in some fishing operations. This gear is fairly efficient at catching weathervane scallops, which comprised 73.8 - 86.1% of the catch during the 2010-2011 season (Rosenkranz & Spafard 2013). Other species caught as bycatch include other benthic invertebrates, such as sea stars, clams, anemones, and fishes (e.g., skates, roundfish, and flatfishes, Table 1). Since 1993, 100% observer coverage has been required for vessels fishing in all but the Cook Inlet registration district, although data from 1993-1995 were not available for our analyses. Nevertheless, this span of onboard observations provides a rich database on the biogeography and biodiversity of benthic communities on scallop beds on the continental shelf off Alaska. Aside from simple summary statistics, bycatch data in the scallop observer dataset have not been analyzed to date, with the exception of the analysis of bycatch of commercially important Tanner crab and snow crab (Rosenkranz 2002).

The aim of this study was to explore the benthic species composition associated with weathervane scallop beds and to investigate the spatiotemporal variability of benthic communities across scallop beds on the continental shelf off Alaska. Specific objectives were to: (1) quantify the spatial distribution and species composition of benthic communities, (2) quantify changes in species composition of benthic communities over 1996-2012, and (3) relate variability in community composition to environmental (sediment type, depth, freshwater input) and anthropogenic variables (commercial trawl and dredge fishing effort). Spatial and temporal differences for a wide variety of fish and invertebrate taxa are related to sediments, climate, oceanography, and fishing for other species in the Gulf of Alaska and Bering Sea (Feder & Jewett 1986, Hare & Mantua 2000, McConnaughey et al. 2000, Turk 2001). Understanding the structure of benthic communities and how they have changed over time, whether due to environmental- or anthropogenic-related changes, is critical to managing commercially important species in the North Pacific with an ecosystem-based approach. The scallop observer database provides a unique opportunity to examine benthic communities over a 17-yr time frame.

METHODS

Bycatch data

Observer data were obtained from scallop fishing vessels during 1996-2012 (R. Burt, ADF&G, Kodiak, AK, pers. comm.). Detailed observer sampling protocols are described by Rosenkranz and Spafard (2013). In summary, tows are randomly selected for sampling prior to retrieval. Complete haul composition is determined for one dredge per day. Dredge contents are sorted by species (or lowest possible taxon level) into baskets and weighed. Small quantities are weighed entirely, whereas large contents are subsampled. Vessel operators also maintain a logbook provided by the Alaska Department of Fish and Game (ADF&G). For each tow, the operator records the combined width of the dredges towed, gear performance, set date, haul number, set position (latitude/longitude), tow duration, average depth, average speed, estimated retained weight of whole scallops, estimated discarded scallop catch, and ADF&G Statistical Area.

Environmental data

Haul depths were extracted from vessel logbook data. Contoured surficial sediment maps of regions in the Gulf of Alaska were obtained directly from the U.S. Geological Survey (J. Reid, USGS Pacific Coastal & Marine Science Center, Santa Cruz, CA, pers. comm.). Collection methods for these data are described in Evans et al. (2000). Sediment data in the eastern Bering

Sea and Aleutian Islands were obtained from the National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center (R. McConnaughey, AFSC, Seattle, WA, pers. comm.; http://www.afsc.noaa.gov/RACE/groundfish/bathymetry/). Sediment collection methods in the eastern Bering Sea and Aleutian Islands are described in Smith & McConnaughey (1999) and Zimmermann et al. (2013), respectively. Based on the sediment classification methods for each dataset, we constructed numerical classifications (1 – 8) to reflect the sediment type, ranging from the largest grain size (bedrock) to the smallest (silty clay/mud). Sediment values were spatially overlaid with scallop haul points using the QGIS software (Quantum GIS Development Team 2014), and a sediment value was assigned to each overlapping haul. Sediment data were not available for many fishery management districts in the Gulf of Alaska (Fig. 1), including Kodiak Semidi Islands, Kodiak Southwest, Alaska Peninsula, and the entire Kodiak Shelikof district except the largest bed, KSH 1 (Table 2). Bottom-layer (75-250 m) temperature data from 1996 – 2011 were extracted from the GAK1 monitoring station in the northern Gulf of Alaska, maintained by the University of Alaska Fairbanks (http://www.ims.uaf.edu/gak1/), and from NMFS summer bottom trawl surveys. Data from annual bottom trawl surveys on the continental shelf of the eastern Bering Sea were obtained from NMFS (http://www.afsc.noaa.gov/RACE/groundfish/ebs.htm). The GAK1 data were averaged over summer months (May-July) to be consistent with bottom trawl surveys. Model estimates of freshwater discharge (m^3/s) were obtained from the GAK1 database (http://www.ims.uaf.edu/gak1/) and used to index flow of the Alaska Coastal Current in the Gulf of Alaska from 1996 – 2011 (Royer 1982). Owing to the absence of similar regional discharge estimates, beds located in the Bering Sea, Aleutian Islands and Alaska Peninsula management districts were excluded from this portion of the analysis. Temperature and freshwater discharge were excluded from the spatial analyses due to a lack of bed-specific data, and depth was excluded from the temporal analyses because fishing depths were relatively constant within a district over time.

Fishing effort data

Tow data for non-pelagic trawls, as well as tows of pelagic trawls that made contact with the seafloor (indicated by the presence of crab in the fishery observers' samples) on vessels ≥ 18.3 m (60 ft) length overall, were obtained from the Catch in Areas database (S. Lewis, NMFS, Juneau, AK, pers. comm.) and compiled into a time series of fishing disturbance (proportion of each bed disturbed) for scallop beds that had been fished consistently from 2000 – 2012. Data from 1996-1999 were not available due to the lack of vessel monitoring systems aboard commercial trawling vessels during those years. The index of fishing disturbance was estimated by dividing the total area swept (km^2) by the total area (km^2) of the bed, which was calculated in QGIS using scallop bed polygons obtained from ADF&G (G. Rosenkranz, ADF&G, pers. comm.). To determine the area swept by trawls, we used trawl width estimates from NMFS (2005a). The fishing disturbance index did not consider the extent to which individual trawl tows overlap one another on a particular bed. A similar time series of scallop dredging effort was also compiled using area swept data from scallop vessel logbooks. We considered the short-term effects of trawling and dredging effort on benthic species composition by lagging values by one year.

Data organization

We compiled two matrices using haul composition and logbook data. The first, a fish log matrix, included information for each haul, including vessel identification, statistical area (management district), bed code, set date, set position (latitude/longitude,) depth, total area swept by the dredge(s), and whether the haul composition was sampled by an observer. The second, a haul composition matrix, contained much of the same information as the fish log matrix including haul ID, set date, haul set position, and area swept, but only for hauls in which the entire composition was sampled by observers. This matrix also included the weight (kg) of each taxon sampled. Haul ID numbers were unique and served as sampling units within the dataset. Area swept (km^2) by the dredge was used to calculate catch per unit effort (CPUE, kg/m^2), which adjusts for differences in observed species densities, as well as variances in dredging effort due to differences in tow duration and dredge widths. To address changes in observer sampling procedures over time, namely a trend toward more detailed classifications of certain taxa during later years of sampling, the CPUE of each taxon was aggregated into taxonomic groups ranging from families to phyla, with most groups classified to family. An initial assumption was that those taxa classified at higher taxonomic resolution (e.g., family) were different than those included in broader taxonomic groups. Separate categories existed for “roundfish,” “skate egg cases” and “gastropod eggs,” which were frequently recorded by observers. Finally, we constructed a third matrix that contained environmental and anthropogenic (fishing effort) data corresponding to each haul ID.

Statistical analyses

Multivariate statistical analyses were conducted using the software package PRIMER (Clarke 1993, Clarke & Gorley 2006). Environmental and anthropogenic data were standardized to mean zero and standard deviation one to account for large differences in measurement units.

Taxa contributing to at least 5% of the total biomass of the dataset were selected, and a 4^{th}-root transformation was applied to the CPUE data to down weight the effects of the most abundant species (Clarke 1993). The biomass of each taxon was then standardized relative to its maximum for the overall dataset, so that each taxon contributed equally (Clarke & Warwick 2001). From that data matrix, we computed pairwise similarities between samples based on the Bray-Curtis similarity coefficient (Bray & Curtis 1957).

Using various groupings (e.g., district, bed, year), non-metric multidimensional scaling (NMDS) was conducted to visualize similarities in CPUE (used as a metric of haul composition) between groups. To test whether haul composition differed significantly among regions at varying spatial scales and across time, analyses of similarity (ANOSIMs) were conducted using the Bray-Curtis resemblance matrices. ANOSIM is a permutation test that is most applicable to multispecies data that do not meet standard assumptions required by multivariate analysis of variance. As differences between species compositions become larger, the test statistic, Clarke's R, approaches one. When significant differences were detected in the ANOSIM ($P < 0.05$), a similarity percentages analysis (SIMPER) was conducted to examine the taxa that contributed most to the differences. To determine the environmental and anthropogenic variables that best explained variations in species compositions, a bio-environmental analysis (Bio-Env; Clarke & Ainsworth 1993, Clarke 1993), was conducted. Bio-Env calculates the Spearman rank correlation between the species similarity matrix and corresponding environmental similarities. The rank correlation coefficient (ρ) indicates the significance of agreement in the multivariate pattern when comparing two similarity matrices.

For some analyses, data were averaged by bed code and year before calculating the similarity matrix to eliminate the risk of pseudoreplication (Hurlbert 1984). For district-scale spatial analyses, hauls were averaged by bed. Scallop beds off Yakutat and in adjacent District 16 (D16) were combined for these analyses, because the latter was represented by a single bed and is contiguous to the Yakutat beds. Analyses were performed separately for two early years (1997 and 2000) and one late year (2010) to investigate spatial differences independently from potentially confounding temporal changes. These three years were selected because they span nearly the entire 1996-2012 time series and contain high levels of sampling effort across the 10 management districts that had observers. We chose 2010 because of reduced observations in 2011 and 2012 owing to fishery closures in some management districts. Both 1997 and 2000 were selected for comparison because preliminary analyses suggested a split in haul composition between 1996-1999 and subsequent years (2000-2012), and we wanted to include “early” samples from both of those groups. We chose 1997 instead of 1996, because the latter was a poorly sampled year.

Bed-scale analyses were limited to districts with large numbers of beds that were consistently sampled. These included the Kodiak Shelikof, Kodiak Northeast, Yakutat, D16, and Prince William Sound districts. Yakutat, D16, and Prince William Sound were analyzed together due to the close proximity of beds in all three districts. Hauls were averaged by bed and year for NMDS ordinations to facilitate visual examination of patterns but were not aggregated for ANOSIM and SIMPER analyses. Bed-scale analyses were conducted in the years 1997, 2000, and 2010. For temporal analyses, hauls in a given district or bed were limited to those that were continuously sampled over 1996-2012 to account for confounding changes due to differing fishing locations across time. These included Kodiak Shelikof, Kodiak Northeast, Yakutat/D16/Prince William Sound, and the Bering Sea. In Kodiak Shelikof, only the KSH 1 bed was sampled consistently, and was the only bed analyzed for temporal differences. Bed Yak

B in the Yakutat district was excluded, because it was only sampled in 2009-2012. Due to preliminary splits in haul composition between 1996-1999 and 2000-2012 observed through CLUSTER analyses in PRIMER, temporal analyses were performed spanning both 1996-2012 and 2000-2012. In the CLUSTER analyses, we tested for the significance of observed splits using a SIMPROF (similarity profile) permutation test, which gives a test statistic (π) indicating whether group structure is significantly different from random. We also looked for patterns of seriation (continual change over time), using the RELATE procedure, which generates a Spearman coefficient (ρ) to indicate whether serial structure across years is present.

RESULTS

Descriptive statistics

A total of 4,420 hauls and 79 taxa (Table 1) from 10 registration districts and 42 individual scallop beds were included in the final data matrix. Most taxa were at the family level (48), followed by class (12), order (10), phylum (4), N/A (3), subclass (1) and infraorder (1). The dataset included 94 taxa before excluding those whose biomass contributed < 5% to the overall dataset. Sampled hauls were dredged in habitats with sediments ranging from bedrock to silty clay/mud (Table 2) at depths of 46 to 172 m (Table 3). The combined proportion of scallop beds swept by both pelagic and non-pelagic trawl gear ranged from 0 – 0.224, depending on the bed and year, with the highest proportion in the Bering Sea. Dredging effort averaged 0.068 overall during 1996-2012 (Table 4) and, on average, was the highest on the KSH 1 bed in the Kodiak Shelikof Strait district, ranging from 0.02 – 0.41 during 1996 – 2012.

Registration district spatial analyses

The ANOSIM test revealed statistically significant differences in CPUE between registration districts in 1997, 2000 and 2010 (Clarke's R = 0.533, 0.646, 0.682, P = 0.001, 0.003, 0.001, respectively). A longitudinal gradient in haul composition was apparent, with significant differences between Yakutat/D16 and all districts to the southwest except the Bering Sea (Table 5). However, a small sample size associated with a single bed hampered significance testing of any comparisons involving the Bering Sea. Large dissimilarities in species composition existed between Yakutat and the Aleutian Islands in both 1997 and 2010; the Aleutian Islands were not sampled in 2000. The adjacent districts of Kodiak Shelikof and Kodiak Northeast were significantly different from one another in 1997 and 2010 (Clarke's R = 0.443, 0.438, P = 0.026, 0.029, respectively). Among the years examined, separation by district was most clearly visualized via NMDS ordination in 2010 (Fig. 2).

The SIMPER analysis revealed the basis for differences in community composition between Yakutat and the Aleutian Islands. In 1997, the Aleutian Islands had higher CPUEs of Pennatulacea, Gastropoda, Cardiidae, roundfish, Decapoda, gastropod eggs, Echinoida, Pleuronectiformes, Porifera, Paguridae, and Oregoniidae, whereas Yakutat contained a higher proportion of skate egg cases, Rajidae, Pectinidae, Hirudinea, Actiniaria, Ophiuroidea, and Cirripedia (Table 6). In 2010, Yakutat again contained more Rajidae, Cirripedia, and skate egg cases, as well as Aphroditidae, Veneridae, Paguridae, and Luidiidae, whereas the Aleutian Islands beds contained more Bryozoa, Echinoida, Asteroidea, Ranellidae, Oregoniidae, and gastropod eggs, among other taxa (Table 6). It is interesting to observe that the top-five taxa contributing to dissimilarities (% contribution) between Yakutat and the Aleutian Islands were different in 2010 than 1997. Yakutat beds consisted mainly of sand, silty clay/mud, and sandy silt sediments, whereas the Aleutian Islands beds contained sand or gravelly sand (Table 2). The Aleutian Islands beds generally exhibited a narrower depth range than the Yakutat/Prince William Sound/D16 beds, and the deepest sampled haul in the Aleutian Island was 26 m shallower than in Yakutat (Table 3).

Three to four taxa contributed most to similarities across all districts. These included Pectinidae, Pleuronectiformes, Rajidae, and Asteroidea. The remaining taxa tended to differ by district. Some of these differences are illustrated in Figure 3, and SIMPER comparisons are listed in Appendix 1.A. Compared to other districts, the Bering Sea had higher relative abundances of Oregoniidae, Paguridae, Ranellidae, Buccinidae, Polynoidae, and Gastropoda. However, Kodiak Shelikof had higher abundances of gastropod eggs than the Bering Sea (and all of the other districts). Compared to other districts, Yakutat had higher relative abundances of skate egg cases, Crangonidae, Hirudinea, Veneridae, Luidiidae, Cirripedia, and Aphroditidae. However, a shift in Cirripedia and Aphroditidae prevalence occurred, with Kodiak Shelikof having higher abundances than Yakutat (and all the other beds) in 1997 and 2000, respectively. Kodiak Shelikof had high relative abundances of Cancridae, Ascidiacea, Brachiopoda, and Nereidae. Relative to Kodiak Northeast and Yakutat, Kodiak Shelikof had a larger representation of Gastropoda as well, except when compared to the Bering Sea. Kodiak Northeast had higher relative abundances of Lithodidae, Solasteridae, Brachiopoda, Goniasteridae, and Pennatulacea. However, there was a shift in higher CPUE of Pennatulacea to the Bering Sea in 2010. Spearman rank correlation with environmental variables was significant in 2010 ($\rho = 0.533$, $P = 0.002$) compared to 1997 ($\rho = 0.149$, $P = 0.270$) and 2000 ($\rho = 0.409$, $P = 0.056$). Sediment, depth and dredging effort were most correlated with district-scale spatial patterns in species composition in 2010.

Bed-scale spatial analyses

Kodiak Shelikof. Significant differences in haul composition were revealed by the ANOSIM test between Kodiak Shelikof beds in 1997 (Clarke's R = 0.336, P = 0.001) and 2010 (Clarke's R = 0.629, P = 0.001). Only bed KSH 1 was fished in 2000. Beds within the Kodiak Shelikof district were distinguished from one another through varying CPUE among taxa rather than differences in presence or absence. We observed large differences between bed KSH 1, the northwestern most bed in Shelikof Strait, and KSH 6, located in southeast Shelikof Strait. The dissimilarity between the two beds was characterized by higher CPUEs of most taxa in KSH 6, some of which are displayed in Table 7. Across all years, bed KSH 1 was characterized mainly by Pectinidae, Rajidae, and Pleuronectiformes. In the Kodiak Shelikof district, dredging effort was significantly correlated with biological differences in both 1997 (ρ = 0.247, P = 0.001) and 2010 (ρ = 0.289, P = 0.001). Dredging effort was nominally higher in KSH 1 than KSH 6, averaging 0.247, compared to 0.046, from 1996-2012. An analysis of the potential association of benthic communities and sediments was not possible due to the lack of sediment data for all beds in the Kodiak Shelikof district except KSH 1. Due to the lack of bed-specific environmental data in this district, environmental mechanisms behind the lower CPUEs in KSH 1 could not be investigated.

Kodiak Northeast. The ANOSIM revealed significant differences in CPUE between beds in the Kodiak Northeast District in 1997 (Clarke's R = 0.427, P = 0.001), 2000 (Clarke's R = 0.224, P = 0.001), and 2010 (Clarke's R = 0.567, P = 0.001). These differences were significantly correlated with depth and dredging effort in 1997 (ρ = 0.295, P = 0.001), depth and sediment in 2000 (ρ = 0.308, P = 0.001), and depth in 2010 (ρ = 0.589, P = 0.001). Beds KNE 3 and KNE 6 had the most distinct sediment and depth profiles in this district, with KNE being fairly shallow (68-88 m) and containing a mix of sand and gravel, and KNE 6 being deeper (80-117 m) and consisting of silty sand. Bed KNE 3 had higher CPUE of Actiniaria, Brachiopoda, Buccinidae, as well as most echinoderms (Table 8). KNE 6 had higher densities of crustaceans and Pennatulacea.

Yakutat, D16, Prince William Sound. Significant differences in CPUE were revealed by the ANOSIM among scallop beds within the Yakutat, D16 and Prince William Sound districts in 1997 (Clarke's R = 0.290, P = 0.001), 2000 (Clarke's R = 0.241, P = 0.001), and 2010 (Clarke's R = 0.303, P = 0.001). Biological differences were significantly, although weakly, correlated with depth in 2000 (ρ = 0.118, P = 0.001) and dredging effort in 2010 (ρ = 0.114, P = 0.008). No anthropogenic or environmental variables were correlated with biological patterns in 1997. Although no latitudinal or longitudinal gradient was evident, beds Yak 2 and Yak 3, as well as Yak 4 and Yak 5, tended to cluster together with similar species compositions (Fig. 4). Apart from these groupings, we did not observe any beds that were consistently and largely different from one another across the sampling period. The beds in the Yakutat, D16 and Prince William Sound districts span a multitude of sediment types and depths. Beds Yak 1, Yak 2, Yak 3, Yak B, Western Kayak Island (WKI), and Eastern Kayak Island (EKI) are predominantly composed of silty clay/mud and sandy silt sediment types, although EKI also contains bedrock. Beds Yak 4 and Yak 5 are predominantly sand, whereas Yak 6 is a mix of sand and silty clay/mud. Beds were generally fished at a wide depth range (49-117 m), with the shallowest being Yak 2 (49-84 m, Table 3). Yak B was the deepest on average, with a depth span of 82 to

106 m. The bathymetry of this region features underwater canyons and banks that shape the formation of the scallop beds and, presumably, their species composition. For example, beds Yak 4 and Yak 5, which span the Yakutat and Alsek canyons and formed a cluster in the NMDS ordination, are physically separated from beds Yak 2 and Yak 3 by Yakutat Bay.

Temporal analyses

Kodiak Shelikof. Haul composition varied significantly on KSH 1 over 1996-2012 (Clarke's R = 0.257, P = 0.001) and 2000-2012 (Clarke's R = 0.158, P = 0.001), with the most significant differences occurring between the early and late years of sampling (Table 9). A NMDS diagram of hauls averaged by year (Fig. 5) revealed a time trajectory, particularly a split between the late 1990s and subsequent years. This split, from 1996-1999, was statistically significant, as indicated by the SIMPROF test within the CLUSTER analysis (π = 3.25, P = 0.001). Effects of seriation were present, implying that changes in community composition occurred sequentially across years, but were more apparent from 1996-2012 (ρ = 0.236, P = 0.001) than 2000-2012 (ρ = 0.063, P = 0.001). A SIMPER comparison of the early (1996-1999) and late years (2010-2012) indicates a higher prevalence of Ranellidae, Aphroditidae, Nereidae, Buccinidae, and Rajidae during 2010-2012. During 1996-1999 there was a higher prevalence of Polychaeta, Bivalvia, Cirripedia, Hirudinea, and Gastropoda in the haul composition samples. Similar patterns were observed when comparing 2000 with 2012. A time series comparing CPUE of select taxa from 1996-2012 suggests little interannual variability (Fig. 6). Dredging effort was significantly, although weakly, correlated with temporal changes on bed KSH 1 (ρ = 0.190, P = 0.001). Dredging effort fluctuated from year to year, ranging from a low of 0.02 in 2008 to a high of 0.41 in 1997.

Kodiak Northeast. Temporal differences in haul composition samples in the Kodiak Northeast District were statistically significant over 1996-2012 (Clarke's R = 0.22, P = 0.001) and over 2000-2012 (Clarke's R = 0.129, P = 0.001). The years with the greatest differences were 2010 and 1996 (Clarke's R = 0.674, P = 0.001). Similar to Kodiak Shelikof, 1996-1999 grouped separately from the later sampling years on the NMDS ordination (Fig. 5), as well as significantly in a CLUSTER analysis (π = 3.28, P = 0.001). Significant seriation occurred from 1996-2012 (ρ = 0.116, P = 0.001) and 2000-2012 (ρ = 0.077, P = 0.001). Annual changes in species composition may play a large role in determining the similarity of haul samples between years. For example, a pairwise comparison between 2010 and 1997 revealed a Clarke's R of only 0.234 (P = 0.001), indicating relatively high similarity, but which increased to 0.671 when comparing 2010 and 1998 (P = 0.001), indicating much greater differences in CPUE in just one year. Interannual variability in CPUE was observed in Ophiuridae, Rajidae and skate egg cases, Aphroditidae, and Polychaeta (Fig. 6). Similar to KSH 1, a SIMPER analysis revealed a comparatively high overlap in haul composition throughout the sampling period, with dissimilarities between years attributed to varying CPUEs of certain taxa. For example, 2010 had higher densities of Rajidae, Roundfish, Ranellidae, Demospongiae, Oregoniidae, Lithodidae, Pleuronectiformes, and Brachiopoda than 1996-1998 and 2000. In 1998, higher CPUEs of Asteroidea and Clypeastroida were observed than in 2010, whereas 1997 had higher densities of those taxa, as well as Polychaeta and Polynoidae. In comparison to 2000, 2010 also had higher CPUEs of Buccinidae and Pennatulacea. More Solasteridae, Nereidae, Crangonidae, Polychaeta, Actiniaria, and Decapoda, among others, were observed in 2000. The Bio-Env analysis revealed a very small but significant correlation between patterns observed in species composition and dredging effort (ρ = 0.085, P = 0.02). Dredging effort in this district ranged from a low of 0.01 in 2007 to a high of 0.07 in 2008.

