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Biology and Management of Sablefish, *Anoplopoma fimbria*

Papers from the
International
Symposium on
the Biology and
Management
of Sablefish
Seattle, Washington,
13–15 April 1993

Edited by
Mark E. Wilkins
Mark W. Saunders

U.S. Department of Commerce

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A Technical Report of the *Fishery Bulletin*

Biology and Management of Sablefish, *Anoplopoma fimbria*

Papers from the International Symposium on
the Biology and Management of Sablefish
Seattle, Washington, 13–15 April 1993

Mark E. Wilkins
Mark W. Saunders (editors)

Cover illustration by Katherine Zecca

Sponsored by:

Technical Subcommittee of the
Canada–U.S. Groundfish Committee

Alaska Fisheries Science Center
NMFS, NOAA, Seattle, Washington

Pacific Biological Station
Fisheries and Oceans Canada
Nanaimo, British Columbia

Pacific Blackcod Fisherman's Association
Vancouver, British Columbia

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Seattle, Washington

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Introduction

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At its June 1990 annual meeting, the Technical Subcommittee (TSC) of the Canada–U.S. Groundfish Committee recommended that scientists and managers working on sablefish, *Anoplopoma fimbria,* issues convene to present and discuss the results of their recent research. Thorough knowledge of the biology and population dynamics of this species is essential for its effective management, especially considering its commercial importance. TSC representatives from both countries recognized that a great deal of active research has been conducted on this species since the International Sablefish Symposium was held in Anchorage, Alaska, in March 1983 (Melteff, 1983). As a result of this recommendation, the International Symposium on the Biology and Management of Sablefish (ISBMS) was convened April 13–15, 1993, at the Alaska Fisheries Science Center in Seattle, Washington.

Warren Wooster's keynote address entitled "PICES and Fishery Research" opened the seminar. Dr. Wooster described the role that the North Pacific Marine Science Organization (PICES) will play in the future of fisheries science, as envisioned by the founders of the organization. Sablefish and other species with similarly wide distributions in the North Pacific Ocean stand to benefit greatly from the integrated research planned by PICES.

The symposium was organized into five sessions: Early Life History, Juvenile and Adult Biology, Stock Delineation and Movement, Stock Assessment, and Management. The agenda allowed sufficient time for open discussion following each session. The active and interested participation by all symposium attendees led to thought-provoking discussions which were often as valuable as the presentations. A list of all participants is appended to this volume.

This volume unfortunately does not include all the papers presented during the ISBMS. Some of those not represented here have been published elsewhere, while some were never developed into finished publications. Further information regarding presentations not included in these proceedings may be obtained from their authors:

Session I, Early Life History

Fecundity, spawning and sexual maturity of sablefish, *Anoplopoma fimbria*
  B. J. Macewicz and J. R. Hunter, NMFS, La Jolla, California
Aspects of early life history of sablefish (*Anoplopoma fimbria*) off Oregon and California
  H. G. Moser, R. L. Charter, P. E. Smith, D. A. Ambrose, C. A. Meyer, E. M. Sandknop, and W. Watson, NMFS, La Jolla, California

Session II, Juvenile and Adult Biology

Geographic patterns in growth and maturity for female sablefish off the U.S. west coast
  R. D. Methot, NMFS, Seattle, Washington
Recruitment curve for sablefish in Alaska based on recoveries of fish tagged as juveniles
  M. F. Sigler, E. R. Varosi, and T. L. Rutecki, NMFS, Auke Bay, Alaska

Session III, Stock Delineation and Movement

Movement of sablefish tagged in the internal waters of southeast Alaska

B. E. Bracken and B. J. Richardson, ADFG, Petersburg, Alaska

Session IV, Stock Assessment

Age-structured modeling of sablefish (*Anoplopoma fimbria*) in the Gulf of Alaska
M. F. Sigler, NMFS, Auke Bay, Alaska

Session V, Management

Application of time series models to management of sablefish in Alaska
J. J. Pella and J. T. Fujioka, NMFS, Auke Bay, Alaska
The implementation of Individual Vessel Quotas in Canada's sablefish fishery
B. Ackerman, DFO, Vancouver, Canada

Many people contributed to the success of the ISBMS. The editors would particularly like to thank the members of the steering committee (listed at the end of this volume) for their time spent planning the symposium, and the chairs of each of the sessions, who kept the symposium running smoothly. Several staff members of the Alaska Fisheries Science Center also provided logistical support in the form of transportation between lodging and meeting sites and assistance with registration, audio-visual equipment, and communications. We would especially like to express our gratitude to the Pacific Coast Blackcod Fisherman's Association of Canada for financial assistance as a sponsor of the symposium.

We would also like to gratefully acknowledge the help that we received in publishing these proceedings. Ron Hardy, as scientific editor, coordinated the review of this collection of papers. Martha Jackson and Julie Olfe handled the monumental task of technical and copy editing. Katherine Zecca produced the artwork for the cover.

Literature Cited

Melteff, B. (ed.)
1983. Proceedings of the International Sablefish Symposium, Lowell Wakefield Fisheries Symposia Series. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8, 317 p.

Development Of Sablefish, *Anoplopoma fimbria*, Larvae off the West Coast of British Columbia, and Transformation to the Juvenile Stage

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ABSTRACT

The early development of sablefish larvae, from preflexion to adult stage, is described and illustrated. Sablefish used in this study were captured in surface neuston tows and bottom trawl tows off the west coast of British Columbia. The fish ranged in size from 7.6 mm standard length (SL) to 795.0 mm SL (*N*=134). Important physical characteristics such as development of the median and paired fins, pigmentation, gut, and lateral line were examined. Criteria were redefined for identifying small sablefish larvae, and established for determining the size at which a larva is considered a juvenile. The transformation from larvae to juveniles occurred when the body proportions—such as pectoral fin length/standard length, interorbital distance/head length, and snout length/head length—of postflexion larvae resembled those of adults. This transformational period started at 30 mm SL and continued until about 70 mm SL or 76 mm fork length, the start of the juvenile stage.

Introduction

Sablefish, *Anoplopoma fimbria*, is an important commercial species off the west coast of British Columbia. The populations and the fishery are dependent on periodic strong year classes. Studies have been conducted to examine the biotic and abiotic factors affecting year-class success (McFarlane and Beamish, 1986, 1992). Understanding how these factors affect production of larvae and survivorship to the adult stage is an important step in developing rational management strategies. By examining the developmental stages of sablefish we hoped to identify critical periods for larval success. This information could be used to predict recruitment and to enhance larval development through the critical stages to ensure successful survival for mariculture.

Information on the early life history of sablefish larvae is documented by Mason et al. (1983), McFarlane and Beamish (1983), and Kendall and Matarese (1987). In 1984, a series of annual ichthyoplankton surveys began to examine the distribution, abundance, and biology of larval sablefish in the surface waters off Vancouver Island (Shaw et al., 1985, 1987a, b). Larvae caught during those surveys provided the specimens for descriptions of the developmental stages presented in this report. Earlier descriptions of sablefish larvae by Gilbert (1915), Brock (1940), Kobayashi (1957), and Ahlstrom and Stevens (1976) provided only preliminary observations of a few larvae. Kendall and Matarese (1987) presented a review of studies describing the early life history of sablefish, with a discussion about the juvenile stage. They concluded that there was no marked transformation from the larval to juvenile stage. Their conclusions, however, were based on observations of larvae up to 26.6 mm standard length.

The purpose of this paper is to provide a more complete description of the developmental stages and other diagnostic characters of sablefish larvae, and to examine the transformation from the larval to the juvenile stage. We also discuss larval development in relation to the environment in which these fish live.

Materials and Methods

Sablefish larvae were collected off the west coast of Vancouver Island in April 1984 and 1985 (Shaw et al., 1985) using a neuston plankton sampler with mesh size of 500 microns (Sameoto and Jaroszynski, 1969). All larvae were preserved in 5% formalin and later transferred to 70% ethanol. During 1985, large juvenile and adult sablefish were captured with bottom trawl gear equipped with a 2.1-cm (stretched mesh) codend liner. The capture of these specimens enabled us to compare the ratios of body development of the larvae with those of the adults.

All larvae were examined under a compound microscope and measured with an ocular micrometer (0.1 mm). Large juvenile and adult sablefish were measured with a vernier caliper (1.0 mm). We studied sablefish morphology by measuring each fish for fork length, body length, total length, head length, snout length, eye diameter, snout-to-anus distance, interorbital distance, upper jaw length, body depth, and pectoral fin length. Morphological measurements for body length were divided into two categories: first, notochord length for larvae in preflexion stages, from the tip of the snout to the tip of the notochord; and second, standard length for flexion and postflexion larvae and juveniles, from the tip of the snout to the posterior margin of the hypural elements. Measurements of these physical characteristics were expressed either as a ratio (percentage) of standard length (SL), or as a ratio of head length (HL). Standardized terminology defined by Moser (1972), Richardson and LaRoche (1979), and Sumida et al. (1979) was used and is described in Table 1. The exception is that we defined standard length as synonymous to body length. In preflexion larvae, notochord length (NL) is equivalent to standard length (SL). Thus we used standard length as the terminology to describe the length of larvae.

Larval development, based on the flexion of the notochord during caudal fin formation, was divided into three stages: preflexion (prior to notochord flexion); flexion (from the time the urostyle begins to slant upward until the urostyle is in the final upward position and the caudal fin is formed); and postflexion (after completion of the notochord flexion where the urostyle may still extend beyond the base of the caudal fin) (Moser and Ahlstrom, 1970; Ahlstrom and Moser, 1976; Moser et al., 1977; Richardson and LaRoche, 1979). We also examined fin development, pigmentation, gut development including development of the musculature, and development of the lateral line in relation to these stages. The term *fin development* describes the changes in size and number of the fin rays of the median fins (dorsal, anal, and caudal) and paired fins (pectoral and pelvic).

Table 1

Terms referring to morphological measurements and developmental stages (after Moser, 1972; Richardson and LaRoche, 1979; and Sumida et al., 1979).

Term	Definition
Fork length	Horizontal distance from the tip of the snout through the midline of the body to the tip of the shortest median ray in the notch or fork of the tail.
Body length	Horizontal distance from the tip of the snout to the tip of the notochord, i.e., notochord length (NL) in preflexion stages. Also, to the posterior margin of the hypural elements, i.e., standard length (SL).
Total length	Horizontal distance from the tip of the snout to the tip of the longest lobe of the tail when maximally extended.
Head length	Horizontal distance from the tip of the snout through the midline of the head to the posterior margin of the cleithrum.
Snout length	Horizontal distance from the tip of the snout to the anterior edge of the bony eye socket.
Eye diameter	Horizontal width of the bony eye socket.
Snout to anus	Horizontal distance from the tip of the snout through the midline of the body to a vertical line through the anus.
Pectoral fin length	Distance midline from the base of the fin ray to the outer tip of the longest ray.
Upper jaw length	Distance from the tip of the snout to the posterior edge of the maxillary.
Body depth	Distance from a point slightly anterior of the first dorsal fin to the origin of the pelvic fins.
Interorbital distance	Narrowest distance between the bony eye sockets, measured on the dorsal surface.
Preflexion	Prior to notochord flexion.
Flexion	Undergoing notochord flexion; from the time the urostyle begins to slant upward until the urostyle is in the final upturned position and the caudal fin is formed. The angle of the urostyle was estimated during flexion and was expressed as a percent of a 90° angle.
Postflexion	After completion of notochord flexion (urostyle may still extend beyond the base of the caudal fin).

Results

Morphology

A total of 131 sablefish were measured. Of these, 94 were from surface neuston net tows, and ranged in length from 7.6 to 89.9 mm SL. The remaining 37 sablefish were caught in bottom trawls and ranged in length from 258.0 to 795.0 mm SL. A selected size range of specimens was used for illustrations. Figure 1 illustrates three larvae ranging in size from 20 to 30 mm. Figure 2 illustrates five larvae ranging from 35 to 100 mm. Early larval developmental stages smaller than 20 mm are presented in Ahlstrom and Stevens (1976).

Results from this study and from McFarlane and Nagata (1988) indicate that preflexion larvae range from 5.5 to 8.6 mm SL. However, in our surface net catches the smallest larvae were 7.6 mm SL. During preflexion the hypural elements were becoming evident. Flexion started between 8.6 and 9.9 mm SL and was about 25% complete at 11.6 mm; 50% at 12.6 mm; 75% at 13.4 mm; and 100% at 15.6 mm. During this period the caudal fin rays increased to 18, which is about half the total complement of rays in adults. Postflexion larvae started at a length of 15.7 mm SL. As the larvae grew the number of caudal fin rays also increased.

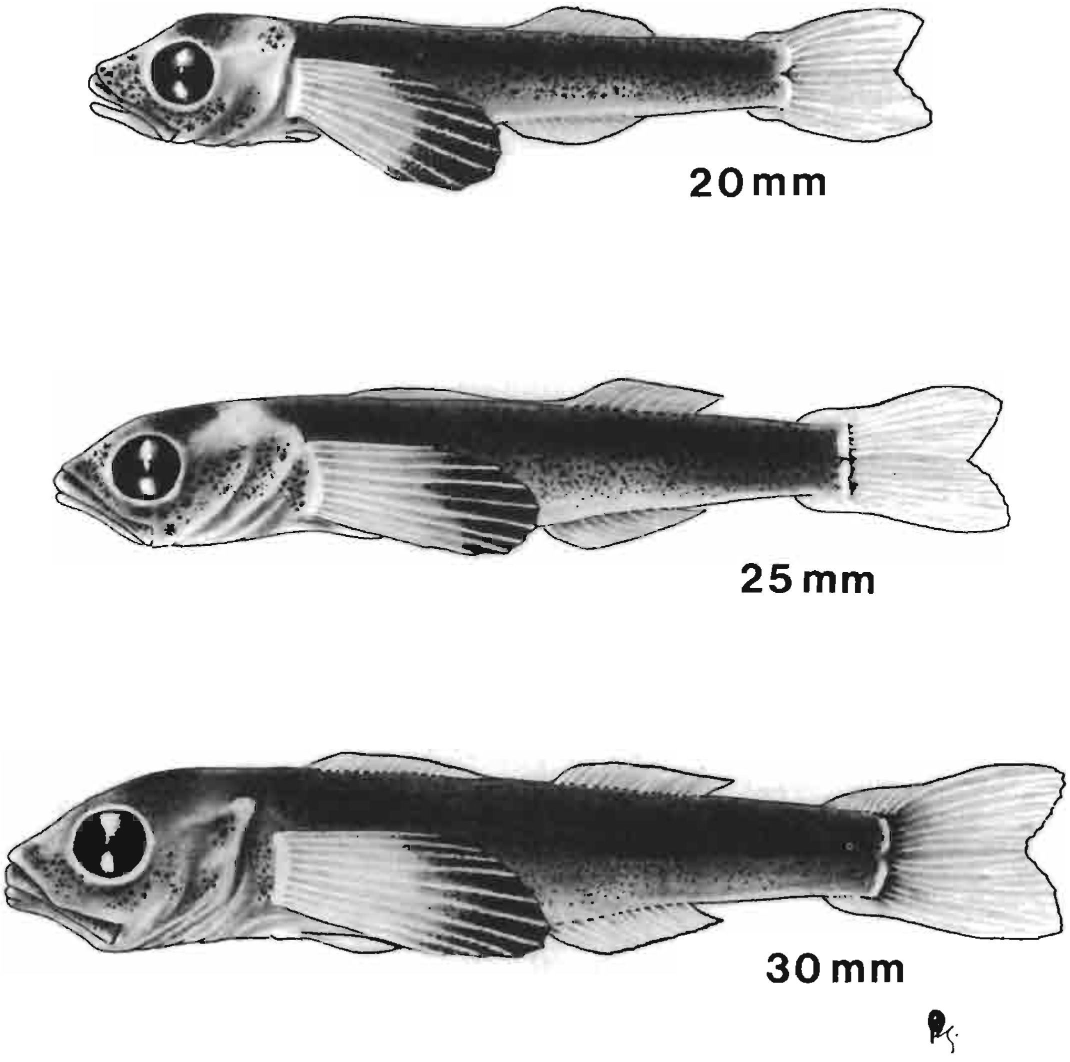

Figure 1
Sablefish development from 20 to 30 mm SL.

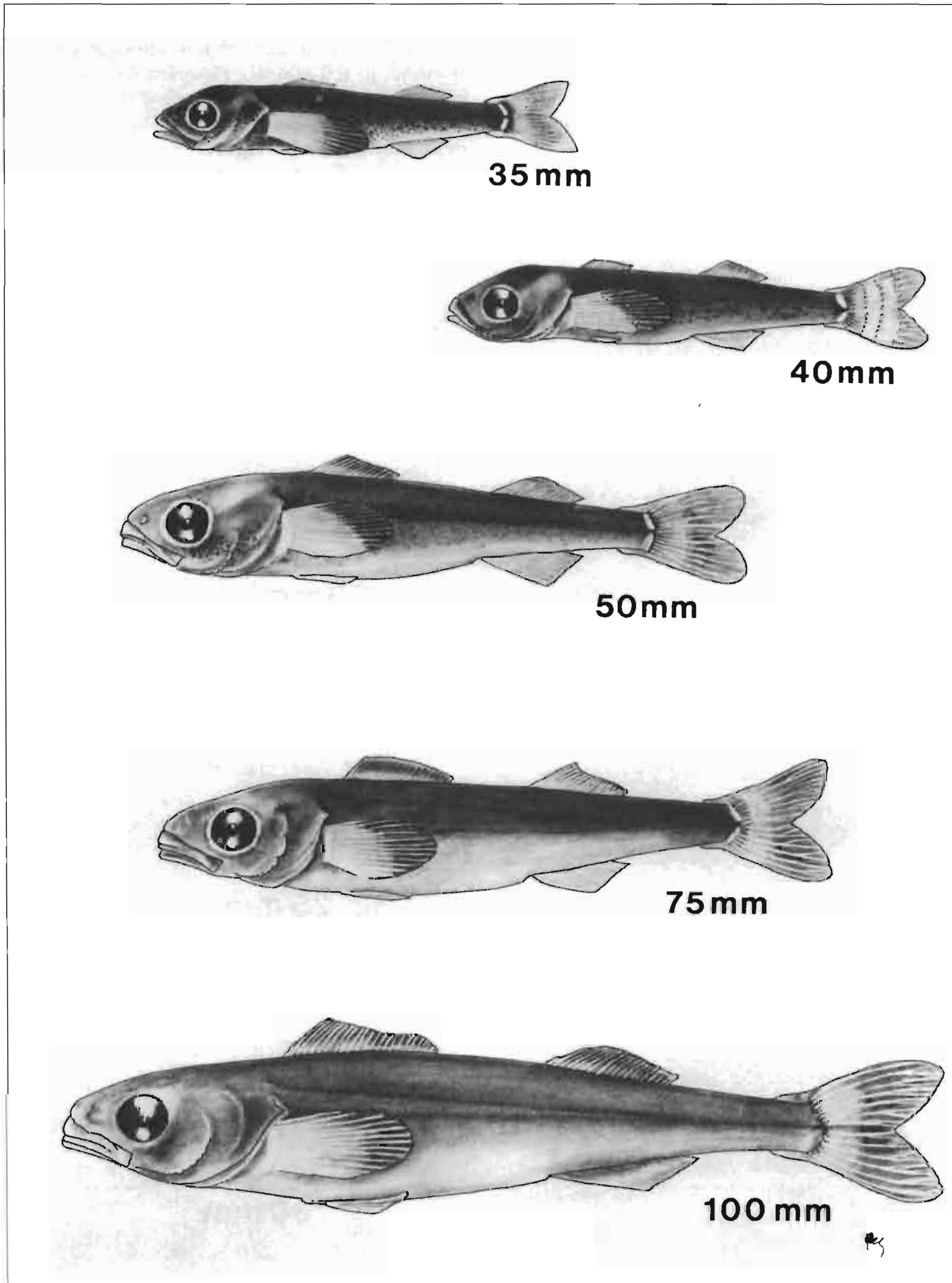

Figure 2
Sablefish development from 35 to 100 mm SL.

Body Proportions vs. Head Length—Snout length, interorbital distance, eye diameter, and upper jaw length expressed as a proportion of HL by developmental stage are presented in Figure 3. During preflexion, snout length and interorbital distance increased rapidly as the head started to conform to adult proportions. The eye diameter and upper jaw length were very large at time of hatch, but decreased rapidly, particularly eye diameter. The change in body proportions for flexion larvae continued the same trend as in preflexion larvae, but less rapidly. During postflexion the snout length and interorbital distance continued to increase in relation to HL, up to 20 mm HL (74 mm SL) and 8 mm HL (32 mm SL), respectively. There was no increase in the snout length ratio for larger fish, but interorbital distance decreased until 19 mm HL (70 mm SL), then increased slightly for larger fish. Eye diameter and upper jaw length proportions decreased until they became similar in late juvenile and early adult fish at 8 mm HL (32 mm SL) and 80 mm HL (288 mm SL), respectively.

Body Proportions vs. Standard Length—Snout-to-anus length, head length, body depth, and pectoral fin length expressed as proportions of SL by developmental stage are presented in Figure 4. During preflexion, all of the body proportions increased rapidly in relation to SL. This increase continued through flexion, but at a reduced rate for snout-to-anus length and body depth. During postflexion, snout-to-anus length and body depth increased more slowly than during flexion; snout-to-anus length peaked for larvae measuring about 50 mm SL, and body depth peaked at 65 mm SL. There was little change thereafter in the snout-to-anus to SL ratio, but the body depth ratio decreased gradually for larger fish. Head length and pectoral fin length proportions increased rapidly into the early phases of postflexion and peaked at 25 mm SL and 30 mm SL, respectively. There was little change thereafter in the head length proportion. The most dramatic change in morphology for larval sablefish was the metamorphosis of the pectoral fins. After 30 mm SL the pectoral fin proportion decreased until larvae reached about 70 mm SL (76.5 mm FL), after which the pectoral fin proportion was similar to that of late juvenile and adult fish.

Fin Development

Preflexion—The hypural bud and pectoral fin rays were visible in the smallest larvae sampled (7.6 mm SL; Table

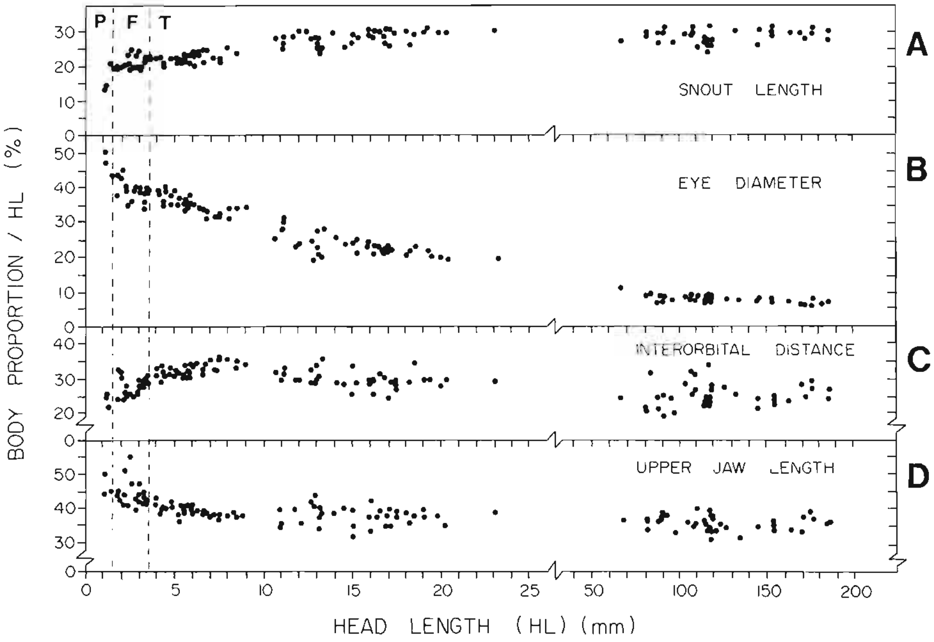

Figure 3

Body proportions for (A) snout length, (B) eye diameter, (C) interorbital distance, and (D) upper jaw length in relation to head length (HL) for fish in the preflexion (P), flexion (F), and postflexion (T) stages.

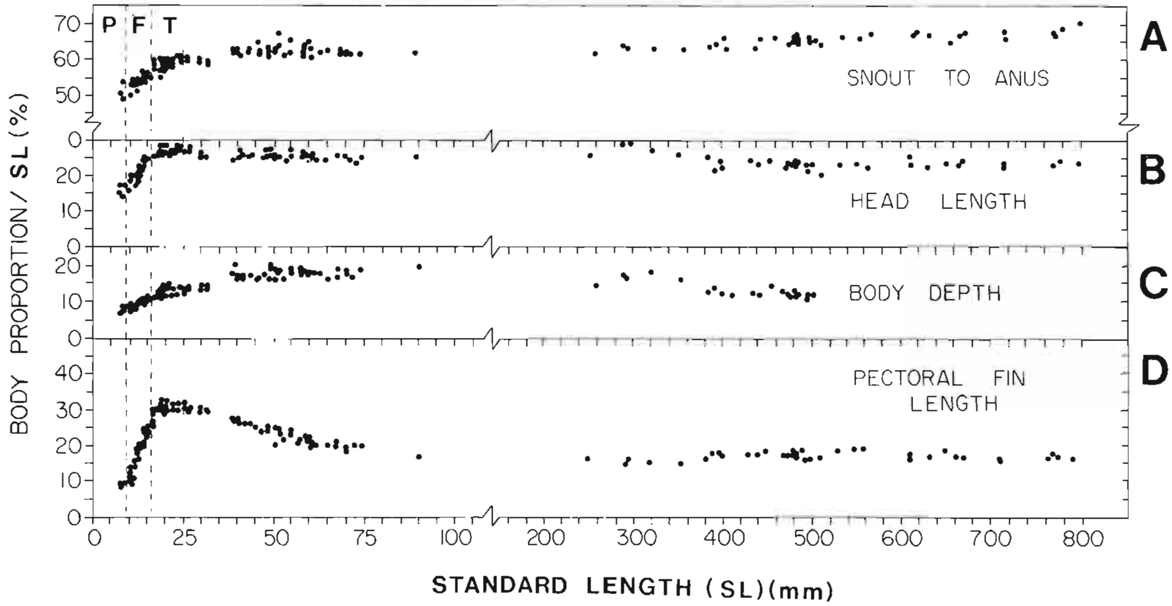

Figure 4

Body proportions for (A) snout-to-anus length, (B) head length, (C) body depth, and (D) pectoral fin length in relation to standard length (SL) for fish in the preflexion (P), flexion (F), and postflexion (T) stages.

2). The pectoral fin was round, and contributed only 9% of the SL. The fin fold was very prominent, extending the full length from the nape of the neck dorsally to the tip of the notochord, and ventrally along the gut to below the pectoral fin base.