Yakutat, D16, Prince William Sound. The ANOSIM revealed a significant difference in CPUE trends in the Yakutat, D16 and Prince William Sound districts over 1996-2012 (Clarke's R = 0.273, P = 0.001) and 2000-2012 (Clarke's R = 0.154, P = 0.001). Clustering of 1996-1999 from 2000-2012 was significant (π = 3.36, P = 0.001). Seriation was detected from 1996-2012 (ρ = 0.251, P = 0.001) and 2000-2012 (ρ = 0.159, P = 0.001). A comparison of early and late years suggests an increase of Aphroditidae, Pandalidae, and Crangonidae over time, and a slight decrease of Pleuronectiformes, roundfish, Cirripedia, Polychaeta, and Actiniaria. This is illustrated by a comparison of the years 2000 and 2012 (Table 10). Large interannual variability in CPUE over 1996-2012 of select taxa, including Ophiuridae, Pennatulacea, Rajidae and skate egg cases, Aphroditidae, and Polychaeta was apparent (Fig. 6). Freshwater discharge was significantly, although weakly, correlated with temporal changes (ρ = 0.107, P = 0.001). Freshwater discharge in these three districts displayed interannual variability. The average annual discharge during 1996-2011 was 15,015 m^3/s, with a maximum value of 21,717 m^3/s in 1999 and a minimum of 11,776 m^3/s in 1998. The average discharge from the first four years (1996-1999) was 16,466 m^3/s, whereas the average for the last four years of available data (2008-2011) was 14,260 m^3/s.

Bering Sea. The ANOSIM revealed that the Bering Sea, consisting of just one bed, exhibited the greatest differences over time of all districts analyzed over 1996-2012 (Clarke's R = 0.485, P = 0.001) and 2000-2012 (Clarke's R = 0.349, P = 0.001). As in other areas, the largest differences occurred between the early years and late years, with a split visualized on an NMDS ordination diagram (Fig. 5) and through a CLUSTER analysis. A significant split was evident between 1996-1999, but also including 2005, and the remaining sampling years ($\pi = 2.15$, $P = 0.001$). This difference may be due, in part, to a serial trend in haul composition over time, which was more prominent from 1996-2012 ($\rho = 0.327$, $P = 0.001$) than 2000-2012 ($\rho = 0.285$, $P = 0.001$). Throughout all years, Oregoniidae, Pectinidae, and Pleuronectiformes were dominant in haul composition samples, with Pennatulacea and Polychaeta becoming more prominent in later years (Fig. 6). From 2003 – 2005, Rajidae were also highly abundant. Major distinctions between early and late years, illustrated by comparing 2000 and 2012 (Table 11), included increases over time in Polychaeta, Porifera, Pennatulacea, Cirripedia, Buccinidae, Gastropod eggs, and Nereidae from 2000 to 2012. The CPUE of gastropod eggs, however, exhibited a large amount of interannual variability (Fig. 6). Scyphozoa and roundfish were more abundant in early years. Dredging effort was the most significant variable correlated with temporal differences in species composition, as indicated by the Bio-Env analysis ($\rho = 0.172$, $P = 0.001$). Dredging effort, which averaged 0.019 in the Bering Sea over 1996-2012, increased after 1996 (0.027), and reached a peak in 2000 (0.040) before dropping to about 0.01 in 2006 and remaining relatively constant thereafter (Fig. 7).

DISCUSSION

Spatial differences

Across weathervane scallop beds in the Gulf of Alaska, Aleutian Islands, and eastern Bering Sea, from 1996-2012, commercial scallop hauls were dominated by Pectinidae, Pleuronectiformes, Rajidae and Asteroidea. However, the remaining taxa differed across registration districts from northeast to southwest, with the strongest differences between the eastern-most (Yakutat/D16) and western-most districts (Aleutian Islands and Bering Sea). These differences were observed in all three years that were examined in detail (1997, 2000 and 2012), implying district-scale differences throughout the entire sampling period. Within districts, spatial differences in community composition at the scale of individual scallop beds were also observed, revealing that benthic communities can differ at relatively small (< 50 km) spatial scales. Spatial differences were most often correlated with dredging effort, sediment and depth. Our results are in accord with past characterizations of benthic communities across Alaska (Feder & Jewett 1986, Yeung & McConnaughey 2006), as well as previous findings of important linkages between benthic community structure, depth and substrate (Grebmeier et al. 1989, McConnaughey & Smith 2000).

Past studies have previously identified scallop beds as occurring predominantly on sandy and sandy silt substrates in the Gulf of Alaska (Turk 2001); indeed, other sediment types were less represented in our study. In some cases, such as between Yakutat and the Aleutian Islands districts, there were clear correlations between the depth and sediment type of a bed that were reflected in differing species compositions. In our study, higher gravel content on the Aleutian Islands beds may have contributed to higher abundances of taxa that require structure, such as Echinoida and Porifera. Yakutat contained more skate egg cases than the Aleutian Islands, consistent with previous findings of skate nurseries in relatively deep environments with sandy and muddy substrates in the Bering Sea (Hoff 2010). In the southeastern Bering Sea, polychaete diversity was lower in shallower water, whereas groundfish diversity was related to sediment type and diversity of the polychaete assemblage (Yeung et al. 2010).

Temporal changes

Temporal changes in taxon CPUEs were observed in beds that were routinely sampled, but no taxa showed consistent changes across all districts over time. Temporal changes were generally weaker than spatial differences and exhibited lower correlations with environmental variables. Serial changes over time were evident in all districts analyzed; trajectories in similarity were less pronounced but still statistically significant when the years 1996-1999 were excluded (Fig. 5). We hypothesize three potential reasons for the split between 1996-1999 and subsequent years: (1) changes in observer protocols, namely that onboard observers classified taxa more finely over time, (2) changes in fishing fleet behavior after formation of a fishing cooperative in 2000, or (3) changes due to other environmental or anthropogenic variables, occurring either before or at the beginning of the sampling period. We sought to eliminate the first possibility by aggregating the taxa to higher taxonomic levels. However, we cannot fully rule out that some of the taxa we examined were initially classified more crudely. For example, in recent years in Kodiak Shelikof, it is possible that observers increasingly classified worms to the family Nereidae (Class: Polychaeta) as opposed to the broader class Polychaeta. Polychaeta were more abundant in 1997, whereas Nereidae were more abundant from 2000-2012. It is not possible to determine how often worms in the family Nereidae were classified as Polychaeta, particularly in the early years. Similar observations of decreased abundance occurred with Bivalvia, for which the CPUE decreased to 0 in 2012 compared to 42 in Kodiak Shelikof and 17 in Yakutat/D16/Prince William Sound in 1996. Increases over time in the CPUE of two less common bivalve families, Cardiidae and Tellinidae, occurred in Kodiak Shelikof, while Veneridae increased in Yakutat/D16/Prince William Sound.

The only environmental variable significantly correlated with temporal changes was freshwater discharge in Yakutat, D16 and Prince William Sound, although the correlation was weak. It is difficult to attribute specific changes in haul composition to patterns of freshwater discharge, given that freshwater discharge is not necessarily a good indicator of bottom currents. Yet, given the regime shift in the North Pacific in the late 1990s, we decided to include this variable. The highest amount of variability in freshwater discharge in Yakutat, D16 and Prince William Sound occurred from 1996-1999, with an overall low for our sampling period occurring in 1998, shifting to an overall high in 1999. In 1997, anomalous weather conditions occurred in the North Pacific, influenced by El Niño and other decadal-scale atmospheric processes (Napp & Hunt 2001, Overland et al. 2001). This was followed by a shift from a warm to cold regime in 1998 (Peterson 2003), resulting in cooler sea surface temperatures, anticyclonic winds, and shifts in zooplankton and some pelagic fish abundances. No stark differences were evident in scallop haul compositions between 1998 and 1999 that could be distinguished from natural interannual variability, but large differences are not expected for multi-aged taxa. For example, weathervane scallops live to 29 yr (Hennick 1973) and red king crab *(Paralithodes camtschaticus)* live >20 yr (Matsuura & Takeshita 1990). Nevertheless, these fluctuations may have contributed to the observed splits between the late 1990s and remaining years. When freshwater discharge was excluded from the Bio-Environmental analyses, there were no significant correlations between biological patterns and any other environmental variables in the Yakutat/D16/Prince William Sound districts. Better estimates of bottom currents from current meters are needed to more fully evaluate this potential relationship.

Interestingly, we found no significant correlation between temporal changes in species composition and bottom temperature. Other studies in Alaska have indicated strong effects of temperature on marine species compositions (Grebmeier et al. 1989, Anderson & Piatt 1999, Mueter & Litzow 2008, Siddon et al. 2011), although the haul composition samples in this study contain many sessile taxa, which are unlikely to show short-term shifts in distribution. As benthic communities in other regions demonstrate long-term stability (Dunton et al. 2005, Renaud et al. 2007), identifying changes in community composition may require longer, multi-decadal examinations.

Fishing effects

No changes in species composition, either spatial or temporal, were correlated with bottom trawling effort. In contrast, bottom trawl fishing significantly reduced macrofauna abundance and diversity relative to unfished areas in the southeastern Bering Sea (McConnaughey et al. 2000). These divergent results are likely due to differences in fishing intensity. An intensive yellowfin sole (*Limanda asper*) fishery occurs in the southeastern Bering Sea, whereas commercial trawl fisheries occurred on only a few scallop beds, and in those cases the overlap was quite small.

On the other hand, dredging effort was significantly correlated with spatial changes in haul composition in the district- and bed-scale analyses, as well as with temporal changes in the Kodiak Shelikof, Kodiak Northeast and Bering Sea districts. The most apparent effects of dredging were observed as much lower CPUE for most taxa on bed 1 versus bed 6 in the Kodiak Shelikof district. The CPUE of Aphroditidae, a family composed of carnivore and detritivore polychaetes, was higher on KSH 1 than KSH 6; higher CPUE of Aphroditidae may be indicative of repeated dredging disturbance (Yeung et al. 2010). In the early 1990s (1990-1994), before our sampling period, dredging effort was significantly higher across the state, with a statewide harvest of 795 mt in 1992, four times higher than the average harvest during the past decade. In the Bering Sea, 227 mt of shucked meats were harvested in 1994. Dredging effort in this district decreased after 2000. Though not statistically significant, commercial trawling effort in the Bering Sea also decreased from 0.22 in 2000 to 0.04 in 2012, likely due in part to a reduction in pelagic trawling effort in the Bering Sea over this time period (Zador 2013), but perhaps also due to geographical shifts in trawling effort outside of the scallop bed. The Bering Sea bed is composed of sand, which is more naturally dynamic and tolerant of disturbance than substrates such as mud or silt (Kaiser et al. 2006). Increases in the relative abundance of certain organisms over this time period, including Polychaeta, and sessile taxa such as Porifera, Pennatulacea and Gastropod eggs, might be indicative of a recovering system. Research in the northwest Atlantic identified higher abundances of Polychaeta in undisturbed sites (Collie et al. 1997). However, in the Bering Sea errant polychaetes may benefit from sediment disruption caused by trawling, implying that polychaete reactions to disturbance are taxon-specific (Yeung et al. 2010). In the Bering Sea, we observed increases in the carnivorous Polychaete family Nereidae, with conflicting decreases in the carnivorous family Polynoidae from 2000-2012, both of which were classified separately from Polychaeta. Unfortunately, without further taxonomic resolution, we are unable to identify other families within Polychaeta that showed increasing trends over the sampling period. However, the CPUE of Aphroditidae was higher in later years in three (Kodiak Shelikof, Kodiak Northeast, and Yakutat/D16/Prince William Sound) out of the four districts analyzed temporally, perhaps consistent with repeated dredging disturbance. Dredging effort in these districts fluctuated over time and exhibited no consistent trend during our sampling period.

Given the relatively weak correlation with dredging effort, lack of correlation with trawling effort, and uncertainty in taxonomic resolution, it is difficult to discern whether observed temporal changes in haul composition in the Bering Sea are indicative of a recovering system, a result of differences in sampling protocols, or due to other environmental variables not included in this study. Relative abundances of many taxa fluctuated from year to year, undoubtedly in part due to observational error, but more detailed analyses of individual taxa were beyond the scope of our community analysis. Also, finer-scale analyses of the most heavily fished portions of some beds might shed more light on potential changes due to dredging, but State of Alaska confidentiality limitations restricted our analysis to the bed level. Separation of the effects of dredging from those of natural disturbances is difficult without a controlled experimental design, such contrasting areas open to heavy fishing versus long-term (1959-present) no-fishing closure areas (McConnaughey et al. 2000). In another such study, submersible transects were conducted to compare distribution and abundance of epifauna in two areas near Kodiak Island that were closed to scallop dredging and bottom trawling for 11-12 yr with adjacent areas open to fishing (Stone et al. 2005). Species richness and abundances of low-mobility and prey species were lower in open areas. Interestingly, weathervane scallop density was not significantly lower in the open than in the closed area (Masuda & Stone 2003). Elsewhere in Alaska, a model of the effects of bottom trawling on deep-sea corals and sponges along the Aleutian Islands demonstrated 2-3 decades of recovery subsequent to cessation of disturbance (Rooper et al. 2011), and subtle but significant differences in several grain size and organic matter parameters were detected in shallow (<26 m), sandy habitats among fished versus unfished areas in the southeastern Bering Sea (Brown et al. 2005b). Likewise, placer gold mining with bucket-line dredges in 9-20 m of water in Norton Sound, northeastern Bering Sea, resulted in minor alteration of substrate granulometry with no clear trends, but led to significantly reduced total abundance, biomass, and diversity of benthic macrofaunal communities at mined stations composed of sand and cobble substrates (Jewett et al. 1999). Globally, intense bottom trawling and dredging have had severely detrimental effects on benthic communities, such as decreased species abundance, biomass, richness and diversity, as well as altered ecosystem structure (Thrush & Dayton 2002, Brown et al. 2005a).

Research caveats, implications, and recommendations

There are spatial and temporal limitations to the data used in this study. For one, observations are confined to commercial scallop beds fished during July through February. Thus, seasonal variability in abundance and distribution cannot be addressed. Also, representation of benthic species in scallop dredges depends on gear selectivity, which is relatively high for scallops, but unknown for other taxa. Differences in observer knowledge and sampling ability may have affected the recorded taxa, and observer identification requirements have evolved since 1996. Additionally, differences in spatial scale of environmental and biological data may have adversely affected our ability to detect relationships. For example, availability of set positions of trawl and dredge tows did not allow us to distinguish between spatially overlapping versus unique tow paths, constraining our evaluation of specific bed locations impacted by mobile bottom contact gear during any given year. Similarly, the scallop beds are designated by ADF&G based on past fishing effort, and the delineated area of the bed may not reflect the area of most intensive fishing. Lastly, as with all such observational studies, we are limited to describing correlations between haul composition and environmental variables, which do not necessarily reflect causation. Despite these limitations, we feel that we were able to characterize meaningful differences in haul composition at the regional and bed-scale on the continental shelf off Alaska.

Results from our study bear on EFH designations for weathervane scallops and associated species. Extant information for weathervane scallop EFH does not allow linkage of scallop geographic distribution with habitat characteristics, including habitat complexity and connectivity (NMFS 2005b). Although the dispersal habits are unknown for weathervane scallops, advancements in habitat mapping techniques will contribute to improving EFH definitions for scallops and their associated benthic organisms, specifically related to habitat requirements and connectivity, given relationships among certain taxa and sediment type. Our analysis demonstrated effects of sediment and depth on community composition on scallop beds throughout the Gulf of Alaska, Aleutian Islands, and Bering Sea. Collecting bed-specific environmental information, such as temperature, salinity, pH, and dissolved oxygen may contribute to more detailed understanding of factors shaping scallop habitat. Haul-specific conductivity, temperature, and depth recordings were collected in the late 1990s and early 2000s using instruments attached to scallop dredges, but were later discontinued (G. Rosenkranz, ADF&G, Kodiak, AK, pers. comm.). Whereas our research quantified broad associations between scallops and other benthic species indicated by contents of dredges towed over large distances, underwater camera surveys can more easily identify specific associations among scallops and other taxa. For instance, spatial analyses of submersible observations provided evidence of associations between adult weathervane scallops and both anemones and large sea whips, and negative associations with sunflower sea stars (*Pycnopodia helianthoides*), whereas juvenile scallops exhibited association with anemones (Masuda & Stone 2003). Relationships such as these, in combination with data collected by scallop fishery observers and on scallop surveys, could lead to the development of simple habitat suitability index models (e.g., Brown et al. 2000), which would improve EFH definitions for weathervane scallops. Identifying links between benthic communities, physical variables and pelagic fish communities are important steps towards a true implementation of ecosystem-based management (Fluharty 2000, Peterson et al. 2000).

Our study provides a quantitative baseline of benthic community composition on weathervane scallop beds against which future changes can be assessed. Significant baseline research has been conducted recently in the Arctic (Piepenburg et al. 2011), but some of the most comprehensive benthic characterizations across the Gulf of Alaska were collected over three decades ago (Feder & Jewett 1986), and no data have been collected with a specific focus on the weathervane scallop fishery. Given unpredictable effects of climate change and ocean acidification on shellfish resources, gathering baseline data is essential to monitoring future changes in benthic communities. The effects of ocean acidification on weathervane scallops and associated taxa is yet unknown given species-specific responses to changing ocean conditions (Ries et al. 2009), but recent die-offs of farmed weathervane-Japanese scallop hybrids in British Columbia have been attributed to declining pH levels (Shore 2014). Climate change brings threats to ocean circulation, food supplies, and larval development, with detrimental economic impacts (Byrne 2011, Narita et al. 2012). Given few changes in dredging gear over the course of the weathervane scallop fishery, coupled with consistent fishing participants, the observer dataset provides robust catch estimates of benthic species. Gathering benthic baseline data in Alaska is also critical in light of oil and natural gas exploration. After the Exon Valdez oil spill in 1989, for example, a significant amount of overlap was observed between weathervane scallop beds in Shelikof Strait and sites where oil drifted with the currents, but no scallop observer data were being collected at that time (G. Rosenkranz, ADF&G, pers. comm.). A lack of pre-spill baseline data severely hampered analyses of oil effects associated with this spill (Rice et al. 2007).

To deepen our understanding of spatiotemporal variability of benthic communities and effects of anthropogenic and environmental factors, additional research studies are recommended. With respect to weathervane scallops, studies of physiology and ecology, such as larval advection and metapopulation dynamics, would inform connectivity of habitats. Food habits studies of scallop predators would shed further light on trophic interactions and provide key insight into scallop ecology. More broadly, studies on the selectivity of the scallop dredges would clarify the size spectra of species that are indexed by haul contents. Examination of benthic species composition in dredged versus un-dredged areas across Alaska's continental shelf would further elucidate potential fishing effects. Opening some closed areas to fishing and closing some current open areas, and monitoring the results, would provide an even more powerful study of fishing effects and recovery from cessation of fishing. Other research needs concerning potential effects of fishing on benthic communities on weathervane scallop beds were identified during a workshop in 2000 (ADF&G and UAF 2000).

Acknowledgments. We thank Dr. Stephen Jewett, Scott Miller, and Dr. Franz Mueter for their helpful reviews and suggestions. We also thank Gregg Rosenkranz, Ryan Burt, Ric Shepard, Steve Lewis, Jane Reid, and Craig Rose for their support with data collection and analysis. This project was supported by the National Science Foundation Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) IGERT (Award DGE-0801720), the National Science Foundation Graduate Research Fellowship Program, the Northern Gulf of Alaska Applied Research Award, the H. Richard Carlson Fellowship, the North Pacific Research Board (NPRB, Project No. F5307), and the University of Alaska Coastal Marine Institute with funding from the US Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental

Studies Program, Washington, D.C., Cooperative Agreement Award No. M13AC00004. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.

LITERATURE CITED

ADF&G (Alaska Department of Fish and Game), UAF (University of Alaska Fairbanks) (2000) A workshop examining potential fishing effects on population dynamics and community structure of scallops with emphasis on weathervane scallop *Patinpoecten caurinus* in Alaskan waters. Alaska Department of Fish and Game, Division of Commercial Fisheries, Special Publication 14, Juneau, AK 99801

Anderson PJ, Piatt JF (1999) Community reorganization in the Gulf of Alaska following ocean climate regime shift. Mar Ecol Prog Ser 189:117–123

Atlas RM, Horowitz A, Busdosh M (1978) Prudhoe crude oil in Arctic marine ice, water, and sediment ecosystems: degradation and interactions with microbial and benthic communities. J Fish Res Board Can 35:585–590

Austen MC, Lambshead PJD, Hutchings PA, Boucher G, Snelgrove PVR, Heip C, King G, Koike I, Smith C (2002) Biodiversity links above and below the marine sediment–water interface that may influence community stability. Biodivers Conserv 11:113–136

Blanchard AL, Feder HM, Shaw DG (2003) Variations in benthic fauna underneath an effluent mixing zone at a marine oil terminal in Port Valdez, Alaska. Mar Pollut Bull 46:1583–1589

Bray JR, Curtis JT (1957) An ordination of the upland forest communities of southern Wisconsin. Ecol Monogr 27:325–349

Brown EJ, Finney B, Hills S, Dommisse M (2005a) Effects of commercial otter trawling on benthic communities in the southeastern Bering Sea. Am Fish Soc Symp 41:439–460

Brown EJ, Finney B, Dommisse M, Hills S (2005b) Effects of commercial otter trawling on the physical environment of the southeastern Bering Sea. Cont Shelf Res 25:1281–1301

Brown SK, Buja KR, Jury SH, Monaco ME, Banner A (2000) Habitat suitability index models for eight fish and invertebrate species in Casco and Sheepscot Bays, Maine. N Am J Fish Manage 20:408–435

Byrne M (2011) Impact of ocean warming and ocean acidification on marine invertebrate life history stages: Vulnerabilities and potential for persistence in a changing ocean. In: N GR, Atkinson RJA, Gordon JDM, Smith IP, J HD (eds) Oceanography and Marine Biology: an Annual Review. Taylor & Francis, p 1–42

Clarke KR (1993) Nonparametric multivariate analyses of changes in community structure. Aust J Ecol 18:117–143

Clarke KR, Ainsworth M (1993) A method of linking multivariate community structure to environmental variables. Mar Ecol Prog Ser 92:205–219

Clarke KR, Gorley RN (2006) PRIMER v6: User manual/tutorial. PRIMER-E, Plymouth, UK.

Clarke KR, Warwick RM (2001) Change in marine communities: an approach to statistical analysis and interpretation, 2nd edition: PRIMER-E. Plymouth Marine Laboratory, Plymouth, UK.

Collie JS, Escanero GA, Valentine PC (1997) Effects of bottom fishing on the benthic megafauna of Georges Bank. Mar Ecol Prog Ser 155:159–172

Dunton KH, Goodall JL, Schonberg SV, Grebmeier JM, Maidment DR (2005) Multi-decadal synthesis of benthic-pelagic coupling in the western arctic: Role of cross-shelf advective processes. Deep-Sea Res Pt II 52:3462–3477

Evans KR, Carlson PR, Hampton MA, Marlow MS, Barnes PM (2000) Map of distribution of bottom sediments on the continental shelf, Gulf of Alaska: U.S. Geological Survey Miscellaneous Field Studies MF-2335, scale 1:1,000 at 60^{o}. Available at http://pubsusgsgov/mf/2000/2335/

Feder HM, Jewett SC (1986) The subtidal benthos. In: Hood DW, Zimmerman ST (eds) The Gulf of Alaska: physical processes and biological resources. US Dept of Commerce, NOAA, NOS, Office of Oceanography and Marine Assessment, Ocean Assessments Div, Alaska Office: US Dept of the Interior, MMS, Alaska OCS Region, Springfield, VA, p 347–396

Feder HM, Jewett SC, Blanchard A (2005) Southeastern chukchi sea (Alaska) epibenthos. Polar Biol 28:402–421

Fluharty D (2000) Habitat protection, ecological issues, and implementation of the Sustainable Fisheries Act. Ecol Appl 10:325–337

Gili J-M, Coma R (1998) Benthic suspension feeders: their paramount role in littoral marine food webs. Trends Ecol Evol 13:316–321

Grebmeier JM, Feder HM, McRoy CP (1989) Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. II. Benthic community structure. Mar Ecol Prog Ser 51:253–268

Hare SR, Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog Oceanogr 47:103–145

Hennick DP (1973) Sea scallop, *Patinopecten caurinus*, investigations in Alaska. Commercial Fisheries Research and Development Act Completion Report 5-23-R, Alaska Department of Fish & Game, Juneau, AK 99801

Hoff GR (2010) Identification of skate nursery habitat in the eastern Bering Sea. Mar Ecol Prog Ser 403:243–254

Hurlbert SH (1984) Pseudoreplication and the design of ecological field experiments. Ecol Monogr 54:187–211

Jewett SC, Feder HM, Blanchard AL (1999) Assessment of the benthic environment following offshore placer mining in Northeastern Bering Sea. Mar Environ Res 48:91–122

Jewett SC, Clough LM, Blanchard AL, Ambrose WG, Feder HM, Hoberg MK, Whiting AV (2009) Nearshore macrobenthos of northern Kotzebue Sound, Alaska, with reference to local sewage disposal. Polar Biol 32:1665–1680

Kaiser MJ, Clarke KR, Hinz H, Austen M, Somerfield PJ, Karakassis I (2006) Global analysis of response and recovery of benthic biota to fishing. Mar Ecol Prog Ser 311:1–14

Kennedy AD, Jacoby CA (1999) Biological indicators of marine environmental health: Meiofauna – a neglected benthic component? Environ Monit Assess 54:47–68

Kruse GH, Barnhart JP, Rosenkranz GE (2005) Management of the data-limited weathervane scallop fishery in Alaska. In: Kruse GH, Gallucci VF, Hay DE, Perry RI, Peterman RM, Shirley TC, Spencer PD, Wilson B, and Woodby D (eds). Fisheries assessment and management in data-limited situations Alaska Sea Grant College Program AK-SG-05-02, University of Alaska Fairbanks, p 51–68

Latour RJ, Brush MJ, Bonzek CF (2003) Toward ecosystem-based fisheries management. Fisheries 28:10–22

Lenihan HS, Peterson CH, Kim SL, Conlan KE, Fairey R, McDonald C, Grabowski JH, Oliver JS (2003) Variation in marine benthic community composition allows discrimination of multiple stressors. Mar Ecol Prog Ser 261:63–73

Masuda MM, Stone RP (2003) Biological and spatial characteristics of the weathervane scallop *Patinopecten caurinus* at Chiniak Gully in the central Gulf of Alaska. Alaska Fish Res Bull 10:104–118

Matsuura T, Takeshita K (1990) Longevity of red king crab, *Paralithoides camtschatica*, revealed by long-term rearing study. In: Proceedings of the International Symposium on King and Tanner Crabs University of Alaska Fairbanks, Alaska Sea Grant Coll Prog Rep 90-04, p 181–188

McConnaughey RA, Smith KR (2000) Associations between flatfish abundance and surficial sediments in the eastern Bering Sea. Can J Fish Aquat Sci 57:2410–2419

McConnaughey RA, Mier KL, Dew CB (2000) An examination of chronic trawling effects on soft-bottom benthos of the eastern Bering Sea. ICES J Mar Sci 57:1377–1388

Mueter F, Megrey BA (2005) Distribution of population-based indicators across multiple taxa to assess the status of Gulf of Alaska and Bering Sea groundfish communities. ICES J Mar Sci 62:344–352

Mueter FJ, Litzow MA (2008) Sea ice retreat alters the biogeography of the Bering Sea continental shelf. Ecol Appl 18:309–320

Napp JM, Hunt GL (2001) Anomalous conditions in the south-eastern Bering Sea 1997: linkages among climate, weather, ocean, and Biology. Fish Oceanogr 10:61–68

Narita D, Rehdanz K, Tol RSJ (2012) Economic costs of ocean acidification: a look into the impacts on global shellfish production. Climatic Change 113:1049–1063

NMFS (National Marine Fisheries Service) (2005a) Environmental impact statement for essential fish habitat identification and conservation in Alaska. Appendix B. Evaluation of fishing activities that may adversely affect essential fish habitat. US Dept of Commerce, NOAA, NMFS; Alaska Region, P.O. Box 21668, Juneau, AK 99802-1668

NMFS (National Marine Fisheries Service) (2005b) Environmental impact statement for essential fish habitat identification and conservation in Alaska. Appendix F4 Essential fish habitat assessment report for scallop resources in the Gulf of Alaska, Bering Sea, and Aleutian Islands regions US Dept of Commerce, NOAA, NMFS: Alaska Region, PO Box 21668, Juneau, AK 99802-1668

Orejas C, Gili J-M, Arntz W, Ros JD, López P, Teixidó N, FILIPE P (2000) Benthic suspension feeders, key players in Antarctic marine ecosystems? Contr Sci 1:299–311

Overland JE, Bond NA, Adams JM (2001) North Pacific Atmospheric and SST Anomalies in 1997: Links to ENSO? Fish Oceanogr 10:69–80

Peterson CH, Summerson HC, Thomson E, Lenihan HS, Grabowski J, Manning L, Micheli F, Johnson G (2000) Synthesis of linkages between benthic and fish communities as a key to protecting essential fish habitat. Bull Mar Sci 66:759–774

Peterson WT (2003) A new climate regime in northeast pacific ecosystems. Geophys Res Lett 30:1896-1899

Piepenburg D, Archambault P, Ambrose WG Jr, Blanchard AL, Bluhm BA, Carroll ML, Conlan KE, Cusson M, Feder HM, Grebmeier JM (2011) Towards a pan-Arctic inventory of the species diversity of the macro-and megabenthic fauna of the Arctic shelf seas. Mar Biodiv 41:51–70

Renaud PE, Wlodarska-Kowalczuk M, Trannum H, Holte B, Weslawski JM, Cochrane S, Dahle S, Gulliksen B (2007) Multidecadal stability of benthic community structure in a high-Arctic glacial fjord (van Mijenfjord, Spitsbergen). Polar Biol 30:295–305

Rice SD, Short JW, Carls MG, Moles A, Spies RB (2007) The Exxon Valdez oil spill. In: Spies RB (ed) Long-term ecological change in the northern Gulf of Alaska. Elsevier, Amsterdam, p 419–520

Ries JB, Cohen AL, McCorkle DC (2009) Marine calcifiers exhibit mixed responses to CO2-induced ocean acidification. Geology 37:1131–1134

Rooper CN, Wilkins ME, Rose CS, Coon C (2011) Modeling the impacts of bottom trawling and the subsequent recovery rates of sponges and corals in the Aleutian Islands, Alaska. Cont Shelf Res 31:1827–1834

Rosenkranz GE (2002) Mortality of *Chionoecetes* crabs incidentally caught in Alaska's weathervane scallop fishery. In: Paul AJ, Dawe EG, Elner R, Jamieson GS, Kruse GH, Otto RS, Sainte-Marie B, Shirley TC, Woodby D (eds) Alaska Sea Grant College Program AK-SG-02-01, University of Alaska Fairbanks, p 717–732

Rosenkranz GE, Spafard M (2013) Summary of observer data collected during the 2010/11 Alaska weathervane scallop fishery. Alaska Department of Fish and Game, Fishery Data Series No 13-09, Anchorage, AK 99518

Royer TC (1982) Coastal fresh water discharge in the northeast Pacific. J Geophys Res 87:2017–2021

Shore R (2014) Acidic water blamed for west coast scallop die-off. The Vancouver Sun. 2-25-2014. URL http://www.vancouversun.com/life/Acidic+water+blamed+West+Coast+scallop/9550861/story.html (accessed 4-30-14)

Siddon EC, Duffy-Anderson JT, Mueter FJ (2011) Community-level response of fish larvae to environmental variability in the southeastern Bering Sea. Mar Ecol Prog Ser 426:225–239

Smith KR, McConnaughey RA (1999) Surficial sediments of the eastern Bering Sea continental shelf: EBSSED database documentation. US Dept of Commerce, Seattle, WA, NOAA Tech Memo NMFS-AFSC 104

Stone RP, Masuda MM, Malecha PW (2005) Effects of bottom trawling on soft-sediment epibenthic communities in the Gulf of Alaska. Am Fish S S 41:439–453

Thrush SF, Dayton PK (2002) Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity. Annu Rev Ecol Syst 33:449–473

Turk TA (2001) Spatial distribution and selected habitat preferences of weathervane scallops in Alaska. In: Kruse GH, Bez N, Booth A, Dorn MW, Hills S, Lipcious RN, Pelletier D, Royer, Smith SJ, Witherell D (eds) Spatial Processes and Management of Marine Populations, Alaska Sea Grant College Program AK-SG-01-02, University of Alaska Fairbanks, p 463–477

Witherell D, Pautzke C, Fluharty D (2000) An ecosystem-based approach for Alaska groundfish fisheries. ICES J Mar Sci 57:771–777

Yeung C, McConnaughey RA (2006) Community structure of eastern Bering Sea epibenthic invertebrates from summer bottom-trawl surveys 1982 to 2002. Mar Ecol Prog Ser 318:47–62

Yeung C, Yang M-S, McConnaughey RA (2010) Polychaete assemblages in the south-eastern Bering Sea: linkage with groundfish distribution and diet. J Mar Biol Ass UK 90:903–917

Zador, S (ed.) (2013) Ecosystem considerations 2013. Stock assessment and fishery evaluation report. North Pacific Fishery Management Council, 605 W. 4th Ave, Suite 306, Anchorage, AK, 99501

Zimmermann M, Prescott MM, Rooper CN (2013) Smooth sheet bathymetry of the Aleutian Islands. US Dept of Commerce, Seattle, WA, NOAA Tech Memo NMFS-AFSC 250

Table 1. Taxa included in the analysis after excluding the rarest 5%.

Taxonomic Level	Name	Taxonomic Level	Name
Family	Myxinidae (Hagfishes)	Class	Bivalvia (Bivalve molluscs)
Family	Petromyzontidae (Lampreys)	Family	Mytilidae (Mussels)
Subclass	Elasmobranchii (Sharks)	Family	Pectinidae (Scallops)
Family	Rajidae (Skates)	Family	Hiatellidae (Rock borer clams)
N/A	skate egg cases	Family	Nuculanidae (Clams)
Family	Chimaeridae (Chimeras)	Family	Thyasiridae (Clams)
Order	Pleuronectiformes (Flatfishes)	Family	Cardiidae (Cockles)
N/A	Roundfish	Family	Veneridae (Venus clams)
Class	Hydrozoa (Hydrozoans)	Family	Mactridae (Surf clams)
Class	Scyphozoa (Jellyfish)	Family	Tellinidae (Tellin clams)
Order	Alcyonacea (Soft corals)	Family	Solenidae (Razor clams)
Order	Pennatulacea (Sea pens)	Family	Myidae (Softshell clams)
Order	Actiniaria (Sea anemones)	Family	Pandoridae (Clams)
Class	Polychaeta (Annelid worms)	Family	Anomiidae (Jingle shell clams)
Family	Aphroditidae (Sea mice)	Family	Octopodidae (Octopus)
Family	Nereidae (Polychaete worms)	Order	Teuthoidea (Squids)
Family	Polynoidae (Scale worms)	Family	Sepiolidae (Bobtail squids)
Class	Hirudinea (Leeches)	Class	Asteroidea (Sea stars)
Order	Amphipoda (Amphipods)	Family	Echinasteridae (Sea stars)
Order	Isopoda (Isopods)	Family	Goniasteridae (Sea stars)
Class	Cirripedia (Barnacles)	Family	Luidiidae (Sea stars)
Order	Decapoda (Decapods)	Family	Poraniidae (Sea stars)
Family	Pandalidae (Pandalid shrimp)	Family	Solasteridae (Sea stars)
Family	Hippolytidae (Cleaner shrimp)	Family	Pterasteridae (Sea stars)
Family	Crangonidae (Crangon shrimp)	Family	Porcellanasteridae (Sea stars)
Infraorder	Brachyura (True crabs)	Family	Goniopectinidae (Mud stars)
Family	Cancridae (Rock crabs)	Family	Astropectinidae (Sea stars)
Family	Oregoniidae (Tanner/snow crabs)	Family	Benthopectinidae (Sea stars)
Family	Paguridae (Hermit crabs)	Order	Echinoida (Sea urchins)
Family	Lithodidae (King crabs)	Order	Clypeasteroida (Sand dollars)
Family	Cheiragonidae (Helmet crabs)	Class	Ophiuroidea (Brittle stars)
N/A	Gastropod eggs	Family	Gorgonocephalidae (Basket stars)
Family	Onchidoridae (Sea slugs)	Family	Ophiuridae (Brittle stars)
Family	Tritoniidae (Nudibranchs)	Class	Holothuroidea (Sea cucumbers)
Class	Gastropoda (Snails and slugs)	Phylum	Porifera (Sponges)
Family	Naticidae (Moon snails)	Class	Demospongiae (Demosponges)
Family	Buccinidae (Whelks)	Phylum	Platyhelminthes (Flatworms)
Family	Capulidae (Sea snails)	Phylum	Bryozoa (Bryozoans)
Family	Ranellidae (Tritons)	Phylum	Brachiopoda (Brachiopods)
		Class	Ascidiacea (Sea squirts)

Table 2. Surface sediment types assigned to each registration district based on overlap of surficial sediment observations with commercial scallop hauls. Sediment data were sourced from Evans et al. (2000)[1], Smith & McConnaughey (1999)[2], and Zimmerman et al. (2013)[3].

District	Sediment types
Alaska Peninsula	N/A
Aleutian Islands[3]	gravelly sand
	sand
Bering Sea[2]	sand/mud
Kodiak Northeast[1]	bedrock
	gravelly sand
	muddy to sandy gravel
	sand
	sandy silt
	silty clay/mud
Kodiak Shelikof (Bed KSH 1)[1]	muddy to sandy gravel
	gravelly mud
	sandy silt
	silty clay/mud
Kodiak Southwest	N/A
Prince William Sound[1]	bedrock
	sand
	sandy silt
	silty clay/mud
Kodiak Semidi Islands	N/A
Yakutat[1]	gravelly sand
	muddy to sandy gravel
	gravelly mud
	sand
	sandy silt
	silty clay/mud
District 16[1]	gravelly sand
	sand
	silty clay/mud

Table 3. Depth ranges (m), sample sizes (N, number of tows sampled for complete haul composition), and years sampled for each state registration district and individual scallop beds off Alaska. Note that fishing still occurred during some years on certain beds that were not sampled for complete haul composition by observers, and that some hauls in a district did not fall within a delineated bed.

District/Bed	Depth range	N	Years sampled
Alaska Peninsula	69-137	165	’96-’00, ’06, ‘08
C 1	69-130	16	’98, ‘99
C 2	101-102	2	’98, ‘99
C 3	90-137	12	’97-’99, ‘06
C 4	93-113	87	’96-’00, ‘06
WC 1	99-124	3	’97, ‘98
WC 2	99-128	10	’97-’99, ‘08
WC 3	88-102	3	’97, ‘99
UB 1	106	1	‘12
UB 2	88-102	13	‘12
UB 3	108-113	6	‘12
UB 4	88-101	2	‘12
UB 5	101-108	2	‘12
Aleutian Islands	55-91	49	’97-’99, ’08-‘12
O 1	64-71	7	’09-‘11
O 2	55-64	7	‘99
O 3	59-91	5	’97-’99, ’08
O 4	75-90	23	’10-‘12
Bering Sea			’96-‘12
Q 1	90-115	563	’96-‘12
Kodiak Northeast	68-155	547	’96-‘12
KNE 1	88-126	27	’96, ’97, ’03-’06, ’08, ’12
KNE 2	88-155	98	’96-’98, ’03-’06, ’08-‘12
KNE 3	68-88	280	’97-‘11
KNE 4	77-82	18	’96, ’98, ’01, ’03, ’07-’10
KNE 5	73-95	54	’96-’00, ’02, ’04-’06, ’08, ’09, ’12
KNE 6	80-117	67	’97, ’98, ’00-‘06, ’08-‘12

District/Bed	Depth range	N	Years sampled
Kodiak Shelikof	46-172	1339	’96-‘12
KSH 1	46-172	1262	’96-‘12
KSH 2	64-119	31	’96-’99,’01, ’03, ‘12
KSH 3	64-84	17	’96, ’01, ’02, ’11, ‘12
KSH 4	51-106	12	’97, ’03, ’04, ‘10
KSH 5	57-106	8	’96, ’97, ’03, ‘10
KSH 6	62-68	5	’97, ’02, ‘10
KSH 7	64-69	3	‘97
Kodiak Southwest	69-82	31	’09-12
KSW 1	73	1	‘09
KSW 2	69-82	29	’09, ’11, ‘12
Prince William Sound	57-101	164	’98-’00, ’02-‘11
EKI	60-97	79	’98, ’99, ’00, ’02, ’04-‘11
WKI	57-101	85	’98, ’99, ’00, ’02-‘09
Kodiak Semidi Islands	46-124	38	’96-‘99
KSEM 1	80-88	2	’96, ‘97
KSEM 2	73-110	6	’96-‘98
KSEM 3	91	3	‘96
KSEM 4	95-124	5	’97, ‘98
KSEM 5	46-97	18	’96-‘99
KSEM 6	93-119	4	‘96
Yakutat	49-117	1517	’96-‘12
Yak B	82-106	23	’09, ’11, ‘12
Yak 1	69-108	95	’98-’02, ’05-’10, ‘12
Yak 2	49-84	291	’96-‘12
Yak 3	55-102	252	’96-’02, ’04-‘12
Yak 4	55-110	395	’96-‘12
Yak 5	55-117	264	’96-‘12
District 16			’96-’06, ’08-‘12
Yak 6	55-101	196	’96-’06, ’08-‘12

Table 4. Average scallop dredging effort (proportion of beds dredged) by year on all beds that were actively fished for weathervane scallops. Dredging effort for a given year was calculated by dividing the total area swept by dredges on a bed (km^2) by the area of that bed (km^2).

Year	Proportion Dredged
1996	0.0537
1997	0.0865
1998	0.0647
1999	0.0639
2000	0.0602
2001	0.0852
2002	0.1042
2003	0.0549
2004	0.0594
2005	0.0683
2006	0.0449
2007	0.0505
2008	0.0980
2009	0.0731
2010	0.0639
2011	0.0566
2012	0.0691
Total:	**0.0681**

Table 5. Clarke's R values indicating strength of pairwise spatial differences in haul composition samples among Alaska scallop registration districts in (a) 1997, (b) 2000, and (c) 2010. Significant values (*P* < 0.05) are indicated by an asterisk (*).

a) 1997

	Yakutat/D16	Kodiak Shelikof	Kodiak Northeast	Semidi Islands	Alaska Peninsula	Aleutian Islands
Kodiak Shelikof	0.805*					
Kodiak Northeast	0.744*	0.443*				
Semidi Islands	0.831*	0.635*	0.600*			
Alaska Peninsula	0.616*	0.411*	0.164*	0.469*		
Aleutian Islands	1.000*	0.833*	0.600*	0.179	0.055	
Bering Sea	0.760	0.622	0.360	-0.167	-0.080	1.000

b) 2000

	Yakutat/D16	Kodiak Shelikof	Kodiak Northeast	Prince William Sound	Alaska Peninsula
Kodiak Shelikof	0.622				
Kodiak Northeast	0.741*	-0.333			
Prince William Sound	0.438	-1.000	0.333		
Alaska Peninsula	1.000	undef	-0.333	1.000	
Bering Sea	1.000	undef	-0.111	1.000	undef

c) 2010

	Yakutat/D16	Kodiak Shelikof	Kodiak Northeast	Prince William Sound	Aleutian Islands
Kodiak Shelikof	0.798*				
Kodiak Northeast	0.905*	0.438*			
Prince William Sound	0.000	0.333	1.000		
Aleutian Islands	0.875*	0.321	0.536	-1.000	
Bering Sea	1.000	0.333	0.667	undef	0.000

Table 6. Comparison of relative contributions of each taxon to 90% of the cumulative dissimilarities between Yakutat and Aleutian Islands districts in (a) 1997 and (b) 2010. The average CPUEs for each taxon in each district are shown, along with the percentage that each taxon contributes to the total (Contrib. %) and the cumulative percentage contribution (Cum. %).

a) 1997: Average dissimilarity = 57.21				
Taxa	Yakutat Avg. CPUE	Aleutian Islands Avg. CPUE	Contrib. %	Cum. %
Pennatulacea	0.00	41.75	8.64	8.64
Gastropoda	3.03	39.56	7.32	15.96
Cardiidae	1.91	36.43	7.06	23.02
Roundfish	16.01	49.46	6.94	29.96
Decapoda	8.41	31.87	6.02	35.99
skate egg cases	29.10	0.00	5.96	41.95
Gastropod eggs	11.51	37.44	5.49	47.44
Echinoida	0.00	28.21	5.20	52.64
Rajidae	38.50	26.46	5.15	57.79
Pleuronectiformes	26.46	52.32	5.09	62.88
Porifera	0.00	23.78	4.86	67.74
Paguridae	14.72	33.66	3.89	71.62
Oregoniidae	7.30	19.32	3.70	75.32
Pectinidae	49.74	33.65	3.48	78.80
Hirudinea	15.55	0.00	3.06	81.86
Actiniaria	14.15	11.33	2.59	84.45
Ophiuroidea	12.88	0.00	2.58	87.03
Cirripedia	13.16	8.85	2.33	89.36
Bivalvia	9.95	0.00	1.97	91.33

Table 6 continued

b) 2010: Average dissimilarity = 56.89

	Yakutat	Aleutian Islands		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Bryozoa	0.00	50.00	9.66	9.66
Rajidae	42.11	0.00	7.30	16.96
Aphroditidae	40.25	0.00	6.93	23.89
Cirripedia	29.64	0.00	5.22	29.10
Veneridae	27.47	0.00	4.56	33.66
Echinoida	0.00	26.13	4.02	37.68
Asteroidea	37.42	46.15	3.59	41.28
skate egg cases	30.18	10.78	3.21	44.49
Paguridae	23.15	17.81	3.18	47.67
Luidiidae	39.01	19.17	3.18	50.85
Buccinidae	13.06	14.19	2.95	53.80
Ranellidae	1.54	18.54	2.88	56.68
Gastropod eggs	0.96	18.56	2.87	59.55
Oregoniidae	11.45	16.62	2.76	62.31
Naticidae	20.88	8.12	2.74	65.06
Actiniaria	20.52	13.56	2.73	67.79
Pennatulacea	18.23	8.62	2.68	70.47
Roundfish	16.81	7.42	2.37	72.84
Decapoda	13.26	0.00	2.24	75.08
Goniasteridae	6.22	13.45	2.21	77.30
Cheiragonidae	0.00	13.72	2.11	79.41
Octopodidae	7.27	8.35	2.10	81.51
Goniopectinidae	7.97	9.43	2.04	83.55
Pleuronectiformes	38.25	47.09	1.77	85.32
Demospongiae	2.90	10.44	1.67	86.99
Cardiidae	9.10	9.03	1.62	88.61
Pectinidae	49.75	43.03	1.41	90.02

Table 7. Comparison of relative contributions of each taxon to 50% of the cumulative dissimilarities between beds KSH 1 and KSH 6 in the Kodiak Shelikof district in (a) 1997 and (b) 2010. The average CPUEs for each taxon in each district are shown, along with the percentage that each taxon contributes to the total (Contrib. %) and the cumulative percentage contribution (Cum. %).

a) 1997

Average dissimilarity = 61.37

Taxa	KSH 1 Avg. CPUE	KSH 6 Avg. CPUE	Contrib. %	Cum. %
Brachiopoda	2.51	81.98	9.10	9.10
Cancridae	2.86	50.75	5.50	14.60
Polychaeta	12.83	47.98	5.14	19.74
Ascidiacea	0.85	39.03	4.34	24.08
Holothuroidea	4.84	39.00	4.16	28.24
Gorgonocephalidae	1.70	35.34	3.84	32.08
Rajidae	46.39	48.29	3.80	35.89
Demospongiae	1.91	34.24	3.73	39.62
Gastropoda	20.15	52.24	3.48	43.11
Onchidoridae	0.00	31.47	3.48	46.58
Echinoida	14.05	34.17	3.42	50.00

b) 2010

Average dissimilarity = 51.99

Taxa	KSH 1 Avg. CPUE	KSH 6 Avg. CPUE	Contrib. %	Cum. %
Cancridae	1.74	72.87	10.34	10.34
Nereidae	31.73	76.38	7.02	17.36
Holothuroidea	6.11	51.35	6.64	24.00
Aphroditidae	43.58	0.00	6.09	30.09
Gastropod eggs	13.83	47.85	4.96	35.05
Ascidiacea	1.81	35.38	4.90	39.95
Goniasteridae	1.85	34.65	4.77	44.72
Paguridae	33.43	0.00	4.71	49.44

Table 8. Comparison of relative contributions of each taxon to 50% of the cumulative dissimilarities between beds KNE 3 and KNE 6 in the Kodiak Northeast district in (a) 1997 and (b) 2010. The average CPUEs for each taxon in each district are shown, along with the percentage that each taxon contributes to the total (Contrib. %) and the cumulative percentage contribution (Cum. %).

a) 1997
Average dissimilarity = 49.83

Taxa	KNE 3 Avg. CPUE	KNE 6 Avg. CPUE	Contrib. %	Cum. %
Clypeastroida	37.45	0.00	8.21	8.21
Actiniaria	33.83	0.00	7.34	15.55
Rajidae	25.93	34.50	6.21	21.76
Polynoidae	7.58	26.78	5.81	27.57
Ascidiacea	0.00	25.16	4.94	32.51
Pennatulacea	35.77	56.76	4.33	36.84
Gastropoda	14.44	23.24	4.17	41.01
Onchidoridae	12.61	14.17	3.71	44.72
Roundfish	15.82	9.64	3.46	48.18
Asteroidea	56.05	44.37	3.36	51.53

b) 2010
Average dissimilarity = 47.17

Taxa	KNE 3 Avg. CPUE	KNE 6 Avg. CPUE	Contrib. %	Cum. %
Lithodidae	0.00	51.44	7.16	7.16
Actiniaria	48.84	6.82	5.84	13.00
Brachiopoda	39.04	21.49	5.30	18.30
Buccinidae	39.00	6.00	4.78	23.08
Rajidae	31.48	45.79	4.16	27.24
Roundfish	29.93	31.14	3.82	31.06
Ophiuridae	26.12	0.00	3.61	34.68
Luidiidae	26.85	0.00	3.57	38.24
Pennatulacea	27.63	54.16	3.57	41.81
Solasteridae	28.73	3.53	3.53	45.34
Clypeastroida	24.76	3.84	3.21	48.55
Gorgonocephalidae	4.02	23.62	2.79	51.33

Table 9. Clarke's R values indicating strength of pairwise spatial differences in haul composition samples between years (1996 – 2012) on bed KSH 1 in the Kodiak Shelikof district. Non-significant values ($P \geq 0.05$) have been removed.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1996																
1997	0.199															
1998	0.204	0.056														
1999	0.423	0.111	0.131													
2000	0.588	0.154	0.276	0.131												
2001	0.561	0.155	0.305	0.197	0.072											
2002	0.670	0.285	0.401	0.283	0.172	0.202										
2003	0.548	0.331	0.472	0.325	0.183	0.145	0.070									
2004	0.570	0.220	0.357	0.208	0.098	0.109	0.103	0.078								
2005	0.656	0.260	0.431	0.306	0.163	0.185	0.173	0.089	0.084							
2006	0.775	0.232	0.525	0.288	0.210	0.277	0.283	0.041	0.087	0.131						
2007	0.826	0.419	0.686	0.480	0.363	0.410	0.409	0.198	0.279	0.222	0.115					
2008	0.664	0.146	0.304	0.234		0.202	0.188				0.360	0.379				
2009	0.692	0.389	0.582	0.401	0.261	0.214	0.234	0.149	0.134	0.099	0.054	0.222				
2010	0.724	0.336	0.547	0.303	0.229	0.225	0.242	0.133	0.171	0.154	0.010	0.122		0.175		
2011	0.671	0.163	0.318	0.173	0.088	0.139	0.181	0.143	0.066	0.148	0.155	0.339		0.161	0.132	
2012	0.710	0.171	0.418	0.208	0.139	0.201	0.209		0.061	0.120		0.161	0.361	0.068		0.081

Table 10. Comparison of relative contributions of each taxon to 50% of the cumulative dissimilarities between 2000 and 2012 in the combined Yakutat (D16) and Prince William Sound districts. The average CPUEs for each taxon in each year are shown, along with the percentage that each taxon contributes to the total (Contrib. %) and the cumulative percentage contribution (Cum. %).