Flexion—The number of rays in the pectoral fin increased from 12 for larvae measuring 10.8 mm SL and to 14 for 15.6-mm larvae (Table 3). The pectoral fin elongated from 8.8% to 26.2% SL, resulting in a long, paddle-shaped fin. During flexion the fin fold reduced posteriorly at a quicker rate on the dorsal surface than on the ventral surface. At the end of flexion (15.6 mm SL) the fin fold was greatly reduced from the nape of the neck to the start of the second dorsal fin. The first dorsal fin was visible in 12.6-mm larvae, and ray development started at 15.6 mm. The fin fold on the ventral side was present from the vent to the anterior portion of the anal fin. Between 14 and 16 rays were counted in the second dorsal fin, and from 16 to 18 rays in the anal fin. The anal fin rays were longer than the second dorsal fin rays. Pelvic fin buds were evident, with no ray development at 12.6 mm SL. The caudal fin fold differentiated into the caudal fin by 12.1 mm. At this size the caudal fin had 10–12 rays, which increased to 19 rays at the end of flexion. The fork, or indentation, on the caudal fin was noticeable in larvae measuring 13.9 mm SL.

Table 2

Physical developmental changes of preflexion larvae.

SL (mm)	Development
6.1[1]	Eye pigmentation
7.6	Hypural bud visible
7.6	4 melanophore zones on cranial cap
7.6	1 melanophore over each operculum
7.6	20 melanophores from anal vent to caudal
7.6	Pectoral fin rays visible
7.6	Angle of vent about 90°
7.7[1]	Pigmentation of alimentary canal

[1] Data from McFarlane and Nagata (1988).

Postflexion—The ratio of pectoral fin to body length decreased to 17% for 70-mm SL larvae, becoming similar to that in larger fish. A total of 17 rays were counted in the pectoral fin for 24.9-mm larvae, as in larger fish (juvenile/adult fish have 17 rays; Table 4). The fin fold receded at a slower rate on the ventral side and disappeared by the time larvae reached 24.1 mm. The second dorsal fin continued developing before the first dorsal fin: 17 rays were visible on the second dorsal fin for 17.0-mm larvae, and 18 rays were visible for larvae >35.0 mm (juvenile/adult fish have 18 rays). Longer

Table 3
Physical developmental changes of flexion larvae.

SL (mm)	Development
10.8	Pectoral fin with 12 rays
12.1	Second dorsal fin with 14 rays visible
12.1	Caudal fin developed with 10–12 rays
12.1	Anal fin and rays visible
12.1	Angle of anal vent decreasing from 90°
12.6	Pelvic fin visible
12.6	First dorsal fin visible
12.6	Distal portion of pectoral fin is black
13.4	Melanophore color changed from olive brown to blue green
13.4	Half of pectoral fin is black
13.9	Fork in caudal fin is noticeable
15.1	Lateral line visible, and 2% SL
15.6	Dorsal fin fold disappears
15.6	First dorsal fin rays are visible
15.6	Anal fin with 16–18 rays

rays were found in the anterior portion of the second dorsal fin for 19.0-mm larvae; the fin looked like the adult fin by 21.0 mm SL. The spines in the first dorsal fin initially appeared in 21.0-mm larvae, with the longest spines on the anterior and posterior margins of the fin. A total of 18 spines were evident in the first dorsal fin for 47.5-mm larvae (juvenile/adult fish, 19 rays). The number of rays in the anal fin totaled 19 for 19.2-mm larvae (juvenile/adult fish, 19 rays). Pelvic fin rays (I,5) were visible in 17.5-mm larvae (juvenile/adult fish, 6 rays). New ray development in the dorsal and ventral caudal peduncle region was noticed for 16.4-mm larvae, and by 26.4 mm SL the caudal peduncle had 36 rays (juvenile/adult fish, 36 rays). The indentation on the caudal fin increased such that the proportion of FL to TL decreased from 98.7% to 93.3% for 30-mm SL (34-mm FL) larvae, similar to this proportion in adult fish.

Pigmentation

Preflexion—Preflexion larvae (7.6 to 8.6 mm SL) had four melanophore zones on the cranial cap (Table 2). The interorbital area had one melanophore. The operculum had two melanophores, one over each side. Both lateral sides had light pigmentation, which became more concentrated in the caudal region. The ventral surface and the entire digestive tract were unpigmented except for 20 melanophores located on the ventral midline, extending posterior from the anal vent to the caudal peduncle.

Table 4
Physical developmental changes of postflexion larvae.

SL (mm)	Development
17.0	Second dorsal fin with 17 rays
17.5	Pelvic fin with rays
19.2	Anal fin has 19 rays, similar to larger fish
24.1	Ventral fin fold disappears
24.9	Pectoral fin has 17 rays
25.0	Head length ratio similar to larger fish
26.4	Caudal fin has 36 rays, similar to larger fish
29.9	Second dorsal fin pigmented
30.0	Caudal fin fork ratio similar to larger fish
32.0	Upper jaw ratio similar to larger fish
35.4	First dorsal fin with 17 rays, similar to larger fish
47.0	Second dorsal fin with 18 rays
47.0	Three-quarters of pectoral fin is black
47.5	Scales visible along body
47.5	Lateral line extends full length of body
50.0	Snout-to-anus ratio similar to larger fish
65.0	Body depth ratio similar to larger fish
67.0	Caudal fin heavily pigmented
70.0	Pectoral fin ratio similar to larger fish
70.0	Interorbital distance ratio similar to larger fish
74.0	Snout length ratio similar to larger fish
89.9	Black pigmentation on pectoral fin less noticeable

Flexion—First noticed on the upper and lower jaw in 9.9-mm larvae, pigmentation continued to spread with the size of the fish. Throughout flexion, individual melanophores on the cranial cap became less distinct as the pigmentation spread over the cap. The interorbital area contained more than one melanophore (9.9-mm larvae). Each operculum still contained a single large melanophore (12.9 mm SL) and numerous smaller melanophores, which covered the operculum by the end of flexion. Black pigmentation was visible between the rays of the distal portion of the pectoral fin on 12.6-mm larvae. By 13.4 mm SL, half of the pectoral fin was covered by black pigmentation (Table 3). The anterior portion of the hypural elements was pigmented (11.9 mm SL). At the start of flexion, the dorsal surface darkened as pigmentation began to spread; by 13.9 mm SL, about 1/4 of the dorsal surface from the nape to the caudal fin contained solid pigmentation. At this stage the dorsal pigmentation changed from olive brown to dark blue green. Simultaneously, the ventral surface was silver with the 20 melanophores, and the ventral midline was almost totally covered by the developing musculature. A row of melanophores covered the dorsal surface of the intestinal tract and the entire stomach region except for the ventral midline in 12.1-mm larvae. As the larvae grew longer, the musculature developed ventrally and covered the intestinal tract and the pelvic girdle.

Postflexion—The cranial cap, interorbital region, and operculum continued to darken as a result of increased pigmentation. Melanistic pigmentation covered about three-quarters of the pectoral fin in 47.5-mm larvae; by 89.9 mm SL this pigmentation could not be differentiated from the coloration of the fin (Table 4). By 15.6 mm SL, the 20 melanophores posterior to the anal vent were difficult to see. On the first dorsal fin, a few melanophores were visible on the distal fringe in 21.4-mm larvae. The pigmentation darkened on the anterior rays and distal fringe of the first dorsal fin in 30-mm larvae, and became black as the larvae reached 89.9 mm SL. By 35.4 mm SL, the pigmentation had spread to the base of all spines in the first dorsal fin, as in larger fish. The second dorsal fin was pigmented for 29.9-mm larvae. In larvae between 47.0 and 89.0 mm SL, the distal quarter of the fin was unpigmented. By 67.0 mm SL the caudal fin was heavily pigmented; the distal fringe was unpigmented. The lateral surface had dark pigmentation above the lateral line, while the ventral surface remained silver with light spotting.

Gut Development

Preflexion—The intestine in larvae from 7.6 to 8.6 mm SL was long, straight, and ended at the anal vent located midway (51% SL) along the body, and angled at 90° (Table 2). The entire gut was visible from the liver to the vent.

Flexion—In flexion larvae, musculature developed along the ventral side and started covering the gut area. For 12.1-mm larvae, the angle of the vent started to decrease from 90° (Table 3); the vent was located at about 54% SL. The concentration of melanophores increased around the stomach and liver area. The intestinal tract was still visible at the end of flexion.

Postflexion—In 18.1-mm larvae, the musculature enveloped the stomach area to the anal vent, and myomeres were differentiated. The anal vent was anterior to the anal fin at about 59% SL.

Lateral Line Development

Preflexion—The lateral line was not visible on preflexion larvae.

Flexion—The lateral line was visible on 15.1-mm larvae during late flexion (Table 2). The line first appeared high on the dorsolateral surface anterior of the pectoral fin insertion and measured about 2% SL.

Postflexion—The lateral line increased to 10% SL (17.0 mm SL) and was completely visible along the body, as in the adult form, for 47.5-mm larvae (Table 3). Interestingly, scales were initially visible in 47.5-mm larvae.

Discussion

Identification Characteristics

Identification of sablefish larvae was initially based on criteria developed by Brock (1940) and Kobayashi (1957), and highlighted the large, pigmented pectoral fins and the anal vent. As we examined the larvae it was apparent that a number of additional characteristics could help with identification, particularly in the larval to early juvenile stages. The additional characteristics include the 20 melanophores on the ventral midline posterior to the anal vent; the elongated body form with the long, straight intestine terminating at a 90° angle midway along the body; the long, paddle-like pectoral fins measuring about 30% of the body length, with black pigmentation on their distal half; and the four melanophore zones on the cranial cap.

Fish in the initial postflexion stage were easily identified. Their bodies were elongated and relatively slim, with long pectoral fins. Each pectoral fin still had black pigmentation on its distal half. This feature made the fins look like black-tipped wings. During this stage the pigmentation changed from olive to blue green on the dorsal half, and to silver white on the ventral half of the body. Also, by studying how the body proportions relate to adult proportions, we could determine the period of transformation.

In summary, we believe that these characteristics will enhance our ability to identify sablefish. In addition, although not all species will have proportions similar to sablefish, we have provided a technique for defining the transformation period for other species.

Transformation to Juvenile Stage

The criteria for determining the transition from the late larval to the juvenile stage were based on characteristics that gave the fish an adult appearance, such as formation of the full complement of fin rays (Berry 1959; Harya 1980) and an increase in body pigmentation and scale formation (Richardson and Washington 1980). In addition, we used the body proportions for postflexion larvae to determine at what size the larval body began to resemble that of adults. For example, pectoral fin length/SL, interorbital distance/HL, and snout length/HL proportions started to change around 30 mm SL and resembled the proportions of adults around 70 mm. Other body proportions that resembled the adult stage at 30 mm, with little change thereafter, were the ratio of snout-to-anus length/SL, head length/SL, and upper jaw length/HL. The period of change, or "transformation," to the juvenile stage, when the larvae start to resemble adults, therefore is defined as occurring from 30 to 70 mm. During this period the scales were becoming evident; body pigmentation became very concentrated; the body narrowed; and the fins took on adult proportions. On the basis of these criteria, we propose that the transformation stage is complete at 70 mm SL (76.5 mm FL).

Functional Aspects

Changes during the developmental stages of sablefish larvae affect their adaptation to their environment. According to McFarlane and Beamish (1992), sablefish spawn along the continental slope, deeper than 300 m. Eggs hatch in deep water and the larvae sink to approximately 1,000 m, remaining there until they begin feeding (McFarlane and Beamish, 1992). At this time the alimentary canal, eyes, head, and body become pigmented. The mouth is functional, and the larvae begin showing prey-capture movements. After about 20 days (preflexion stage) at this depth, the larvae begin to swim up in the water column to follow prey, attracting predators.

Pigmentation—Pigmentation began early in the preflexion stage. This is considered an important adaptation of sablefish larvae to their environment. Newly-hatched larvae (4.5 mm) were transparent but quickly became camouflaged as they reached surface waters (7.6 mm SL) and pigmentation developed. During this stage they were elongated, with a linear pattern of 20 melanophores posterior to the anal vent. Pigment was visible inside the body cavity along the dorsal side of the gut. Also, some pigmentation occurred externally along the dorsal surface of the body. The linear postanal pigment probably functions to confuse a predator with the phenomenon of "flicked fusion," which depends on the rapidly beating tail fin (Moser, 1981). Pigmentation dorsal to the gut helps to mask light refracting through the gut contents, especially in shallow waters. Early pigmentation on the dorsal surface is probably an adaptation by the larvae to their habitat in surface waters, which is characterized by predators and solar radiation. Moser (1981) suggested that ultraviolet (UV) radiation is the primary factor selecting for the heavy melanistic pigmentation found universally among neustonic fish larvae. In the case of sablefish, the heavy melanistic pigment at an early stage probably contains a high concentration of xanthic pigment, characterized by a brown-black color. This pigment would cloak the dorsal surface of the larvae and protect against the destructive effects of UV rays, and also against visible light radiation. As the larvae continued to grow (13.4 mm), the color on the dorsal surface changed from olive brown to blue green with black melanophores. By 35.4 mm SL, the fish were relatively well cloaked in the dark pigment, thus beginning to resemble adults.

Fin Development—Contraction of the fin fold appeared to coincide with enlargement of the pectoral fins. In the earlier stages of larval development, particularly in deep water, the fin fold probably helps larvae overcome negative buoyancy (larvae have no swim bladder), acting as preliminary dorsal and ventral fins. During preflexion and flexion, the enlargement of the pectoral fins could have a hydrostatic function for conserving energy by acting as wings to glide the larvae through the water; provide rapid mobility, since the tail fin is not fully differentiated; and deter potential predators by enhancing larval size.

We speculate that as the larvae begin to inhabit shallower waters, the black pigmentation on the tips of the pectoral fins acts as a form of mimicry, changing the appearance of the larvae when the fins are extended and making them look like predators. When the pectoral fins are beside the body, the black pigmentation helps to break the pattern of the body color and possibly to mislead predators. Around the start of the transformation period (30 mm SL), survival techniques such as camouflage and mimicry probably begin to be less important to the larvae.

Adapting to Food Availability—Survival of sablefish larvae is closely linked with calanoid copepod production, and an increase in copepod abundance would be expected to improve sablefish survival (McFarlane and Beamish, 1992). During the preflexion stage, larvae equipped with a generous fin fold, large mouth, and large eyes prey on copepod eggs and nauplii in the depths from 600 to 800 m. Grover and Olla (1986) noted that sablefish larvae between 12.5 and 20.5 mm SL changed the size of prey they consumed. The diet of larger larvae is more diverse than that of smaller larvae. In order to respond to varying abundance and availability of prey at the time of hatching, the larvaes' rounded caudal fin develops early into the deeply forked tail, thus enabling these small fish to increase their swimming speed and maneuverability. This period coincides with the onset of transformation.

As the larvae grow in length, the mouth-opening ratio decreases, and becomes similar to that of adult sablefish.

The reduced pectoral fin and increased forked tail would allow these fish to catch food more easily and to target different prey species and sizes, thus becoming more efficient feeders. This period coincides with the end of transformation and the onset of the juvenile stage.

In this report we have described the development of sablefish larvae to the juvenile stage. We have also proposed how the development from larvae to juvenile relates to their environmental adaptability. We believe that determining the developmental stages of sablefish larvae will facilitate the study of factors that influence larval year-class success.

Acknowledgments

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Literature Cited

Ahlstrom, E. H., and H. G. Moser.
1976. Eggs and larvae of fishes and their role in systematic investigations and in fisheries. Rev. Trav. Inst. Peches Marit. 40:379–398.
Ahlstrom, E. H., and E. Stevens.
1976. Report of neuston (surface) collections made on an extended CalCOFI cruise during May 1972. Calif. Coop. Oceanic Fish. Invest. Rep. 18:167–180.
Berry, F. H.
1959. Young jack crevalles (*Caranx* species) off the southeastern Atlantic coast of the United States. U.S. Fish Wildl. Serv. Fish. Bull. 152, vol. 59:417–535.
Brock, V. A.
1940. Note on the young of the sablefish, *Anoplopoma fimbria*. Copeia 4:268–270.
Gilbert, C. H.
1915. Fishes collected by the United States fisheries steamer "Albatross" in southern California in 1904. Proc. U.S. Nat. Mus. 48:305, 380.
Grover, J. J., and B. Olla.
1986. Morphological evidence for starvation and prey size selection of sea caught larval sablefish, *Anoplopoma fimbria*. Fish. Bull. 84:484–489.
Haryu, T.
1980. Larval distribution of walleye pollock (*Theragra chalcogramma*) (Pallas), in the Bering Sea, with special reference to morphological changes. Bull. Fac. Fish. Hokkaido Univ. 31:121–136.
Kendall, K., and A. C. Matarese.
1987. Biology of eggs, larvae, and epipelagic juveniles of sablefish (*Anoplopoma fimbria*), in relation to their potential use in management. Mar. Fish. Rev. 49(1):1–13.
Kobayashi, K.
1957. Larvae and young of the sablefish, *Anoplopoma fimbria* (Pallas), from the sea near the Aleutian Islands. Bull. Jpn. Soc. Sci. Fish. 23(7):376–382.
Mason, J. E., R. J. Beamish, and G. A. McFarlane.
1983. Sexual maturity, fecundity, spawning, and early life history of sablefish (*Anoplopoma fimbria*) off the Pacific coast of Canada. Can. J. Fish. Aquat. Sci. 40:2,126–2,134.
McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters off western Canada. *In* Proceedings of the International Sablefish Symposium, p. 59–80. Alaska Sea Grant Rep. 83-3.
1986. Production of strong year-classes of sablefish (*Anoplopoma fimbria*) off the west coast of Canada. INPFC Bull. 47:191–202.
1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 49:743–753.
McFarlane, G. A., and W. Nagata.
1988. Overview of sablefish mariculture and its potential for industry. Alaska Sea Grant Rep. 88-4:105–120.
Moser, H. G.
1972. Development and geographic distribution of the rockfish, *Sebastes macdonaldi* (Eigenmann and Beeson, 1893), Family Scorpaenidae, off southern California and Baja California. Fish. Bull. 70:941–958.
1981. Morphological and functional aspects of marine fish larvae. *In* R. Lasker (ed.), Marine fish larvae. Washington Sea Grant Program, Seattle.
Moser, H. G., and E. H. Ahlstrom.
1970. Development of lantern fishes (family Myctophidae) in the California Current. Part 1. Species with narrow-eyed larvae. Bull. Los Angel. Cty. Mus. Nat. Hist. Sci. 7, 145 p.
Moser, H. G., E. H. Ahlstrom, and E. M. Sandknop.
1977. Guide to the identification of scorpion fish larvae (family Scorpaenidae) in the eastern Pacific with comparative notes on species of *Sebastes* and *Helicolenus* from other oceans. U.S. Dep. Commer., NOAA Tech. Rep. NMFS Circ. 402, 71 p.
Richardson, S. L., and W. A. LaRoche.
1979. Development and occurrence of larvae and juveniles of the rockfishes *Sebastes crameri*, *Sebastes pinniger* and *Sebastes helvomaculatus* (family Scorpaenidae) off Oregon. Fish. Bull. 77(1):1–46.
Richardson, S. L., and B. B. Washington.
1980. Guide to identification of some sculpin (Cottidae) larvae from marine and brackish waters off Oregon and adjacent areas in the northeast Pacific. U.S. Dep. Commer., NOAA Tech. Rep. NMFS Circular 430, 56 p.
Sameoto, D. D., and L. O. Jaroszynski.
1969. Otter surface sampler: a new neuston net. J. Fish. Res. Board Can. 25:2,240–2,244.
Shaw, W., G. A. McFarlane, and D. Davenport.
1987a. Distribution and abundance of larval sablefish (*Anoplopoma fimbria*) off the west coast of Vancouver Island, April 3–18 and May 10–18, 1986. Can. Manuscr. Rep. Fish. Aquat. Sci. 1970, 130 p.
1987b. Distribution and abundance of larval sablefish (*Anoplopoma fimbria*) in the surface waters off the west coast of Vancouver Island, April 9–24, 1985. Can. Manuscr. Rep. Fish. Aquat. Sci. 1945, 49 p.
Shaw, W., G. A. McFarlane, D. Davenport, and W. T. Andrews.
1985. Distribution and abundance of larval sablefish (*Anoplopoma fimbria*) in the surface waters off the west coast of Vancouver Island, April 16 to May 10, 1984. Can. Manuscr. Rep. Fish. Aquat. Sci. 1835, 41 p.
Sumida, B. Y., E. H. Ahlstrom, and H. G. Moser.
1979. Early development of seven flatfishes of the eastern North Pacific with heavily pigmented larvae (PISCES, Pleuronectiformes). Fish. Bull. 77(1):105–145.

Distribution of Sablefish, *Anoplopoma fimbria*, Larvae in the Eastern Gulf of Alaska: Neuston-net Tows versus Oblique Tows

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ABSTRACT

Sablefish larvae in the eastern Gulf of Alaska were sampled January–July, 1984 to 1991. Neuston nets (50-cm Sameoto neuston nets and 100-cm ring nets towed at the surface) caught more and larger sablefish larvae than 60-cm bongo nets towed obliquely from 300 m (or from near bottom if less than 300 m) to the surface. Neuston tows caught sablefish larvae from mid-April to late July, whereas oblique tows caught sablefish larvae from May through June. No sablefish larvae were caught during January, February, or March.

Neuston catches of sablefish larvae were larger at night than during daylight hours. Catches of sablefish larvae in oblique bongo net tows were not statistically larger at night. Average length of sablefish larvae caught in neuston tows at night was less than during the day. Average length of sablefish larvae caught in oblique bongo tows at night was greater than the average length of larvae caught in daylight. Suspected spatial differences were less apparent in oblique-tow catches than in neustonic catches because of the lower catch rates and lesser diel variation. Regardless of net, the greatest numbers of sablefish larvae were caught offshore, beyond the continental shelf and slope.

Future studies of sablefish larvae distribution and abundance should emphasize sampling the neuston and near-surface layers, and should include the continental shelf and offshore waters in the Alaska Gyre. Additional studies of the diel depth distribution of sablefish larvae are needed to provide adjustment values where both day and night sampling are used during synoptic surveys.

Introduction

Sablefish, *Anoplopoma fimbria* (Pallas), ranks fourth in value of Alaskan groundfish. Seasonal and areal harvest quotas are based on annual longline surveys by the National Marine Fisheries Service and Alaska Department of Fish and Game. Sablefish recruit to the fishery at age 4 or 5 years. Recruitment is characterized by large variations in year-class strength, and catches may be dominated by a single year class for 5 or more years. Early forecasts of recruitment depend on an understanding of the ecology of prerecruits, particularly of eggs and larvae. A better understanding of the physical and biological determinants of larval growth and survival may contribute to recruitment forecasts 3 to 5 years before a year class enters the fishery (Kendall and Matarese, 1987).

Recent ichthyoplankton surveys of the eastern Gulf of Alaska by the Auke Bay Laboratory (ABL) have targeted sablefish eggs and larvae. Before the 1972 neuston collections off the coast of Washington (Ahlstrom and Stevens, 1976), few sablefish larvae had been reported in the scientific literature. Subsequent ichthyoplankton surveys using neuston nets found sablefish larvae widely distributed from California to British Columbia in spring and early summer (Mason et al., 1983; Shenker, 1988; Doyle, 1992; Moser et al., 1994). Data on distribution of sablefish larvae along the southeastern Alaska coast are sparse, partly due to sampling conducted with the wrong equipment and in the wrong place. Sablefish spawn deep on the continental slope, and their larvae are distributed offshore (Mason et al., 1983; Kendall and Matarese, 1987; Moser et al., 1994); previous ichthyoplankton studies in Alaska concentrated on nearshore species such as Pacific herring, *Clupea pallasi*, and walleye pollock, *Theragra chalcogramma*, or were ancillary to studies of juvenile salmon, *Oncorhynchus* spp. (e.g., Wing and Reid, 1972; Mattson and Wing, 1978; Cooney, 1987; Kendall and Picquelle, 1990).

In 1984, ABL initiated surveys to examine the larval life history of sablefish and the environmental factors affecting their distribution, survival, and recruitment in the eastern Gulf of Alaska. In this paper I address three questions: 1) Are geographic distributions of sablefish larvae caught by standard oblique tows and neuston tows similar? 2) Are the two methods of sampling similarly affected by day–night differences? 3) Do the two methods effectively sample the same proportion of the larval sablefish population?

Materials And Methods

Data Sources

Zooplankton samples from 14 cruises in the eastern Gulf of Alaska, 1984–91, were sorted in their entirety for fish eggs and larvae (Table 1, Fig. 1). Although sampling methods, sampling periods, and station locations varied among cruises, on 9 cruises we towed nets both at the surface and obliquely to the surface from 300 m. Catch data were standardized for type of gear and tow, and time of day. Catches are expressed in terms of actual count, number per 1,000 m^3, and number per 10 m^2 (Table 2, 3). Geographic coverage by cruises varied too much to define population boundaries or estimate population size within the study area.

Surface samples for April 1984 were taken with a 1-m-diameter, 333-μ-mesh ring net towed at 2.8–3.7 km/h. The January–February 1985 surface samples were taken with a 60-cm bongo net towed just below the water surface. The January–April 1985 surface samples were taken with a 0.5-m, 505-μ-mesh ring net towed from an open skiff. The ring nets were positioned to tow with the top of the ring submerged but less than 15 cm below the surface. On all other cruises, surface samples were taken using a 50-cm Sameoto net with 505-μ mesh (Sameoto and Jaroszynski, 1969) towed 15 minutes at 7.4 km/h. This neuston net samples the top 15–30 cm of the water column. Because these nets did not have flowmeters, volume filtered and area covered were estimated from time (distance) towed, assuming 95%–100% net efficiency, one-half immersion for the Sameoto net, and full immersion for the ring nets. The ring nets were used only during periods of low phytoplankton abundance when the meshes used were unlikely to clog.

Table 1

Cruise dates, number of stations (*S*), and number of samples (*N*) of larval sablefish collected in the eastern Gulf of Alaska, 1984–91. Dashes indicate that tows were not made.

	Neuston–net tows				Oblique tows			
	Total		Positive		Total		Positive	
Cruise dates	*S*	*N*	*S*	*N*	*S*	*N*	*S*	*N*
1984 Apr 21–May 6	8	7	3	3	8	7	0	0
1985 Jan 29–Feb 2	3	3	0	0	5	5	0	0
1985 Jan 3–Apr 28	9	9	0	0	—	—	—	—
1985 May 23–May 25	15	16	10	11	—	—	—	—
1985 Jul 8–Jul 25	20	20	3	3	—	—	—	—
1986 Jan 28–Feb 8	32	32	0	0	13	26	0	0
1986 Mar 21–Mar 27	6	8	0	0	2	4	0	0
1986 Jun 12–Jun 18	15	15	6	6	—	—	—	—
1987 Feb 18–Mar 19	2	2	0	0	1	2	0	0
1987 Jul 7–Jul 21	36	36	9	9	31	62	1	1
1988 Jun 24–Jun 29	—	—	—	—	35	70	0	0
1990 May 7–May 23	73	86	60	73	70	137	43	64
1991 May 19–May 25	26	26	20	20	24	48	15	24
1991 Jun 19–Jun 25	19	26	11	11	11	27	0	0

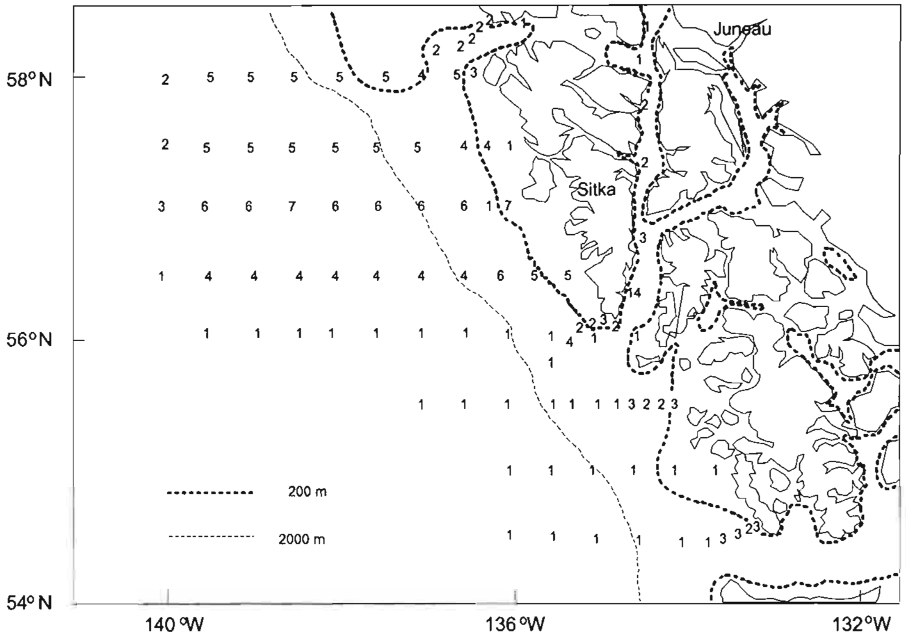

Figure 1

Sampling locations in the Gulf of Alaska, and the number of times stations were sampled for sablefish larvae, 1984–91.

Table 2

Sablefish larvae catches in the eastern Gulf of Alaska, May 1990. Values for oblique tows indicate mean of two bongo-net samples at each station.

	Count	#/1,000 m^3	#/10 m^2	Count	#/1,000 m^3	#/10 m^2
			All stations			
	Neuston-net tows (n=74)			Oblique tows (n=70)		
Mean	174.43	1,232.38	1.83	1.82	4.61	14.31
Median	3.00	35.40	0.05	0.50	1.30	3.98
SD	577.40	4,089.97	6.13	3.70	9.18	30.08
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	4,337.00	30,749.33	45.97	25.50	61.60	197.09
			Day stations			
	Neuston-net tows (n=50)			Oblique tows (n=48)		
Mean	30.46	216.32	0.14	1.65	4.22	12.77
Median	3.00	21.24	0.02	0.50	1.24	3.94
SD	123.11	876.50	0.26	3.91	9.58	30.84
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	875.00	62.30	9.36	25.50	61.60	197.09
			Night stations			
	Neuston-net tows (n=24)			Oblique tows (n=22)		
Mean	474.36	3,349.17	5.02	2.20	5.46	17.67
Median	97.36	683.08	1.01	0.75	1.41	4.20
SD	929.11	6,583.73	9.86	3.18	8.20	28.06
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	4,337.00	30,749.33	74.00	14.00	36.22	30.00

Table 3

Sablefish larvae catches in the eastern Gulf of Alaska, May 1991. Values for oblique tows indicate mean of two bongo-net samples at each station.

	Count	#/1,000 m^3	#/10 m^2	Count	#/1,000 m^3	#/10 m^2
			All stations			
	Neuston-net tows (*n*=26)			Oblique tows (*n*=24)		
Mean	84.11	615.58	0.91	2.90	7.88	26.20
Median	4.00	32.40	0.04	1.00	2.79	9.03
SD	210.23	1,510.52	2.27	5.16	13.27	47.12
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	964.00	6,940.22	10.41	23.00	58.31	213.90
			Day stations			
	Neuston-net tows (*n*=18)			Oblique tows (*n*=18)		
Mean	3.83	42.04	0.04	1.75	4.91	15.24
Median	3.00	21.60	0.03	0.50	2.02	6.16
SD	3.73	65.60	0.04	3.17	8.52	27.51
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	12.00	288.80	0.13	13.00	35.31	114.99
			Night stations			
	Neuston-net tows (*n*=8)			Oblique tows (*n*=6)		
Mean	264.75	1,906.04	2.87	6.33	16.80	59.07
Median	183.00	1,317.49	1.98	3.00	9.62	32.86
SD	310.61	2,236.14	3.35	7.82	19.50	71.90
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	964.00	6,940.22	10.41	23.00	58.31	213.90

Oblique tows were made from 300 m (or near bottom at stations shallower than 300 m) to the surface, with 60-cm-diameter, 505-µ-mesh bongo nets (Posgay and Marak, 1980) equipped with General Oceanics[1] flowmeters and Benthos bathykymographs. Vessel speeds were 2.3–3.2 km/h with tow cable deployed at 50 m/min and retrieved at 30 m/min. Oblique tows were standardized to number per 1,000 m^3 and number per 10 m^2 on the basis of flowmeter readings, net mouth area, and depth of tow (Smith and Richardson, 1977).

All samples were preserved with 4% buffered formaldehyde, and sorted for fish eggs and larvae at ABL. Standard lengths of sablefish larvae were measured to 0.1 mm by means of a stereomicroscope equipped with an ocular micrometer.

Statistical Analyses

Nonparametric rank correlation and chi-square tests were applied to the standardized catch data to determine the relationship between paired neuston-net and bongo-net catches. To examine geographical distribution, I assigned the most complete data sets, 1990 neuston tows and 1990 oblique tows, to three geographic categories: 1) continental shelf (inshore of the continental shelf break at about 200 m); 2) continental slope (from the shelf break near 200 m to about 2000 m); and 3) oceanic (bottom >2000 m); and two diel categories: night and day. The nonnormality of raw count and standardized catches required data transformation (Barnes, 1952). The standardized catches were transformed to $\ln(n + 1)$.

Results

Sablefish Samples

Sablefish larvae were caught during 8 of 13 cruises in which neuston-net tows were made (Table 1). Sablefish larvae were collected from late April through July; small juveniles (less than 50 mm) have been seen at the surface in August (pers. observation). Largest catches occurred in the May 1990 and May 1991 surveys, in which neuston tows caught sablefish larvae at 77%–86% of the stations. Catches in May 1990 ranged from 0

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

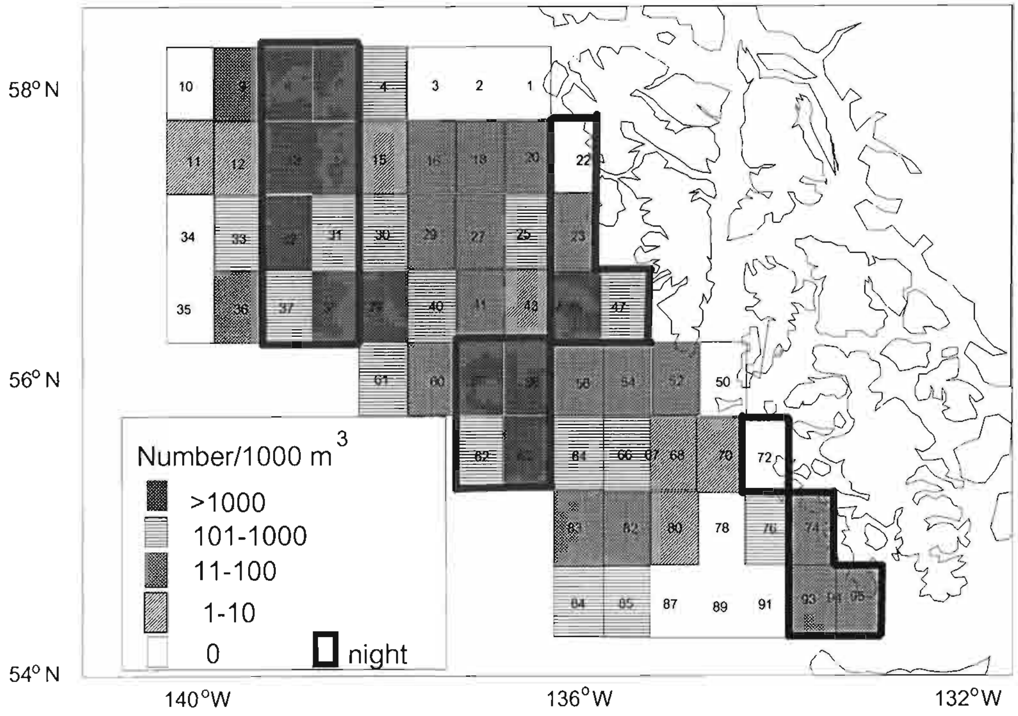

Figure 2

Distribution of sablefish larvae from Sameoto neuston-net tows at stations 1–95 in May 1990. Night stations are enclosed by heavy lines.

to 875 (mean 30.46) at 50 day stations, and 0 to 4,337 (mean 474.36) at 24 night stations (Table 2). Catches in May 1991 were lower at 18 day stations (0 to 12, mean 3.83) and at 8 night stations (0 to 964, mean 264.75; Table 3). In both years, sablefish larvae were most abundant seaward of the continental shelf, 100–120 km offshore (Fig. 2, 3). Except for these two May cruises, the number of stations occupied and the small number of sablefish larvae caught precluded rigorous statistical treatment.

Sablefish larvae were caught in oblique tows during only 3 of 10 cruises (Table 1). The July 1987 cruise yielded only two sablefish larvae from one station. Sablefish larvae were caught by oblique tows at 61%–63% of the stations in May 1990 and May 1991 (Fig. 4, 5). The average catch per positive station was 2.0 (maximum 51) in 1990 and 4.6 (maximum 46) in 1991.

Statistical Analyses

Spearman's rank correlation values for paired neuston and oblique-tow samples from 1990 (r_s=0.46) and 1991 (r_s=0.27) were not significant, indicating no correlation of the number of sablefish larvae per 1,000 m^3 caught by the two types of sampling gear (Fig. 6, 7). The presence or absence of sablefish larvae in the neuston samples did indicate presence or absence of sablefish larvae in the oblique samples for each of the two years 1990 (χ^2_{69}=35.37) and 1991 (χ^2_{23}=8.17, p<0.01).

A diel effect was noted in the neuston catches during both 1990 and 1991 (Fig. 8, 9). A suspected diel effect observed in the 1991, but not in the 1990 bongo net catches was not statistically verifiable. Theoretically, the oblique tow catches should not be affected by diel migration, but may be affected by net avoidance and visual cues. The smaller catches in daytime neuston tows may be due to visual net avoidance or to vertical migration below the fishing depth of the net (Shenker, 1988). The catch per area indicates that only about 1% of the larval fish were susceptible to the Sameoto neuston net during the day, while at night possibly more than 28% of the sablefish were in the neuston layer (Table 2, 3).

Mean length of sablefish larvae captured in day neuston tows of May 1990 was 13.5 mm (n=942, s=2.97) compared to mean length of 12.6 mm (n=2,927, s=2.40) from night tows.[2] The overall mean length was 12.8 mm (n=3,869, s=2.58). The mean length of sablefish larvae from day oblique tows was 9.8 mm (n=142, s=2.40) and from night oblique tows 10.3 mm (n=108, s=2.29).

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[2] Mean lengths of sablefish larvae at one neuston station occupied both day and night were 16.4 mm and 14.0 mm, respectively.

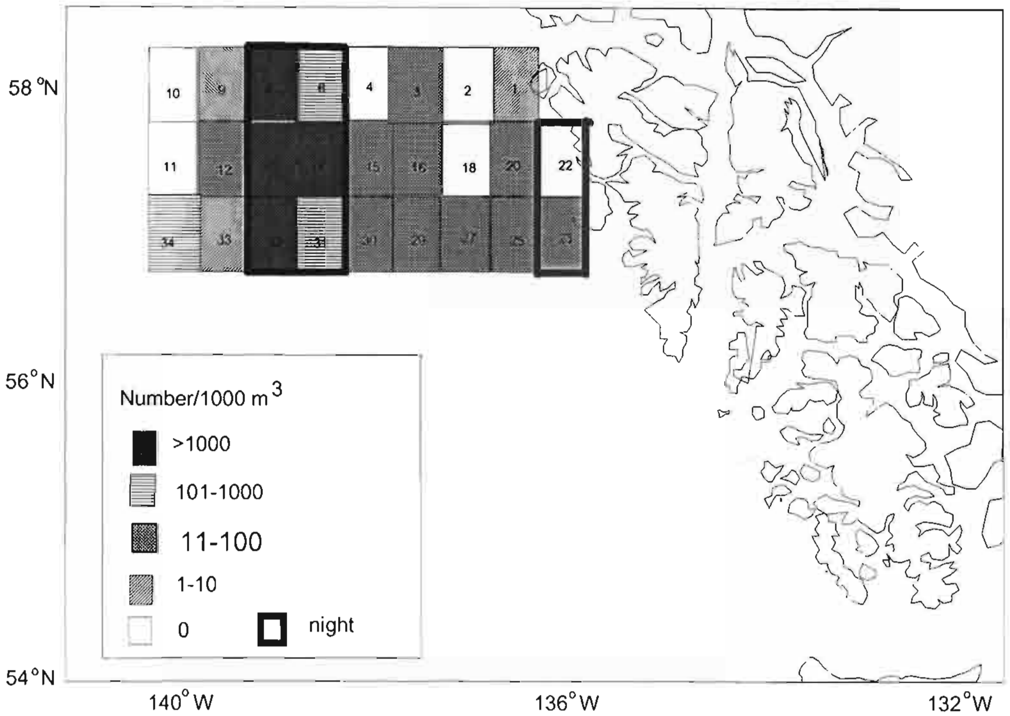

Figure 3
Distribution of sablefish larvae from Sameoto neuston-net tows at stations 1–34 in May 1991. Night stations are enclosed by heavy lines.

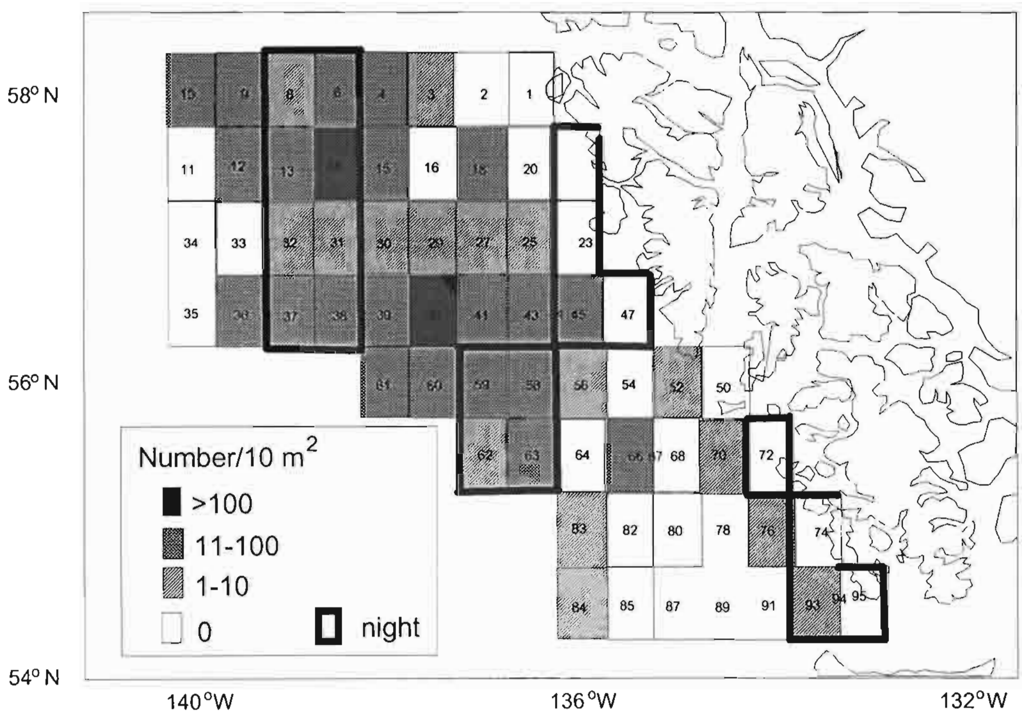

Figure 4
Distribution of sablefish larvae from oblique bongo-net tows at stations 1–95 in May 1990. Night stations are enclosed by heavy lines.

Length-frequency distributions show that the oblique tows are more biased toward capture of smaller larvae than the neuston tows, both day and night (Fig. 10).

Analyses of spatial distribution of larvae from neuston and oblique-tow samples were inconclusive before the data were transformed. Although there were sev-

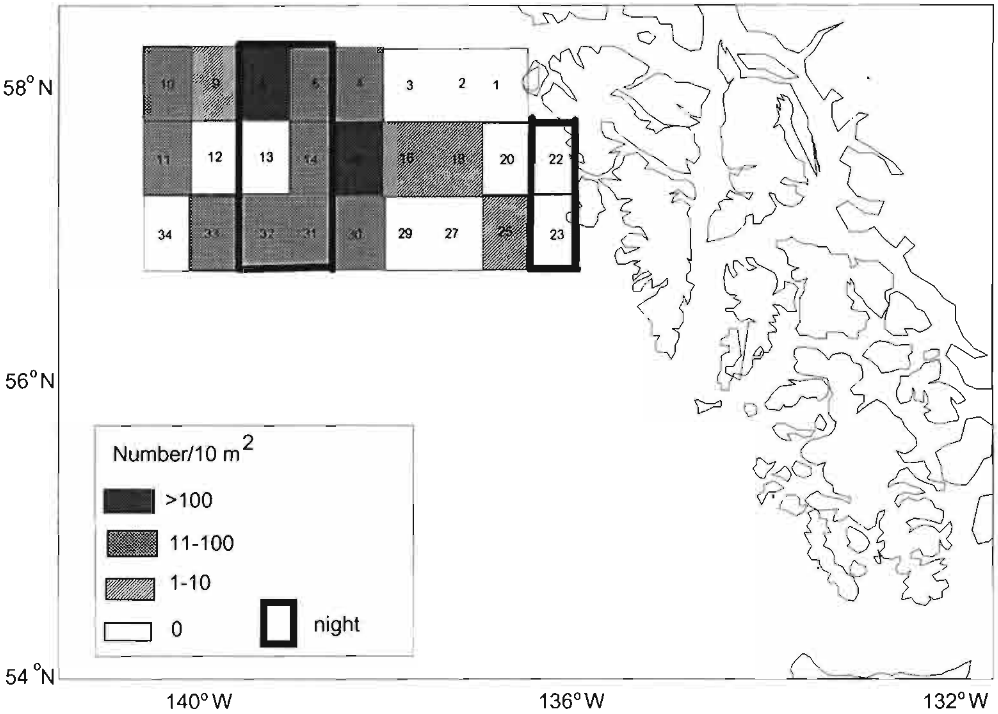

Figure 5
Distribution of sablefish larvae from oblique bongo-net tows at stations 1–34 in May 1991. Night stations are enclosed by heavy lines.

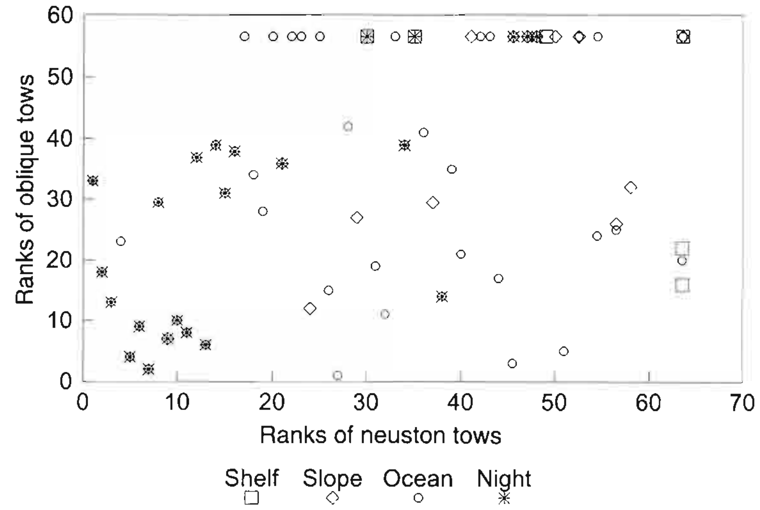

Figure 6
Graphic comparison of ranks of abundance of sablefish larvae used for calculation of Spearman's rank correlation coefficient (r_s) for paired neuston-net and oblique-tow samples, 1990.

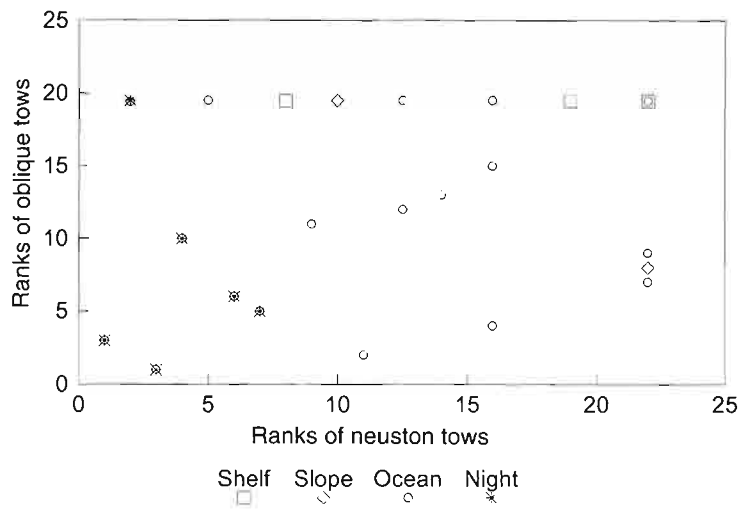

Figure 7
Graphic comparison of ranks of abundance of sablefish larvae used for calculation of Spearman's rank correlation coefficient (r_s) for paired neuston-net and oblique-tow samples, 1991.

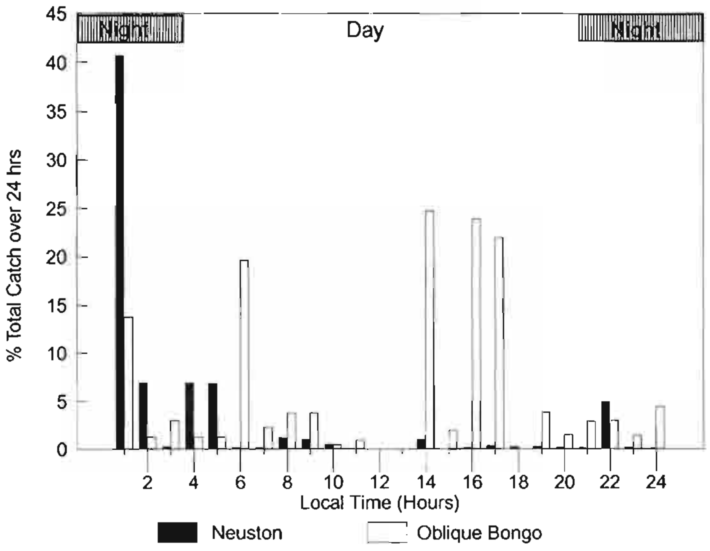

Figure 8
Diel variation of sablefish in neuston-net and oblique tows from 1990.

eral-fold differences in mean density among shelf, slope, and ocean strata (Fig. 11), a test of the sum of squared deviations from the expected mean was found insignificant at 5% by means of a randomization test (Edgington, 1987) on the untransformed data. This insignificance largely results from a small sample size and high variance of the neuston-tow catches. Following log transformation, a statistically significant area effect was observed in the 1990 catches (Table 4). The offshore concentration apparent in both neuston and oblique tows is confounded by the exceptionally large catches in some night samples. The consistently small catches in oblique tows and resultant lower variances give an impression of absence or rarity in nearshore waters (Fig. 4, 5). But the presence of small numbers of sablefish larvae in the nearshore neuston tows at night

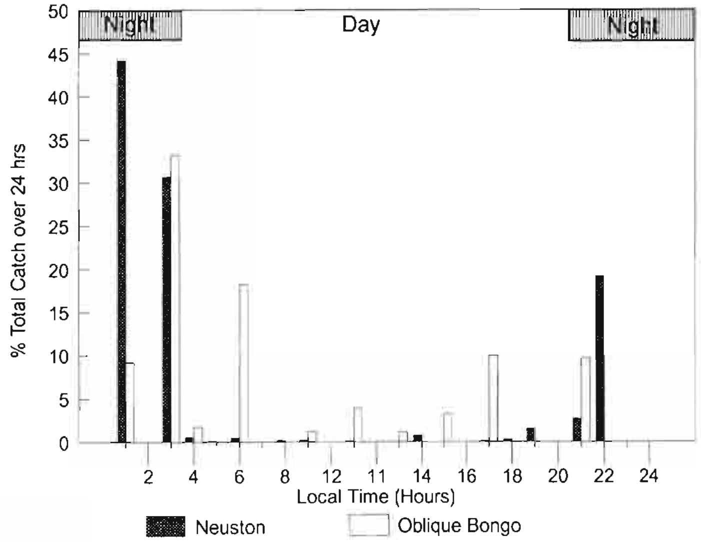

Figure 9

Diel variation of sablefish in neuston-net and oblique tows from 1991.

Table 4

Results of analysis of variance of differences in the distribution of sablefish larvae caught in neuston-net tows and oblique tows in May 1990. Neuston-net catch data are $\ln(n+1)$ for number per 1,000 m^2. Oblique-tow catch data are $\ln(n+1)$ for number per 10 m^2.

	Neuston tows				Oblique tows			
Variation	df	SS	MS	F[1]	df	SS	MS	F[1]
Mean	1	463.60	463.60		1	177.26	177.26	
Time	1	131.29	131.29	61.28^{**}	1	2.76	2.76	1.39^{ns}
Area	2	86.66	46.33	20.22^{**}	2	18.43	9.21	4.64^{*}
Time × area	2	31.73	15.86	7.40^{**}	2	9.51	4.75	2.40^{ns}
Error	67	143.53	2.14		63	14.94	0.22	
Total	73	847.44			69	29.64		

[1] ns = not significant; * = $P < 0.05$; ** = $P < 0.005$.

counters that conclusion, although it still indicates low abundance near shore, and ubiquitous but variable offshore distribution.

Discussion

The relatively high frequency of sablefish larvae in neuston-net tows, in contrast to the low frequency in oblique tows, results from several factors. First, the sablefish larvae are neustonic—that is, concentrated near the surface (Kendall and Matarese, 1987; Moser et al., 1994; Doyle[3]). Although there is evidence for diel migration (Doyle[3]), it is not likely that the larvae range far below the surface during daylight. Neuston tows are wholly within the larvae's habitat, whereas oblique tows to 200–300 m are mostly below the depth range of the neustonic larvae. Second, much of our oblique sampling before 1990 was limited to nearshore areas where the numbers of sablefish larvae were low in neuston nets (Fig. 11) and in oblique tows. Also, roughly half of

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[3] Doyle, M. J. 1992. Patterns in distribution and abundance of ichthyoplankton off Washington, Oregon, and northern California (1980–1987). AFSC Proc. Rep. 92-14, 344 p. Alaska Fish. Sci. Cent., NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070.