Average dissimilarity = 57.74				
	2000	2012		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Aphroditidae	22.79	38.60	5.51	5.51
Pandalidae	11.51	31.88	5.27	10.78
Rajidae	28.04	33.75	4.88	15.66
Crangonidae	19.30	22.22	4.50	20.16
Luidiidae	0.00	25.21	4.36	24.51
Pleuronectiformes	31.75	28.57	3.97	28.48
Roundfish	21.12	20.27	3.78	32.26
Cirripedia	23.50	7.11	3.56	35.82
Polychaeta	24.88	0.70	3.38	39.20
Echinasteridae	25.18	0.00	3.19	42.39
Paguridae	23.93	23.57	3.09	45.48
Nereidae	15.47	11.61	3.02	48.50
Actiniaria	22.17	16.66	2.83	51.33

Table 11. Comparison of relative contributions of each taxon to 50% of the cumulative dissimilarities between 2000 and 2012 in the Bering Sea district. The average CPUEs for each taxon in each year are shown, along with the percentage that each taxon contributes to the total (Contrib. %) and the cumulative percentage contribution (Cum. %).

Average dissimilarity = 51.17				
	2000	2012		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Polychaeta	1.62	59.19	9.00	9.00
Porifera	1.35	50.23	7.57	16.57
Pennatulacea	0.00	43.48	6.77	23.34
Cirripedia	12.15	41.55	5.53	28.87
Buccinidae	29.97	45.51	5.15	34.03
Gastropod eggs	5.15	35.42	4.97	39.00
Nereidae	0.00	28.90	4.26	43.26
Scyphozoa	20.43	9.42	3.58	46.84
Roundfish	24.44	17.01	3.44	50.27

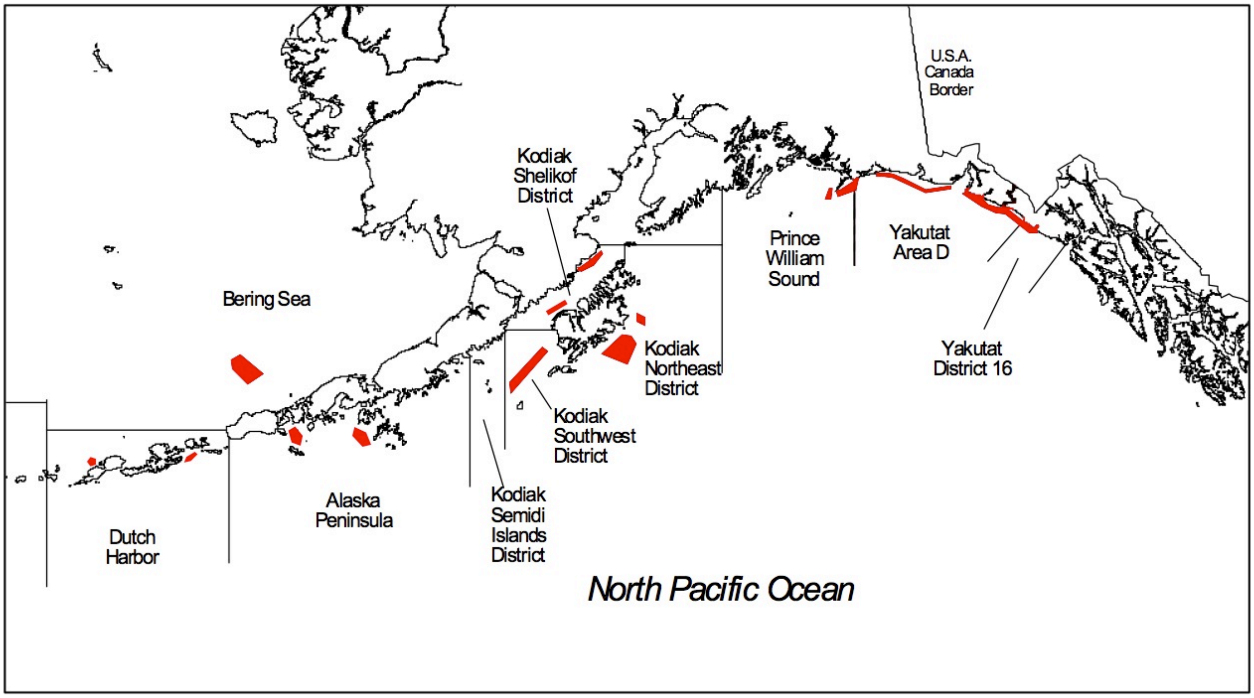

Figure 1. Map of State of Alaska registration areas (labels) for the weathervane scallop fishery and general areas of commercial effort (red polygons). Figure modified from Rosenkranz and Spafard (2013). The Cook Inlet registration area (north of Kodiak) is not included because onboard observers are not required for this area.

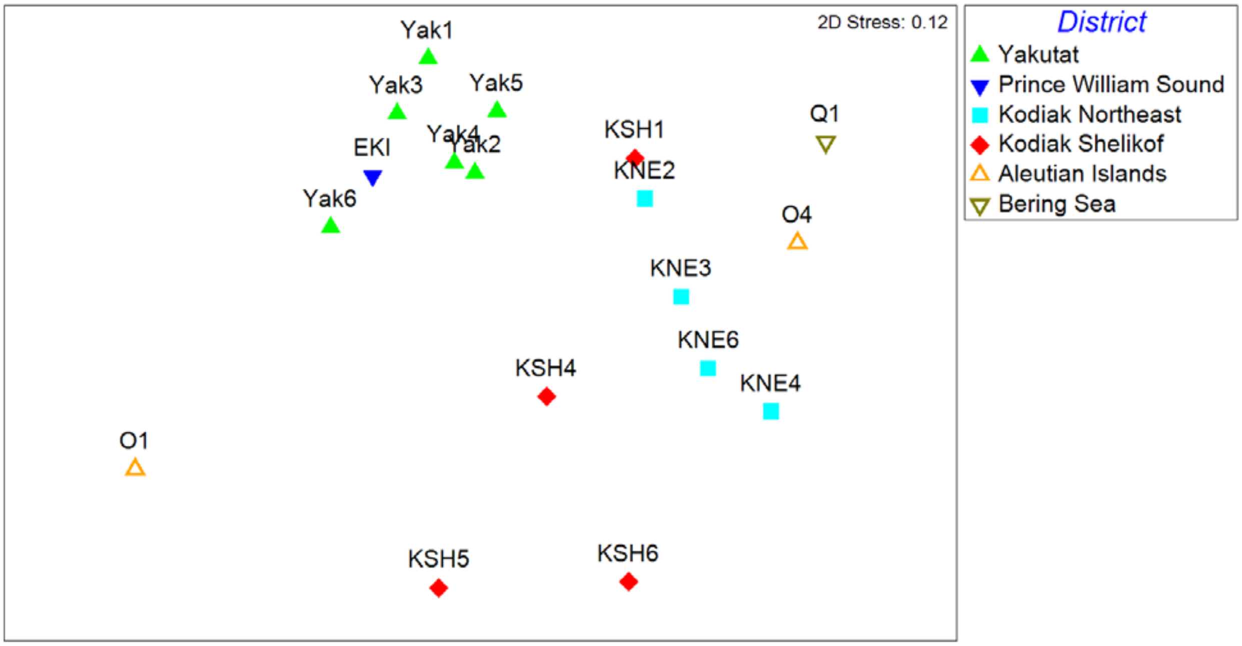

Figure 2. Non-metric multidimensional scaling ordination for Alaska scallop registration districts in 2010. Data are aggregated by individual beds and points are labeled with bed codes listed in Table 3.

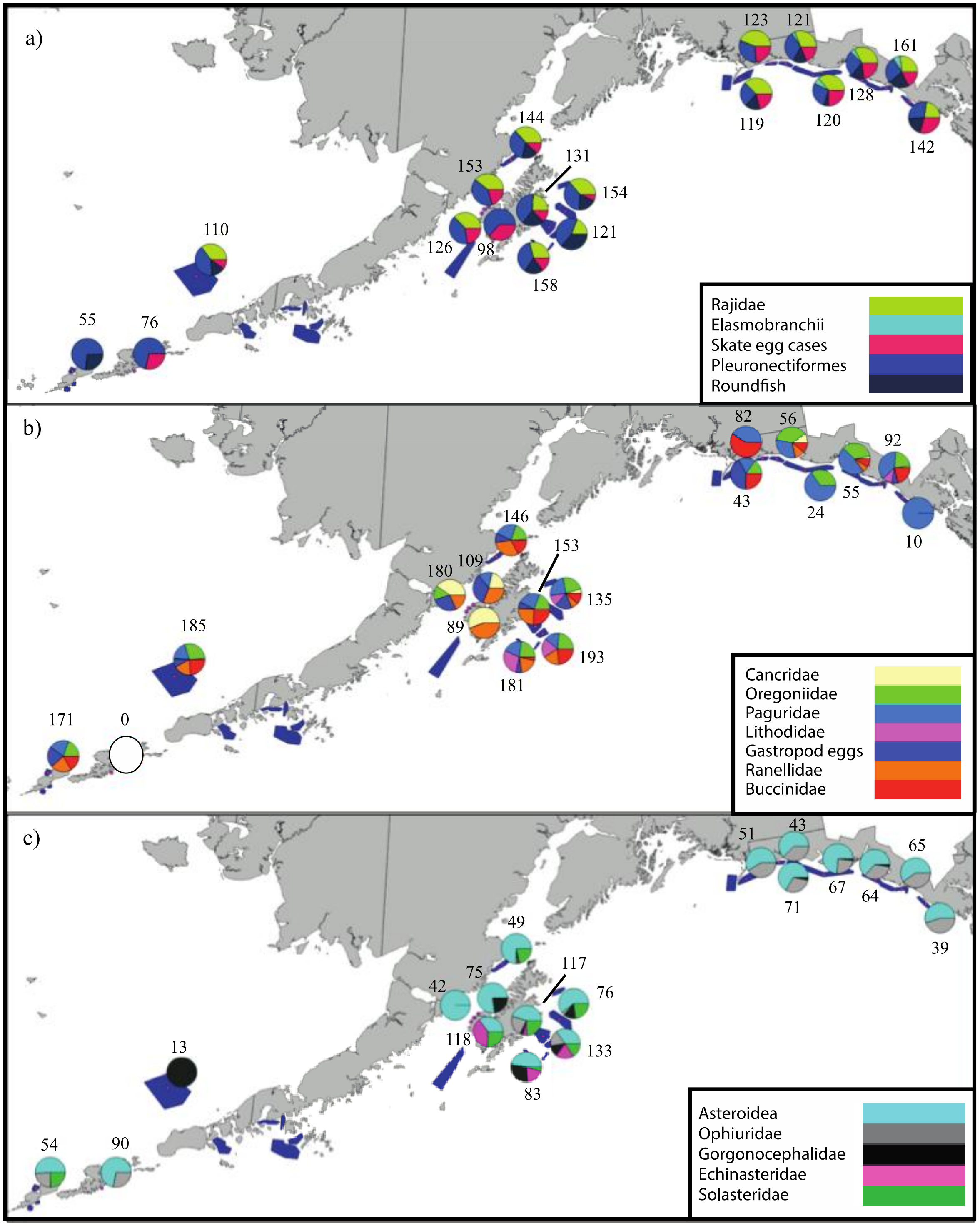

Figure 3. Proportional contributions (pie slices) of taxa contributing to differences between districts, with mean CPUE (numbers) by bed, of (a) vertebrates (including skate egg cases), (b) crabs and gastropods (including gastropod eggs), and (c) brittle stars and other sea stars. Data are presented for 2010 only.

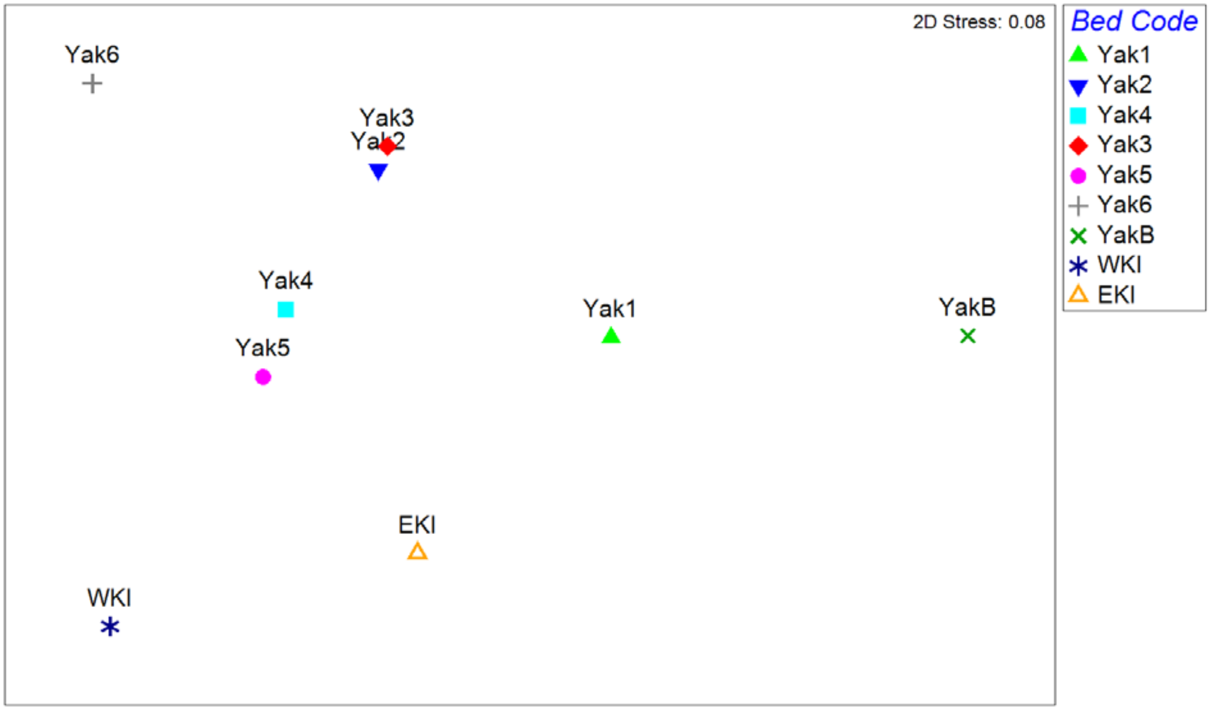

Figure 4. Non-metric multidimensional scaling ordination of individual beds in the Yakutat (Yak 1-5, Yak B), D16 (Yak 6), and Prince William Sound (WKI, EKI) districts. CPUE was averaged by bed across all sampling years 1996 – 2012.

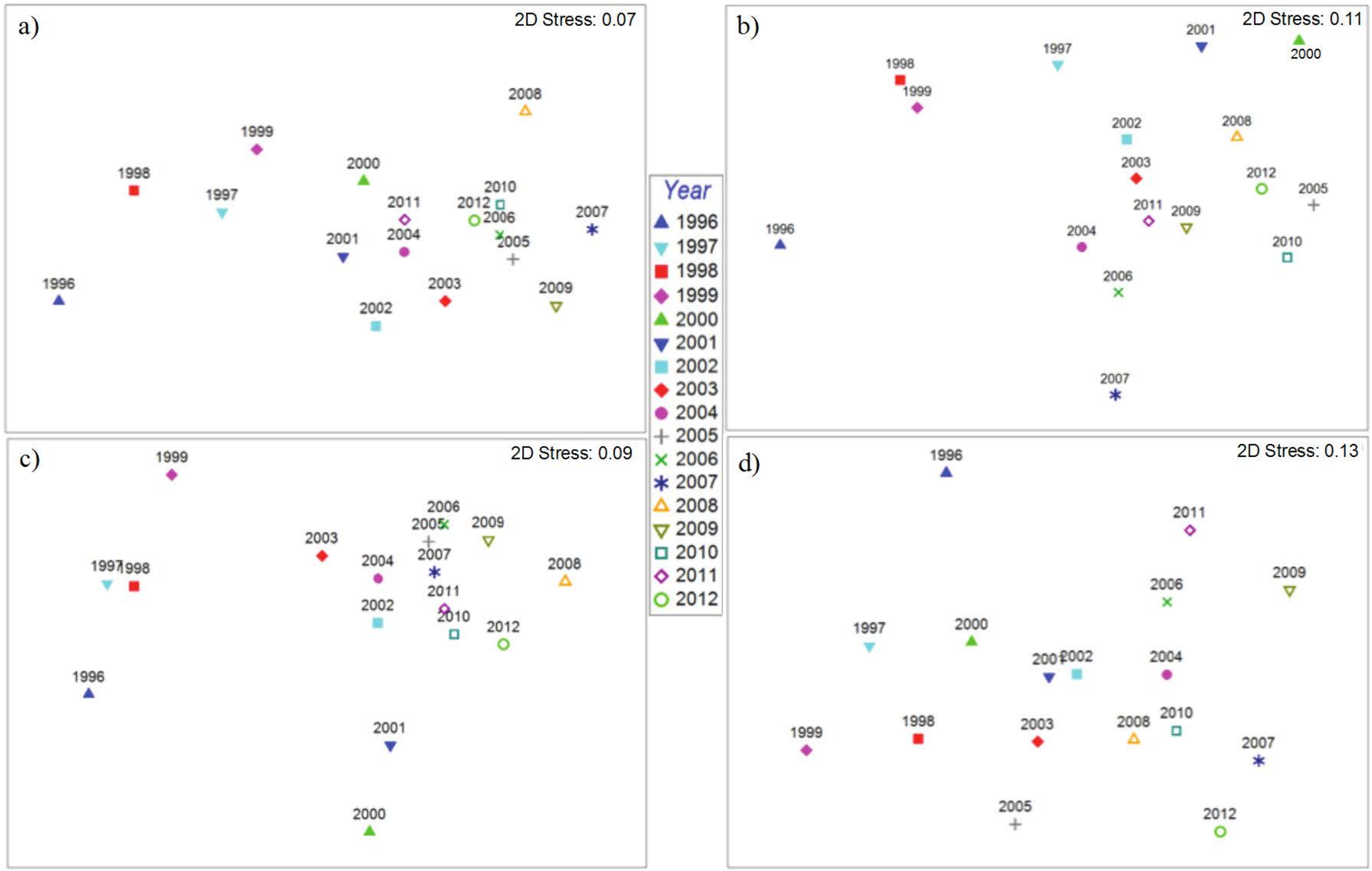

Figure 5. Non-metric multidimensional scaling ordination of haul composition samples aggregated by year (1996-2012) in the (a) Kodiak Shelikof, (b) Kodiak Northeast, (c) Yakutat/D16/Prince William Sound, and (d) Bering Sea districts.

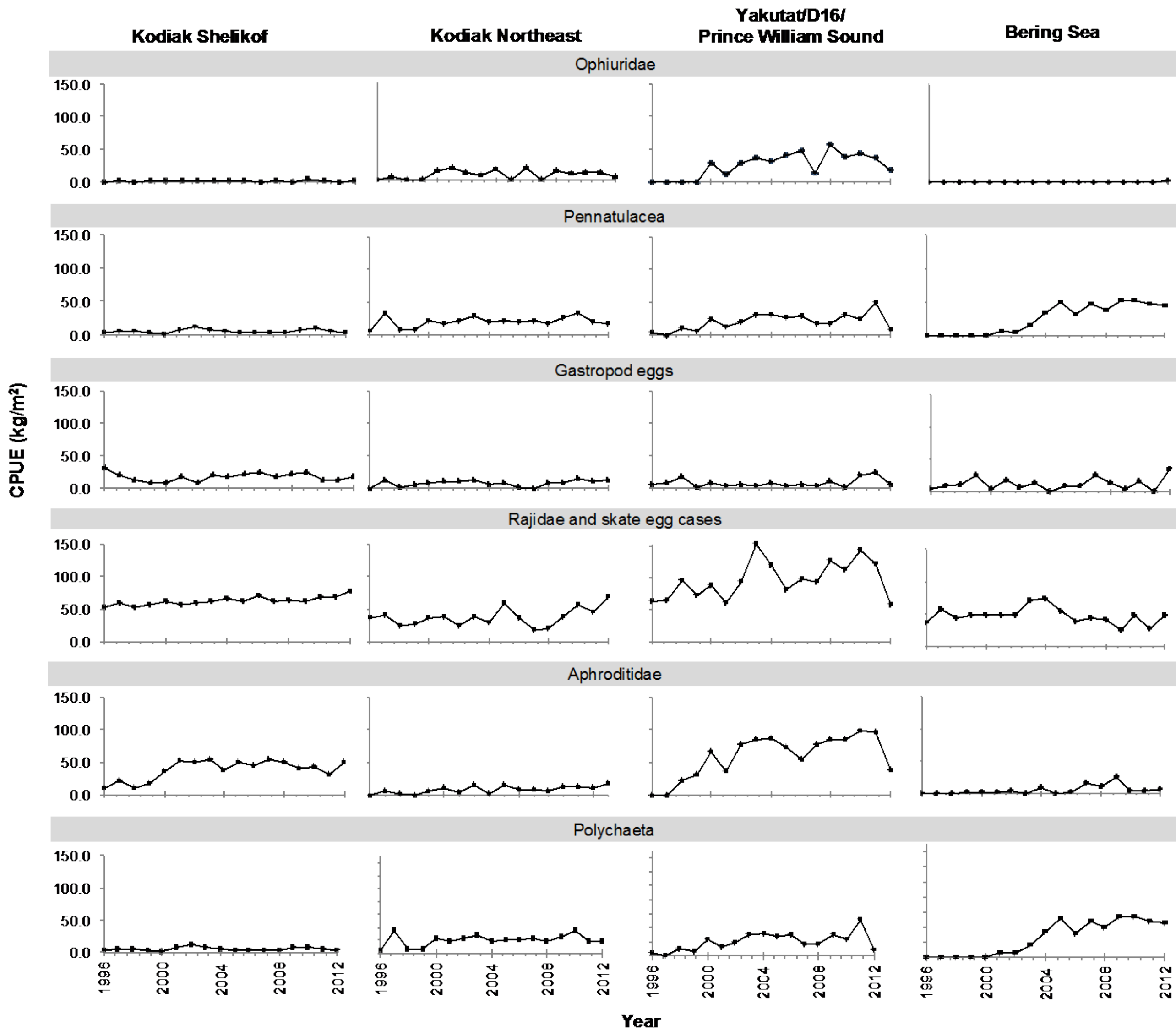

Figure 6. Average catch per unit effort (CPUE, kg/m^2) of taxa exhibiting temporal changes over 1996 to 2012 across four registration districts. Yakutat/D16/Prince William Sound incorporates the sum of CPUE values in these three districts.