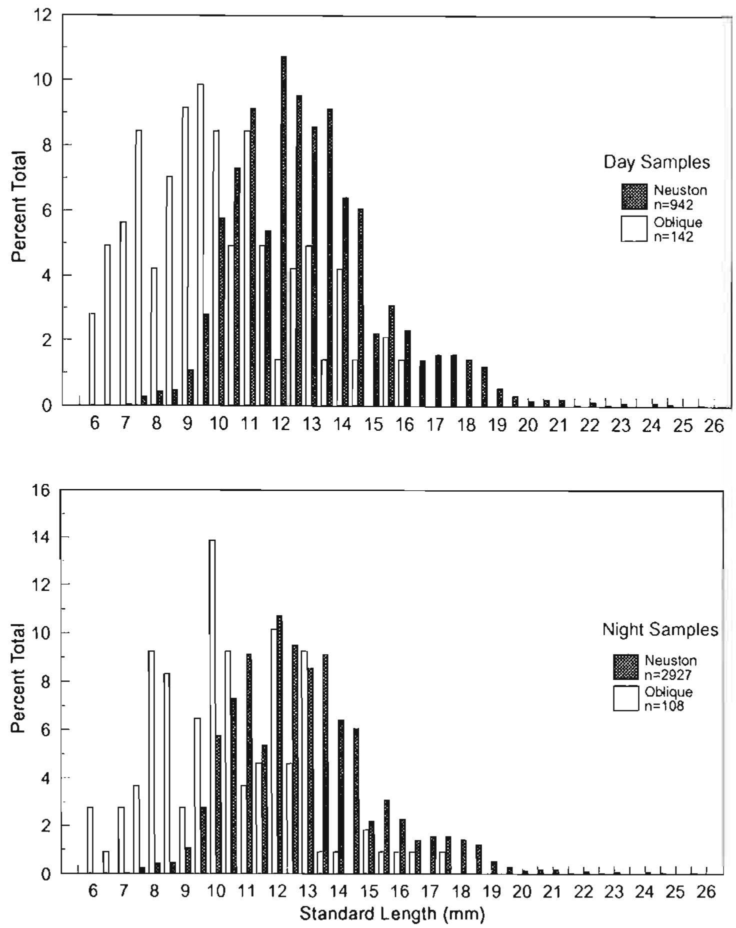

Figure 10
Length-frequency distributions of sablefish larvae taken during the day and night by oblique tows and neuston-net tows in May 1990.

our effort was made during seasonal periods when larvae may not have been present (January–March) or were present only in low numbers.

The high frequency of sablefish larvae in oblique tows during two cruises (May 1990 and May 1991) may be the result of sampling during peak seasonal abundance or during years of exceptional abundance. In both years, the actual catch per station was low in oblique tows compared to neuston tows. However, when standardized to number per 10 m^2, abundance estimates from the bongo tows are higher than from the neuston tows, indicating a large proportion of the sablefish larvae below the neuston layer.

The temporal distribution of sablefish larvae in both neuston and oblique tows indicates peak abundance and highest frequency of occurrence in May in the eastern Gulf of Alaska (Table 1). This continues the south-to-north trend of progressively later but higher abundance from California to British Columbia (Kendall and Matarese, 1987; Moser et al., 1994). Although there is some spawning in the eastern Gulf of Alaska as early as January (Kendall and Matarese, 1987; Wing, 1993), peak spawning appears to be in late February or early March (Wing, unpubl. data). The earliest neustonic larvae we collected in late April 1984 were 7–9 mm, larger than the smallest larvae (6–7 mm) collected in May 1990. Moser et al. (1994) propose a 14-day incubation period for sablefish eggs. McFarlane and Beamish (1992) hypothesize 20 days from hatching to half-yolk utilization at 6–8 mm, and 40 days to full yolk utilization when larvae >10 mm reach the surface waters. Boehlert and Yoklavich (1985) suggest that 25-mm larvae off the Oregon coast may be only 50 days old. Our smallest larvae (6 mm) may be from late March spawning; most larvae (8–13 mm) from mid-March spawning; and the largest (20–25 mm) from February or earlier spawning.

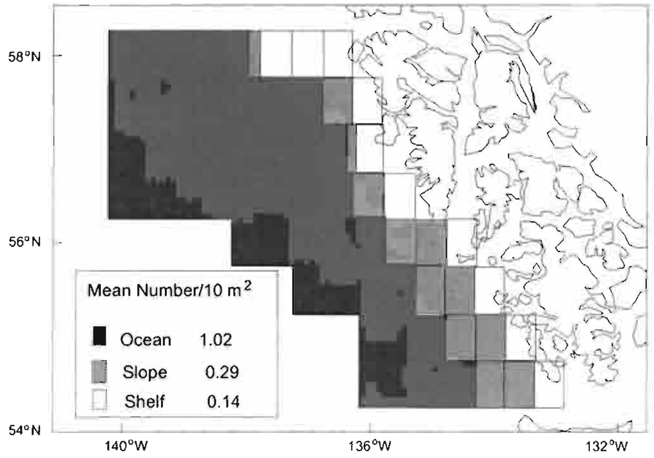

Figure 11
Mean distribution of sablefish larvae in shelf, slope, and ocean strata in 1990 neuston-net tows.

The vertical distribution of sablefish larvae in the eastern Gulf of Alaska has not been studied. Although we and others (Brock, 1940) have observed sablefish larvae at the surface in day and at night, we have no information on their abundance below the sampled 15–30 cm. How diel migration affects depth distribution below 15 cm was not determined because we occupied only one station where sablefish larvae were caught both day and night. The size distribution of larvae at that station may indicate that during the day the larger larvae are predominately in the top few centimeters of the water column. Future studies of sablefish larvae should determine their depth distribution, and emphasize sampling the neuston and near-surface layers of the water column. Although the diel depth range of sablefish larvae is not known, observations of sablefish larvae at the surface during both day and night, and the high frequency of catches in neuston tows indicate that it is probably no more than a few meters. Sampling methods, station locations, and schedules should be developed that overcome undersampling by oblique tows and biasing toward high or low abundance by day–night variance in neuston tows.

Continental shelf and offshore waters in the Alaska Gyre should be included in studies of the distribution and abundance of sablefish larvae. We need to know how and when sablefish larvae or early juveniles reach nearshore nursery areas. For instance, are they passively carried onto the shelf by the general summer downwelling of the eastern Gulf of Alaska and by irregular events such as the Sitka Eddy, or do they actively seek nearshore habitats by directed migration?

How oceanographic variables, especially the seasonally and annually variable currents of the eastern Gulf of Alaska (Fig. 12), affect growth and survival of sablefish larvae is unknown. This study has shown that sablefish larvae are most numerous beyond the continental shelf at the edge of the Alaska Gyre in May. The larvae may have been transported offshore from the continental-slope spawning areas by the Haida Current, Sitka Eddy, or perhaps by coastal upwelling (Wing, 1993; Wing and Kamikawa, 1995). What portion of the offshore larvae survive, and how they reach the inshore waters in summer and fall are unknown. The Sitka Eddy may transport larvae and juveniles from the offshore areas to northern southeast Alaska, but cannot account for other areas. The Alaska Coastal Jet, confined to the continental shelf and within 5–10 km of the coast, probably does not have a large effect on distribution of eggs and larvae, but may affect the distribution of juveniles as they seek inshore nursery areas.

Future efforts directed specifically toward sablefish larvae will require efficient survey designs with specified sampling depths, times, and areas. These surveys should be coordinated with physical and biological oceanographic studies of the currents in the eastern Gulf of Alaska.

Acknowledgments

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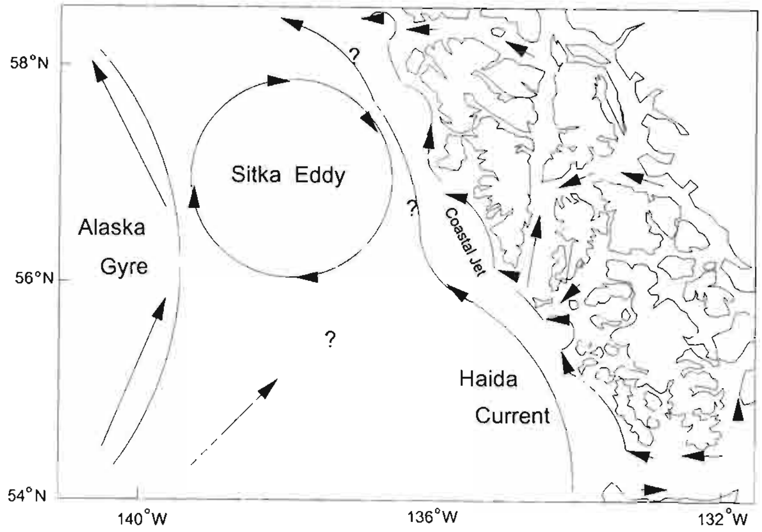

Figure 12
Hypothetical circulation in the eastern Gulf of Alaska, showing the Alaska Gyre, Haida Current, Sitka Eddy, and Coastal Jet based on Favorite et al. (1976), Royer (1983), Tabata (1982), Thomson and Emery (1986), and Wing (1993).

Literature Cited

Ahlstrom, E. H., and E. Stevens.
1976. Report of neuston (surface) collections made on an extended CalCOFI cruise during May 1972. Calif. Coop. Oceanic Fish. Invest. Rep. 18:167–180.

Barnes, H.
1952. The use of transformations in marine biological statistics. J. Cons. Int. Explor. Mer 18(1):61–71.

Boehlert, G. W., and M. M. Yoklavich.
1985. Larval and juvenile growth of sablefish, *Anoplopoma fimbria*, as determined from otolith increments. Fish. Bull. 83:475–481.

Brock, V. E.
1940. Note on the young of the sablefish, *Anoplopoma fimbria*. Copeia 1940:268–270.

Cooney, R. T.
1987. Zooplankton. *In* D. W. Hood and S. T. Zimmerman (eds.), The Gulf of Alaska: physical environment and biological resources, p. 285–303. U.S. Gov. Printing Office, Washington, D.C.

Edgington, E. S.
1987. Randomization tests, 2nd ed. Marcel Dekker, New York, 341 p.

Favorite, F., A. J. Dodimead, and K. Nasu.
1976. Oceanography of the subarctic Pacific region, 1960–71. Int. North Pac. Fish. Comm. Bull. 33, 187 p.

Kendall, A. W., Jr., and A. C. Matarese.
1987. Biology of eggs, larvae, and epipelagic juveniles of sablefish, *Anoplopoma fimbria*, in relation to their potential use in management. Mar. Fish. Rev. 49:1–13.

Kendall, A. W., Jr., and S. J. Picquelle.
1990. Egg and larval distributions of walleye pollock *Theragra chalcogramma* in Shelikof Strait, Gulf of Alaska. Fish. Bull. 88:133–154.

Mason, J. C., R. J. Beamish, and G. A. McFarlane.
1983. Sexual maturity, fecundity, spawning, and early life history of sablefish (*Anoplopoma fimbria*) of the Pacific coast of Canada. Can. J. Fish. Aquat. Sci. 40:2,126–2,134.

Mattson, C. R., and B. L. Wing.
1978. Ichthyoplankton composition and plankton volumes from inland coastal waters of Southeastern Alaska, April–November 1972. U.S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF-723, 11 p.

McFarlane, G. A., and R. J. Beamish.
1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 49:743–753.

Moser, H. G., R. L. Charter, P. E. Smith, N. C. H. Lo, D. A. Ambrose, C. A. Meyer, E. M. Sandknop, and W. Watson.
1994. Early life history of sablefish, *Anoplopoma fimbria*, off Washington, Oregon, and California with application to biomass estimation. Calif. Coop. Oceanic Fish. Invest. Rep. 35:144–159.

Posgay, J. A., and R. R. Marak.
1980. The MARMAP bongo zooplankton samplers. J. Northwest Atl. Fish. Sci. 1:91–99.

Royer, T.
1983. Observations of the Alaska Coastal Current. *In* H. Gade, A. Edwards, and H. Svendeen (eds.), Coastal oceanography, p. 9–30. Plenum, New York.

Sameoto, D. D., and L. O. Jaroszynski.
1969. Otter surface sampler: a new neuston net. J. Fish. Res. Board Can. 26:2,240–2,244.

Shenker, J. M.
1988. Oceanographic associations of neustonic larval and juvenile fishes and Dungeness crab megalopae off Oregon. Fish Bull. 86:299–317.

Smith, P. E., and S. Richardson.
1977. Standard techniques for pelagic fish and larval surveys. FAO Fish. Tech. Pap. 175, 100 p.

Tabata, S.
1982. The anticyclonic, baroclinic eddy off Sitka, Alaska, in the northeast Pacific Ocean. J. Phys. Oceanogr. 12:1,260–1,282.
Thomson, R. E., and W. J. Emery.
1986. The Haida Current. J. Geophys. Res. 91(C1):845–861.
Wing, B. L.
1993. Winter oceanographic conditions in the eastern Gulf of Alaska, January–February 1986. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-8, 53 p.
Wing, B. L., and D. J. Kamikawa.
1995. Distribution of neustonic sablefish larvae and associated ichthyoplankton in the eastern Gulf of Alaska, May 1990. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-53, 55 p.
Wing, B. L., and G. M. Reid.
1972. Surface zooplankton from Auke Bay and vicinity, Southeastern Alaska, August 1962 to January 1964. U.S. Dep. Commer., NOAA Data Rep. NMFS-72, 765 p.

Distribution and Abundance of Larval Sablefish, *Anoplopoma fimbria*, off the West Coast of Vancouver Island, and Linkages to Physical Oceanography

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ABSTRACT

The distribution and abundance of larval sablefish in the surface waters off the west coast of Vancouver Island were surveyed each April from 1984 to 1989 with a neuston sampler. Oceanographic conditions were monitored concurrently with a CTD. The distribution of sablefish varied considerably among years and areas. Centers of abundance were typically found off the shelf (300–1,000-m depth) in the La Perouse and Brooks Peninsula areas. In some years larval fish were found on the shelf. Examination of distribution in relation to geostrophic currents indicated that sablefish larvae were most abundant in areas where mean currents were weakest, allowing larvae to accumulate. After the spring transition, the prevailing current patterns inhibit the onshore transport of near-surface larvae but may enhance the onshore transport of deep (>200 m) larvae. This suggests that the distribution of larvae in the water column at the onset of upwelling-favorable conditions in spring determines the region of greatest larval aggregation. An index has been developed to relate abundance of larvae to the subsequent recruitment of adults.

Introduction

Understanding recruitment variation is one of the most important aspects of fisheries science. McFarlane and Beamish (1986, 1992) examined the relation between the environment and production of strong year classes of sablefish, *Anoplopoma fimbria*. They incorporated information on larval development, salinity of neutral buoyancy, and ocean temperature at depth into an interactive model and estimated development times at depth in the open ocean. From a spawning depth assumed to be approximately 300–500 m in continental slope waters with a bottom depth >1,000 m, the eggs rose to between 200 and 300 m immediately after fertilization (McFarlane and Nagata, 1988). They remained suspended at this depth until approximately 24 h before hatching (12 d at 6°C). At this time, egg density increased and the eggs sank. The newly hatched larvae became denser and continued sinking in the water column during early development (approximately 6 or 7 d), reaching a maximum depth between 1,000 and 1,200 m. When the yolk sac had been approximately half used, the mouth became functional and the larvae began swimming movements. Larvae began to ingest small food organisms within 2–3 d (approximately 20 d after hatching) and moved up in the water column, presumably following copepod nauplii. By the time the yolk sac had been fully depleted (approximately 40 d after hatching) larvae were in the surface waters at or seaward of the shelf break (200-m depth contour). McFarlane and Beamish (1992) concluded that favorable climatic and oceanographic conditions increase the amount of food available for sablefish larvae (at depth), resulting in production of a strong year class throughout the North Pacific. When environmental conditions are favorable, all other factors affecting year-class success are overridden, and year-class strength is determined before larval sablefish reach surface waters. McFarlane and Beamish also suggested that during most years, year-class variation in localized areas could depend, in part, on favorable physical oceanographic conditions, specifically, ocean circulation.

In this study, we present an analysis of the distribution of sablefish larvae in spring in relation to physical oceanography for one such area—the west coast of Vancouver Island—and develop an index of relative abundance of larvae in surface waters as an indicator of year-class success.

The west coast of Vancouver Island lies at the northern extent of the Coastal Upwelling Domain (Fig. 1), which extends along the west coast of North America from Baja California to Queen Charlotte Sound (Ware and McFarlane, 1989). The region supports large fisheries for groundfish, herring, and salmon.

Although complicated by variability on a wide range of time and space scales, the current pattern off the west coast of Vancouver Island has several salient features of particular relevance to the distribution and abundance of sablefish larvae. Thomson et al. (1989) report that the circulation along the coast has a strong seasonal cycle characterized by marked changes in flow direction and intensity throughout the year. In winter, currents over the entire continental margin flow to the northwest in response to strong southeasterly winds and a peak in freshwater runoff along the outer coast. These downwelling-favorable wind and current conditions persist from about December through February, and northerly flow prevails throughout the water column. By summer (June through August), currents in the upper few hundred meters of the water column have reversed direction along the outer shelf and slope but continue to flow in a northwesterly direction along the inner shelf. Currents at depth generally continue to flow northward. Reversal of the upper-layer currents along the outer shelf in summer accompanies the onset of upwelling-favorable northwesterly winds along the coast. The persistent northward flow along the inner shelf is linked to low-density surface water which exits Juan de Fuca Strait in summer.

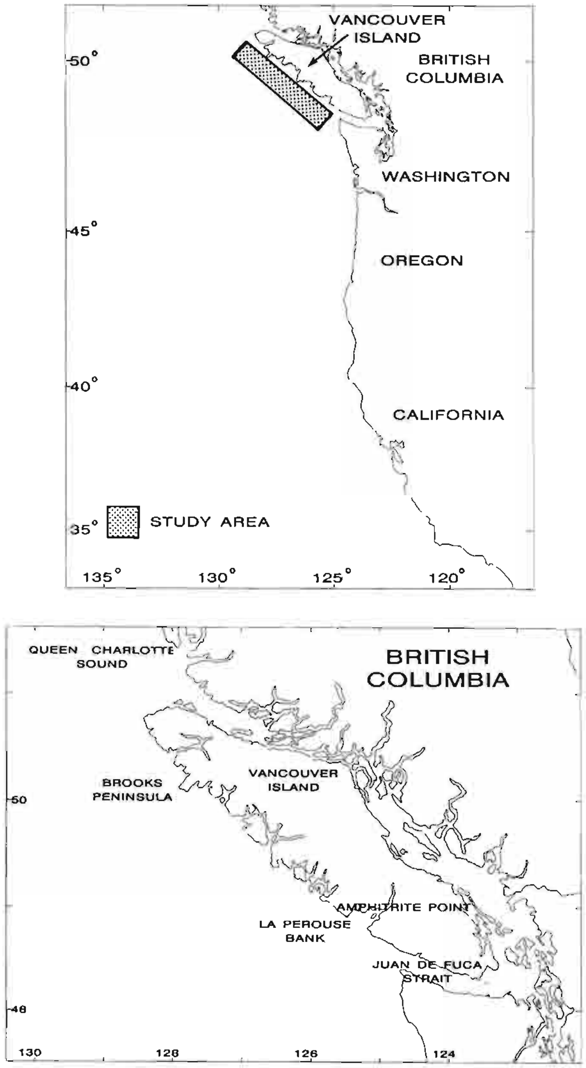

Figure 1

Top, Study area off the west coast of Vancouver Island, at the northern terminus of the Coastal Upwelling Domain identified by Ware and McFarlane (1989). Bottom, Study area showing place names referred to in the text.

Spring (March through May) marks a confused transition between winter downwelling-favorable oceanic conditions and summer upwelling-favorable conditions. During this transition, the near-homogeneous upper ocean (0–100-m depth) begins to stratify as solar heating increases and vertical wind mixing and convective overturning diminish. Stratification of the upper ocean is accompanied by highly variable winds and surface currents along the outer coast. Upwelling and downwelling conditions can exist alternately for brief periods of several days, but no persistent flow pattern is established. A somewhat less complex transition from summer to winter oceanic conditions takes place in fall (September through November).

Seasonal flow conditions can have an important effect on the transport of sablefish larvae. For example, during downwelling conditions, larvae in near-surface waters over the continental margin may be advected toward the coast with the prevailing onshore Ekman transport. The reverse occurs during upwelling conditions, when larvae in the near-surface waters are more likely to be transported seaward with the prevailing offshore Ekman transport. The situation is not the same for larvae that enter the coastal regime at depth (>200 m) during times of persistent upwelling. Then onshore flow in the lower layer of the water column can bring deeper water and associated larvae onto the shelf, for example, through Juan de Fuca Canyon and other canyons that cut across the continental slope on the southwest coast.

Materials and Methods

Sampling Methods

Larval fish were collected during six April surveys conducted annually from 1984 to 1989. Sampling stations were located on eight tracklines normal to the coastline (Fig. 2). Tracklines ranged from 27 to 67 km apart; stations on a trackline ranged from 2 to 38 km apart. Stations on tracklines extended from 4 to 190 km offshore and covered a north–south distance of approximately 240 km.

Surface samples were taken at night with a modified Sameoto sampler—a neuston sampler equipped with a flowmeter (Sameoto and Jaroszynski, 1969). During 1984, 1985, and 1986, surface samples also were taken at selected stations during daylight. The sampler was 45 cm high × 45 cm wide with a 500-µm mesh Nitex net. The codend was PVC with a 351-µm stainless steel mesh window. At each station, two 15-minute tows were made at a speed of 3 knots. The recovered nets were thoroughly washed, and the catch was preserved in 5% buffered formaldehyde.

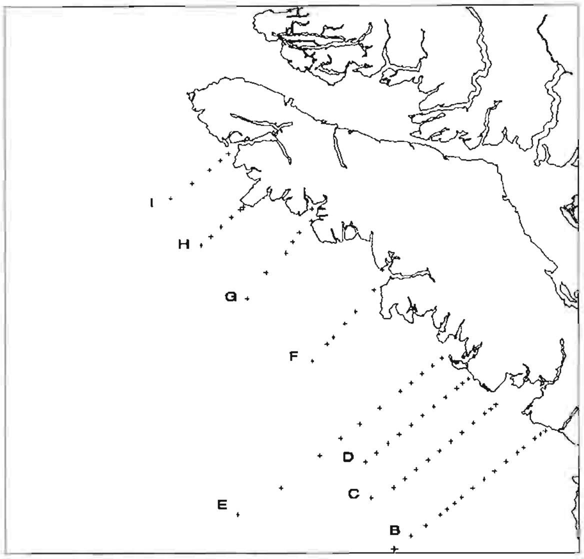

Figure 2
Survey tracklines and sampling stations (+). Stations on each trackline are numbered consecutively from shore seaward.

Physical oceanographic data were collected at selected stations on all tracklines during each cruise. All oceanographic stations occupied on tracklines corresponded with the positions of surface neuston and vertical plankton haul stations. Additional oceanographic stations were occupied in the vicinity of the trackline off Brooks Peninsula. An Applied Microsystems STD-12[1] was used to measure temperature and salinity as a function of depth at each station. These data were used to calculate sigma-t, specific volume anomaly, and dynamic height. STD casts were made to 10 m from the seafloor or to a maximum depth of 500 m, whichever was shallower.

Laboratory Processing and Analysis

Preserved samples from each tow were individually sorted. All sablefish larvae were counted and measured. Sablefish larvae longer than 15 mm were measured for fork length (mm), since bifurcation in the tail fin was becoming noticeable; larvae 15 mm and smaller were measured for total length (mm). In this report all measurements are referred to as fork length. All larvae were preserved in 70% isopropanol.

Relative abundance (R), expressed as number of larvae per 1,000 m^3, was estimated in the following manner:

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

$$R = \frac{N}{(D \times A)} \times 1{,}000$$

where A = mouth area of the neuston net (0.203 m^2) and N = number of larvae per tow, and

$$D = \frac{(T_2 - T_1) \times F_c}{999{,}999}$$

where D = distance the net traveled, T_1 and T_2 are the flowmeter counts recorded at the start and end of a tow, respectively; and F_c is the ratio constant of the flowmeter.

Digital temperature and salinity profiles were recorded internally at several scans per second by the STD-12, with absolute accuracies of 0.01°C and 0.01 ppt. Before analysis, the data were edited with an interactive procedure in which profiles can be displayed and modified on a computer screen. Obvious spikes and other erroneous data were systematically replaced with interpolated values, and the profile data were converted to 1-m-averaged files. Most discarded data points were located in the upper portion of the cast, where temperature and salinity gradients are largest. Failure to allow time for the sensors to equilibrate upon entering the water was a further source of near-surface data errors. We used the corrected data to derive oceanic parameters such as density and geopotential anomaly by means of standard international computer algorithms (Fofonoff and Millard, 1983).

Three indices of larval abundance were calculated to examine interannual variation in year-class strength. The indices included 1) annual mean abundance of sablefish larvae (# of larvae/1,000 m^3) for all stations off the west coast of Vancouver Island combined; 2) annual mean abundance of larvae for stations occupied in shelf areas south of and including line E; and 3) annual mean abundance of larvae for stations occupied in slope areas south of and including line E. Stations with bottom depths less than or equal to 200 m were coded as shelf, and stations with bottom depths greater than 200 m were coded as slope.

Results and Discussion

Approximately 40 stations were fished at night during April to early May in 1984 and 1985; from 1986 to 1989 approximately 70 stations located on eight tracklines (Fig. 2) were occupied (Table 1). In 1984, 6 stations were occupied between tracklines; in 1985, 4 stations (Fig. 3A, B). In 1984, trackline H, and in 1985, tracklines H and I were not occupied due to search-and-rescue operations by the survey vessel. From 1984 to 1986, between 10 and 15 stations were reoccupied during daylight hours. Detailed data records for each cruise are presented in Shaw et al. (1985, 1987, 1988) for 1984, 1985, and 1986. Data for 1987–89 cruises are included in the biological database at the Pacific Biological Station (McFarlane, unpubl. data). The catch rates of larvae during daylight hours were significantly lower than night catch rates (Shaw et al., 1985, 1987); most sablefish larvae were captured in night tows. We have therefore confined this analysis to nighttime survey results.

Table 1

Cruise dates for larval surveys conducted off the west coast of Vancouver Island, 1984–89.

Year	Dates
1984	April 17–May 5
1985	April 10–17
1986	April 3–16
1987	April 22–May 3
1988	April 6–17
1989	April 6–20

Larval Distribution

The relative abundance of sablefish larvae in surface waters off the west coast of Vancouver Island varied considerably among surveys, both alongshore and in relation to the shelf break (inshore/offshore waters; Fig. 3). In 1984, larvae were distributed along the entire west coast of Vancouver Island. On the northern transects, larvae were concentrated seaward of the shelf break. Larvae were relatively abundant along every transect in the south. In contrast, during 1985, 1986, and 1989 most larvae were captured on the southern transects; in 1987 and 1988 there were also concentrations along the northernmost transects. During 1985, 1987, and 1989 larvae were concentrated offshore along the southern transects, and in 1986 and 1988 there were large concentrations over the shelf (inshore) waters.