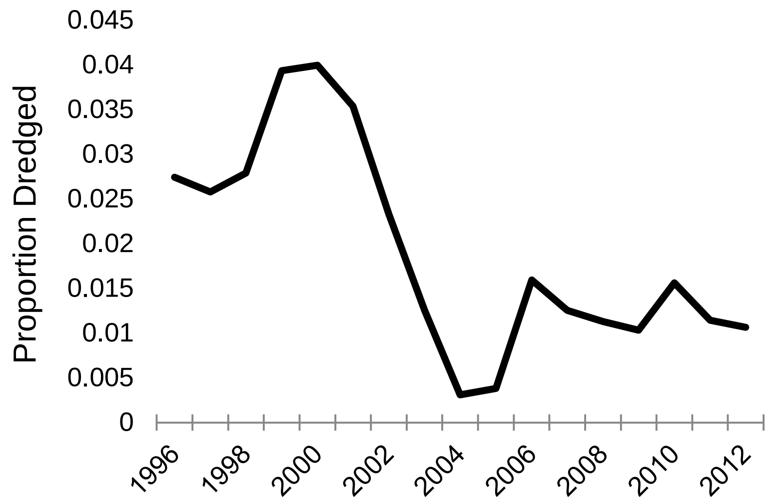

Figure 7. Proportion of the Bering Sea Bed Q dredged from 1996 to 2012 (no lag). Dredging effort for a given year was calculated by dividing the total area swept by dredges on a bed (km^2) by the area of that bed (km^2).

Appendix 1.A

Table 1.A-1. Results of similarity percentages (SIMPER) analyses from (a) 1997, (b) 2000, and (c) 2010 for the Kodiak Shelikof, Kodiak Northeast, Yakutat/District 16, and Bering Sea districts. Shown are the average CPUEs for each taxon contributing to ~50% of the dissimilarities between two districts, along with the percentage that each taxon contributes to the total (Contrib. %) and the cumulative percentage contribution (Cum. %).

a) 1997

Yakutat & Kodiak Shelikof
Average dissimilarity = 50.12

Taxa	Yakutat Avg. CPUE	Kodiak Shelikof Avg. CPUE	Contrib. %	Cum. %
Polychaeta	0.00	52.55	9.86	9.86
Gastropoda	3.03	32.53	5.43	15.29
Cancridae	2.17	30.20	5.07	20.36
Ascidiacea	0.00	25.06	4.44	24.80
Brachiopoda	0.00	25.53	4.38	29.18
Pleuronectiformes	26.46	45.98	4.13	33.31
Cirripedia	13.16	26.39	4.07	37.38
Gastropod eggs	11.51	29.28	3.95	41.33
Echinoida	0.00	21.41	3.85	45.19
Demospongiae	0.00	20.14	3.61	48.79

Kodiak Shelikof & Kodiak Northeast
Average dissimilarity = 46.08

Taxa	Kodiak Shelikof Avg. CPUE	Kodiak Northeast Avg. CPUE	Contrib. %	Cum. %
Polychaeta	52.55	28.02	5.44	5.44
Pennatulacea	2.73	31.75	5.29	10.73
Cancridae	30.20	0.96	4.82	15.54
Cirripedia	26.39	7.71	4.36	19.90
Ascidiacea	25.06	5.03	3.86	23.76
Brachiopoda	25.53	9.22	3.71	27.48
Hirudinea	21.86	3.47	3.26	30.74
Gastropoda	32.53	14.81	3.23	33.97
Rajidae	47.41	34.09	3.16	37.13

Gastropod eggs	29.28	11.55	3.14	40.27
Polynoidae	0.78	18.72	3.14	43.40
Demospongiae	20.14	7.45	2.97	46.38
Echinoida	21.41	5.71	2.94	49.32
Actiniaria	19.22	18.40	2.63	51.96

Kodiak Shelikof & Bering Sea

Average dissimilarity = 46.85

	Kodiak Shelikof	Bering Sea		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Polychaeta	52.55	1.45	9.53	9.53
Oregoniidae	22.79	63.44	7.79	17.33
Cancridae	30.20	0.00	5.28	22.61
Cirripedia	26.39	0.00	4.96	27.57
Ascidiacea	25.06	0.00	4.44	32.00
Brachiopoda	25.53	0.00	4.38	36.39
Gastropod eggs	29.28	7.66	4.10	40.49
Asteroidea	38.62	18.27	3.84	44.32
Scyphozoa	0.05	19.37	3.71	48.03
Demospongiae	20.14	0.00	3.60	51.63

Kodiak Northeast & Bering Sea

Average dissimilarity = 44.83

	Kodiak Northeast	Bering Sea		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Oregoniidae	20.21	63.44	10.45	10.45
Asteroidea	52.00	18.27	7.96	18.40
Pennatulacea	31.75	0.00	7.59	26.00
Polychaeta	28.02	1.45	6.39	32.39
Gastropoda	14.81	39.44	5.77	38.16
Rajidae	34.09	50.91	4.80	42.96
Actiniaria	18.40	23.66	3.83	46.79
Polynoidae	18.72	4.86	3.69	50.48

Yakutat & Aleutian Islands

Average dissimilarity = 57.21

	Yakutat	Aleutian Islands		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Pennatulacea	0.00	41.75	8.64	8.64
Gastropoda	3.03	39.56	7.32	15.96
Cardiidae	1.91	36.43	7.06	23.02
Roundfish	16.01	49.46	6.94	29.96

Decapoda	8.41	31.87	6.02	35.99
skate egg cases	29.10	0.00	5.96	41.95
Gastropod eggs	11.51	37.44	5.49	47.44
Echinoida	0.00	28.21	5.20	52.64

Yakutat & Kodiak Northeast

Average dissimilarity = 50.33

Taxa	Yakutat Avg. CPUE	Kodiak Northeast Avg. CPUE	Contrib. %	Cum. %
Pennatulacea	0.00	31.75	7.39	7.39
Polychaeta	0.00	28.02	6.40	13.80
skate egg cases	29.10	8.31	4.96	18.76
Pleuronectiformes	26.46	46.70	4.76	23.52
Polynoidae	0.00	18.72	4.23	27.75
Cirripedia	13.16	7.71	3.66	31.41
Oregoniidae	7.30	20.21	3.63	35.03
Paguridae	14.72	29.86	3.55	38.59
Actiniaria	14.15	18.40	3.40	41.98
Lithodidae	1.72	15.03	3.23	45.22
Rajidae	38.50	34.09	3.18	48.39
Hirudinea	15.55	3.47	3.17	51.57

Yakutat & Bering Sea

Average dissimilarity = 46.19

Taxa	Yakutat Avg. CPUE	Bering Sea Avg. CPUE	Contrib. %	Cum. %
Oregoniidae	7.30	63.44	16.44	16.44
Gastropoda	3.03	39.44	10.69	27.13
Pleuronectiformes	26.46	51.76	7.36	34.49
Asteroidea	41.89	18.27	6.92	41.42
skate egg cases	29.10	6.30	6.78	48.20
Scyphozoa	0.00	19.37	5.69	53.88

b) 2000

Yakutat & Kodiak Shelikof

Average dissimilarity = 38.61

Taxa	Yakutat Avg. CPUE	Kodiak Shelikof Avg. CPUE	Contrib. %	Cum. %
Ranellidae	3.38	36.10	7.40	7.40
Echinasteridae	25.63	0.48	5.36	12.76
Rajidae	32.40	51.74	4.37	17.13
Cirripedia	22.37	4.16	3.95	21.09

Aphroditidae	20.64	35.64	3.88	24.97
Polychaeta	24.54	6.63	3.87	28.84
skate egg cases	26.10	10.45	3.46	32.29
Crangonidae	20.19	7.05	3.43	35.72
Buccinidae	15.95	18.13	3.17	38.90
Echinoida	0.47	14.39	3.12	42.02
Ophiuridae	14.91	1.05	3.09	45.11
Hirudinea	16.49	3.20	2.98	48.09
Pleuronectiformes	30.93	42.91	2.75	50.84

Yakutat & Kodiak Northeast
Average dissimilarity = 50.41

	Yakutat	Kodiak Northeast		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Lithodidae	2.76	43.36	7.18	7.18
Solasteridae	0.00	39.76	6.49	13.67
Ranellidae	3.38	29.50	4.19	17.86
skate egg cases	26.10	5.14	3.39	21.25
Polychaeta	24.54	10.78	3.26	24.51
Oregoniidae	16.54	36.25	3.25	27.77
Echinasteridae	25.63	6.70	3.24	31.01
Cirripedia	22.37	10.76	3.00	34.02
Crangonidae	20.19	11.06	2.97	36.99
Aphroditidae	20.64	12.03	2.81	39.80
Hirudinea	16.49	0.00	2.59	42.39
Pennatulacea	13.37	26.98	2.57	44.96
Decapoda	7.27	18.12	2.54	47.50
Pleuronectiformes	30.93	45.09	2.51	50.00

Kodiak Northeast & Kodiak Shelikof
Average dissimilarity = 42.41

	Kodiak Northeast	Kodiak Shelikof		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Lithodidae	43.36	0.00	9.51	9.51
Solasteridae	39.76	4.75	7.37	16.88
Pennatulacea	26.98	2.03	5.17	22.05
Aphroditidae	12.03	35.64	4.63	26.68
Actiniaria	34.67	14.93	3.85	30.53
Rajidae	32.40	51.74	3.64	34.17
Decapoda	18.12	7.45	3.24	37.41
Buccinidae	8.37	18.13	3.04	40.44
Crangonidae	11.06	7.05	2.48	42.92

Oregoniidae	36.25	25.46	2.47	45.39
Polychaeta	10.78	6.63	2.39	47.78
Pandalidae	1.99	13.39	2.37	50.15

Yakutat & Bering Sea

Average dissimilarity = 51.61

Taxa	Yakutat Avg. CPUE	Bering Sea Avg. CPUE	Contrib. %	Cum. %
Ranellidae	3.38	55.30	8.69	8.69
Oregoniidae	16.54	56.91	6.72	15.41
Asteroidea	38.46	11.57	4.62	20.03
Echinasteridae	25.63	0.00	4.06	24.09
Paguridae	25.67	47.55	3.76	27.85
Buccinidae	15.95	30.35	3.74	31.59
Polychaeta	24.54	1.65	3.70	35.29
Pleuronectiformes	30.93	52.27	3.60	38.90
Crangonidae	20.19	0.00	3.27	42.16
Scyphozoa	1.83	20.69	3.18	45.34
Aphroditidae	20.64	1.94	2.98	48.32
skate egg cases	26.10	9.25	2.77	51.09

Kodiak Northeast & Bering Sea

Average dissimilarity = 48.78

Taxa	Kodiak Northeast Avg. CPUE	Bering Sea Avg. CPUE	Contrib. %	Cum. %
Lithodidae	43.36	0.00	8.20	8.20
Solasteridae	39.76	0.00	7.19	15.39
Pennatulacea	26.98	0.00	4.81	20.20
Ranellidae	29.50	55.30	4.43	24.63
Buccinidae	8.37	30.35	4.08	28.71
Actiniaria	34.67	11.27	3.96	32.67
Gastropoda	0.00	20.14	3.50	36.17
Oregoniidae	36.25	56.91	3.41	39.57
Scyphozoa	1.80	20.69	3.34	42.91
Polynoidae	0.00	19.17	3.33	46.25
Asteroidea	31.88	11.57	3.28	49.53
Decapoda	18.12	5.02	2.90	52.43

Kodiak Shelikof & Bering Sea
Average dissimilarity = 36.70

	Kodiak Shelikof	Bering Sea		
Taxa	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Aphroditidae	35.64	1.94	8.55	8.55
Oregoniidae	25.46	56.91	7.98	16.54
Ranellidae	36.10	55.30	4.87	21.41
Polynoidae	0.00	19.17	4.87	26.28
Asteroidea	30.39	11.57	4.78	31.06
Gastropoda	1.64	20.14	4.70	35.75
Paguridae	29.26	47.55	4.64	40.39
Scyphozoa	3.37	20.69	4.40	44.79
Ascidiacea	0.00	16.34	4.15	48.94
Echinoida	14.39	0.49	3.53	52.47

c) 2010

Yakutat & Kodiak Shelikof
Average dissimilarity = 53.09

	Yakutat	Kodiak Shelikof		
Species	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Cancridae	1.41	36.94	5.83	5.83
Ranellidae	1.54	37.50	5.82	11.65
Cirripedia	29.64	0.28	4.81	16.46
Aphroditidae	40.25	17.72	4.30	20.76
Luidiidae	39.01	11.63	4.26	25.03
Veneridae	27.47	1.86	4.19	29.21
Nereidae	2.23	27.03	4.09	33.30
Gastropod eggs	0.96	24.63	3.76	37.06
Goniasteridae	6.22	25.08	3.64	40.70
Rajidae	42.11	39.86	3.35	44.05
Naticidae	20.88	1.98	3.15	47.20
Ophiuridae	19.80	0.25	3.14	50.33

Yakutat & Kodiak Northeast
Average dissimilarity = 50.64

	Yakutat	Kodiak Northeast		
Species	Avg. CPUE	Avg. CPUE	Contrib. %	Cum. %
Aphroditidae	40.25	9.66	4.45	4.45
Cirripedia	29.64	0.00	4.38	8.83
Ranellidae	1.54	29.36	4.01	12.84
Veneridae	27.47	0.00	3.88	16.72
Brachiopoda	1.14	28.09	3.86	20.59

Demospongiae	2.90	28.98	3.78	24.37
Lithodidae	1.55	26.23	3.75	28.12
Oregoniidae	11.45	36.62	3.71	31.83
Luidiidae	39.01	16.39	3.45	35.28
Buccinidae	13.06	26.58	3.17	38.45
Actiniaria	20.52	33.32	3.04	41.49
Goniasteridae	6.22	23.67	2.97	44.46
Pennatulacea	18.23	33.27	2.70	47.16
Astropectinidae	0.00	19.83	2.69	49.85
Pleuronectiformes	38.25	56.08	2.64	52.49

Kodiak Shelikof & Kodiak Northeast

Average dissimilarity = 47.96

Species	Kodiak Shelikof Avg. CPUE	Kodiak Northeast Avg. CPUE	Contrib. %	Cum. %
Cancridae	36.94	1.67	5.45	5.45
Roundfish	5.95	33.54	4.19	9.64
Lithodidae	0.00	26.23	4.00	13.64
Brachiopoda	1.78	28.09	3.97	17.61
Nereidae	27.03	7.70	3.93	21.53
Oregoniidae	13.33	36.62	3.62	25.16
Buccinidae	6.32	26.58	3.53	28.68
Demospongiae	9.73	28.98	3.50	32.18
Paguridae	12.18	34.11	3.44	35.63
Rajidae	39.86	39.12	3.38	39.01
Pennatulacea	15.01	33.27	3.31	42.32
Gastropod eggs	24.63	10.95	3.02	45.34
Astropectinidae	0.16	19.83	2.80	48.13
Echinasteridae	11.59	11.76	2.67	50.80

Yakutat & Bering Sea

Average dissimilarity = 57.00

Species	Yakutat Avg. CPUE	Bering Sea Avg. CPUE	Contrib. %	Cum. %
Oregoniidae	11.45	52.73	6.18	6.18
Luidiidae	39.01	0.00	5.78	11.96
Asteroidea	37.42	0.00	5.49	17.46
Polynoidae	0.29	35.54	5.23	22.68
Aphroditidae	40.25	5.17	5.16	27.84
Pennatulacea	18.23	52.65	5.12	32.96
Ranellidae	1.54	33.87	4.80	37.76
Buccinidae	13.06	43.93	4.78	42.54

Cirripedia	29.64	0.00	4.45	46.99
Porifera	0.00	27.73	4.11	51.10

Kodiak Shelikof & Bering Sea
Average dissimilarity = 54.32

Species	Kodiak Shelikof Avg. CPUE	Bering Sea Avg. CPUE	Contrib. %	Cum. %
Asteroidea	44.48	0.00	6.80	6.80
Oregoniidae	13.33	52.73	6.13	12.93
Pennatulacea	15.01	52.65	5.84	18.77
Buccinidae	6.32	43.93	5.79	24.56
Cancridae	36.94	2.30	5.35	29.91
Polynoidae	4.17	35.54	4.82	34.73
Polychaeta	1.29	29.22	4.27	39.00
Porifera	0.28	27.73	4.19	43.18
Goniasteridae	25.08	0.00	3.93	47.11
Nereidae	27.03	0.00	3.85	50.96

Kodiak Northeast & Bering Sea
Average dissimilarity = 42.24

Species	Kodiak Northeast Avg. CPUE	Bering Sea Avg. CPUE	Contrib. %	Cum. %
Asteroidea	46.15	0.00	7.82	7.82
Polynoidae	7.21	35.54	4.79	12.61
Polychaeta	1.78	29.22	4.64	17.25
Brachiopoda	28.09	0.00	4.59	21.84
Porifera	1.78	27.73	4.40	26.25
Lithodidae	26.23	1.52	4.35	30.60
Goniasteridae	23.67	0.00	3.94	34.54
Pennatulacea	33.27	52.65	3.35	37.89
Astropectinidae	19.83	14.04	3.27	41.16
Buccinidae	26.58	43.93	3.24	44.40
Roundfish	33.54	15.85	2.96	47.37
Solasteridae	17.57	0.00	2.93	50.30

Chapter 2:

Socioeconomic considerations of the commercial weathervane scallop fishery off Alaska using a SWOT analysis[1]

ABSTRACT

We conducted a socioeconomic assessment of the commercial weathervane scallop *(Patinopecten caurinus)* fishery off Alaska. The research was structured within the framework of a SWOT (strengths, weaknesses, opportunities, threats) analysis, a strategy commonly used to analyze the internal (strengths, weaknesses) and external (opportunities, threats) components of an industry. Specifically, we focused on five categories: social, technological, economic, environmental, and regulatory. Semi-structured interviews were conducted with 29 participants who had detailed knowledge of the fishery, including industry members, fishery managers, biologists, and members of coastal communities affected by the fishery. We addressed topics such as attitudes of the Alaskan public towards scallop dredging, impacts of the scallop industry on Alaskan coastal communities, market influences of U.S. east coast and imported scallops, changes in the management of the fishery, and a number of environmental considerations. Several unifying opinions emerged from this study, including a lack of awareness of the fishery in many Alaskan communities and fears about rising fuel costs and diminishing harvest levels. Whereas the data-poor status of the stock appears to be the fishery's biggest weakness, the largest strengths come in the form of conservative management, industry self-regulation, and the small footprint of the fishery. Impending threats include stock decline, unknown long-term detrimental effects of dredging, and changes in the management and structure of the fishery with

[1] Glass, J. R, G. H. Kruse, and S. A. Miller. Prepared for submission to Ocean and Coastal Management.

the sunset of the State of Alaska's limited entry permit program. The majority of participants consider the fishery to be managed sustainably, although the lack of data available on scallop recruitment and abundance is a large concern. This analysis provides relevant information to both fishery managers and scallop industry members to contribute to the environmental, economic, and social sustainability of the scallop fishery.

Introduction

The commercial weathervane scallop (*Patinopecten caurinus*) fishery in Alaska has occurred since 1967. Prominent scallop beds in Alaska are located in the Gulf of Alaska (GOA) off Yakutat Bay, southeast of Prince William Sound (near Kayak Island), in lower Cook Inlet, off Kodiak Island, along the Alaska Peninsula and Aleutian Islands, and in the eastern Bering Sea (Fig. 1). Approximately 80% of scallop dredging occurs in federal waters off Alaska's coast (3-200 miles), while 20% occurs in state waters (0-3 miles). The weathervane scallop fishery is small, with annual harvests averaging 210 mt (460,000 lbs) over the past decade. In comparison, the fishery for Atlantic sea scallops (*Placopecten magellanicus*) off the east coast of the United States harvested over 26,000 mt (58,000,000 lbs) in 2010 (NEFSC, 2010).

The history of the weathervane scallop fishery in Alaska was reviewed by Kruse et al. (2005). In brief, the weathervane scallop fishery had an open-access, open-season management structure until 1993, at which point the State of Alaska developed a management plan. Until then, the fishery experienced common patterns of discovery (1967-1973), fallback (1974-1979), redevelopment (1980-1989) and bandwagon growth (1990-1993, Kruse et al., 2005, Fig. 2). Ex-vessel value peaked at $11.7 million (inflation-adjusted 2013 dollars) in 1992.

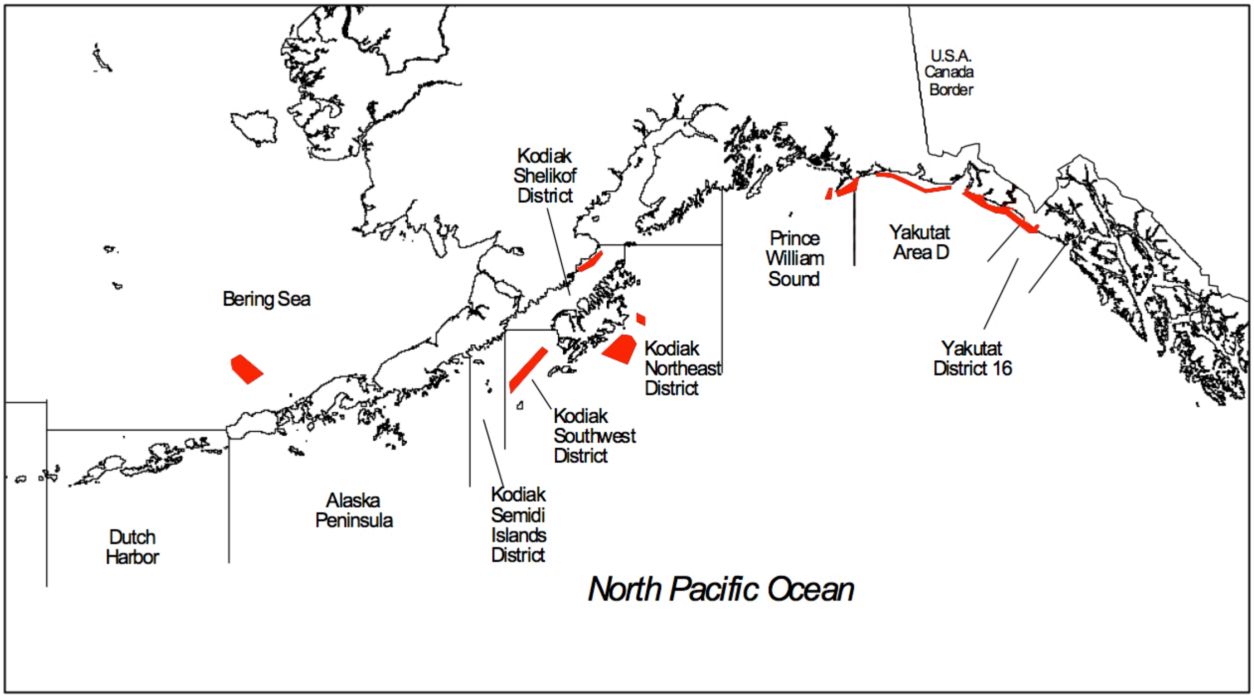

Figure 1. Map of Alaskan weathervane scallop fishery registration districts and general areas of scallop fishing effort, indicated by red polygons. The Cook Inlet registration area (north of Kodiak) is not labeled.

Currently, the fishery is managed jointly by the National Marine Fisheries Service (NMFS) and the Alaska Department of Fish and Game (ADF&G) under the auspices of a federal fishery management plan (NPFMC, 2014a), although most of the management is handled by the state. Guideline harvest limits are determined by managers from three different regional offices of ADF&G: Southeast (District 16 and Yakutat), Central (Prince William Sound and lower Cook Inlet), and Westward (Kodiak, Alaska Peninsula, Aleutian Islands, and Bering Sea). Each region maintains autonomy in setting harvest quotas, referred to as guideline harvest levels (GHLs), with consideration of the constraints of the federal fishery management plan. A federal license limitation program (LLP) was implemented by the North Pacific Fishery Management Council in 2000, restricting the fishery in federal waters to nine vessels, two of which were granted exclusive rights to fish in the Cook Inlet registration area (NPFMC, 2014a). A state limited entry permit (LEP) program was initiated in 2004 and also permitted nine vessels statewide, two of which were allowed to fish in Cook Inlet. In 2000, six out of the nine permit holders formed the North Pacific Scallop Cooperative, a fishery cooperative, now known as the Alaskan Scallop Association, which was incorporated as an Alaska Cooperative Corporation in 2011. The cooperative functions by sharing observer data among vessels to avoid crab and to allocate quota and crab bycatch to individual vessels (Brawn and Scheirer, 2008). In recent years, only four of the nine available permits have been actively fishing, with three out of those four vessels belonging to the cooperative (NPFMC, 2014b).

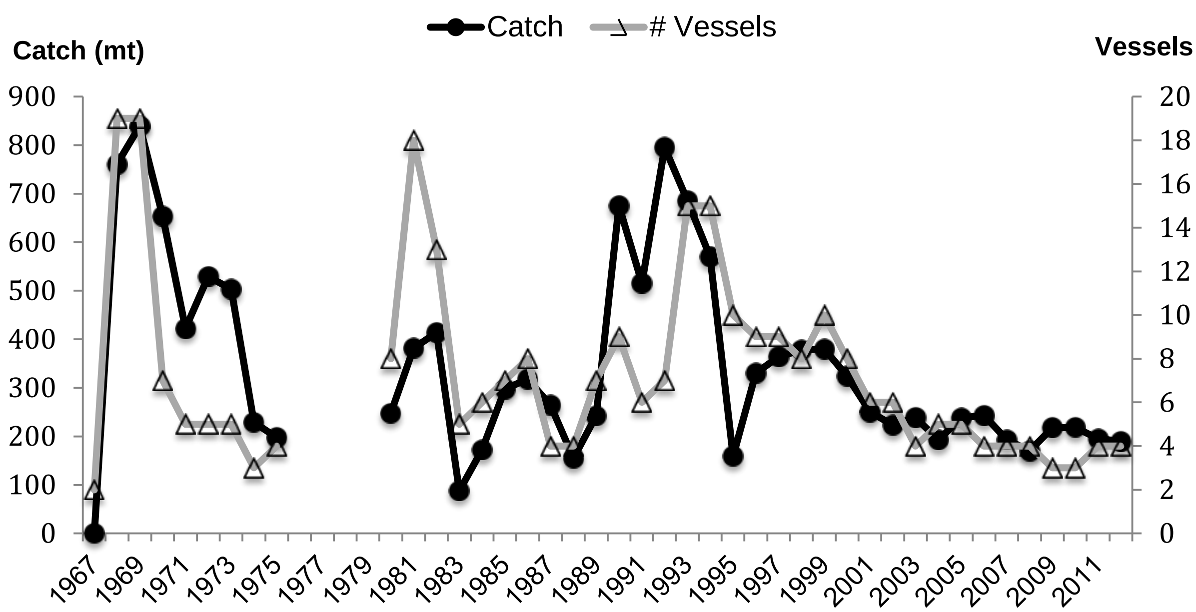

Figure 2. Catch (mt) and the number of vessels fishing in the weathervane scallop fishery off Alaska from 1967 – 2012. Landings from 1967 – 1993 come from Barnhart (2003). Landings from 1993 – 2012 were gathered from NPFMC (2014b). Data from 1976-1979 were excluded due to confidentiality constraints caused by a low number of participating vessels and a closed fishery in 1978.

The weathervane scallop fishery is considered a “hard-on-bottom” fishery. Vessels fish by towing two New Bedford style dredges, typically 4.57 m (15 ft) wide (Barnhart, 2003). Two permit-holders are limited to a single 1.8 m dredge while fishing in the Cook Inlet registration area, and two 3 m dredges outside of Cook Inlet. Attached to the frame is a bag made of 10.16-cm (4 inch) steel rings, the diameters of which are regulated to prevent the catch of small scallops. Aside from scallops, other species caught as bycatch include benthic invertebrates (e.g., sea stars, anemones, brittle stars, crab, and octopus) and fishes (e.g., skates, Pacific cod [*Gadus macrocephalus*] and flatfishes). Strict bycatch limits are established for Tanner crab (*Chionoecetes bairdi*), snow crab (*C. opilio*), and red king crab (*Paralithodes camtschaticus*) in the Central and Westward management regions. Throughout the geographic range of the commercial weathervane scallop fishery, many areas are closed to dredging, primarily to protect king and Tanner crab. All vessels catching and processing scallops off Alaska are required to carry onboard observers at their expense, with the exception of vessels fishing in Cook Inlet (NPFMC, 2014b). Observer duties include the collection of biological information and fishery data, including bycatch information (Rosenkranz and Spafard, 2013).

Recently, there has been political tension concerning the amount of consolidation that has taken place in the fleet. As a result, the LEP program was not renewed by the Alaska State Legislature, leading to an open-access fishery in state waters in 2014. Failure to extend the program was driven by the perception of some legislators that consolidation within the Alaska Scallop Association hindered economic opportunities for Alaskan residents. Aside from these resource allocation issues, there are other recent concerns about stock status, as GHLs for all management districts have generally declined since 1993 (NPFMC, 2014b). On the other hand, some areas containing viable scallop beds were closed in the 1960s to protect king and Tanner crab, yet, after decades of declines in many crab populations, ongoing closures may inhibit weathervane scallop fishery development with little or no benefits to crab stocks.

Prompted by such concerns, our goal was to identify a comprehensive suite of social and economic factors influencing the current state and future prospects of the commercial weathervane scallop fishery in Alaska. To achieve this, we conducted an analysis of the strengths, weaknesses, opportunities, and threats (SWOTs) to the fishery. A SWOT analysis is a simple and flexible tool, consisting of gathering opinions from a knowledgeable body of people familiar with a particular business or industry to help evaluate internal strengths and weaknesses, as well as external opportunities and threats (Helms and Nixon, 2010). SWOTs are most commonly used to initiate strategic planning in the fields of business and management. Recent use of SWOT analyses in academic research has been reviewed by Helms and Nixon (2010). Although relatively uncommon, some applications of SWOT to marine systems have appeared in recent years (Bolton et al., 2009; e.g. Cowx et al., 2010; Çelik et al., 2012; Panigrahi and Mohanty, 2012). In our study, we used the analysis as a vehicle to solicit opinions of those involved with the weathervane scallop industry in Alaska as a means to identify, clarify, and offer potential solutions to current socioeconomic issues, as well as to foster a more comprehensive dialogue about future fishery options among fishery participants, policy makers, scientists, fishery managers, community members, and other stakeholders.

Methods

We collected perceptions of SWOTs by conducting semi-structured interviews with 29 participants who were identified as having detailed knowledge of the fishery through professional involvement. The participant group consisted of industry members (n=8), fishery managers (n=7), biologists (n=8), and “others” (n=6). Within the “other” category were those who could not be classified in the first three categories, including members of coastal communities affected by the fishery. Participants were interviewed from communities in Alaska, including Anchorage, Cordova, Juneau, Kodiak, Homer, and Yakutat. Participants were also interviewed in Seattle, Washington. Respondents were asked to answer questions from a questionnaire (Appendix 2.A) and were interviewed in person, over the phone, or in writing.

Within the SWOT framework, the questionnaire focused on five themes: social, technological, economic, environmental, and regulatory. Social aspects included questions related to stakeholder perceptions of weathervane scallop fishery impacts on Alaskan coastal communities, as well as current and historical changes in the public’s perception of the fishery. Technological questions involved vessel technology, industry efficiency, gear types, and bycatch avoidance – anything related to the harvesting, processing, and market delivery components of the fishery. Economic questions addressed the value and stability of the weathervane scallop market, market competition, industry expansion, aquaculture, and latent permits. Environmental aspects addressed the biology of scallops and their habitat, including meat condition, bycatch species, climate change, and the respondents’ perceptions of the sustainability of the fishery. Regulatory aspects included the management and legislation of the weathervane scallop fishery, including expected outcomes of the LEP program expiration.

All interviews were recorded unless the respondent requested otherwise (n=2). Interviews were transcribed and responses from each section of the questionnaire (e.g., social, technological, etc.) were grouped into SWOT categories and entered into a spreadsheet. Statements that were known to be false were recorded as misperceptions, but not included in the compilation of information. All remaining statements were summarized as SWOTs for each social, technological, economic, environmental, and regulatory theme (Tables 1-5). Categorizing responses is a challenging part of the SWOT process (Helms and Nixon, 2010), and we recognize that there is overlap among topics. For instance, some issues can represent both opportunities and threats at the same time, and other issues apply to multiple themes, such as many social and economic topics. Thus, in addition to detailed tables of SWOT results under the five themes, we aggregated our results into cross-cutting common topics under which results and discussion are presented: (1) public perceptions of the fishery, (2) marketing, (3) fishery efficiency, (4) fishery expansion, (5) fishery cooperative members versus non-members, (6) expiration of the LEP program, (7) environmental impacts, and (8) research needs and data gaps.

Results and Discussion

Public perceptions of the fishery

Most, but not all, participants were aware that all weathervane scallop vessels are home-ported in Kodiak, AK, and employ mostly Alaskan crewmembers, both of which were viewed as strengths (Table 1). Also, many participants noted socioeconomic benefits to certain Alaskan communities through landing taxes, vessel expenditures (e.g. fuel, equipment, repairs, food), crew earnings, deliveries, and processing. Indeed, all scallop catches are landed in Alaskan ports, including Kodiak, Homer, Dutch Harbor, Yakutat, Sitka, and sometimes Juneau and Cordova (NPFMC, 2014b). Significant historical landings also occurred in Seward, Petersburg, and Whittier; during the 1960s scallop vessels were primarily based out of Seward (Turk, 2000). Participants generally noted an improved perception of the fishery in recent years through industry community involvement (e.g., seafood festivals, sponsoring community events), participation in meetings of the Scallop Plan Team of the North Pacific Fishery Management

Council, and promotion of direct scallop sales in farmers markets, road-side stands, and grocery stores in some Alaskan communities. In-state sales by the cooperative have increased since fishery inception. Homer residents identify Cook Inlet scallops as "local" and formerly enjoyed dockside purchases. As one participant from Homer stated, *"[The vessel captain] sold right off the boat [in Homer], and so the people came down by the hundreds. Socially it was unreal. They got a good price because they got the boat price… it was just an amazing thing."* Just one vessel consistently delivers to Homer. That vessel no longer sells dockside, but scallops are available from a local processing plant and at the Homer farmer's market.

However, most participants indicated that, because the fishery is small, the benefits and awareness of the fishery in Alaska are limited; no community in Alaska depends heavily on scallop fishing. Many respondents thought that the public is generally unaware of the fishery unless one knows a vessel captain or a crewmember. However, there is a perception that Homer residents are more aware of the fishery than residents of other communities. Some communities (e.g. Yakutat, Cordova) infrequently receive scallop deliveries and hardly interact with fishery participants that fish in nearby waters. In general, weaknesses are rooted in many misconceptions about the fishery (e.g., how it operates, where the fleet is based, and the amount of bycatch), even among some SWOT survey participants (Table 1). For instance, in reference to the LEP program, one Alaska legislator was quoted by the *Homer Tribune* in April 2013 as saying, "*That policy led to a rapid and extreme consolidation, leaving 90 percent of the scallop fishery in the hands of a Washington-based corporation.*" Some participants held negative perceptions of the fishery due to its environmental impacts, including bycatch (particularly crab), and a professed history of rowdy scallop fishermen coming to town. This is particularly true in the community of

Yakutat, where some members of the public mistakenly attribute the scallop fishery to the collapse of local Tanner and Dungeness crab (*Metacarcinus magister*) fisheries.

Opportunities for the fleet to improve the overall image of the fishery in Alaska include increasing public awareness of the Alaska-based nature of the fleet, as well as ongoing bycatch reduction practices that result in low crab bycatch rates (Table 1). Also, there are opportunities for the fishery to reallocate revenue to Alaska by expanding the in-state proportion of product sales and increasing markets to more communities across the state.

Marketing

Survey participants in all stakeholder groups consider weathervane scallops to be high-quality, valuable products that are rendered more desirable through branding as "Alaska" or "Kodiak" weathervane scallops (Table 1). They perceived the "Alaskan" label as a better marketing strength in Alaska than the Monterey Bay Aquarium's Seafood Watch "Best Choice" rating, which the Alaskan weathervane scallop fishery earned in 2012. Most participants believed that the Seafood Watch label is not effective in Alaska, because Alaskans generally do not pay attention to seafood sustainability ratings and some even distrust them, given recent controversies within the Alaskan salmon fishery about the Marine Stewardship Council's certification program (Bauman, 2012). As one respondent said, "*Alaskans have a deeper understanding of the seafood industry and not brand loyalty, but locale loyalty. They don't care about green, yellow or red, they want 'Alaskan this' or 'Alaskan that'*." The Seafood Watch rating, however, is important to restaurants and other markets outside of Alaska, and the weathervane scallop industry benefits both socially and economically by promoting both "Alaskan" and "Best Choice" labels.

Table 1. Social SWOT.

Strengths	Weaknesses	Opportunities	Threats
• Boats home-ported in Kodiak, AK, with mostly Alaskan crewmembers.	• Fishery is small; benefits and awareness in Alaska are limited. Primary market is out of state.	• Improve public image in Alaska, especially that boats are Kodiak-based and have low bycatch.	• Declining community benefits (e.g., jobs, revenue) due to decreasing harvests and area closures.
• Benefits to some communities via landing taxes, expenditures (fuel, food, repairs), crew earnings, deliveries, processing.	• Many misconceptions about the fishery (e.g., how it operates, where vessels are based, bycatch).	• Potential to contribute revenue into local economy by increasing in-state product sales and enhanced marketing to other communities.	• Negative perceptions about consolidation and bycatch can lead to legislative actions that constrain the current fishery.
• Seafood Watch is influential for non-Alaskan markets and influences other seafood sustainability programs.	• Seafood Watch label does not influence general public in Alaska.	• Promote Seafood Watch "Best Choice" rating within the state and improve perception of Seafood Watch.	• Favorable opinion of the Seafood Watch program could degrade, as occurred with the Marine Stewardship Council.
• High-quality, valuable product is very desirable and sought-after.	• Negative perceptions on the effects of dredging on bycatch (especially crab) and habitat.	• Increased effort to hire Alaskan crewmen, particularly from Yakutat, and improve image in Yakutat on misconceptions about crab bycatch.	• Awareness of the fishery may not increase due to its small size and limited product supply.
• Market branding as “Alaska” or “Kodiak” brings a more favorable opinion and higher value.	• Negative perceptions of too much effort consolidation within the fleet.	• Potential for increased demand for scallops by Alaskans with increased awareness of fishery.	• Further fleet consolidation could lead to diminished community benefits, such as decreased interest and buy-in.
• General perceptions of the fishery have improved over time due to efforts from the fleet. Homer has a highly positive view of the fishery.	• Competition between non-cooperative and cooperative vessels leads, in some cases, to a "race to fish" within the industry.	• Improve direct connection with vessels and local communities, especially in Homer; bring back dockside sales. Joining a Community Supported Fishery would raise awareness.	• Increased awareness of the fishery may create more opponents who hold steadfast anti-trawling and anti-dredging beliefs.
• Some direct sales of scallops in farmers markets, restaurants, plants, and grocery stores in Alaska.	• Diminished impact In Homer; only one vessel delivers to Homer, and no longer sells from the dock.		• Increased overseas demand for scallops will push more product internationally at a high price.
• Current fishery participants are aware of management issues, especially reducing bycatch.	• High prices make scallops less accessible to many Alaskans.		

Table 2. Technological SWOT.

Strengths	Weaknesses	Opportunities	Threats
• GPS technology allows industry to pinpoint fishing locations and improve efficiency by fishing with informed decisions and mapping habitat.	• Inefficiencies are largely due to regulations (e.g. limited crew size, no automatic shucking, maximum dredge widths).	• Increase value-added processing (e.g. fresh product, new product type) if the markets for these products exist.	• Few forces driving innovation in gear and vessel technology because fishery is so small.
• Current system allows effort to be spread out over space and time.	• Limitations of gear efficiency (e.g. towing multiple times in an area, rings clogging with small scallops).	• Boats can make small changes to boost efficiency and reduce overhead costs.	• Initiation of soaking scallops in sodium triphosphate would affect the price and quality.
• Dredges do not have high levels of bycatch.	• Dredge is invasive on the seafloor and damages scallops on deck; bycatch is unpredictable and cannot consistently be avoided.	• Build off of international research on dredge improvements, (e.g. bottom contact sensors or sensors that monitor the pitch) to allow fishing in less-optimal conditions.	• Problems with new product types include potential increases in shipping and operating costs.
• 3-4 boats are able to catch the entire quota. Consolidation was driven by the need for efficiency.	• Limited in expansion; bigger dredges require more fuel, larger engines, more crew, etc.	• Vessel electronics will keep improving, which will lead to more accurate reporting, including observer technology (electronic data submission, electronic scales).	• Return of automatic shucking would lead to fewer crewmembers, plus processing of smaller scallops.
• Hand shucking increases product quality and value.	• High operating costs. Labor-intensive operation with high fuel prices.	• Efforts to reduce bycatch by changing fishing behavior (e.g. shorter tows, timing with tides).	• Regulations that further restrict gear modifications.
• Vessel captains are experienced and communicate with one another.	• Some perceived that at-sea communication among captains, and between observers and managers, is limited.	• Long-term opportunities for fishing via other methods (e.g. diving, trawling, aquaculture).	• Open-access nature of the fishery would make the fishery less efficient because of altered fishing behavior driven by competition.
• Cooperative benefits from processing efficiencies; being able to catch, shuck, freeze, and package on board, thus allowing longer trips.	• Some vessels do not freeze at sea whereas others have freezing systems with limited capacities.	• Survey technology (e.g. sled-dredge & video surveys) will keep improving, to the benefit of fishery management.	

Table 3. Economic SWOT.

Strengths	Weaknesses	Opportunities	Threats
• “Alaska seafood” branding and “best-choice” Seafood Watch ratings are value-added labels.	• Fishery is dwarfed by Atlantic and international scallop fisheries; so market strength is limited ("price-takers").	• Increase development of value-added products and keep expanding Alaskan, niche and foreign markets.	• Competition with latent permit holders or new entrants would spread revenue out thinly among participants.
• Premium product for high-end, luxury markets. Targeting different sectors than U.S. east coast to capture unique markets.	• Prospecting for and opening new beds is challenging because of opportunity costs, closed areas, and bycatch concerns.	• Potential to increase harvest through undiscovered beds, re-opening closed beds, or increasing quotas for highly productive beds.	• Aquaculture may be a long-term threat, if prices get low enough for products of similar quality.
• Cooperative has led to increased prices and expanded markets.	• Resource-limited fishery; 3 out of 4 boats must also fish for other species at other times of year.	• Price increases because of declining U.S. east coast harvests and a general domestic economy improvement.	• Increasing overhead costs (fuel, observers, labor, insurance).
• Demand in Europe and Asia is high because the depressed dollar makes scallops more affordable overseas.	• Non-cooperative vessels limited by distance to beds, costs of fuel, and product quality.	• An open-access fishery may provide more economic benefits to Alaskan communities.	• Stock collapse would lead to lost clients.
• Large size of scallops opens up new niche markets and makes it difficult for farmed scallops to compete.	• Difficult to sell off the dock because of inconsistent arrival times, coordination, and limited time onshore.	• Aquaculture development for weathervanes or other species can earn higher prices with no bycatch.	• Lower prices due to unpredictable market changes, or increased US and foreign scallop production.
• Excellent product traceability.	• Too expensive to ship fresh product from catcher vessels.	• Individual vessel quotas would slow down the fishery and eliminate competition.	
• Economic advantage to having the same players in the fishery (e.g. for self-regulated closures). Consolidation driven by economic efficiency.	• New entrants face a steep learning curve to enter the fishery because of high costs, limited resources, and competition with experienced participants.		
• Product prices are fairly stable, even with fluctuations on the U.S. east coast and internationally.	• Delivering to a plant gives catcher vessels less control over prices		

Table 4. Environmental SWOT.

Strengths	Weaknesses	Opportunities	Threats
• Footprint of fishery is small due to many closed areas, providing a buffer for the stock and climate change.	• No fishery-independent surveys to generate abundance estimates in Southeast and Westward regions.	• Opportunities for industry and observers to assist in research and record environmental variables.	• Continuing decline of older, larger scallops.
• Bycatch of crab is tightly controlled and monitored, with fixed caps that are a tiny % of estimated crab population.	• Dredging is invasive; poorly known effects on habitat and bycatch species, especially molting crab.	• Assessment of dredging and other fishery impacts on scallops, benthic communities and habitat.	• Climate-change and ocean acidification threaten recruitment, larval transplant, productivity, food supply to scallops, and larval development.
• Most Tanner crab caught are very small and subject to high natural mortality anyway.	• Stock is data-poor; Recruitment and larval transport are not understood.	• Increased research on discard mortality, including small Tanner crab.	• Bycatch will be a continuing issue, especially if Tanner crab stocks rebound.
• Fishermen are invested in sustaining the longevity of the resource through self-regulation of bycatch.	• Substantial cut in quota last 3-5 years because of declining CPUE and shell heights in many beds.	• Improve Tanner crab surveys to more accurately estimate crab caps for scallops.	• Opening new beds would decrease the buffer capacity for the stock.
• Not much overlap with other fisheries; bycatch of scallops in other fisheries isn't an issue.	• No research being conducted on climate change and its implications (e.g. growth, recruitment, diseases).	• Increased research on climate change and ocean acidification on scallops and their larvae.	• Potential substantial effects of long-term dredging on habitat and ecosystem.
• Scallops are often found on dynamic substrates (e.g. sand) that are more tolerant of fishing disturbance.	• Weak meats and boring worms are poorly understood and unpredictable, with little recorded documentation.	• Studies of ocean currents and how they bring in food sources and affect weak meats.	• Declines in Yakutat could affect statewide abundance, if Yakutat hosts the source population.
• Stable trends in many beds since limited access, plus small size of fleet and latent permits add to sustainability	• Unknown effects of high-grading larger scallops.	• Research to address genetic diversity, recruitment, and metapopulation structure.	• Boring worm and mud blister effects on meat quality unknown.
	• Tanner crab catch limits for Kayak Island beds are generated from population estimates to the west, in Prince William Sound.	• Potential to keep bycatch, if it were driven by industry or environmental concerns.	• Stock fluctuations with unknown cycles; swings in natural mortality and environmental events.
	• Disturbance of dredging can attract Tanner crab and affect bycatch rates.	• Initiate scallop research at the Kodiak NOAA lab, given the high volume of the fishery in federal waters and importance to Kodiak.	

Table 5. Regulatory SWOT.

Strengths	Weaknesses	Opportunities	Threats
• Conservative management structure: 100% observer coverage, closed areas, limited effort, effective catch accounting.	• Lack of a statewide stock assessment survey and biomass or abundance estimate upon which quotas should be based.	• Latent permits re-entering fishery could increase quality of data used for management.	• Study of optimum number of permits might change vessel eligibility and revoke latent permits.
• Central Region conducts fishery-independent dredge surveys and is developing an age-structured stock assessment.	• CPUE is a poor and risky metric for measuring population size or condition.	• Start surveys in regions that don't have them; incorporate CamSled into other projects and abundance estimates.	• LEP expiration could lead to closures if fishing effort becomes unmanageable.
• Cooperative, productive relationship between managers and industry.	• High costs of management; fishery is too small for agencies to devote lots of time & effort towards it.	• Increase cohesion and communication between managers and researchers across the state.	• Bed-scale management, without a stock assessment, brings a threat of overfishing individual beds.
• Scallop plan team meeting is a way for industry and managers to connect and talk about issues; entire fleet comes to the meetings.	• Management regions have different approaches; each region determines GHL's separately with little communication.	• Spatial management plan; could manage at the bed-level or local-scale with a stock assessment.	• Fishery could be vulnerable to regulatory actions to limit bottom contact fishing gear, or threaten expansion or product innovation.
• Because the fleet is so small, not a lot of industry politics/lobbying; don't deal with competing interests of buyers, processors, etc.	• Present management structure is not flexible to readily allow for research projects involving vessels.	• Individual vessel quota would eliminate competition between vessels.	• New inexperienced entrants might catch more crab or overharvest an area, leading to closures.
• Central Region makes survey data available to public to increase management transparency.	• State of Alaska does not have the staff and fiscal resources for biological research on scallops.	• All boats can fish in state waters after LEP program expiration.	• Forced federal policies take time and money away from doing basic research and reduce management flexibility.
• Separate management areas allow for flexibility.	• Hard to identify areas that may need protection because recruitment and transport are unknown.		• Increasing costs of management, including observer costs.
• Vessels save fuel by being able to register in more than one statistical area at a time.			• Owners of new boats might lobby to eliminate observers in state waters, as occurred in Cook Inlet.