Larval Distribution in Relation to Oceanographic Features

In a previous analysis Perry and McFarlane (1992) examined the relation between larval fish assemblages, the geopotential anomaly, and the density anomaly (sigma-t) across the continental shelf off southwestern Vancouver Island. They found a significant relation between species composition and abundance and the

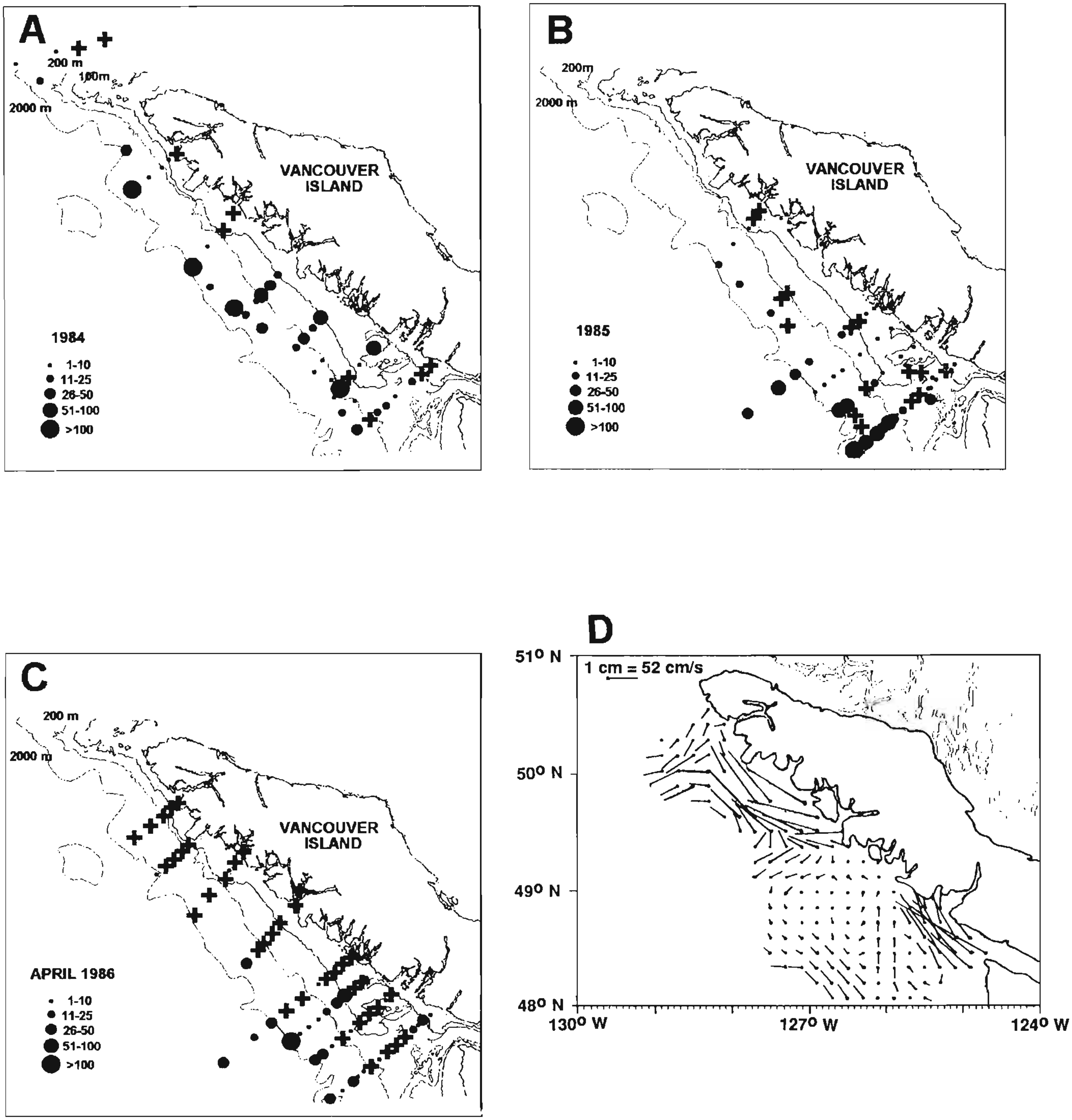

Figure 3

(A–C, E, G, I) Distribution and relative abundance of sablefish larvae off the west coast of Vancouver Island, 1984–89. Units are no./1,000m^2; + indicates stations where no larvae were captured. (D, F, H, J) Surface currents (calculated) for survey area during annual April surveys, 1986–89.

occurrence of marked horizontal density gradients associated with the coastal current. We examined this relationship for sablefish larvae on southern (tracklines C + D) and northern (trackline H) transects (Fig. 4). Horizontal surface-density gradients derived from density at 10-m depth appear related to relative abundances of larvae. For example, in years and areas when the gradient is strong and displaced seaward (as indicated by the location of the 24.0 sigma-t isopycnal), the relative abundance of larvae is lower. This change in gradi-

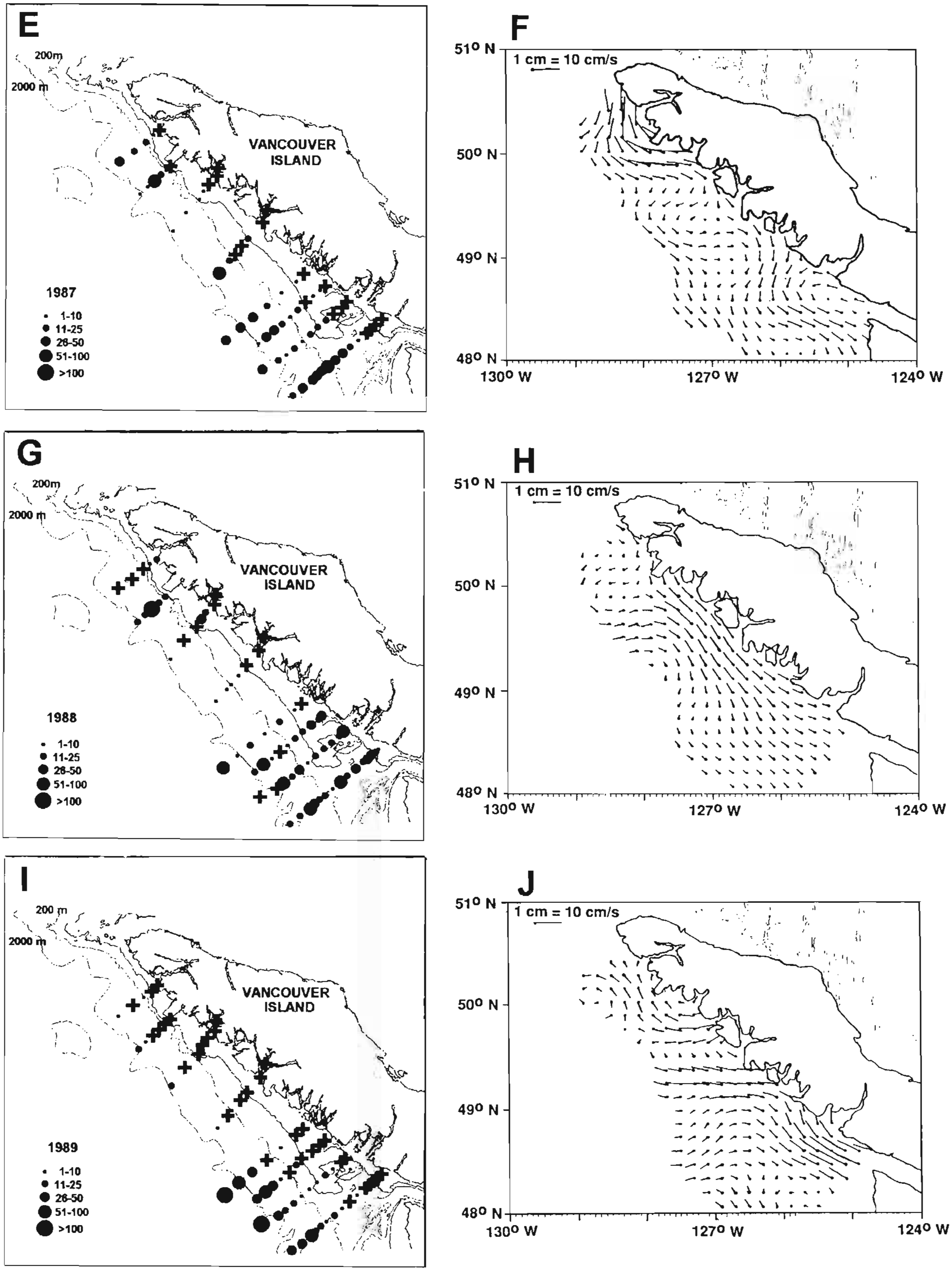

Figure 3 (continued)

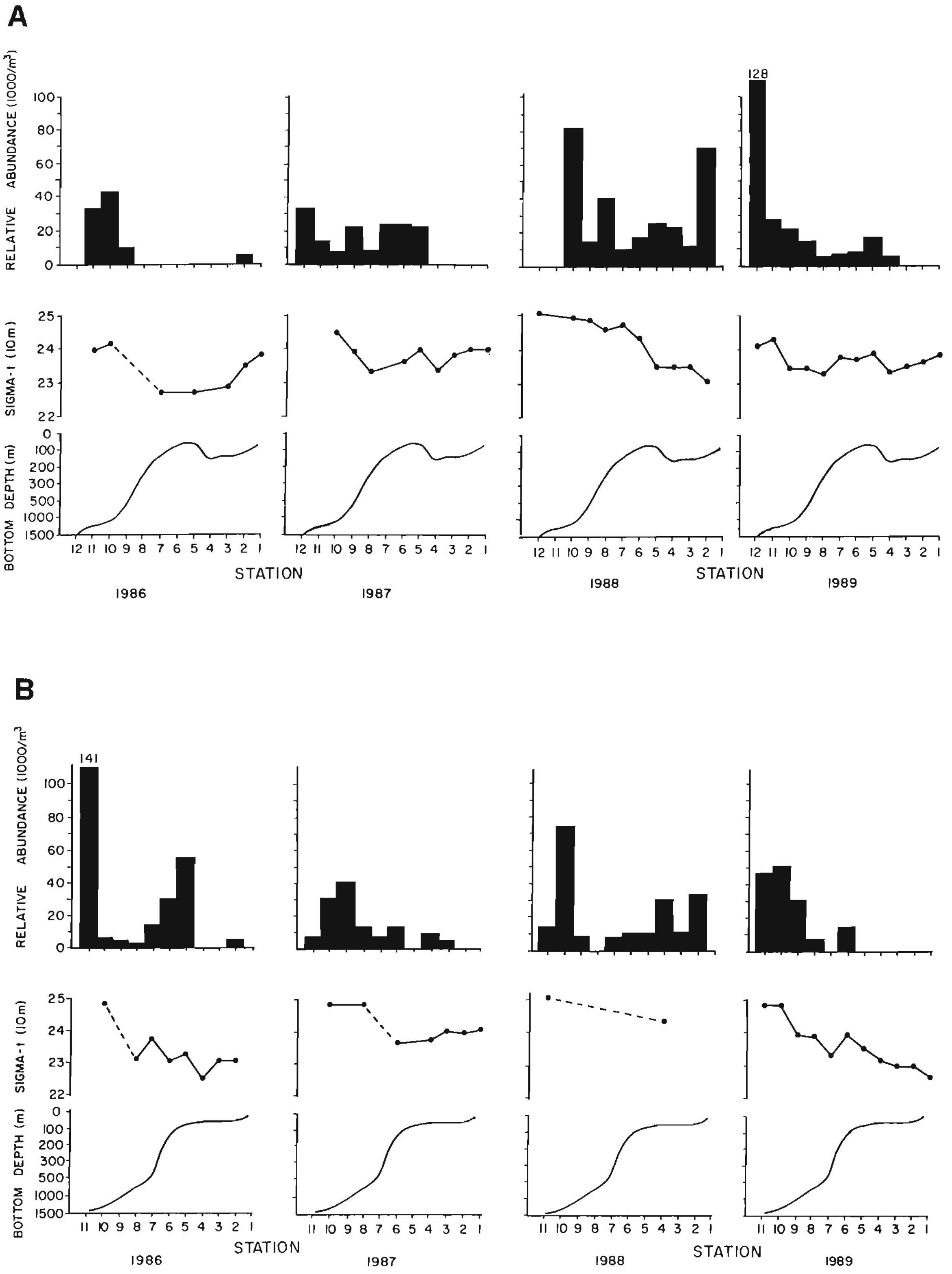

Figure 4

Cross-shelf sections along (A) trackline C and (B) D for 1986–89, and (C) trackline H for 1987–89. Top, abundance of sablefish larvae (no./1,000 m^3) at each station; middle, surface density (sigma-t at 10 m); bottom, bottom profile along each trackline.

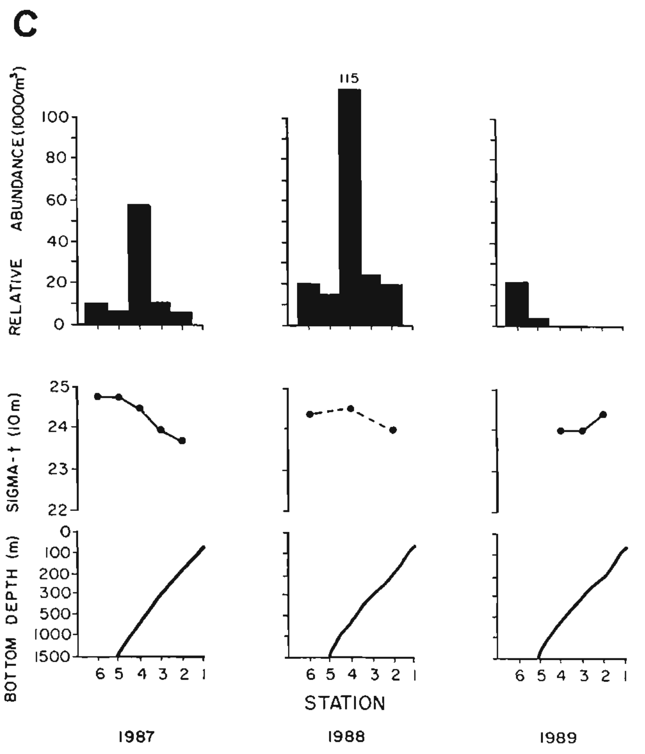

Figure 4 (continued)

ent reflects the area, intensity, and extent of the coastal current.

We then examined larval distribution in relation to surface currents for 1986 to 1989 (years for which surface-current data were available). In general, distribution of larvae off the west coast of Vancouver Island appears related to the position and intensity of two major components of the circulation—components which tend to be most variable during spring and fall transitions: 1) the wind-driven shelf-break current which flows parallel to the coast with core speeds centered over the upper portion of the continental slope seaward of the shelf break (200-m depth contour); and 2) the runoff-driven northward-flowing coastal current which hugs the inner 20 to 30 km of the shelf (Thomson et al., 1989).

Larval distribution also appeared to depend on the size, and presumably age, of the larvae. For example, in 1988 (Fig. 3G, H) the northward-flowing coastal current was weak. In the southern area, currents were less than 5 m/sec in offshore slope waters and extended over the shelf break to nearshore areas. Larvae in these nearshore shelf areas were larger (≈15 mm) and presumably older than those over slope waters (≈12 mm; Table 2), indicating that as larvae first reached surface waters over the slope spawning areas they were able to move inshore and remain in these areas of relatively weak currents. In the northern area, off Brooks Peninsula, currents were very weak (<2 m/sec), and a weak gyre was present. Larvae were smaller (≈12 mm) and also accumulated where currents were weakest, off the tip of Brooks Peninsula.

In contrast, during 1989 a stronger coastal current persisted out to the shelf break in southern areas (Fig 3J), where the geostrophic flow slowed considerably and appeared to form a weak gyre. In this area, larvae were abundant and exhibited a broad size range (Table 2), indicating that as they reached surface waters they remained in this area where currents were weaker. In the northern area, currents flowed southward. The southward- and northward-flowing currents met off central Vancouver Island and flowed seaward. Few larvae were captured in the northern area, and no larvae were captured in the seaward-flowing currents.

In 1987, the cruise took place later. Currents were weak off the shelf, and there was a weak, meandering, northward-flowing coastal current (Fig. 3F). Larvae at this time were much larger in all areas (16 to 22 mm) and were distributed more broadly along the coast.

In 1986, few larvae were captured in northern areas, where currents were the strongest recorded in this study (Fig. 3C, D). In the southern area, currents were strong

Table 2

Mean length of larval sablefish by transect line on the west coast of Vancouver Island, 1984–89. Dashes indicate no data were available.

		Northern							Southern					
		<200 m			>200 m				<200 m			>200 m		
Yr	Line	Mean	SD	*N*	Mean	SD	*N*	Line	Mean	SD	*N*	Mean	SD	*N*
1984	F	15.7	4.3	60	18.3	5.1	29	B	15.9	3.1	24	19.3	5.7	11
	G	—	—	—	15.6	3.6	122	C	16.4	3.4	59	—	—	—
	I	17.4	4.0	9	19.1	3.6	74	D	—	—	—	19.6	9.3	5
								E	19.9	8.5	38	22.1	7.5	11
1985	F	—	—	—	16.9	3.0	8	B	13.3	2.9	11	14.6	3.0	325
	G	16.0	1.2	5	—	—	—	C	13.2	4.1	25	14.6	3.2	118
								D	14.4	3.1	5	16.8	3.6	12
								E	18.4	3.4	8	14.8	2.6	72
1986	F	—	—	—	13.8	1.5	11	B	16.4	4.3	27	13.6	3.2	48
	G	18.0	0.0	1	—	—	—	C	13.6	3.9	5	12.1	4.4	23
	H	—	—	—	12.0	0.0	1	D	13.0	4.1	25	10.1	2.8	71
								E	17.0	—	1	13.3	2.9	38
1987	F	15.6	2.7	17	15.4	3.3	43	B	19.1	5.7	105	21.3	6.0	262
	G	16.5	3.9	6	18.4	3.2	8	C	21.7	4.2	34	19.2	6.4	36
	H	15.7	5.0	7	17.4	4.8	29	D	20.3	3.6	12	20.0	5.4	56
	I	15.9	4.6	15	16.2	3.4	36	E	19.7	2.9	7	19.7	4.4	83
1988	F	12.7	2.9	3	13.3	2.0	8	B	13.1	3.4	140	13.1	2.1	213
	G	10.8	4.9	5	11.0	0.0	1	C	14.1	2.7	54	11.9	2.0	87
	H	12.3	2.1	14	11.0	2.0	46	D	16.2	3.5	47	11.7	2.4	54
	I	10.2	0.8	6	—	—	—	E	12.8	1.0	4	12.7	1.4	35
1989	F	20.0	0.0	1	10.8	3.6	12	B	13.8	6.0	21	14.2	3.9	190
	G	—	—	—	9.0	0.0	2	C	17.3	2.9	15	12.8	4.0	124
	H	—	—	—	10.7	1.8	12	D	16.3	1.6	9	16.0	3.1	76
	I	12.0	0.0	1	11.0	1.3	6	E	14.3	4.1	4	12.9	3.6	193

but much weaker than in the northern area, and formed a gyre encompassing both shelf and slope waters (Fig. 3D). Larval abundance was the lowest of all survey years, and larvae were most abundant where currents were weakest.

Influence of Spring Transition

As indicated in Figure 5, all surveys were conducted during, or just after, the spring transition. The transition period plotted in this figure is derived from current-meter data collected at a mooring station in 500 m of water over the continental slope seaward of the La Perouse Bank region (Ware and Thomson[2]). Estimates of the duration of the spring transition for each year are based on the observed ending of the persistent downwelling period (winter) and the start of the persistent upwelling period at this location. This estimate considers the direction of the surface flow within the shelf-break current and also its gradient with depth. According to this current-derived index, there is considerable year-to-year variability in the timing and duration of the spring transition. The timing of the transition period and the subsequent strength of the upwelling regime influence the presence and intensity of the shelf-break current, whereas wind and runoff affect the intensity of the coastal current. These two factors, we believe, influence the distribution of sablefish larvae.

The cross-shelf larval distributions integrate events that occur days to weeks before the survey. Previous studies (Boehlert and Yoklavich, 1985) reported that larvae of the sizes we collected have been in surface waters for 2 to 4 weeks. There is a relation between persistent upwelling winds and increasing coastal salinity at Amphitrite Point at the mouth of Barkley Sound.

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[2] Ware, D. M., and R. E. Thomson. 1992. La Perouse Project: eigth annual progress report. Pacific Biological Station, Nanaimo, B.C., Canada V9R 5K6, 74 p.

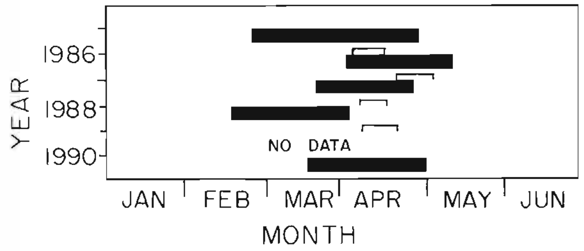

Figure 5
Seasonal timing of spring transition period for 1985–90 (black bar) derived from current-meter data collected at a mooring station (500-m depth) located on continental slope waters. Time period of annual April surveys (⊓), 1986–89.

This relation can be used to indicate the influence of upwelling winds prior to the surveys. An examination of coastal salinity at Amphitrite Point (Fig. 6) suggests that upwelling began before the 1987 survey, after the 1988 survey (the year of maximum larval sablefish concentration over the inner shelf), and during the 1989 survey.

These results contrast with the current-based oceanic index, which suggests that upwelling had just begun during the 1987 survey but was under way by the time of the 1988 survey (Fig. 5). Some of these differences may involve variability in wind direction and the time required to fully establish the summer (upwelling) circulation pattern at the shelf break, the intensity of freshwater facing of the coastal current, and the surface runoff pattern in Barkley Sound. When increased coastal salinity is used as the index, it appears that 1988 was an anomalous year for larval concentrations on the shelf, possibly because of onshore upper-layer transport associated with prevailing downwelling conditions and reduced flow in the runoff-driven coastal current. However, the current-based oceanic index indicates that larvae may have been deeper in the water column in 1988 at the time of the early-onset coastal upwelling and were brought onto the shelf through upwelling of deep water through Juan de Fuca Canyon and other canyons along the outer shelf. Although it is unknown which of these indices accurately reflects the timing of the transition from downwelling to upwelling conditions, it is clear that the shoreward transport of larvae at the surface or at mid-depth could occur when either of these mechanisms is in effect.

Relative Indices of Abundance

We developed three indices of abundance and examined their use for predicting year-class strength of sablefish (Table 3). All three indices produced variations in annual larval relative abundances which can be equated to strong, moderate, and weak year-class strengths.

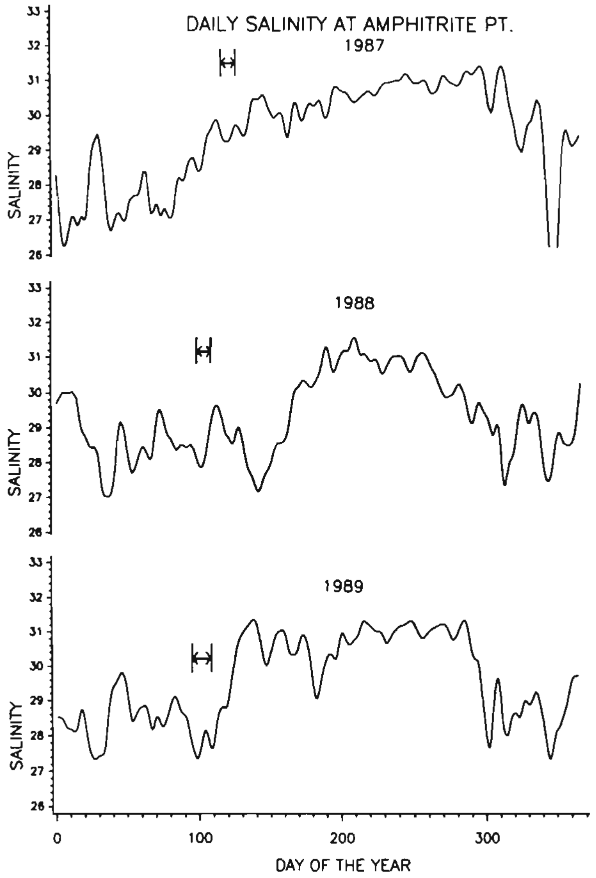

Figure 6
Surface salinity measured at Amphitrite Point, 1987–89. Horizontal arrow indicates period of the annual April surveys. Daily salinity measurements have been smoothed with a cubic spline.

We believe indices one and three are more realistic because they include slope stations where larvae consistently were present. In index one and three the 1984 year class appears strong, and the 1986 year class weak. In addition, both indices show the 1987 and 1988 year classes as moderate. But there is a discrepancy between the two indices for the 1985 and 1989 year classes: index one indicates moderate to weak year classes, and index three indicates moderate to strong year classes.

Conclusions

Once sablefish larvae reach surface waters, their distribution is influenced by surface oceanographic features.

Table 3

Relative indices of abundance of larval sablefish found off the west coast of Vancouver Island, 1984–89.

Year	No. of stations	Larvae/1,000 m^3
Index 1: Relative index of larval sablefish for all stations		
1984	45	32.1
1985	53	14.9
1986	70	9.0
1987	67	15.9
1988	68	17.0
1989	68	14.0
Index 2: Relative index of larval sablefish for the shelf area		
1984	19	17.0
1985	29	4.0
1986	39	4.7
1987	36	6.9
1988	37	13.3
1989	37	1.6
Index 3: Relative index of larval sablefish for the slope area		
1984	26	43.1
1985	24	28.1
1986	31	14.5
1987	31	24.4
1988	31	21.4
1989	31	28.8

In particular, larval distributions appear related to the position and intensity of the northward-flowing coastal current. This, in turn, is influenced by the timing and intensity of the spring transition from a downwelling to an upwelling regime. For example, the highest abundance of sablefish on the shelf occurred in 1988, when the coastal current was closer to shore, and after a period of relatively strong downwelling-favorable winds (which would induce onshore transport of surface waters). In contrast, the strongest difference in sablefish abundances on and off the shelf was in 1989, when the coastal current was located over the shelf break, and upwelling-favorable winds were beginning. Thomson et al. (1989) have suggested that the coastal current spreads seaward over the shelf with upwelling winds.