Weathervane scallops are often sold to four-star or five-star restaurants or other high-end, luxury markets, particularly along the U.S. west coast (Table 3). Since the cooperative began marketing the product, the domestic demand for, and price of, weathervane scallops has steadily increased. Demand for Alaskan scallops in foreign markets is also growing, particularly in Europe and Asia, with the depression of the dollar making the product more affordable overseas. Targeting niche markets and promoting the large size and high quality of Alaskan scallops (e.g., hand-shucked, not soaked in chemicals), has helped the industry distinguish its product from Atlantic sea scallops, farmed scallops, and foreign scallops. The value-added benefit of promoting these scallops as luxury items can be compared to the salmon industry's successful marketing of "Copper River Reds," an early season run of sockeye salmon *(Oncorhynchus nerka)*, which commands high prices in fresh seafood markets in the U.S. Pacific Northwest and Alaska, despite heavy competition from the farmed salmon industry (Babcock and Weninger, 2004). Another strength is that the scallop industry has also exhibited excellent product traceability, of which restaurants, seafood markets, and even governments internationally are becoming increasingly aware (Table 3).

Some participants remarked that weathervane scallops command a high price that is relatively robust to market fluctuations. One respondent colorfully stated, "*These [scallops] are kind of inflation-proof. The '1-percenters'- they're the ones who buy this stuff.*" However, other participants pointed out that, due to its small volume, the fishery is dwarfed by landings from the U.S. east coast and international fisheries, and prices continue to depend heavily on other markets. For example, increased supplies of foreign scallops or products that quickly enter and overrun the market, such as diver-caught or farmed scallops, can drive prices down, creating worrisome, unpredictable market changes (Table 3). In the future, prices of scallops may continue to increase if quotas remain low because of rising demand, an improving global economy after the 2008 recession, as well as declining quotas in the Atlantic sea scallop fishery (NMFS, 2013). From a market delivery standpoint, there are opportunities to expand niche markets, both domestic and internationally, to raise the price of weathervane scallops and increase market strength.

Economic benefits, however, may come as a threat to social benefits to Alaskan communities (e.g., jobs, product availability) due to increased fleet consolidation or increased amounts of product going out-of-state (Table 1). Processing plants that want to keep products in Alaska are already finding it difficult to compete with international markets, according to one industry respondent. One means to expand local markets and awareness would be for the industry to join a Community Supported Fishery (CSF) as an alternative business model for selling fresh, locally sourced seafood. Re-establishment of direct marketing by vessels to local communities, as was formerly the case in Homer, would enhance product demand and fleet popularity in that community.

Fishery efficiency

Technology was identified as the greatest strength contributing to efficiency of the modern weathervane scallop industry (Table 2). Adoption of onboard freezing technology revolutionized the fishery in the early 1990s by drastically improving product quality, and also allowing longer trips between landings. Implementation of the LLP and LEP programs in federal and state waters, respectively, led to reduced fishing effort and an increase in efficiency and profits for vessels remaining in the fishery. Moreover, in the past two decades, improvements in sonar and global positioning systems (GPS) enabled captains to readily relocate prime fishing beds, fish in a wider range of weather, and make better-informed decisions to avoid bycatch. Crew retention is a strong aspect of the fishery, promoting reliable processing rates. Current vessel captains are experienced and routinely share catch and bycatch information among cooperative members and non-members alike, although some respondents suggested that communication among vessel skippers and fishery managers can be improved. A technological weakness is that onboard observers still record data on paper forms; adoption of modern electronic recording systems may significantly reduce transcription errors, data processing time, and data entry costs (Table 2).

There were mixed views among some respondents of each stakeholder group on the efficiency of the fishing gear (Table 2). In supporting a case for gear efficiency, one respondent noted that just four boats are able to catch the entire harvest limit. In fact, only one out of the four vessels currently fishes full-time for scallops. Others noted that vessels tow repeatedly over an area to harvest scallops, so perhaps the gear is not efficient. The survey dredge used by the ADF&G Central Region has an estimated efficiency of 0.83, which is used in setting guideline harvest limits for the Kayak Island and Kamishak Bay areas (Gustafson and Goldman, 2012). Yet, it is widely recognized that gear efficiency varies with such factors as weather, tides, vessel operator, and bottom type. Few participants foresee any major future changes in the New Bedford-style dredge, which hardly changed over the last four decades, particularly because there are currently few forces (e.g. industry competition, regulations, funding) to drive innovation, especially given the small size of the fishery. As one respondent stated:

> A lot of innovation and development is going on [worldwide], in terms of gear design. Often it’s driven by the price of fuel, but in many cases it’s also driven by spatial

boundary closures and benthic impacts, and those haven't landed heavily on the fishery in Alaska.

The fishery experiences high operating costs, particularly fuel prices, and is limited in gear expansion. Bigger dredges, for example, would require more fuel, more powerful engines, and more crew. However, some participants noted that vessel captains could adopt small changes to make their vessels more efficient to reduce operating costs (e.g., improving engines) and bycatch (e.g., shorter tows). As one member of the industry expressed, "*[We are] always looking for a better harvesting method… we're fishermen, we'll never stop looking for a better way to do it.*" Long-term opportunities include further improvements in bottom mapping technology and navigation electronics, freezing technology, and international research to develop dredge modifications that reduce habitat impacts and avoid bycatch (Table 2). One participant wondered whether fishermen could minimize their seafloor impact by developing a technology for finding scallops without having to dredge the seafloor searching for them. Harvesting scallops using methods other than dredging (e.g., diving, trawling, aquaculture) may also be viable long-term opportunities. Regulations may pose threats to further efficiency gains; for instance, it was frequently pointed out that many existing regulations (e.g., area closures, season limits, bans on automatic shucking and other regulations that limit gear and crew size) limit fishery efficiency.

Fishery expansion

Survey participants, particularly many industry members, frequently mentioned possibilities for fishery expansion. This includes discovering new beds, re-opening closed beds, or increasing the harvest limit on already exploited but highly productive beds (Table 3). The scallop fishery is considered quite resource-limited, particularly with recent declines in harvest limits in some areas (e.g., Yakutat district) and closures in other areas (e.g., Cook Inlet and Prince William Sound districts). Some closed beds were re-opened in the past few years, specifically with exploratory fisheries opening in the Kodiak Southwest district and Unimak Bight in the Alaska Peninsula district. However, prospects of exploring new beds are limited due to opportunity costs, concerns about habitat impacts, and bycatch. The latter two reasons have also prevented re-opening currently closed areas. It was pointed out that some of those closures might be archaic and no longer necessary, given the lack of recovery in crab stocks and likely contraction of crab distribution. Some participants stated that discovering new commercially viable beds is unlikely, and that fishery managers would be wary of increasing harvest limits, given the declines in some regions of the state. Others thought that there are unexplored beds that have commercial potential. Scallop surveys do not offer opportunities to discover new beds, because they are conducted on actively fished beds. Apart from dredge surveys on known beds in the Cook Inlet and Prince William Sound districts, a statewide scallop survey has not been conducted since the 1960s (Turk, 2000). Also, NMFS biennial bottom trawl surveys reveal some information about weathervane scallop distribution, but these groundfish surveys are unsuccessful at identifying commercial-scale beds, given the patchy distribution of scallop beds (Turk, 2000) and use of the Poly Nor'Eastern high-opening trawls rigged with roller gear (Stauffer, 2004). Given the bleak outlook for increased fishery catches, it was almost unanimous among participants in all stakeholder groups that the current fishery cannot support any more fishing effort.

Long-term opportunities exist for expanding the fishery to other scallop species, such as the Pacific pink scallop (*Chlamys rubida*) or purple-hinged rock scallop (*Crassadoma gigantea*), although the current dredge gear would require significant modifications. Another opportunity for expansion is aquaculture (Table 3). There are existing aquaculture ventures involving both purple-hinged rock scallops in Alaska (Brenner, 2011) and weathervane scallop – Japanese scallop (*Patinopecten yessoensis*) hybrids in British Columbia (Lauzier and Bourne, 2006; Saunders and Heath, 1994). Farmed scallops might facilitate new product types (e.g., fresh, roe-on) that might command higher prices and avoid bycatch and habitat issues. Partnerships between aquaculture organizations and the weathervane scallop fishery participants could lead to efficiencies in marketing and distribution. However, successful large-scale aquaculture operations run the risk of price depression. Most respondents did not perceive aquaculture to be a threat, and were not very familiar with any aquaculture ventures using weathervane scallops. Other threats to the development of new products, especially fresh (not frozen) scallops, include increased shipping and operating costs and a handful of new requirements and permits through the State of Alaska.

Fishery cooperative members versus non-members

Significant differences in fishery operations exist among members and non-members of the North Pacific Scallop Cooperative. Members are catcher processors, capable of realizing efficiencies gained from shucking, freezing and packaging all products at sea. Freezing at sea ensures a high product quality and allows for longer fishing trips, fuel reduction, and adds product consistency. The cooperative has modified its product type by packaging scallops in smaller quantities to better suit customer needs. Catcher vessels, which choose not to become members of the fishery cooperative, experience several economic weaknesses relative to catcher processors. For catcher vessels, distance to and from the fishing grounds and associated fuel costs, as well as product quality, are significant issues that constrain their operations. For smaller vessels with lower catch rates, observer costs pose a disproportionately higher operating cost than for catcher processors. In addition, catcher vessels have greater constraints on marketing. For instance, they have a limited ability to target niche markets seeking only large scallops, because they do not have size-grading equipment onboard and size-grading by hand requires additional time and labor. Although catcher vessels are in a better position to deliver fresh product to local markets than catcher processors, it is too expensive to deliver fresh scallops to the U.S. west coast or internationally due to the high costs of shipping from Alaska. Also, selling off of the local dock is difficult for scallop vessels because of inconsistent arrival times and the complexities of coordinating sales with limited time at shore. However, the alternative of delivering to a shoreside processing plant gives vessel owners less control of their product and prices. Finally, an impending threat to non-cooperative vessels is that they may experience disproportionately higher levels of competition than cooperative vessels once state waters become open access, because cooperative vessels are better able to operate in federal waters, and new entrants will only operate in state waters because they do not hold Federal LLP licenses.

Expiration of the LEP program

The most frequently identified threat to the weathervane scallop industry was the sunset of the LEP program in state waters (Table 5). All industry members perceived this as a threat, whereas views were more mixed in other stakeholder groups. A central argument of opponents versus proponents of the LEP sunset centered on profits versus jobs, respectively. For instance, as one respondent stated:

> You add more permits into the system and the individuals currently fishing will get less of a harvest, make less money, and it will be more capitalization in the fishery for the

> same end product. So from a purely economic standpoint, it does not make sense; it would not be a benefit for the industry. On the other hand it would employ more people, so it's not necessarily just about efficiency.

However, other participants held negative impressions that the inactivity of five out of nine permits after the formation of the cooperative was too much consolidation, which is limiting economic and social opportunities. As one proponent of open access stated:

> Although it's an expensive fishery to get involved with… anytime you start limiting the number of participants, that causes the local people to feel that they're taking a public resource and privatizing it, and that goes back to why we [Alaska] became a state.

Proponents articulated additional arguments in favor of the open-access fishery in state waters. Some felt that an increase in vessels participating in the fishery would likely bring increased economic activity to Alaskan ports associated with increased taxes, crew wages, deliveries, supply purchases, and vessel maintenance. One participant in Yakutat considered the pending open-access state-waters fishery to be a potential opportunity for Yakutat, which has suffered substantially since the collapse of local crab fisheries. This respondent stated that if people in Yakutat were more involved with the fishery, there would likely be more community support for the scallop industry. One respondent also suggested that more vessels in the fishery would, over the long term, increase the quality of catch per unit effort (CPUE) data used for management due to a larger sample size. This respondent commented:

> You have so few boats now that the CPUE information is almost meaningless. In fact, it's worse than meaningless because you think you know something. If you track the CPUE off of Yakutat, all you do is see them searching, and then they find a bed and catch their

allocation, and then they leave… it doesn't necessarily reflect anything [about] the stock in that region. So, having a few more boats could actually help.

Although many opponents of open access did not anticipate significant fleet restructuring to result, many concerns were expressed. A consistent core fleet of just a few participants was viewed by many as a strength of this fishery. For example, representatives of the entire fleet often attend the annual meeting of the Scallop Plan Team of the North Pacific Fishery Management Council, a rare, positive attribute for any fishery in Alaska, providing an effective way for industry and managers to connect and discuss issues. Fleet consolidation within the cooperative has fostered good communication among vessels with a fair amount of self-regulation (Table 2). This has led to a cooperative fishing strategy in which effort is spread out over both space and time, alleviating pressure for a "race to fish." Concerns were expressed that this race may return with an open-access fishery in state waters, possibly eroding communication, reintroducing competition, and leading to inefficient fishing and higher bycatch. In response to this threat, one participant suggested the opportunity of allotting individual vessel quotas, which would serve to slow down the fishery and reduce competition, especially if the fleet size increases significantly with the expiration of the LEP program (Table 5). Many respondents also worried that the LEP expiration could lead to state and federal fishery closures if fishing effort becomes unmanageable or state waters become overfished. Scallop abundances in state waters are not high enough to support a large number of new fishing participants, who would also struggle to overcome high overhead costs (e.g., mandatory onboard observers) and competition with current participants.

Another concern is that inexperienced entrants are more likely to catch Tanner crab and other bycatch species. Some respondents noted that small vessels fishing in the Cook Inlet registration area are not required to carry onboard observers, and a successful petition for exemption in other state waters could undermine the entire bycatch monitoring program. Owing to such concerns, some respondents worried that an open-access fishery in state waters could draw the attention of environmental groups, potentially leading to additional future regulatory actions limiting bottom contact fishing gear, such as new area closures. Additionally, although most respondents did not anticipate this occurring, some identified the threat of new vessels beginning to soak scallops in sodium tripolyphosphate, or STP, a chemical used in other scallop fisheries to retain moisture in the scallop adductor muscle. Soaking the scallops would lead to larger apparent meat-sizes, until cooked, and would affect the price-by-size of the product.

Still other concerns about the sunset of the LEP program include the creation of costly uncertainties in the fishery. The lack of reauthorization of the LEP program has introduced the destabilizing role of politics in fishery management. An expanded fleet will increase costs of fishery management associated with a larger fleet and expanded onboard observer program, which may threaten the viability of joint state-federal fishery management, especially given the already high relative costs of management (Table 5). New requirements to manage state and federal waters separately could pose threats to management flexibility. Bed-scale management may be a successful option in the future, if a stock assessment is developed that considers metapopulation structure, but as one industry member pointed out, once the rigidity is in place it is difficult to make quick changes in quota allocations.

Environmental impacts

When asked if they considered the weathervane scallop fishery to be sustainable, most respondents replied that fishery management is conservative, the fishery has a small footprint, and large areas containing scallops are closed to dredging throughout the state (Table 4). The small fleet size, effective catch monitoring, and modest harvest limits, which have been reduced over the years to reflect changes in scallop size distributions and fishery CPUE, are touted as further evidence of sustainable fishery management. The predominance of landings from the Kodiak and Yakutat districts since the 1960s is offered as additional evidence of sustainability. Finally, the presence of scallops in unexplored beds and closed areas are viewed as providing an additional conservation buffer for the weathervane scallop population as a whole.

Depending on the registration area, bycatch of species other than weathervane scallops accounted for approximately 14-28% of the catch (by weight) during the 2010/2011 season (Rosenkranz and Spafard, 2013). Although the discard mortalities of bycatch species caught in dredges in the scallop fishery are unknown, all species are considered to have 100% mortality, which is purposefully a conservative estimate for estimation of fishing mortality. For such reasons, most participants did not consider bycatch to be a problematic issue in the weathervane scallop fishery (Table 4). However, bycatch was a contentious topic among some community members, specifically with reference to Tanner crab, given failures of crab populations to recover. The bycatch of Tanner crab is closely monitored, with fixed bycatch caps that are a small percentage (0.5-1.0%) of the estimated crab abundance in each management district, based on crab assessment surveys. Moreover, crab of all sizes count equally toward the cap, even though most Tanner crab caught are very small and experience high rates of natural mortality before being recruited to crab fisheries as adults. An additional strength is that most current vessel captains have been involved with the scallop fishery for decades and portray a strong resource conservation ethic (Table 4). There is much self-regulation within the industry, particularly after the formation of the cooperative, and the fleet actively avoids bycatch (Brawn and Scheirer, 2008). For example, during the 2013-14 season, vessels unanimously agreed to leave the Shelikof Strait fishing district and to return later in the season due to higher than average catches of Tanner crab.

Despite such efforts, bycatch remains unpredictable and further reductions may be difficult without major modifications to the New Bedford-style dredge. Tanner crab catches are highly variable, due to seasonal and ontogenetic movements, and if stocks were to fully recover to historical levels, increased overlap poses a threat to the scallop industry of additional area closures to protect crab. Some participants expressed additional concerns about dredge impacts on crab during molting. One industry participant mentioned politics as a threat to bycatch management:

> Obviously it is always a problem, and we're well aware of it. It's a political problem, a perception problem, it's a legitimate problem at times, and we work really hard to reduce it by working together. If the regulations change and encourage us to drop the work-together attitude and compete with each other, that will worsen the bycatch situation.

Some participants held negative perceptions of the effects of dredging on seafloor habitats (Table 4). If, in response to such concerns, additional constraints (e.g., effort reductions, additional area closures) are enacted to further mitigate seafloor impacts of the fishery, such actions would pose a serious threat to the viability of the fishery given its small size and low quotas. Weathervane scallops are found on dynamic substrates with high amounts of water flow and sediment transport, such as silt, sand, and gravel (Turk, 2001). These types of substrates are relatively tolerant of repeated dredging impacts. However, scallops are also harvested from deeper clay and muddy substrates, which are less dynamic and take longer to recover from dredging or trawling (Hiddink et al., 2006; Kaiser et al., 2006). A study from 1998-1999 in the central Gulf of Alaska examined the impacts of trawling and dredging on sediments by comparing two areas open to fishing with two adjacent areas that had been closed since 1987 (Stone et al., 2005). The authors suggested that areas open to fishing showed signs of increased disturbance, as indicated by differences in epifaunal abundance between closed and open areas (Stone et al., 2005). The long-term effects of dredging and bycatch removals, in terms of changing ecosystem function and modifying habitat, are unknown. One participant remarked:

> I think the minute you say the word 'dredge,' people's hackles are going to go up. In some way, shape or form you're deforming the ocean floor. You can say they're not doing any damage, but how do you know? You don't.

To address these questions, a few respondents recommended performing Before-After-Control-Impacts (BACI) studies to address the effects of dredging on known scallop beds that are currently closed to fishing, as well as more studies focused on discard mortality and fishery impacts on scallops and crab, including during the molting period (Table 4). An additional intriguing option, if resulting from industry demand or environmental concerns, is the potential to keep and sell bycatch species so as to eliminate wastage. The U.S. Magnuson-Stevens Fishery Conservation and Management Act of 2006 defines bycatch as *fish which are harvested in a fishery, but which are not sold or kept for personal use, and includes economic discards and regulatory discards.* Thus, any retention of discards would reduce bycatch by definition. This, however, would require a great deal of logistical overhead, including restructuring the processing and storage facilities on the vessels, regulatory changes, and adjustments in the observer sampling protocol.

Research needs and data gaps

One major weakness identified by many survey participants, namely fishery managers and biologists, was that the weathervane scallop fishery is one of the most data-poor fisheries in Alaska (Table 4, also see Kruse et al., 2005). Most glaring among these data limitations is the lack of abundance or biomass estimates, due to a lack of fishery-independent surveys. There are high costs associated with these research approaches, and the fishery is too small to cost-effectively devote a lot of time and money towards it. As one fishery manager commented:

> We have bigger issues all the time, so [the weathervane scallop fishery] really drops down in terms of spending staff time and effort when you have all of these other things to consider. It doesn't diminish it at all, but that's just the reality.

One notable exception is that dredge surveys have been conducted routinely on scallop beds in Kamishak Bay (Cook Inlet) and off Kayak Island since the mid 1990s (e.g., Gustafson and Goldman, 2012). An additional strength is that an age-structured stock assessment is currently being developed for these two Central Region stocks, which will improve the quality of management advice (Table 5). Experimental scallop surveys have been conducted in several areas using a CamSled, a towed underwater imaging system (NPFMC, 2014b; Rosenkranz and Byersdorfer, 2004; Rosenkranz et al., 2008). Although resultant abundance estimates are considered too preliminary for use in fishery management, many participants felt that the CamSled provides a significant opportunity for specification of abundance-based harvest quotas in other areas in the future (Table 5). Development of a camera "sled-dredge," which consists of both a camera and a dredge, by the Central Region of ADF&G, poses additional opportunities, including the possibility to compare differences in selectivity among different survey methods.

Given the current lack of comprehensive surveys and uncertainty about scallop abundance, quota management using fishery CPUE from four boats is recognized as a weakness, particularly because all vessels do not fish all areas in any one year (Table 5). As one respondent stated:

> Without having a population model or any idea of actual population size, CPUE is our best metric for percentage of extraction. It's a poor metric. It's definitely a poor metric. Fishery-dependent data does not give you a good metric of population size or population condition; there are too many variables there. [The fleet] are always looking for maximum production so you don't see the small scallops or the low density areas.

In the face of data limitations, declining fishery CPUE and a lack of small scallops have sparked conservation concerns in some areas among state fishery managers and the Scientific and Statistical Committee of the North Pacific Fishery Management Council (NPFMC, 2014b), leading to substantial cuts in weathervane scallop GHLs over the last 3-5 years. Cuts in GHLs, coupled with increasing overhead costs, pose a large threat to the industry (Table 4). As one industry member stated, "*The maintenance never stops, regardless of whether you fish more or less. The pay, the mortgage, insurance… everything is still there*."

A number of gaps in understanding weathervane scallop biology, life history, and ecology were noted. Source-sink dynamics and the metapopulation structure of the stock (i.e., retention and connectivity) are not understood; such knowledge, perhaps informed by studies of population genetics or oceanographic models of larval drift, would allow improved spatial fishery management (NPFMC, 2014b). Some participants observed stock fluctuations on approximately 10-yr time frames due to natural mortality and unknown causes. Fluctuations observed in Yakutat district are perceived as a strong threat, because of the perception that scallops from this area serve as a brood source for stocks throughout the rest of Alaska's continental shelf, owing to presumed larval drift with the westward-flowing Alaska Coastal Current. Weathervane scallops from some areas of the eastern Gulf of Alaska have adductor muscles characterized as "weak meats" that are off color with a stringy consistency that makes them unacceptable for marketing (NPFMC, 2014b). Compared to standard adductor muscles, weak meats have higher moisture content, lower glycogen content, and lower muscle condition indices (Brenner et al., 2012). The cause of weak meats is unknown and not well documented by observers or fishery participants, nor is the prevalence of scallop boring worms, although past research has noted instances of boring worms around Yakutat (Feder and Jewett, 1986), and recent studies have been initiated in Cook Inlet (B. Harris, Alaska Pacific University, pers. comm.). Worsening of the boring worm and mud blister prevalence, which negatively affects meat quality, was viewed as a threat to the industry. Increasing the role of observers in recording the prevalence of boring worms, mud blisters and weak meats, as well as collecting environmental data that might correlate with these issues (e.g., temperature, pH) were suggested as opportunities.

A wide range of environmental threats to the industry were identified, including long-term climatological changes, such as global warming and ocean acidification, changes in currents that affect larval advection, retention and recruitment, and, as previously mentioned in section 3.5, the unknown effects on the ecosystem of decades of dredging and trawling (Table 4). Climate change poses threats to ocean circulation, seasonality and nature of food supply, larval development and recruitment, among other unknown ecological interactions, with resulting negative economic impacts (Byrne, 2011; Narita et al., 2012). Likewise, future effects of ocean acidification on weathervane scallops are uncertain; responses of marine calcifiers to acidic conditions have been shown to be species-specific (Byrne, 2011; Ries et al., 2009). The effects of climate change or ocean acidification on weathervane scallops have not been investigated and were suggested as research priorities. Recent declines in farmed weathervane scallop-Japanese scallop hybrid populations in British Columbia have been attributed to low ocean pH levels (Shore, 2014). There are also opportunities for the industry to become involved in addressing research questions by contributing funding for research and by cooperative use of scallop vessels for surveys and collection of environmental data while fishing. Some scallop vessels are chartered for CamSled surveys (G. Rosenkranz, Alaska Dept. of Fish and Game, pers. comm.), but are otherwise not involved in additional research projects due to their participation in other fisheries.