It is also possible that the distribution of larvae in the surface waters may be influenced by oceanographic conditions at depth during approximately the first 40 days before the larvae reach surface waters (McFarlane and Nagata, 1988). For example, the presence of larval fish in the surface waters over the shelf could result from larvae rising directly to the surface over the slope spawning area and being transported shoreward. Alternatively, larvae could be transported shoreward at depth during upwelling conditions. In addition, the California Undercurrent could be advecting larvae from spawning locations to the south. It is probable that both mechanisms contribute to the transport and distribution of sablefish larvae in waters off the west coast of Vancouver Island. The relation between these oceanographic processes and the dynamics of larvae must be further investigated if we are to fully understand the factors that regulate successful recruitment to the population.

Our initial examination of relative indices of abundance indicates that variation in abundance is detectible at the time of the survey. It is not possible at this time to relate these indices to actual year-class strength, because many of the year classes studied have not yet fully recruited to the commercial fishery. We recognize that these indices are just three of many possible forms an index may take, depending on the mechanisms controlling year-class success off the west coast of Vancouver Island. But at the very least these indices will be useful for predicting year-class strength at a gross level (i.e., strong, average, or weak year classes). For a long-lived marine organism, this may be sufficient for current stock assessment purposes.

Acknowledgments

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Literature Cited

Boehlert, G. W., and M. M. Yoklavich.
1985. Larval and juvenile growth of sablefish, *Anoplopoma fimbria*, as determined from otolith increments. Fish. Bull. 83:475–481.

Fofonoff, N. P., and R. C. Millard Jr.
1983. Algorithms for the computation of fundamental properties of sea water. UNESCO Tech. Pap. Mar. Sci. 44, 53 p.

McFarlane, G. A., and R. J. Beamish.
1986. Production of strong year-classes of sablefish, *Anoplopoma fimbria*, off the west coast of Canada. Int. North Pac. Fish. Comm. Bull. 47:191–202.
1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 19:743–753.

McFarlane, G. A., and W. D. Nagata.
1988. Overview of sablefish mariculture and its potential for industry. *In* Proceedings of the Fourth Alaska Aquaculture Conference, p. 105–120. Alaska Sea Grant Rep. 88-4.

Perry, R. I., and G. A. McFarlane.
1992. Larval fish assemblages off Vancouver Island and the potential impacts of climate variability. *In* International Symposium on Climate Change and Northern Fish Populations, p. 104. Victoria, B.C., 13–16 October 1992 (abstract).

Sameoto, D. D., and L. O. Jaroszynski.
1969. Otter surface sampler: a new neuston net. J. Fish. Res. Board Can. 25:2,240–2,244.

Shaw, W., G. A. McFarlane, D. Davenport, and W. T. Andrews.
1985. Distribution and abundance of larval sablefish,

Anoplopoma fimbria, in the surface waters off the west coast of Vancouver Island, April 16 to May 10, 1984. Can. Manuscr. Rep. Fish. Aquat. Sci. 1835, 41 p.

Shaw, W., G. A. McFarlane, and D. Davenport.

1987. Distribution and abundance of larval sablefish, *Anoplopoma fimbria*, in the surface waters off the west coast of Vancouver Island, April 9 to 24, 1985. Can. Manuscr. Rep. Fish. Aquat. Sci. 1945, 49 p.

1988. Distribution and abundance of larval sablefish, *Anoplopoma fimbria*, off the west coast of Vancouver Island, April 2–18, and May 10–18, 1986. Can. Manuscr. Rep. Fish. Aquat. Sci. 1970, 130 p.

Thomson, R. E., B. M. Hickey, and P. H. LeBlond.

1989. The Vancouver Island coastal current: fisheries barrier or conduit. *In* R. J. Beamish and G. A. McFarlane (eds.), Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models, p. 265–269. Can. Spec. Publ. Fish. Aquat. Sci. 108.

Ware, D. M., and G. A. McFarlane.

1989. Fisheries production domains in the Northeast Pacific Ocean. *In* R. J. Beamish and G. A. McFarlane (eds.), Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models, p. 359–379. Can. Spec. Publ. Fish Aquat. Sci. 108.

Sablefish, *Anoplopoma fimbria*, Observed from a Manned Submersible

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ABSTRACT

In-situ observations of adult sablefish, *Anoplopoma fimbria*, were made from a manned submersible in May 1992 in the eastern Gulf of Alaska. Sablefish were observed at ten sites (300–365 m deep) on the continental slope. Sablefish were either motionless on the seafloor or swimming within 1 m of the seafloor. Their abundance ranged from 1 to 23 at nine sites, to an aggregation of more than 500 at one site. The sablefish responded only minimally to the submersible, indicating that quantitative population studies and behavioral studies can be made from a submersible.

Introduction

A manned submersible was used to observe commercially important fish in the eastern Gulf of Alaska. Although rockfish, *Sebastes* spp., were the target species, other demersal and semidemersal fish were observed, including sablefish, *Anoplopoma fimbria*. The behavior of sablefish observed from the submersible is described, and possible future studies of sablefish from submersibles are discussed.

Materials and Methods

Sablefish were observed in May 1992 from the two-person submersible *Delta* chartered by the National Undersea Research Center of the National Oceanic and Atmospheric Administration. Dive sites were on the continental slope between latitudes 56° and 58°N at depths of 300–365 m (Fig. 1). Longline catch rates during annual surveys indicate that sablefish are abundant at depths of 300–1000 m at these latitudes (Zenger and Sigler, 1992).

Ten dive sites were monitored for sablefish during daylight, between 0600 and 1900. The submersible descended to 300–365 m and then usually traveled parallel to the shelf break at 2–3 km/h, stopping occasionally for detailed observations of rockfish. The distance between the descent and ascent positions at the ten sites was 0.9–1.9 km. The submersible traveled an additional 10%–30% of this distance while following the shelf-break contour. Illumination was entirely by ten 150-W halogen lights attached to the submersible. The lights illuminated about 7 m; visibility was measured by using sonar to define the distance between the submersible and the seafloor while descending and ascending. The pilot maintained the submersible within 1 m of the bottom while the scientist observed fish through starboard portholes. The pilot provided information on the behavior of sablefish around the submersible from his panoramic view 2 m above the scientist.

Observations were audio- and video-recorded on two 8-mm video cameras from the starboard side: an external camera was aimed downward 60° from horizontal, and an internal camera was aimed through a porthole parallel to the seafloor. Sablefish counts were determined from the audio portion of the recordings. Counts were not converted to densities because the horizontal viewing distance along the seafloor changed frequently with the slope of the terrain, so the total area viewed was difficult to estimate.

Fish behavior was determined from the video portion of the recordings. Video-recorded distances depended on the slope of the terrain, and ranged from <1 to 5 m for the internal camera and from 1 to 3 m for the external camera. Behavior observations included spa-

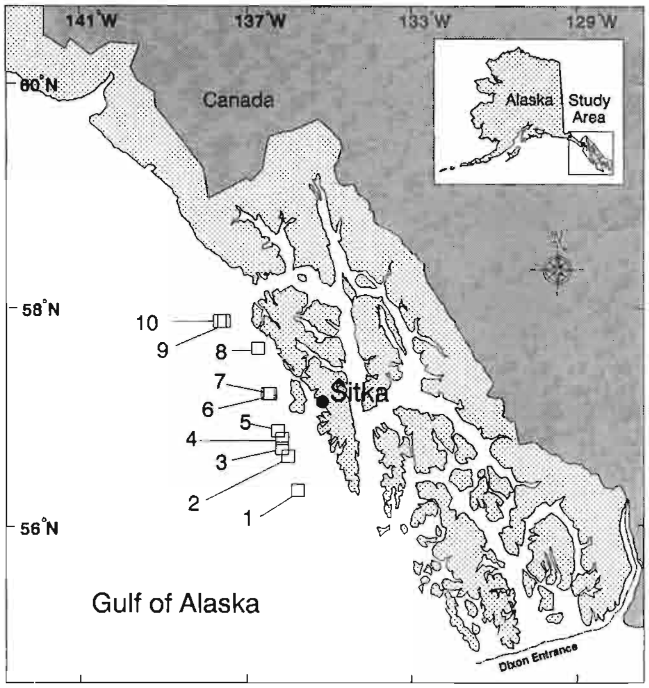

Figure 1
Sites surveyed by manned submersible in the eastern Gulf of Alaska, May 1992.

Table 1
Numbers of sablefish and seafloor habitat at ten manned submersible dive sites in the eastern Gulf of Alaska, May 1992.

			Seafloor habitat		
Site	Distance[1] (km)	Sablefish	Substrate	Cobble & boulders[2]	Slope (°)
1	1.6	4	Pebble	Common	10–30
2	1.0	8	Clay	Present	10–30
3	1.9	23	Pebble, sand	Common	10–30
4	1.0	7	Pebble, clay	Common	20–40
5	1.2	5	Sand, clay	Common	2–10
6	0.9	6	Sand	Present	0–2
7	1.4	12	Pebble	Present	5–40
8	0.9	1	Clay, bedrock	Rare/ common	20–90
9	1.1	1	Pebble	Common	2–90
10	1.1	>500	Sand, clay, bedrock	Rare/ common	10–60

[1] The submersible traveled an additional 10%–30% of this straight-line distance between the descent and ascent positions.
[2] Diameter of cobble and boulders ranged from 0.5 to 5.0 m.

tial distribution, orientation, and swimming speed. The distance between sablefish was determined from the speed of the submersible and lapsed time between encounters with the fish. Sablefish <15 apart were considered associated and those >50 m apart not associated; no sablefish were between 15 m and 50 m apart. Sablefish orientation was categorized in relation to the starboard side of the submersible as toward, away, forward, or backward (Fig. 2). Swimming speed was calibrated against the speed of the submersible and classified as slow (<1 km/h), moderate (1–4 km/h), and fast (>4 km/h).

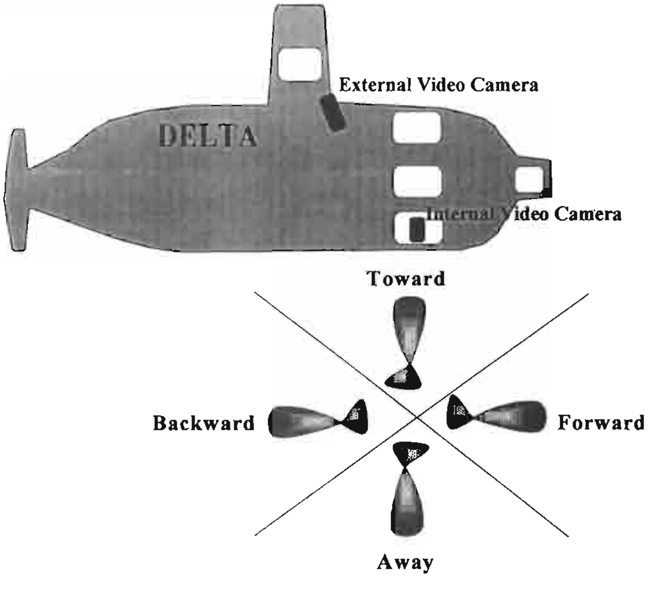

Figure 2
Orientation of sablefish toward, forward, away, and backward as viewed from the starboard side of the submersible.

Results and Discussion

Sablefish were observed at all 10 dive sites, either motionless on the seafloor (sedentary) or moving within 1 m of the seafloor. Sablefish were associated with a wide range of bottom slopes and substrates (Table 1). An aggregation estimated at >500 was observed at site 10, and accounted for most of the sablefish observed from the submersible. Sablefish were not individually counted at site 10 because of the large number and the time required to observe the target rockfish species. The >500 estimate was based on the frequency of sablefish on the video and the audio comments made by the pilot; the pilot could see sablefish at all times during a 22-min period and noted "more than 100" within his panoramic view on two occasions. The aggregation began 0.4 km from the start of the transect and was continuous while the submersible traveled 0.30 km southward, 0.08 km eastward, and 0.30 km northward. The boundaries of the aggregation extended beyond the pilot's view.

Behavioral observations were based on 168 sablefish (120 of them at site 10) that were video recorded by the external or internal cameras. Thirty of the 168 sablefish were sedentary and 138 were active, either swimming, drifting, or hovering with slight movements of fins.

Behavior of Sedentary Sablefish

The orientation of the sedentary sablefish was 4 toward, 7 away, 6 forward, and 13 backward (Table 2). A chi-square test indicates no significant difference ($p>0.05$) in the orientation of the sedentary sablefish. Most sedentary sablefish were not associated with other sablefish; only 3 were within 50 m of other sablefish. Sedentary sablefish did not move as the submersible passed them. Movement was observed only when the submersible stopped within 1.0 m of a sedentary sablefish. This fish remained stationary for 40 seconds before darting away, disturbing the sediment (Fig. 3). All other observed sediment disturbances were associated with flat-

Table 2

Orientation of sedentary sablefish, and orientation and speed of swimming sablefish determined from video recordings collected from a manned submersible.

	Sedentary sablefish				Active sablefish						
	Orientation[1]				Orientation[1]				Speed (km/h)		
Site	T	A	F	B	T	A	F	B	<1	1–4	>4
1		1	1			1					1
2			1		1	1			1		1
3	1			5	3	2	1	1		7	
4	1			1		1	1		1	1	
5			1	1			1			1	
6					1	3	1	1	2	3	1
7	1		1	4	2	2	1	3	7	1	
8					1					1	
9			1								
10	1	6	1	2	12	43	26	29	65	37	8
Total	**4**	**7**	**6**	**13**	**20**	**53**	**31**	**34**	**76**	**51**	**11**

[1] T = Toward submersible; A = Away from submersible; F = Forward, the same direction as the submersible; B = Backward, the opposite direction to the submersible.

Figure 3

Photographic sequence of a sedentary sablefish approached by a manned submersible: top left, stationary on the seafloor; top right, coiling; lower left, swimming away; and lower right, departed, causing sediment disturbance.

Figure 4
Photograph from a manned submersible of a pair of sablefish swimming in the same direction at the same speed.

fish movements, indicating that sedentary sablefish did not depart before the submarine arrived.

Behavior of Active Sablefish

The orientation of the active sablefish was 20 toward, 53 away, 31 forward, and 34 backward. A chi-square test indicates a significant difference ($p<0.001$) in the orientation of active sablefish; the sablefish were apparently reacting to the submersible. Sablefish within 2 m of the submersible would often turn away and sometimes dart short distances, which probably accounts for the significant difference in orientation. Perhaps they were reacting to the brightness of the lights, because they would dart <2 m away and then resume slower swimming movements. The submersible remained within the aggregation for 22 min, so overall avoidance of the submersible was not occurring.

Most active sablefish were associated with other sablefish: 114 of 138 were within 15 m of other active sablefish, including 109 of 110 at site 10. Sablefish appeared to move independently of each other, except for 11 "pairs" at site 10. Individuals within a pair were separated by <1 m and swam in the same direction at the same speed (Fig. 4). Swimming speeds of the active sablefish were 76 slow, 51 moderate, and 11 fast (Table 2). Slow-swimming fish were mostly hovering or drifting. Moderately swimming fish appeared calm and unhurried. The only fast-swimming fish were those that darted short distances away from the submersible.

Future Sablefish Studies

Because of the minimal response of most sablefish to the submersible, distribution and abundance studies from a submersible appear feasible. Possible studies include habitat associations and spatial distribution, longline monitoring, and population estimates for calibrating catch-rate data for longline gear and bottom trawls.

Understanding sablefish habitat associations and spatial distribution should result in more efficient index sampling and more accurate analysis of catch-rate data. Manned submersibles have been used to describe habitats and spatial distribution of several commercially important Alaskan groundfish, including Pacific ocean perch, *Sebastes alutus* (Krieger, 1993); shortraker rockfish, *Sebastes borealis* (Krieger, 1992); yelloweye rockfish, *Sebastes ruberrimus* (O'Connell and Carlile, 1993); and lingcod, *Ophiodon elongatus* (O'Connell, 1993).

Examples of information about distribution that is obtainable by direct observation are the aggregating behavior and pairing observed in this study. The observations reported in this paper, however, are considered preliminary because they were limited to a narrow geographic area and depth range, and did not include detailed observations of the environment. Directed studies of sablefish habitat and spatial distribution should include a wider depth range and geographic area, and more detailed observations of physical and biological features such as current, substrate, slope, and prey.

Longline catch rates, assumed to be proportional to sablefish abundance, are the main source of information for estimating sablefish abundance (Sigler, 1993). But catch rates may be affected by factors other than population density, including bait competition, currents, hooked fish attracting other fish, and fish depletion (Sigler, 1993). Factors affecting catch rates may be identified by observing longline gear on the seafloor. For example, Løkkeborg et al. (1989) used underwater television to identify factors that affect catch rates of Atlantic cod, *Gadus morhua*, and haddock, *Melanogrammus aeglefinus*, on longline gear, including stimulation by hooked fish, currents, and feeding cycles. High (1980) observed longline gear from a manned submersible to describe how Pacific halibut, *Hippoglossus stenolepis*, were caught with different types of bait.

Catch quotas of sablefish are determined from the product of exploitation rates and absolute biomass estimates. Currently, an unverified catchability coefficient of 1.0 is used to convert bottom trawl catch rates to absolute biomass estimates; a 1.0 catchability coefficient assumes that the seafloor area swept by the horizontal spread of the trawl is 100% efficient for capture of sablefish, and that sablefish densities are similar in trawlable and untrawlable areas (Sigler, 1993). No catchability coefficients are available for longline gear. Sablefish counts from a submersible may provide a reliable population estimate to calibrate catchability coefficients of bottom trawls and longline gear.

Gunderson (1993) summarizes biases associated with submersible observations of fish, and undoubtedly some of these biases apply to sablefish. But observations in this study indicate that submersibles can be used to improve our understanding of sablefish distribution and behavior. Further studies are needed to develop methods of quantifying sablefish from a submersible, and to determine the feasibility of observing sablefish longline gear in use.

Acknowledgments

I thank the crews of the submersible *Delta* and the support vessel *Jolly Roger* for completing safe and successful dives. I also thank Dan Ito and John Karinen for participating in the submersible diving.

Literature Cited

Gunderson, D. R.
1993. Survey of fisheries resources. John Wiley & Sons, New York, 248 p.
High, W. L.
1980. Bait loss from halibut longline gear observed from a submersible. Mar. Fish. Rev. 42(2):26–29.
Krieger, K. J.
1992. Shortraker rockfish, *Sebastes borealis*, observed from a manned submersible. Mar. Fish. Rev. 54(4):35–38.
1993. Distribution and abundance of rockfish determined from a submersible and by bottom trawling. Fish. Bull. 91:87–96.
Løkkeborg, S., Å. Bjordal, and A. Fernö.
1989. Response of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) to baited hooks in the natural environment. Can. J. Fish. Aquat. Sci. 46:1,478–1,483.
O'Connell, V. M.
1993. Submersible observations of lingcod, *Ophiodon elongatus*, nesting below 30 m off Sitka, Alaska. Mar. Fish. Rev. 55(1):19–24.
O'Connell, V. M., and D. W. Carlile.
1993. Habitat-specific density of adult yelloweye rockfish *Sebastes ruberrimus* in the eastern Gulf of Alaska. Fish. Bull. 31:308–313.
Sigler, M. F.
1993. Stock assessment and management of sablefish *Anoplopoma fimbria* in the Gulf of Alaska. Ph.D dissert., Univ. of Washington, Seattle.
Zenger, H. H., Jr., and M. F. Sigler.
1992. Relative abundance of Gulf of Alaska sablefish and other groundfish based on National Marine Fisheries Service longline surveys, 1988–90. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-216, 103 p.

Distribution, Age, and Growth of Juvenile Sablefish, *Anoplopoma fimbria*, in Southeast Alaska

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ABSTRACT

From 1985 through 1991, 131 surveys were conducted at 74 sites to study the distribution and abundance of juvenile sablefish, *Anoplopoma fimbria*, in southeast Alaskan waters. The widespread distribution and above-average abundance of juvenile sablefish throughout the waters of southeast Alaska in 1985 probably indicated a strong 1984 year class. During 1986–91, juvenile sablefish were consistently abundant at only one sample site—St. John Baptist Bay, Baranof Island. Juvenile sablefish were distributed throughout the water column. Vertical distribution was related somewhat to age: younger sablefish (age 0) were usually caught nearer the surface, whereas older juveniles (ages 1 and 2) were caught on or near the bottom. Hand-jigging was the most consistently effective method for sampling juvenile sablefish. Pots suspended off the bottom were more effective than pots placed on the bottom. Catch per unit of effort in St. John Baptist Bay was highest in spring, declined during summer, and was lowest in winter. Catch rates were higher from larger vessels (26–28 m long) than from small skiffs (5 m). Juvenile sablefish grew most rapidly during fall, when they entered the inland waters. Growth slowed during winter but accelerated in spring and became rapid in summer. Lengths averaged 25.6, 39.8, and 45.0 cm by end of the first, second, and third years of growth, respectively.

Introduction

Sablefish, *Anoplopoma fimbria*, is a slow-growing, long-lived demersal fish of the continental slope of the North Pacific. Most commercially caught sablefish range in age from 4 to 35 years but can be as old as 70 (McFarlane and Beamish, 1983). The sablefish fishery is the third most economically important of Alaska's groundfish fisheries: ex-vessel landings of 22,000 t were worth about $58.3 million in 1991 (Kinoshita et al., 1996). In Alaska, sablefish are caught primarily in the Gulf of Alaska (GOA) and in the southeast inside waters of Chatham and Clarence Straits.

Few studies of juvenile sablefish have been published. McFarlane and Beamish (1983) discussed sablefish life history from hatching to recruitment into the commercial fishery. Their observations are mostly based on the 1977 year class off British Columbia. Boehlert and Yoklavich (1985) presented information on growth of juvenile sablefish off the coasts of Washington and Oregon. Kendall and Matarese (1987) reviewed information on egg, larval, and epipelagic stages of sablefish along the west coast of North America, primarily in outer coastal waters. In spite of the importance of sablefish to the groundfish fishery in Alaska, the only comprehensive paper on the life history of juvenile sablefish in Alaskan waters is by Bracken,[1] who discusses migration of the 1977 year class in the Gulf of Alaska.

During the summer of 1985, juvenile sablefish were abundant throughout southeast Alaska, including Auke Bay. Their occurrence over a wide area provided an opportunity to study their distribution, relative abundance, and migration. Especially desirable was the establishment of sampling sites that could be used to annually monitor juvenile sablefish abundance in order to predict future year-class strength.

According to Sasaki (1985), nearshore waters extending from off southeast Alaska to British Columbia, Canada, are known to be one of the most important nursery grounds for young sablefish. In this paper we document the surveys conducted in southeast Alaska from 1985 through 1991, and describe the catch rates, distribution, and age and growth of juvenile sablefish in a major nursery area. Information on migration of these juveniles is presented by Rutecki and Varosi (1997).

Methods

Sampling was conducted at 74 sites in southeast Alaska during 131 surveys, 1985–91 (Fig. 1). Surveys were limited by lack of a dedicated research vessel. Most surveys, therefore, were opportunistic, usually resulting from the suspension of other research because of adverse weather during cruises in the eastern Gulf of Alaska.

Various gear types were used because little information was available concerning the best way to capture juvenile sablefish, and because low catches throughout much of the study prompted attempts to increase catch rates by trying different gear. The gear included hand-jigging gear, basket- and Korean-style pots, trawls, longlines, and purse seines. The hand-jigging gear and basket-style pots have been described by Rutecki and Meyers (1992), the Korean-style conical pots by Clausen and Fujioka (1988). Pots and hand-jigging gear used squid for bait.

Pots were fished on bottom and also suspended off bottom several times during the study. In 1985, pots were fished on bottom and suspended off bottom at the Auke Bay Laboratory float (maximum depth about 9 m). On 16 October 1988, a string of pots was fished in St. John Baptist Bay to test their effectiveness for capturing juvenile sablefish. The pots were fished for 24 h at 7, 11, and 15 m below the surface, and on bottom (30 m). Two additional strings of 10 pots each were set on bottom, one string near the suspended pots and the other 68–86 m deep in the outer bay.

A 12.2-m shrimp trawl (described by Carlson et al.[2]) and the standard Marinovich midwater trawl were also used (NMFS[3]). Bottom longlines consisted of J-hooks tied on 45-cm gangions spaced 1 m apart and attached to a 1.5 cm diameter groundline. The purse seine had 3.18-cm mesh and was 18 m deep and 183 m long. Initially, both day and night sampling were tried, but because no juvenile sablefish were caught after dark, all subsequent sampling was done in daylight.

The NOAA ships RV *John N. Cobb* (28.4 m long) and RV *Murre II* (25.9 m) were the primary sampling platforms. Hand-jigging was also done from skiffs (5 m) and from the Auke Bay Laboratory float.

Fish collected for age determination were measured and sexed, and otoliths were extracted. On some occasions, the fish were frozen and the otoliths were extracted in the laboratory. Otoliths were preserved in 50% ethanol and later aged by means of the break-and-burn method (Beamish and Chilton, 1982).

Otoliths were also obtained from sablefish collected at Sitka (1986) and St. John Baptist Bay (1986, 1988). The fish were sampled in July 1986 and in March, May, June, August, and October 1988. The ages of 308 fish total were determined: 57 fish from 1986, and 50 fish from each of the five sampling periods in 1988, except in May, when 51 ages were determined.

Results and Discussion

Abundance and Distribution

Juvenile sablefish were caught at few of the sites sampled except in 1985, when they were present at all nine sites sampled (Fig. 1). Information gathered by the authors from interviews with fishermen and cannery workers indicated that juvenile sablefish were common throughout southeast Alaska in 1985. From 1986 through 1991, the percentages of sites where sablefish were captured were lower than in 1985 (Table 1).

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[1] Bracken, B. E. 1981. Interim report on the results of sablefish (*Anoplopoma fimbria*) tagging experiments in southeastern Alaska 1979–1981. Alaska Dep. Fish Game, P.O. Box 667, Petersburg, AK 99833. Unpubl. manuscr.

[2] Carlson, H. R., R. E. Haight, and K. J. Krieger. 1982. Species composition and relative abundance of demersal marine life in waters of southeastern Alaska, 1969–81. NWAFC Proc. Rep. 82-16, 57 p., Northwest and Alaska Fisheries Center, NMFS, NOAA. Available Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626.

[3] NMFS. 1990. ADP code book. Resource Assessment and Conservation Engineering Div., AFSC, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070.

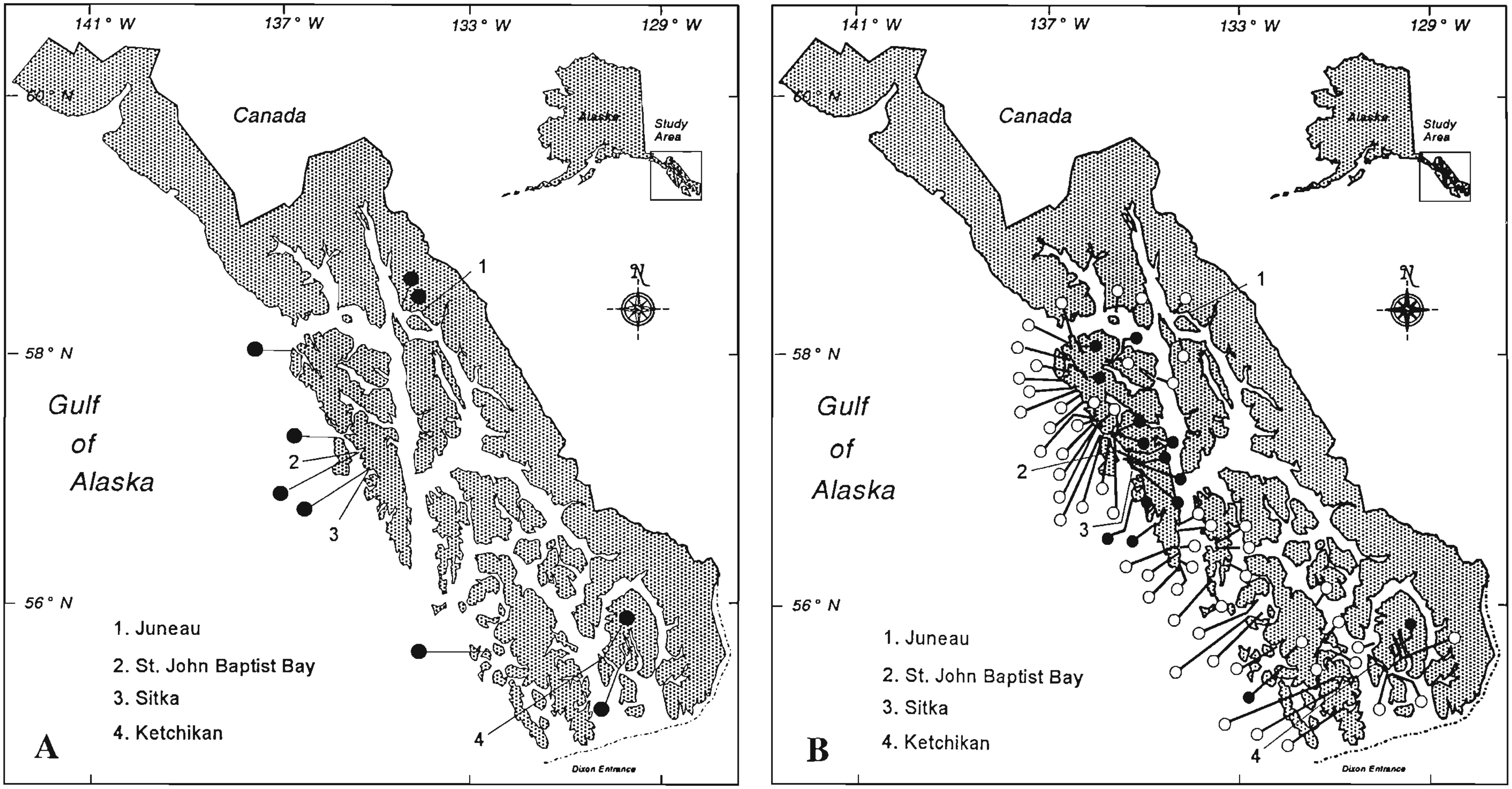

Figure 1
Sites surveyed for juvenile sablefish during (A) 1985 and (B) 1986–91. Dots indicate sites where juveniles were caught; circles indicate sites where none were caught.

Table 1
Total sites surveyed, and number and percentage of sites where juvenile sablefish were captured, 1985–91.

	1985	1986	1987	1988	1989	1990	1991
Sites surveyed	9	17	10	37	4	3	22
Number with sablefish	9	4	2	2	1	1	3
% with sablefish	100	24	20	5	25	33	14

From 1986 through 1991, juvenile sablefish were found consistently at only one site: St. John Baptist Bay, on Baranof Island about 33 km north of Sitka, Alaska. The reason for the continued presence of juvenile sablefish in this bay is unknown. Periodic CTD sampling of this bay indicated no oceanographic uniqueness compared with nearby bays. Plankton collections and stomach contents of sablefish caught in the bay showed only the typical sequence of seasonally abundant organisms (Rutecki, unpubl. data). Bays of similar configuration and location near the outer coast are common throughout the same area, yet had inconsistent juvenile sablefish abundance. More study (comprehensive oceanographic sampling) is being planned to determine the uniqueness of St. John Baptist Bay. This bay was the only site in southeast Alaska useful for monitoring the timing of juvenile immigration to inland waters, and for studies of juvenile sablefish food, vertical distribution, and age and growth.

Vertical Distribution

Little is known about the vertical distribution of juvenile sablefish. According to Kendall and Matarese (1987), small (10–80 mm standard length) sablefish are mostly neustonic. In the coastal waters of British Columbia, juvenile sablefish have been caught at or near the surface and on bottom at depths of 20–60 m (Kennedy, 1969, 1970; Kennedy and Smith, 1972). Juvenile sablefish have been caught in bottom trawls off Oregon at depths of 320–411 m (Heyamoto, 1962). In southeast Alaska, juvenile sablefish have been caught in bottom trawls at 152-m depths (Haight[4]), in purse seines off the outer coast, and in gill nets in southern Chatham Strait (Rutecki and Varosi, 1997). Wing (1985) found 10–17-mm long sablefish in the stomachs of salmon collected in August on the outer coast of southeast Alaska. When juvenile sablefish were abundant throughout southeast Alaska in 1985, they were often caught by anglers fishing near the surface.

Table 2
Percentages of juvenile sablefish caught at various depths and CPUE (fish/h) for pots fished in St. John Baptist Bay, October 1988. Dash indicates no pots were fished.

	Percentage of fish			
Depth (m)	16 Oct. (n=112)	16 Oct. (n=124)	16 Oct. (n=255)	21 Oct. (n=621)
4	—	7	—	—
7	2	10	40	54
11	43	58	42	21
15	55	25	18	17
18	—	—	—	8
Bottom	0	0	0	0
CPUE	22.4	24.8	51	19.4

We caught juvenile sablefish from surface to bottom, but collections differed markedly depending on type and depth of gear. The bait was fished from top to bottom during jigging in St. John Baptist Bay but initially, sablefish were caught only on the bottom. As fishing continued, the sablefish were captured nearer the surface, and eventually they were caught in the upper 1 m of the water column. Apparently the fish were at the bottom when jigging began and followed the bait to the surface.

Most juvenile sablefish were captured in the suspended pots fished off the Auke Bay Laboratory float during the summer of 1985. Catch rates were also high for pots fished off the bottom in St. John Baptist Bay during October 1988. Catches of juvenile sablefish (up to 150 fish per hour) were greatest in pots suspended 7, 11, and 15 m below the surface (Table 2). No fish were caught in the bottom pots of the suspended string or in the two strings of pots set on bottom.

The large catches of juvenile sablefish in suspended pots in St. John Baptist Bay in October 1988 were unique because usually pots—whether suspended or on bottom—caught few, if any, sablefish. Possibly the October 1988 catches were related to the annual immigration of large numbers of fish into the bay.

Catch Rates

Hand-jigging was the simplest and most effective method of those we used for capturing juvenile sablefish. Because hand-jigging can be done from nearly any size platform, is cost effective, and can be used for all depths

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[4] Haight, R. E. 1985. Fishing log R/V *Chapman* groundfish survey off southeastern Alaska, 22 April to 5 May 1984. Available Auke Bay Lab., 11305 Glacier Hwy., Juneau, AK 99801-8626. Unpubl. manuscr.

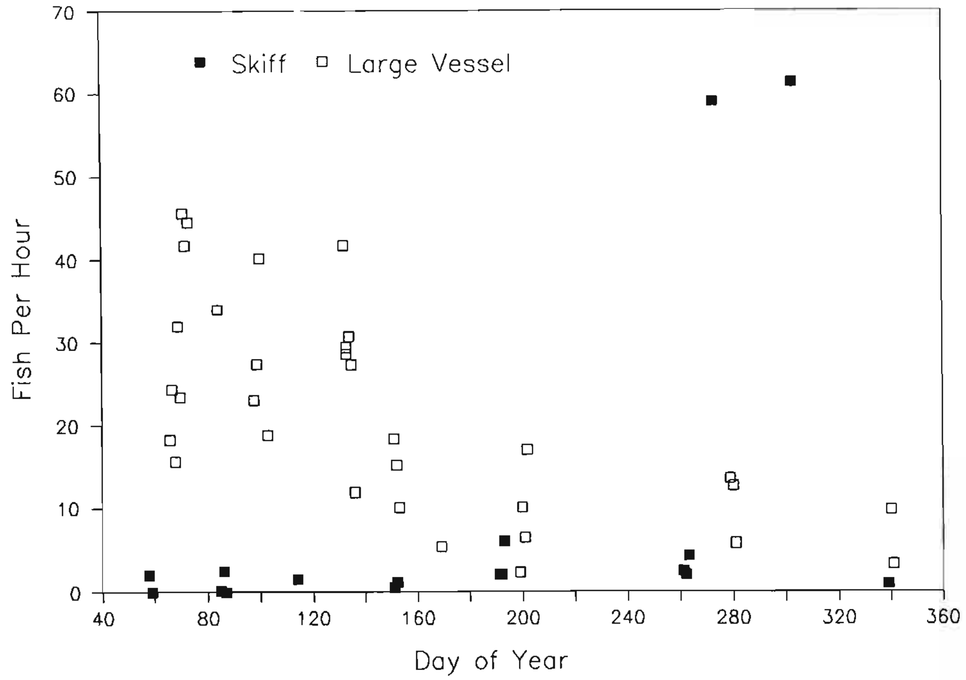

Figure 2

Catch per unit of effort for juvenile sablefish in St. John Baptist Bay, 1987–91.

from surface to bottom, we used it to determine catch per unit of effort (CPUE: number of fish caught per fishing-rod hour, hereafter referred to as fish per hour). Hand-jigging CPUE data were collected from 1987 through 1991 to monitor trends in juvenile abundance. Except for St. John Baptist Bay, no site had a CPUE greater than two fish per hour. Because of the continual abundance of juvenile sablefish in St. John Baptist Bay, we examined CPUE's from this bay for trends of abundance.

A seasonal trend of sablefish abundance was observed in the bay. The combined 1987–91 data showed that CPUE was usually greatest in early spring, declined during the summer, and was lowest late in the year (Fig. 2). CPUE varied considerably during the sampling periods. In March, CPUE ranged from zero to about 45 fish per hour. By midsummer, CPUE had decreased to about 1–20 fish per hour, and by winter to about 1–10 fish per hour. Exceptions to the seasonal trend in CPUE are two collections during September–November, when CPUE's were about 60 fish per hour, the maximum number of fish that could be jigged with sportfishing gear. High CPUE in the fall probably indicates a peak in the annual immigration of sablefish into St. John Baptist Bay (see Rutecki and Varosi, 1997).

The reason for the large range in CPUE is unclear. The jigs were fished throughout the water column (about 30 m) and supposedly would have been available to the sablefish regardless of their depth. Schooling may have contributed to the variable catch rates if the fish were in some part of the bay other than the jigging site (the inner part of the bay, which is separated from the outer bay by a sill). This argument seems implausible, however, since the outer bay was sampled often and only a few sablefish were ever caught.

The CPUE from larger vessels was markedly greater than that from skiffs (Fig. 2), with a few exceptions in October. It is unknown why CPUE from the larger vessels was greater. Jigging equipment and techniques were identical for each vessel. The large vessels fished more gear (up to 10 persons jigging at a given time) than the skiffs (2 people jigging), so perhaps the greater quantity of bait fished from the large vessels attracted juvenile sablefish. Food items discarded from the larger ships into St. John Baptist Bay may also have attracted juveniles.

Age and Growth

In 1986, mean length of age-1 fish was 31.5 cm (range 28–35 cm), and that of age-2 fish was 44.6 cm (range 39–51 cm) (Fig. 3). One fish was age 3 (57 cm). In 1988, all fish collected from March through August were age 1

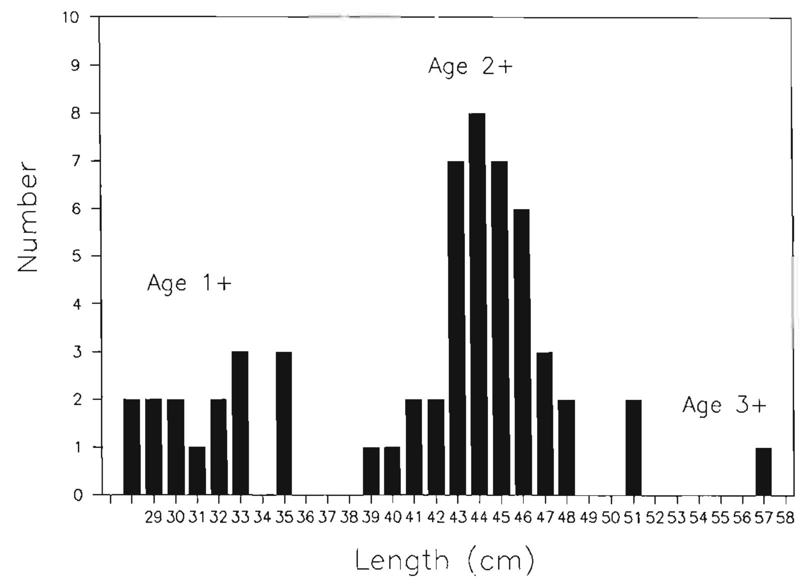

Figure 3
Length and age of juvenile sablefish collected for age determination in St. John Baptist Bay and Sitka Harbor, July 1986. Ages determined from otolith analysis.

(Fig. 4); fish collected in October were age 0. The mean length of fish increased from 26.5 cm (range 23.5–30.5 cm) in March to 30.2 cm (27.0–37.5 cm) in August. In October, fish averaged 23.1 cm (20.0–26.0 cm). This October decrease coincides with the emigration of the age-1 fish from St. John Baptist Bay and immigration of the age-0 fish into the bay.

In some years, two age groups of sablefish were present simultaneously in St. John Baptist Bay (Fig. 5). In July 1986, two age groups averaged 31.4 cm (age 1) and 45.0 cm (age 2) long. In September 1989, two age groups averaged 21.0 cm (age 0) and 39.8 cm (age 1). The older group had emigrated from the bay by the next sampling periods of March 1987 and December 1989.

We examined growth by comparing mean monthly lengths for all fish collected during the study (Fig. 6). The mean lengths show that growth in length is relatively slow during winter, begins to increase in about May, and is most rapid from about June through August. In St. John Baptist Bay, age-0 (young-of-the-year) juvenile sablefish averaged about 22 cm during September. By October, mean length of age-0 fish had increased to about 25 cm. In March, however, age-1 fish still averaged only about 26 cm, indicating that growth is slow during winter. Growth accelerated in spring: fish caught during March and April 1987 and recovered in June 1987 averaged 0.63 cm and 0.74 cm of growth per month, respectively (Rutecki and Varosi, 1997). Mean lengths of juvenile sablefish caught in Auke Bay during summer 1985 increased from 31.3 cm in June to 35.0 cm in August, averaging 1.92 cm of growth per month (Fig. 7). In 1987, mean length in St. John Baptist Bay increased from 27.6 cm in June to 29.7 cm in August; in 1989, it increased from 32.3 cm in July to 39.8 cm in September (Fig. 5). Summer growth of juvenile sablefish in St. John Baptist Bay and Auke Bay, all years combined, averaged 2.24 cm per month.

The growth pattern of juvenile sablefish in southeast Alaska is similar to that described by McFarlane and Beamish (1983) in the coastal waters of British Columbia. They examined length-frequency distributions of the 1977 year class and found that age-0 fish grew rapidly: the fish averaged 28 cm by November. The next spring, fish from that year class averaged only 32 cm, indicating limited growth during winter. After two years, juvenile sablefish had grown to 40 cm, and after three and four years of growth, they averaged 45 and 50 cm, respectively. Juvenile sablefish in southeast Alaska were somewhat smaller (23.7–25.6 cm) near the end of their first year (age 0) than those in British Columbia, but growth was similar in both areas during the second and third years.

Year-class Strength

Sablefish populations in the northeast Pacific Ocean depend upon recruitment from infrequent strong year

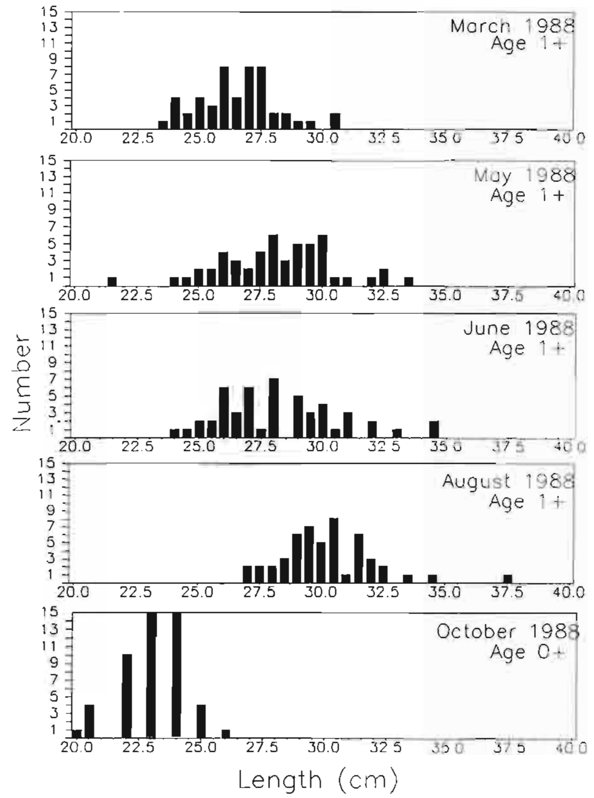

Figure 4

Length and age of juvenile sablefish collected for age determination in St. John Baptist Bay, 1988.

classes (McFarlane and Beamish, 1986). It is difficult to determine year-class strength of sablefish by sampling the fishery because of problems in determining the ages of older adults (McFarlane and Beamish, 1986). Thus the abundance of juvenile sablefish can be an indicator of year-class strength.

The presence of large numbers of juvenile sablefish in southeast Alaska waters in a given year indicates a strong year class. According to Fujioka,[5] the strong 1977 and 1980 year classes were evident from the large number of juvenile sablefish caught by sport and commercial fishermen during the summer of 1978 and 1981. Funk and Bracken (1983) also caught large numbers of juvenile sablefish in Auke Bay during the summer of 1981. Juvenile sablefish were again abundant throughout southeast Alaska during 1985, indicating a strong 1984 year class. This indication was confirmed by the 1986 length frequency distributions and by subsequent offshore resource-assessment survey data. The 1986 length frequency distributions (Fig. 5) show a distinct mode of age-2 fish. This mode is absent in the length distributions during the years when juvenile sablefish were not common in the inland waters. Analysis of lengths of sablefish collected during longline surveys of the Gulf of Alaska in 1986 and 1987 show that the 1984 year class was stronger than average (Sigler and Zenger, 1989). Bracken et al. (1997) conducted longline surveys for sablefish in southeast Alaska from 1988 to 1992; these surveys indicated higher than normal recruitment of the 1984 year class. Although abundance and strength of year class need further definition, clearly a relationship exists between strong year classes and the widespread occurrence of juvenile sablefish in the inland waters throughout southeast Alaska.

It may be possible to detect a strong year class during the spawning year. McFarlane and Beamish (1983) reported large numbers of juvenile sablefish in both the inner and outer coastal waters along the entire coast of British Columbia in 1977 and 1978. According to these authors, such large numbers of sablefish indicated a strong 1977 year class, because most of the 1978 fish were age 1. Similar predictions of strong year classes

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[5] Fujioka, J. T. 1991. Sablefish. *In* Stock assessment and fishery evaluation report for the 1992 Gulf of Alaska groundfish fishery, p. 4.1–4.17. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510.

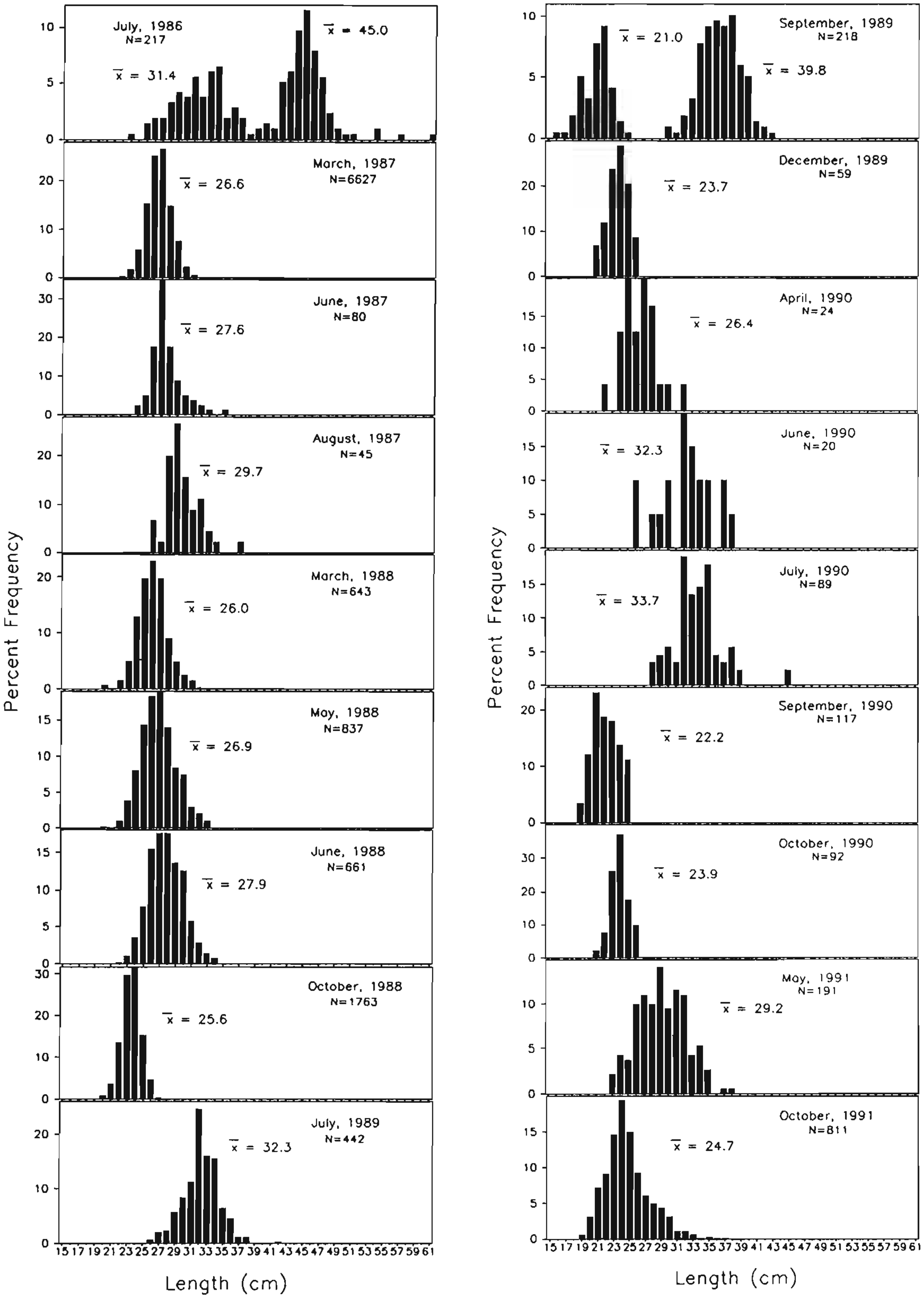

Figure 5

Length frequencies of juvenile sablefish collected in St. John Baptist Bay, July 1986–October 1991. Note variable scale of y axis.

probably can be made for southeast Alaska. In St. John Baptist Bay we collected sablefish in the fall that had been spawned the previous spring. Thus it seems probable that a strong year class of sablefish can be detected in southeast Alaska during the year of spawning by sampling along the outer coast in the fall. In addition to sampling juvenile sablefish after they have migrated to the southeast Alaska nursery area, it may be possible to sample epipelagic juvenile abundance in the Gulf of Alaska before the fish approach the coast, in order to determine year-class strength. According to Kendall and Matarese (1987) year-class strength in fish is thought to be determined mainly during the pelagic egg and larval stages, and sampling epipelagic juveniles when they are several months old could indicate recruitment to the fishery several years later. Little is known of the movements of surface-living juveniles and of the means by which they return to shelf waters for settlement. Future research plans include a survey to examine the distribution of epipelagic juvenile sablefish in the Gulf of Alaska and in coastal waters off British Columbia.

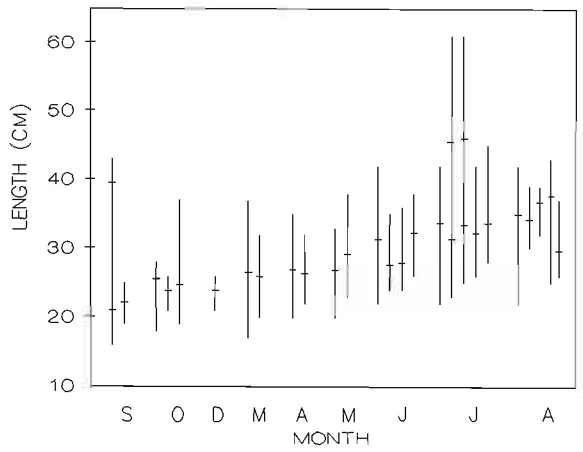

Figure 6
Mean and range of length of juvenile sablefish collected in southeast Alaska, 1985–91.

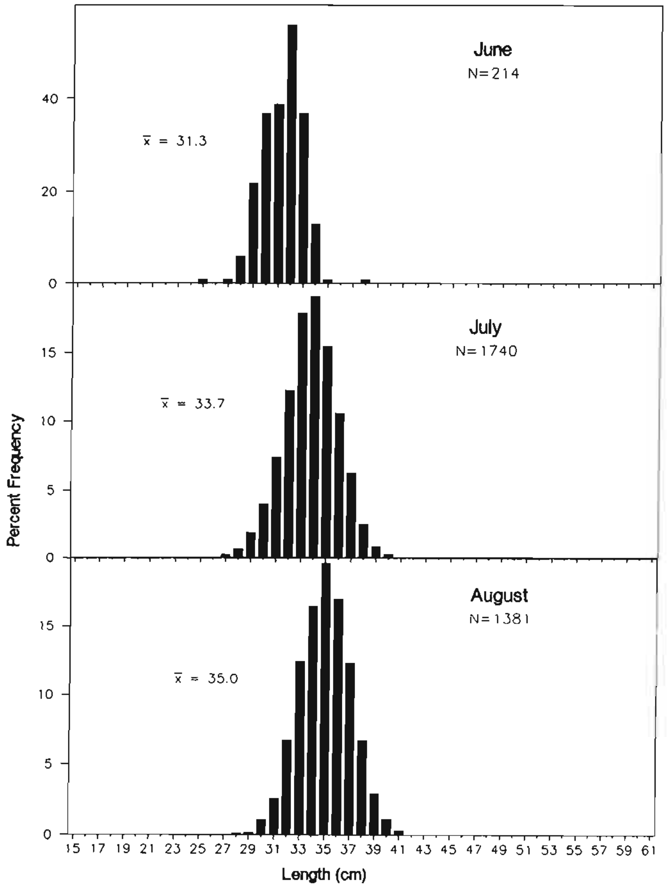

Figure 7
Length frequencies of juvenile sablefish caught in Auke Bay, summer 1985.