Conclusions

Our analysis served as a vehicle to solicit the opinions of those involved with the weathervane scallop industry in Alaska as a means to identify, clarify, and offer potential solutions to current socioeconomic issues, as well as to foster a more comprehensive dialogue about future fishery options among fishery participants, policy makers, scientists, fishery managers, community members, and other stakeholders. Not surprisingly, not all participants in this study uniformly agreed upon some topics. These disagreements were not necessarily defined by differing stakeholder groups, but were often specific to the individual or even to a certain geographic region. Differing perspectives encompassed perceptions about excessive consolidation and the overall effectiveness of the current management structure. Whereas some participants were very confident in the sustainability of the management regime, others felt quite the opposite and expressed large concerns over the data-poor status of the fishery. This concern over long-term sustainability is further driven by apprehension about dredging impacts, as well as unpredictable climatic and environmental changes that might cause fluctuations in scallop abundance and recruitment, in addition to the lack of research programs to monitor potential changes. The data-poor status of the fishery is mitigated by a very cooperative relationship between fishery managers and the scallop industry, which exerts a great deal of self-regulation and is highly intent on maintaining the longevity of weathervane scallop resources. The sunset of the LEP program places the fishery at somewhat of a crossroads, with some Alaska state legislators reacting to perceptions of fairness and equity. It is unclear how industry-manager cooperative relationships will change in response to the LEP program expiration.

The pros and cons of the cooperative must be evaluated objectively. On one hand, the cooperative has raised weathervane scallops into the upper echelon of premium seafood products from Alaska. Yet, if the current structure of the fleet is indeed suppressing economic opportunities for others, there are political and perhaps even legal implications that must be addressed. As one participant summarized:

> The LEP [program] is both a threat and a strength. It has gotten so consolidated that you only have 2 or 3 boats fishing, and politically that's a threat because here you have a major resource that only 2 or 3 groups are benefiting from. [The fleet's] success is their weakness.

Another major conflict among stakeholders is bycatch. Many scallop biologists and fishery managers expressed little or no immediate concerns about the bycatch of the scallop fleet, whereas it was a larger issue among members of Alaskan coastal communities. Thus, a social weakness of this fishery is well illustrated; namely, members of the Alaska public are unaware of the bycatch mitigation efforts of the fleet. Whereas the weathervane scallop fishery has progressed over the past four decades by reducing bycatch, there remains room for improvement and innovation, and perhaps opportunities to learn from other fisheries. For example, in 2012, after successful experimentation with a bycatch avoidance program, the U.S. east coast sea scallop fishery collaborated to create a research fund to pay for research staff to conduct bycatch data analyses and create bycatch advisories (O'Keefe and DeCelles, 2013). This successful program was funded voluntarily by the scallop fleet, and has led to a significant decrease in the bycatch of yellowtail flounder (*Limanda ferruginea*). This program is one example of how industry involvement in research can lead to economic, ecological and social benefits.

Whereas balancing effective management with cost-effectiveness appears to be the most imperative topic for the future of managing Alaska's weathervane scallop fishery, industry members appear most concerned with maintaining high prices in spite of decreasing quotas. Improving the current strengths and taking advantage of available opportunities, particularly research opportunities, will need to be driven by industry or academic involvement, given unlikely increases in agency funding for scallop research. These improvements may in fact be aided by growth within the fleet, assuming the sustainable management regime withstands potential increases in effort.

While SWOT is recognized as a useful tool to profile and enumerate issues, it has been criticized because it does not provide implementation strategies to take advantage of opportunities while leveraging strengths (Helms and Nixon 2010). That is, the framework may result in little or no utilization post-analysis (Helms and Nixon, 2010; Hill and Westbrook, 1997). However, SWOTs are commonly used in the very first stages of long-term planning to brainstorm ideas (Helms and Nixon, 2010), which was our purpose. In our study, the analysis was intended to serve as a medium to foster a dialogue about future fishery options among fishery participants, policy makers, scientists, fishery managers, community members, and other stakeholders with respect to current issues in the fishery. Given the crossroads in the fishery, this analysis is valuable to identify the current issues and instigate dialogue. Decisions made about the management of the scallop fishery are ultimately a matter of public policy. We hope that we have provided a starting point from which the strengths can be reinforced, the weaknesses can be improved upon, the opportunities can be achieved, and the threats can be mitigated.

Acknowledgements

We thank Dr. Stephen Jewett and Dr. Franz Mueter for their helpful reviews and suggestions. This study was carried out with approval through the University of Alaska Fairbanks Institutional Review Board (IRB# 474118-1). This project was supported by the National Science Foundation Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) IGERT (Award DGE-0801720), the National Science Foundation Graduate Research Fellowship Program, the Northern Gulf of Alaska Applied Research Award, the H. Richard Carlson Fellowship, the North Pacific Research Board (Project No. F5307), and the University of Alaska Coastal Marine Institute with funding from the US Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, D.C., Cooperative Agreement Award No. M13AC00004. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.

Literature Cited

Babcock, B.A., Weninger, Q., 2004. Can quality revitalize the Alaskan salmon industry? Iowa State University Center for Agricultural and Rural Development Working Paper 04-WP-359.

Barnhart, J.P., 2003. Weathervane scallop fishery in Alaska with a focus on the Westward Region, 1967-2002. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K03-5, Kodiak, AK 99615.

Bauman, M., 2012. Marine Stewardship Council losing ground with wild salmon fisheries. The Cordova Times. 1-22-2012. URL http://www.alaskadispatch.com/article/marine-stewardship-council-losing-ground-wild-salmon-fisheries (accessed 4-30-2014).

Bolton, J.J., Robertson-Andersson, D.V., Shuuluka, D., Kandjengo, L., 2009. Growing *Ulva* (Chlorophyta) in integrated systems as a commercial crop for abalone feed in South Africa: a SWOT analysis. J Appl Phycol 21, 575–583.

Brawn, T., Scheirer, K., 2008. The Alaskan weathervane scallop cooperative. FAO Fisheries Technical Paper 504, 349–360.

Brenner, K.A., 2011. Quality assessment of weathervane scallop and purple-hinge rock scallop from Alaska. M.S. Thesis, University of Alaska Fairbanks.

Brenner, K., Oliveira, A.C.M, Rosenkranz, G., Burt, R., Spafard, M., Bechtel, P.J., Crapo, C.A., RaLonde, R., 2012. Quality of weathervane scallops *(Patinopecten caurinus)* from eastern and western Gulf of Alaska." J Shellf Res 31, 1123–1132.

Byrne, M., 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: Vulnerabilities and potential for persistence in a changing ocean, in: N, G.R., Atkinson, R.J.A., Gordon, J.D.M., Smith, I.P., J, H.D. (Eds.), Oceanography and Marine Biology: an Annual Review. Taylor & Francis, pp. 1–42.

Cowx, I.G., Arlinghaus, R., Cooke, S.J., 2010. Harmonizing recreational fisheries and conservation objectives for aquatic biodiversity in inland waters. J Fish Biol 76, 2194–2215.

Çelik, A., Metin, İ., Çelik, M., 2012. Taking a photo of Turkish fishery sector: a swot analysis. Procedia Soc Behav Sci 58, 1515–1524.

Feder, H.M., Jewett, S.C., 1986. The subtidal benthos, in: Hood, D.W., Zimmerman, S.T. (Eds.), The Gulf of Alaska: Physical Processes and Biological Resources. US Dept of Commerce, NOAA, NOS, Office of Oceanography and Marine Assessment, Ocean Assessments Div, Alaska Office: US Dept of the Interior, MMS, Alaska OCS Region, Springfield, VA, pp. 347–396.

Gustafson, R.L., Goldman, K.J., 2012. Assessment of weathervane scallops in Kamishak Bay and at Kayak Island, 2004 through 2010. Alaska Department of Fish and Game, Fishery Data Series No. 12-62, Anchorage, AK 99518.

Helms, M.M., Nixon, J., 2010. Exploring SWOT analysis–where are we now?: A review of academic research from the last decade. J Strat Manage 3, 215–251.

Hiddink, J.G., Jennings, S., Kaiser, M.J., Queirós, A.M., Duplisea, D.E., Piet, G.J., 2006. Cumulative impacts of seabed trawl disturbance on benthic biomass, production, and species richness in different habitats. Can J Fish Aquat Sci 63, 721–736.

Hill, T., Westbrook, R., 1997. SWOT analysis: It's time for a product recall. Long Range Plann 30, 46–52.

Kaiser, M.J., Clarke, K.R., Hinz, H., Austen, M., Somerfield, P.J., Karakassis, I., 2006. Global analysis of response and recovery of benthic biota to fishing. Mar Ecol Prog Ser 311, 1–14.

Kruse GH, Barnhart JP, Rosenkranz GE (2005) Management of the data limited weathervane scallop fishery in Alaska. In: Kruse GH, Gallucci VF, Hay DE, Perry RI, Peterman RM, Shirley TC, Spencer PD, Wilson B, and Woodby D (eds). Fisheries assessment and management in data limited situations Alaska Sea Grant College Program AK-SG-05-02, University of Alaska Fairbanks, pp. 51–68.

Lauzier, R.B., Bourne, N.B., 2006. Scallops of the west coast of North America, in: Shumway, S.E., Parsons, G.J. (Eds.), Scallops: Biology, Ecology and Aquaculture. Elsevier B.V., pp. 965–989.

Narita, D., Rehdanz, K., Tol, R.S.J., 2012. Economic costs of ocean acidification: a look into the impacts on global shellfish production. Climatic Change 113, 1049–1063.

NEFSC (Northeast Fisheries Science Center), 2010. 50th Northeast regional stock assessment workshop (50th SAW) assessment report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 10-09; 58 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://www.nefsc.noaa.gov/nefsc/publications/.

NMFS (National Marine Fisheries Service), 2013. Fisheries of the northeastern United States; Atlantic sea scallop fishery and northeast multispecies fishery; framework adjustment 24 and framework adjustment 49. National Marine Fisheries Service. Federal Register. 50 CFR Part 648, RIN 0648-BC81 78, 27088–27112.

NPFMC (North Pacific Fishery Management Council), 2014a. Fishery management plan for the scallop fishery off Alaska, North Pacific Fishery Management Council, 605 West 4th Ave, Suite 306. Anchorage, AK 99587. North Pacific Fishery Management Council, 605 West 4th Ave, Suite 306. Anchorage, AK 99587.

NPFMC (North Pacific Fishery Management Council), 2014b. Stock assessment and fishery evaluation (SAFE) report for the weathervane scallop fishery off Alaska. North Pacific Fishery Management Council, 605 West 4th Ave, Suite 306. Anchorage, AK 99587.

O'Keefe, C.E., DeCelles, G.R., 2013. Forming a partnership to avoid bycatch. Fisheries 38, 434–444.

Panigrahi, J.K., Mohanty, P.K., 2012. Effectiveness of the Indian coastal regulation zones provisions for coastal zone management and its evaluation using SWOT analysis. Ocean Coast Manage 65, 34–50.

Ries, J.B., Cohen, A.L., McCorkle, D.C., 2009. Marine calcifiers exhibit mixed responses to CO2-induced ocean acidification. Geology 37, 1131–1134.

Rosenkranz, G.E., Byersdorfer, S.C., 2004. Video scallop survey in the eastern Gulf of Alaska, USA. Fish Res 69, 131–140.

Rosenkranz, G.E., Gallager, S., Shepard, R., Blakeslee, M., 2008. Development of a high-speed, megapixel benthic imaging system for coastal fisheries research in Alaska. Fish Res 92, 340–344.

Rosenkranz, G.E., Spafard, M., 2013. Summary of observer data collected during the 2010/11 Alaska weathervane scallop fishery. Alaska Department of Fish and Game, Fishery Data Series No. 13-09, Anchorage, AK 99815.

Saunders, R.G., Heath, W.A., 1994. New developments in scallop farming in British Columbia. Bull. Aquacul. Assoc. Canada 94, 3–7.

Shore, R., 2014. Acidic water blamed for west coast scallop die-off. The Vancouver Sun. 2-25-2014. URL http://www.vancouversun.com/life/Acidic+water+blamed+West+Coast+scallop/9550861/story.html (accessed 4-30-14).

Stauffer, G., 2004. NOAA protocols for groundfish bottom trawl surveys of the nation's fishery resources. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/SPO-65.

Stone, R.P., Masuda, M.M., Malecha, P.W., 2005. Effects of bottom trawling on soft-sediment epibenthic communities in the Gulf of Alaska. Am Fish S S 41, 439–453.

Turk, T.A., 2000. Distribution, abundance and spatial management of the weathervane scallop (*Patinopecten caurinus*) fishery in Alaska. M.S. Thesis, University of Washington, School of Fisheries.

Turk, T.A, 2001. Spatial distribution and selected habitat preferences of weathervane scallops in Alaska. In: Kruse GH, Bez N, Booth A, Dorn MW, Hills S, Lipcious RN, Pelletier D, Royer, Smith SJ, Witherell D (eds) Spatial Processes and Management of Marine Populations, Alaska Sea Grant College Program AK-SG-01-02, University of Alaska Fairbanks, pp. 463–477.

Appendix 2.A.

SWOT Questionnaire

Part 1: **Social** aspects of the Alaskan weathervane scallop fishery
I'm interested in your perceptions on Alaskan communities and society as they relate to the weathervane scallop fishery.

How long have you been associated with the Alaskan weathervane scallop fishery and how does the fishery personally affect you?

How do you think the Alaskan weathervane scallop fishery impacts Alaskan communities?

How do you think the **Alaskan public's** perception of the Alaskan weathervane scallop fishery has changed over time and will change in the future?

The Alaskan weathervane scallop fishery currently earns a "Best Choice" rating from Monterey Bay Aquarium's *Seafood Watch* program. Are you aware of this?

YES ☐ NO ☐

If YES, how do you think this rating affects the Alaskan public's opinion of the fishery?

Part 2: **Technological** aspects of the Alaskan weathervane scallop fishery
I'm interested in your thoughts on the harvesting, processing and market delivery components of the fishery, including vessel technology, gear and maintenance, and bycatch avoidance.

Do you foresee any major changes in future technology related to the harvesting, processing and/or market delivery of scallops?

Consider the following statement: "The weathervane scallop fishery is efficient at harvesting scallops." Please state whether or not you agree with this statement and why.

What do you think are the greatest technological **strengths** of the Alaskan scallop fishery?

What do you think are the greatest technological **weaknesses** of the Alaskan scallop fishery?

Part 3: **Economic** aspects of the Alaskan weathervane scallop fishery
Economic aspects include market value and stability, competition, consumer demand, economic efficiency, etc.

Consider the following statement: "The Alaskan weathervane scallop industry enjoys significant market strength and can set its own wholesale prices." Please state whether or not you agree with this statement and why.

Do you think there is a threat to the scallop industry from future aquaculture development in Alaska, including farmed scallops? If so, how?

Do you expect changes in the near future in foreign imports or the domestic harvesting of scallops that will affect the market value of Alaskan scallops?

There are state and federal permits not being fished presently. What would be the economic consequences if these permit-holders started to fish?

What do you think are the greatest economic **opportunities** for the Alaskan scallop fishery?

What do you think are the greatest economic **threats** to the Alaskan scallop fishery?

Part 4: **Environmental** aspects of the Alaskan weathervane scallop fishery
Environmental aspects include the biology of scallops and their habitat, bycatch species, oceanographic factors, the impacts of other fisheries on scallop beds, etc.

Consider the following statement: “The present fishery for Alaskan weathervane scallops is sustainable.” Please state whether or not you agree with this statement and why.

Do you predict climate change (including ocean acidification) to be a threat to the scallop fishery? If so, how?

What are your thoughts, if any, on “weak meat” scallops and/or scallop boring worms? Do you think these issues are becoming worse or staying the same?

Do you think the issue of bycatch species caught by the scallop fishery is a problem now? If so, do you think it will become more or less prevalent in the future?

How do other commercial fisheries impact Alaskan weathervane scallops and their habitat?

Part 5: **Regulatory** aspects of the Alaskan weathervane scallop fishery
I’m interested in your thoughts on the management, legislation and political structure of the Alaskan weathervane scallop fishery.

Do you think the Alaskan weathervane scallop fishery is well managed?

If you could change one or more aspects of scallop management, what would you change?

What do you think will happen to the scallop fishery if the Limited Entry Permits for state waters expire on December 30th, 2013?

What do you think are the greatest regulatory **threats** to the Alaskan scallop fishery?

Appendix 2.B.

Institutional Review Board Exemption Request Approval

Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

June 14, 2013

To:	Gordon Kruse, Dr. Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[474118-1] Socioeconomic analysis of the Alaskan weathervane scallop fishery.

Thank you for submitting the New Project referenced below. The submission was handled by Exempt Review. The Office of Research Integrity has determined that the proposed research qualifies for exemption from the requirements of 45 CFR 46. This exemption does not waive the researchers' responsibility to adhere to basic ethical principles for the responsible conduct of research and discipline specific professional standards.

Title:	Socioeconomic analysis of the Alaskan weathervane scallop fishery.
Received:	June 2, 2013
Exemption Category:	*2*
Effective Date:	June 14, 2013

This action is included on the July 10, 2013 IRB Agenda.

Prior to making substantive changes to the scope of research, research tools, or personnel involved on the project, please contact the Office of Research Integrity to determine whether or not additional review is required. Additional review is not required for small editorial changes to improve the clarity or readability of the research tools or other documents.

General Conclusions

Across the continental shelf off Alaska, hundreds of species are caught as bycatch in the weathervane scallop fishery. These range from commercially important Tanner crab (*Chionoecetes bairdi*), Pacific halibut (*Hippoglossus stenolepis*), Pacific cod (*Gadus macrocephalus*), and skates (Rajidae), to other non-commercial fishes and invertebrates, including sharks (Elasmobranchii), anemones (Actinaria), sea stars (Asteroidea), sea pens (Pennatulacea), snails (Gastropoda), and bivalve molluscs (Bivalvia). Bycatch is a relatively low percentage (< 30%) of the total catch, and most bycatch species are not commercially valuable. Nevertheless, these benthic species serve as the source of food for commercially important groundfish and support ecosystem productivity. Thus, it is valuable to examine the distribution and stability of these communities over time. Benthic communities are used worldwide as indicators of ecosystem health in the context of pollution and contamination, climate change, and fishing effects (Atlas et al. 1978, Kennedy & Jacoby 1999, Stone et al. 2005).

The first purpose of this study was to quantify benthic community composition on weathervane scallop beds, explain spatial patterns and temporal changes, and assess correlations with environmental and anthropogenic variables. This was accomplished using nonparametric methods to generate indices of similarity, which were used to compare haul compositions among registration districts and individual scallop beds. Although between four and five taxa consistently dominated most of the hauls, other bycatch species exhibited spatial differences in their distribution and relative abundance at district-level scales (>1000 km), as well as at the scale of individual beds (< 50 km). Species composition was driven mainly by two environmental variables, sediment and depth, and by anthropogenic dredging effort. Past research has demonstrated regional spatial patterns of the distribution of benthic species and strong variation due to depth and sediment (Feder & Jewett 1986, Yeung & McConnaughey

2006), although not for species directly associated with weathervane scallops.

Similar to the observed spatial patterns, temporal analyses revealed consistency in the top four to five taxa contributing the most to bycatch within a haul. A high amount of interannual variability in catch per unit effort (CPUE) occurred in other taxa. An interesting split between 1996-1999 and 2000-2012 was observed in the temporal analyses, which may reflect changes in the observer sampling procedures over time, indications of changes in fishing behavior of the scallop fleet after the formation of a fishing cooperative in 2000, or may be due to other unknown reasons. Freshwater discharge and dredging effort were significantly correlated with temporal patterns, although it was difficult to identify changes in specific taxa due to freshwater discharge because of differences in the coverage of the environmental datasets versus the scale of the analyses. Decreases in dredge and trawl fishing effort over the sampling period may have led to higher observed CPUE of some taxa in the eastern Bering Sea scallop bed, which exhibited the greatest differences in haul composition over time. Increased relative abundances of sessile invertebrates, including sponges and sea whips, were observed later on in the sampling period compared to early years, a possible indication of recovery from disturbance.

Bycatch and fishing effects on seafloor habitats are two issues that commonly confront fisheries using mobile bottom-contact gear, such as scallop dredge fisheries. In Alaska, these issues have not been thoroughly addressed with respect to the weathervane scallop fishery. Quantifying the spatiotemporal variation of bycatch species is useful for fishery managers when considering the sustainability of the scallop fishery, particularly when identifying characteristics of essential fish habitat (EFH), a definition of which is required by the US Sustainable Fisheries Act for all commercially harvested fish and shellfish resources in federal waters. Ecosystem considerations, including associations with habitat types and other species, are one component of EFH and useful for managing scallop resources sustainably; but there are other components, particularly socioeconomic factors, that also dictate sustainable fishery management.

Therefore, the second chapter of this analysis led to a broader examination of prominent social, political, and economic issues relevant to the current weathervane scallop fishery off Alaska. Many topics were incorporated into this portion of the study, including bycatch in the scallop fishery, the impacts of dredging, consolidation within the fishery, the benefits of the weathervane scallop fishery to Alaskan coastal communities, and expected changes that may come when the state portion of the fishery becomes open-access beginning in the 2014-2015 season. Issues were identified and described in depth by interviewed participants through an analysis of strengths, weaknesses, opportunities, and threats (SWOT). We synthesized perspectives of fishery participants, scientists, fishery managers, community members, and other stakeholders. Not all individuals in this study uniformly agreed upon some topics, but many general perceptions were identified. For example, concerns over the data-poor status of the weathervane scallop fishery and bycatch are mitigated by a cooperative relationship between fishery managers and the scallop industry, which exerts a large amount of self-regulation and is committed to sustainability of the weathervane scallop resources. Most interviewees considered weathervane scallops to be high-quality, valuable products, and communities such as Homer and Kodiak have strong connections with the scallop fishing vessels. Throughout this process, we also generated a list of research needs that, if addressed, would allow biologists and fishery managers to better understand scallop ecology, reproduction, and distribution. The small size of the fishery inhibits large amounts of research funding from state and federal agencies, but supplemental funding venues to progress research are potentially available through industry or other granting organizations. From a socioeconomic perspective, the SWOT analysis serves as a means to foster dialogue among all stakeholders. This study is a starting point for a discourse on favorable and realistic pathways to expand the fishery's strengths, eliminate weaknesses, achieve opportunities, and reduce threats.

Overall, the results of this study demonstrate the importance of long-term baseline data collection because of its value in examining changes over time, allowing scientists to assess the resilience of this continental-shelf ecosystem in the face of anthropogenic and environmental disturbance, particularly fishing impacts. Although weathervane scallop beds constitute a limited portion of the continental shelf, the beds have been in the same locations for the past 40 years and there have not been any major changes in gear type. The relative consistency in fishing effort enhances the scientific value of the scallop observer dataset. Baseline data collection includes collecting, recording and interpreting data from fishery stakeholders, so that future fishery managers can look back and recall human perceptions to evaluate how those have changed over time, if at all, and how those perceptions have shaped the operation and sustainability of the fishery. Humans, being inseparable from the natural world, are a critical component of ecosystem-based management (Grumbine 1994). As ecosystem-based management practices for marine environments become increasingly institutionalized, understanding the roles of benthic species in maintaining habitat function, supporting commercially important species, and contributing to overall ecosystem health will become ever more important (Peterson et al. 2000, Fluharty 2000).

References

Atlas RM, Horowitz A, Busdosh M (1978) Prudhoe crude oil in Arctic marine ice, water, and sediment ecosystems: degradation and interactions with microbial and benthic communities. J Fish Res Board Can 35:585–590

Feder HM, Jewett SC (1986) The subtidal benthos. In: Hood DW, Zimmerman ST (eds) The Gulf of Alaska: physical processes and biological resources. US Dept of Commerce, NOAA, NOS, Office of Oceanography and Marine Assessment, Ocean Assessments Div, Alaska Office: US Dept of the Interior, MMS, Alaska OCS Region, Springfield, VA, p 347–396

Fluharty D (2000) Habitat protection, ecological issues, and implementation of the Sustainable Fisheries Act. Ecol Appl 10:325–337

Grumbine RE (1994) What is ecosystem management? Cons Biol 8:27–38

Kennedy AD, Jacoby CA (1999) Biological indicators of marine environmental health: Meiofauna – a neglected benthic component? Environ Monit Assess 54:47–68

Peterson CH, Summerson HC, Thomson E, Lenihan HS, Grabowski J, Manning L, Micheli F, Johnson G (2000) Synthesis of linkages between benthic and fish communities as a key to protecting essential fish habitat. Bull Mar Sci 66:759–774

Stone RP, Masuda MM, Malecha PW (2005) Effects of bottom trawling on soft-sediment epibenthic communities in the Gulf of Alaska. Am Fish S S 41:439–453

Yeung C, McConnaughey RA (2006) Community structure of eastern Bering Sea epibenthic invertebrates from summer bottom-trawl surveys 1982 to 2002. Mar Ecol Prog Ser 318:47–62