Literature Cited

Beamish, R. J., and D. E. Chilton.
1982. Preliminary evaluation of a method to determine the age of sablefish (*Anoplopoma fimbria*). Can. J. Fish. Aquat. Sci. 39:277–287.

Boehlert, G. W., and M. M. Yoklavich.
1985. Larval and juvenile growth of sablefish (*Anoplopoma fimbria*) as determined from otolith increments. Fish. Bull. 83:475–481.

Bracken, B. E., D. A. Gordon, and D. W. Carlile.
1997. Sablefish, *Anoplopoma fimbria*, stock assessment in the inside waters of southeast Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 195–206. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Clausen, D. M., and J. T. Fujioka.
1988. Relative abundance of sablefish in southeastern Alaska, based on trap indexing surveys, 1978–85. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-134, 51 p.

Funk, F., and B. E. Bracken.
1983. Growth of sablefish in southeastern Alaska. Alaska Dep. Fish Game Info. Leafl. 223, Juneau, AK, 40 p.

Heyamoto, H.
1962. Age of young sablefish, *Anoplopoma fimbria* (Pallas) 1811. J. Fish. Res. Board Can. 19:1,175–1,177.

Kendall, A. W., Jr., and A. C. Matarese.
1987. Biology of eggs, larvae, and epipelagic juveniles of sablefish, *Anoplopoma fimbria*, in relation to their potential use in management. Mar. Fish. Rev. 49(1):1–13.

Kennedy, W. A.
1969. Juvenile sablefish cruises—1969. Fish. Res. Board Can. Manuscr. Rep. 1059, 7 p.

1970. Juvenile sablefish cruises in 1970, including length, weight, girth, and age data. Fish. Res. Board Can. Manuscr. Rep. 1119, 11 p.

Kennedy, W. A., and M. S. Smith.
1972. Juvenile sablefish tagging northwestern Vancouver Island 1972. Fish. Res. Board Can. Manuscr. Rep. 1222, 22 p.

Kinoshita, R. K., A. Greig, and J. M. Terry.
1996. Economic status of the groundfish fisheries off Alaska, 1994. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-62, 108 p.

McFarlane, G. A., and R. J. Beamish.
1983. Preliminary observations on the juvenile biology of sablefish (*Anoplopoma fimbria*) in waters off the west coast of Canada. *In* Proceedings of the International Sablefish Symposium, Anchorage, Alaska, p. 119–135. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.
1986. Production of strong year-classes of sablefish (*Anoplopoma fimbria*) off the west coast of Canada. INPFC Bull. No. 47:191–202.

Rutecki, T. L., and T. R. Meyers.
1992. Mortality of juvenile sablefish captured by hand-jigging and traps. North Am. J. Fish. Manage. 12:836–837.

Rutecki, T. L., and E. R. Varosi.
1997. Migrations of juvenile sablefish, *Anoplopoma fimbria*, in southeast Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 123–130. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Sasaki, T.
1985. Studies on the sablefish resources in the North Pacific Ocean. Bull. Far Seas Fish. Res. Lab. (Shimizu) 22, 108 p.

Sigler, M. F., and H. H. Zenger Jr.
1989. Assessment of Gulf of Alaska sablefish and other groundfish based on the domestic longline survey, 1987. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-169, 54 p.

Wing, B. L.
1985. Salmon stomach contents from the Alaska troll logbook program 1977–84. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-91, 43 p.

Area and Depth Differences in the Age–Length Relationship of Sablefish, *Anoplopoma fimbria*, in the Gulf of Alaska

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ABSTRACT

Sablefish lengths and otoliths were collected in the Gulf of Alaska from June to September 1987 and 1989 in samples stratified by area, depth, and sex. Generally, the age–length relationships among areas differed on the continental shelf (100–200 m) and were similar on the upper continental slope (400–1,000 m). The mean size at age and the mean age at size often were greater on the slope than on the shelf; these differences can be explained by random movement of fish from nearshore rearing areas to the slope, where they remain, with movement rate positively related to fish size. These differences also can be explained by an ontogenetic change such as sexual maturation triggering directed movement to deep water, where the probability of maturation increases with age and size.

Introduction

Sablefish, *Anoplopoma fimbria*, are distributed along the upper continental slope of the North Pacific Ocean from California north through Alaska and the Bering Sea, and westward to Japan (Sasaki, 1985). Their age–length relationship varies between sexes and among large geographic areas (e.g., Bering Sea, Gulf of Alaska, west coast of the coterminous United States; McFarlane and Beamish, 1983; McDevitt, 1990). In this paper we compare age–length relationships within the Gulf of Alaska and among depths and relate the results to the observed movement of sablefish from nearshore rearing areas to outer coastal waters inhabited by adults.

Materials and Methods

Otoliths were collected from sablefish in Alaskan waters from June to September 1987 and 1989 during a Japan–U.S. cooperative longline survey, which annually assesses sablefish abundance in the eastern Bering Sea, Aleutian Islands area, and the Gulf of Alaska (Sasaki, 1985). In the Gulf of Alaska, collections were made in the Shumagin, Kodiak, and Southeastern statistical areas defined by the International North Pacific Fisheries Commission (Wilderbuer, 1989; Fig. 1). The collections were stratified by depth and sex. Sampled depths were 101–200, 201–400, and 401–1,000 m. Samples of five fish per one-centimeter fork-length interval were

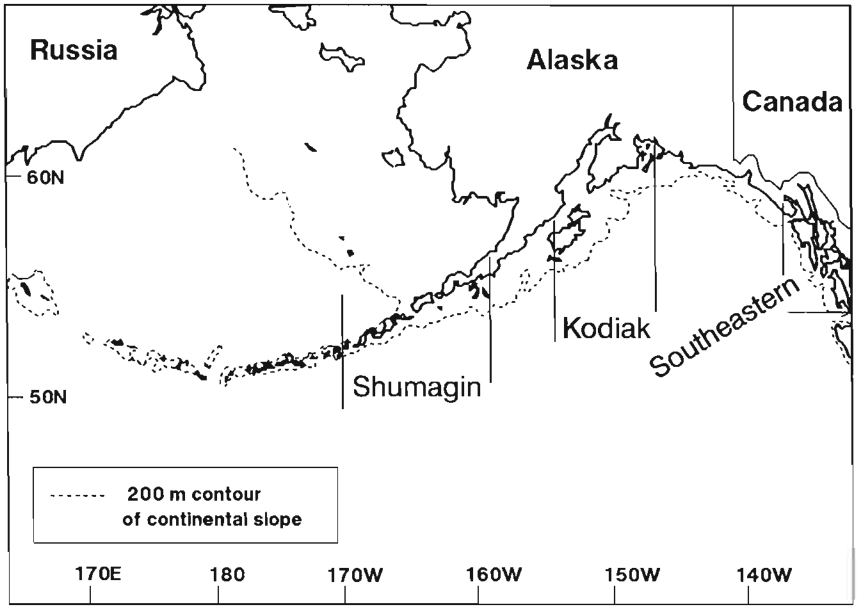

Figure 1
Areas sampled in the Gulf of Alaska: the Shumagin, Kodiak, and Southeastern statistical areas described by the International North Pacific Fisheries Commission.

taken from each area/depth/sex stratum. Both otoliths were removed and preserved in a 50% alcohol solution.

The ages of a subsample of the otoliths were determined by the Alaska Fisheries Science Center (AFSC) ageing unit with the break-and-burn technique (Beamish and Chilton, 1982; Lai, 1985; Kastelle, 1991). Subsampling was necessary because of limited laboratory time. Subsamples of three fish per one-centimeter fork-length interval were randomly chosen from each area/depth/sex stratum, which mimicked the selection of the original sample. Subsample sizes were 2,032 from 1987 and 1,057 from 1989. Only fish from depths of 101–200 and 401–1,000 m were aged. We intentionally focused on the 100–200 and 400–1,000-m collections to emphasize depth differences. The depth range 101–200 m generally corresponds to the continental shelf, and 401–1,000 m corresponds to the upper continental slope, hereafter called shelf and slope.

Mean length at age was computed by area/depth/sex stratum and year from the age–length data. Estimates of mean length at age based directly on the age–length sample are biased because the sample is systematic. The length composition, however, is a random sample from the longline catches and can be used with the age–length sample to estimate length compositions by age class (see discussion in Kimura and Chikuni, 1987). The mean length at age i, L_i, is

$$L_i = \sum_j j q'_{ij},$$

where q'_{ij} is the proportion of the age i fish that are length j and

$$q'_{ij} = \frac{l_j q_{ij}}{\sum_j l_j q_{ij}},$$

where l_j is the proportion of fish that are length j from the length sample, and q_{ij} is the proportion of length-j fish that are age i from the age–length sample. The estimated variance of L_i was approximated by the delta method (Seber, 1982):

$$Var(L_i) = \frac{1}{p_i^4} \sum_j (jp_i - B_i)^2 \left(\frac{l_j(1-l_j)q_{ij}^2}{N_l} + \frac{q_{ij}(1-q_{ij})l_j^2}{n_j} \right)$$
$$- \frac{1}{p_i^4} \sum_k \sum_{j \neq k} \frac{l_j l_k q_{ij} q_{ik} (jp_i - B_i)(kp_i - B_i)}{N_l},$$

where

$$p_i = \sum_j l_j q_{ij},$$
$$B_i = \sum_j j l_j q_{ij},$$

N_l is the size of the length sample, n_j is the size of the length sample at length j, and k is an index of length.

Mean lengths at age by area/depth/sex stratum were pooled across the two years of sampling because the age–length relation should have been stable for a long-lived fish like sablefish:

$$\bar{L}_i = \frac{n_{i1}}{n_i} L_{i1} + \frac{n_{i2}}{n_i} L_{i2},$$

where $\bar{L}_i$ is the pooled mean length at age, and L_{i1} and L_{i2} are the mean lengths at age from 1987 and 1989 based on age–length sample sizes n_{i1} and n_{i2} ($\sum_j n_{ij} = n_i$). Pooled mean lengths at age were fit to the von Bertalanffy age-length model (Ricker, 1975) by nonlinear least squares,

$$\bar{L}_i = L_\infty\left(1 - e^{-K(i - t_0)}\right) + \varepsilon_i,$$

where ε_i is an additive error term, and L_∞, K, and t_0 are model parameters.

Age–length relationships were compared between areas by the likelihood ratio test recommended by Kimura (1980) to determine if a single von Bertalanffy age–length model is common to the compared areas or if areas have area-specific age–length relationships. Age-length relationships were compared by fitting pooled mean length at age, which is appropriate if the corresponding variance of pooled mean length is constant regardless of age (Kimura, 1980). The variance of the pooled mean length, assuming zero covariance, is

$$\operatorname{Var}(\bar{L}_i) = \left(\frac{n_{i1}}{n_i}\right)^2 \operatorname{Var}(L_{i1}) + \left(\frac{n_{i2}}{n_i}\right)^2 \operatorname{Var}(L_{i2}).$$

The variance is assumed constant by age because the width of the length range is generally similar regardless of age (Fig. 2, 3).

Five age–length models were fitted and compared: the full model, M1 = {Shumagin}, {Kodiak}, {Southeastern}, and four reduced models (where areas within brackets have a common age–length relationship): M2 = {Shumagin}, {Kodiak, Southeastern}; M3 = {Shumagin, Southeastern}, {Kodiak}; M4 = {Shumagin, Kodiak}, {Southeastern}; and M5 = {Shumagin, Kodiak, Southeastern}. The increase in the residual sum of squares (RSS) between each of the reduced models and the full model was used to test for area effects. Use of the reduced model, being more parsimonious, was justified when area effects were not statistically significant. Tests were conducted for each of the four data sets: shelf female, slope female, shelf male, and slope male.

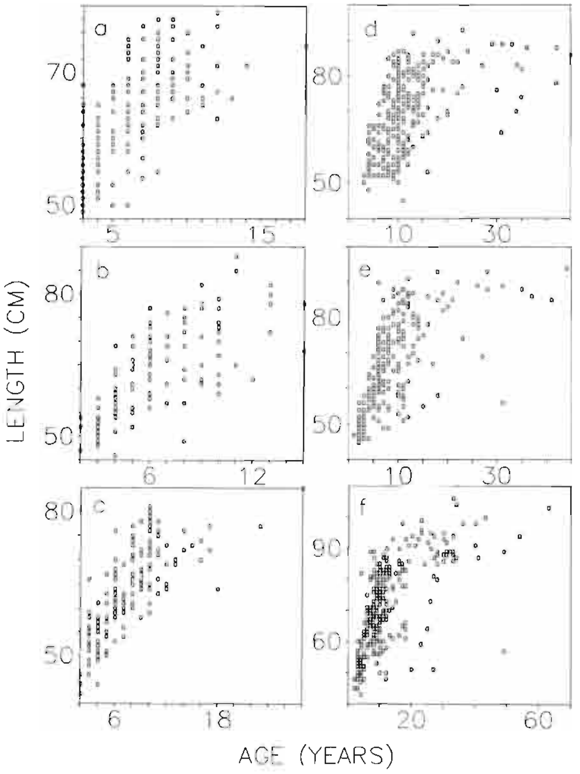

Figure 2
Observed age–length data for female sablefish: (a) Shumagin, (b) Kodiak, and (c) Southeastern shelf; (d) Shumagin, (e) Kodiak, and (f) Southeastern slope. Note variable scale of *x* and *y* axes.

Kimura's (1980) likelihood approach was not used to compare age–length relationships between depth strata. The age range and therefore the sample sizes were smaller for the shelf than for the slope. As a result, the power of the test to detect differences was low because the RSS and fitted von Bertalanffy curve for the reduced model were dominated by the slope data. Instead, mean lengths at age by shelf and slope were compared statistically by the *Z* test,

$$Z = \frac{\bar{L}_i - \bar{L}'_i}{\sqrt{\operatorname{Var}(\bar{L}_i) + \operatorname{Var}(\bar{L}'_i)}}.$$

The null hypothesis is $H_0 = \bar{L}_i = \bar{L}'_i$, and the critical region for $H_a : \bar{L}_i \neq \bar{L}'_i$ is $|Z| \geq Z_{1-\alpha/2}$ where $\alpha = 0.05$. The *Z* test assumes that the true variance is known; thus the stated α is optimistic.

We also computed mean age at length to compare shelf and slope. The computation of mean age at length is simpler than the computation of mean length at age because a random sample for ageing was collected for each length. The mean age at length, A_j, is

$$A_j = \frac{\sum_k a_{jk}}{n_j^*},$$

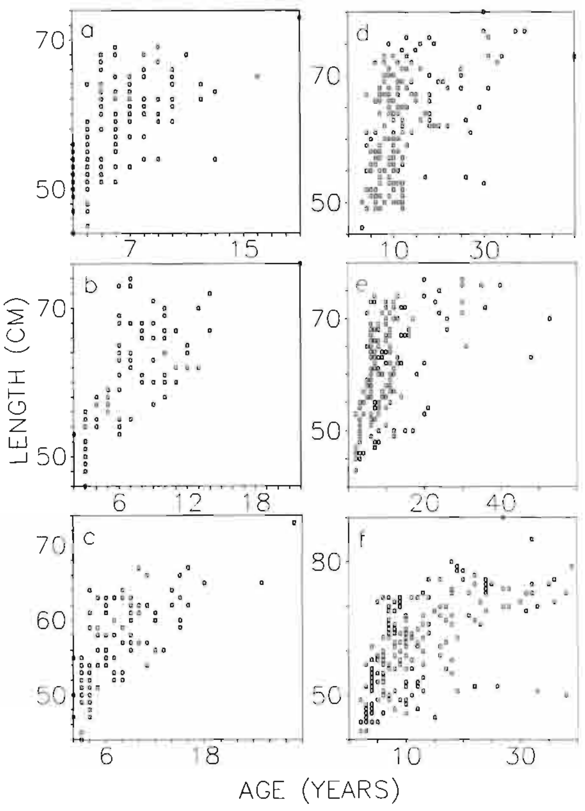

Figure 3

Observed age-length data for male sablefish: (a) Shumagin, (b) Kodiak, and (c) Southeastern shelf; (d) Shumagin, (e) Kodiak, and (f) Southeastern slope. Note variable scale of x and y axes.

where n_j^* is the age sample size at length j, and a_{jk} is the age of the kth individual at length j. The estimated variance of A_j is

$$\mathrm{Var}(A_j) = \frac{\sum_k (a_{jk} - A_j)^2}{n_j^* (n_j^* - 1)}.$$

We used the Z test to compare the mean ages at length between shelf and slope because of the smaller sample size for the shelf.

Results

Table 1

Estimated von Bertalanffy growth parameters (L_∞, K, t_0) and residual sums of squares (RSS) for sablefish collected in the Gulf of Alaska in June–September, 1987 and 1989.

Area	L_∞	K	t_0	RSS
Females				
Shelf				
Shumagin	74.1	0.171	–5.4	123.6
Kodiak	70.7	0.403	–0.9	450.1
Southeastern	75.6	0.169	–4.0	661.7
Slope				
Shumagin	78.9	0.114	–9.4	1,937.6
Kodiak	78.5	0.204	–3.1	3,324.5
Southeastern	85.4	0.112	–6.5	5,036.3
Males				
Shelf				
Shumagin	63.7	0.344	–1.9	343.8
Kodiak	65.2	0.341	–2.0	398.5
Southeastern	70.9	0.069	–16.4	242.7
Slope				
Shumagin	74.8	0.033	–43.9	1,016.7
Kodiak	66.5	0.243	–3.5	1,280.2
Southeastern	67.9	0.190	–4.9	2,625.6

The age range for samples from the shelf was 2–28 years for females (Fig. 2a–c), and 2–29 years for males (Fig. 3a–c). Most fish were under age 20, except for two females and two males from the Southeastern area and one male from the Kodiak area. Slope females were age 1–63 (Fig. 2d–f) and males age 2–53 (Figs. 3d–f). All samples from the slope were under age 54 but one, an age-63 female from the Southeastern area.

The estimated asymptotic lengths (L_∞) for females were much larger than those for males from corresponding depths and areas (Table 1). Shumagin shelf males had the smallest asymptotic length. Southeastern slope females had the largest asymptotic length. The value of t_0 was unusually low for Southeastern shelf males and Shumagin slope males.

The resulting models for age-length relationships by depth are {Shumagin}, {Kodiak}, {Southeastern} for shelf females; {Shumagin, Kodiak}, {Southeastern} for shelf males; and {Shumagin, Kodiak, Southeastern} for slope males (Table 2). For slope females, no significant difference was detected between Shumagin and Kodiak areas—{Shumagin, Kodiak}, {Southeastern}—and between Kodiak and Southeastern—{Shumagin}, {Kodiak, Southeastern}. However, because Shumagin differed significantly from Southeastern, the areas could not be pooled. The von Bertalanffy growth parameters for the pooled areas are listed in Table 3.

Mean length at age often was significantly greater for the slope than for the shelf (Fig. 4). A large number (67) of comparisons were made. From the criterion $\alpha = 0.05$, one would expect about three cases with a statistically significant difference if true mean lengths were

Table 2

Five models of the age–length relationship for sablefish compared within each of the four groups: shelf female, slope female, shelf male, and slope male. The reduced model with a residual sum of squares (RSS) not significantly greater than the RSS for the full model ({Shumagin}, {Kodiak}, {Southeastern}) is the most reasonable. * indicates the most reasonable model within each group.

Model	RSS	χ^2	p	r
Female				
Shelf				
{Shumagin} {Kodiak} {Southeastern}	*1,235.5			
{Shumagin, Kodiak} {Southeastern}	1,514.3	9.158	0.027	3
{Shumagin, Southeastern} {Kodiak}	1,778.5	16.394	0.001	3
{Shumagin} {Kodiak, Southeastern}	2,228.4	26.544	0.000	3
{Shumagin, Kodiak, Southeastern}	2,407.3	30.019	0.000	6
Slope				
{Shumagin} {Kodiak} {Southeastern}	10,298.4			
{Shumagin, Kodiak} {Southeastern}	*11,011.5	6.762	0.080	3
{Shumagin, Southeastern} {Kodiak}	11,536.8	11.469	0.009	3
{Shumagin} {Kodiak, Southeastern}	*10,725.3	4.103	0.251	3
{Shumagin, Kodiak, Southeastern}	12,106.2	16.335	0.012	6
Male				
Shelf				
{Shumagin} {Kodiak} {Southeastern}	985.0			
{Shumagin, Kodiak} {Southeastern}	*1,098.8	4.917	0.178	3
{Shumagin, Southeastern} {Kodiak}	1,355.3	14.360	0.002	3
{Shumagin} {Kodiak, Southeastern}	1,674.3	23.871	0.000	3
{Shumagin, Kodiak, Southeastern}	1,712.1	24.876	0.000	6
Slope				
{Shumagin} {Kodiak} {Southeastern}	4,922.4			
{Shumagin, Kodiak} {Southeastern}	5,179.0	4.826	0.185	3
{Shumagin, Southeastern} {Kodiak}	5,200.0	5.212	0.157	3
{Shumagin} {Kodiak, Southeastern}	4,959.8	0.719	0.869	3
{Shumagin, Kodiak, Southeastern}	*5,253.3	6.180	0.403	6

equal. But 21 cases differed significantly; 18 were cases where mean length at age was greater on the slope. Mean length of several ages between 4 and 8 in the Shumagin area (Fig. 4a, d); between 5 and 12 in the Kodiak area (Fig. 4b, e), and between 4 and 8 in the Southeastern area (Fig. 4c, f) was significantly greater on the slope.

Mean age at length often was greater for the slope than for the shelf (Fig. 5). In the Shumagin area, mean age at length differed significantly for most 52–75-cm FL females and 49–69-cm FL males (Fig. 5a, d). A large number (49) of comparisons were made. Although one would expect about 3 of these to differ significantly at $\alpha = 0.05$ if true mean ages were equal, 30 did. In the Kodiak and Southeastern areas, few differences in mean age at length were statistically significant. Although the differences were not significant, mean age at length was consistently less for the shelf than for the slope: 41 of 54

Table 3

Estimated von Bertalanffy growth parameters (L_∞, K, t_0) and residual sums of squares (RSS) for areas with common age–length relationships.

Pooled areas	L_∞	K	t_0	RSS
Females				
Slope				
{Shumagin, Kodiak}	77.4	0.181	–4.3	5,975.2
{Kodiak, Southeastern}	83.2	0.134	–5.4	8,787.7
Males				
Shelf				
{Shumagin, Kodiak}	64.9	0.303	–2.5	856.1
Slope				
{Shumagin, Kodiak, Southeastern}	67.5	0.176	–6.0	5,253.3

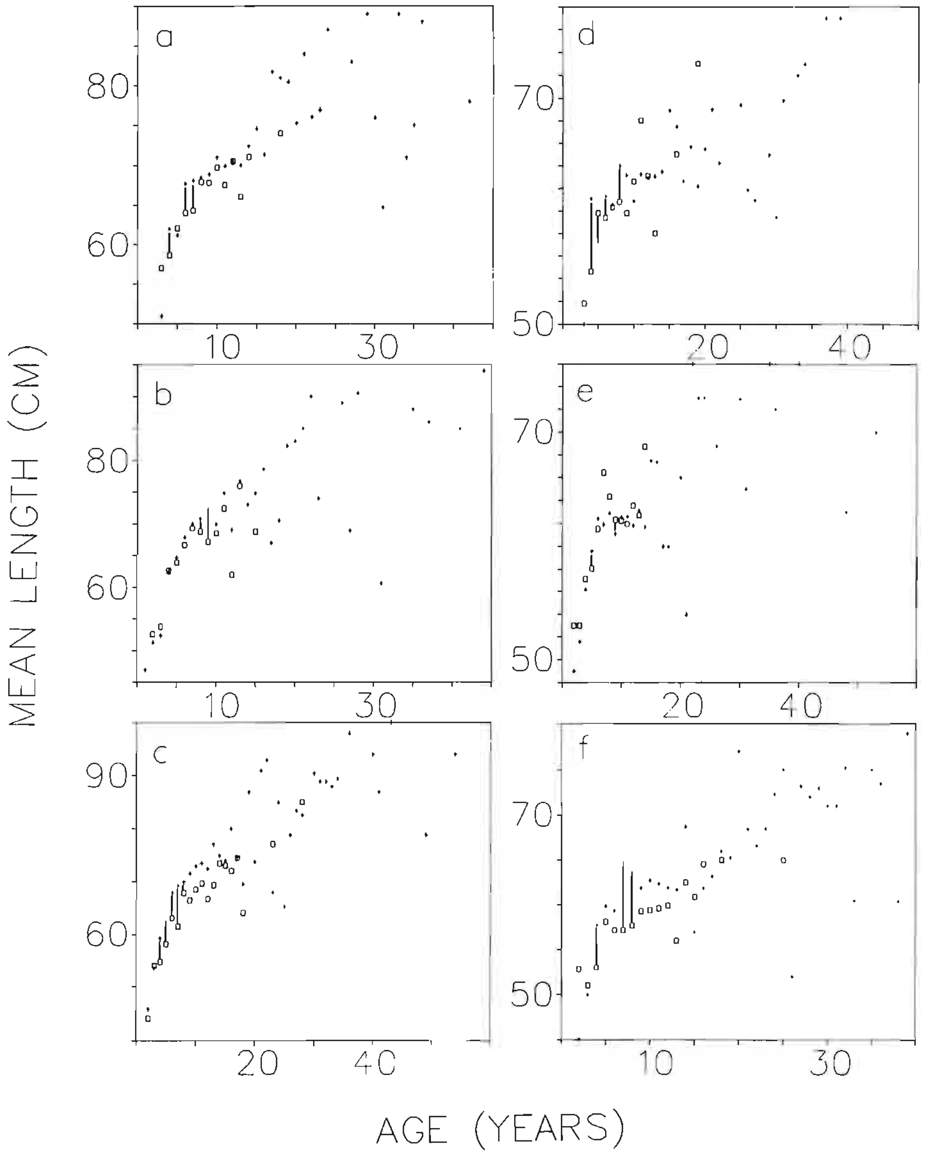

Figure 4

Sablefish mean length (cm) at age for the shelf (☐) and slope (+): (a) Shumagin, (b) Kodiak, and (c) Southeastern females; (d) Shumagin, (e) Kodiak, and (f) Southeastern males. A vertical line indicates that mean length differed significantly (P=0.05) for the shelf and slope.

cases in Kodiak, and 38 of 51 cases in the Southeastern area.

Discussion

The growth parameters estimated in this study (Table 1) are similar to those estimated for Gulf of Alaska sablefish by Lai (1985) and McDevitt (1990) and for British Columbia sablefish by McFarlane and Beamish (1983). For example, we found that female sablefish had greater asymptotic lengths than males, a result in agreement with other Gulf of Alaska growth studies (Lai, 1985; McDevitt, 1990). Also, females from the Southeastern area clearly had a much greater asymptotic length than other females. Lai (1985) also found that Southeastern females reached a markedly greater asymptotic length than females from the Yakutat and Shumagin-Chirikof areas.

The values of t_0 for shelf males in the Southeastern area and slope males in the Shumagin area were unusu-

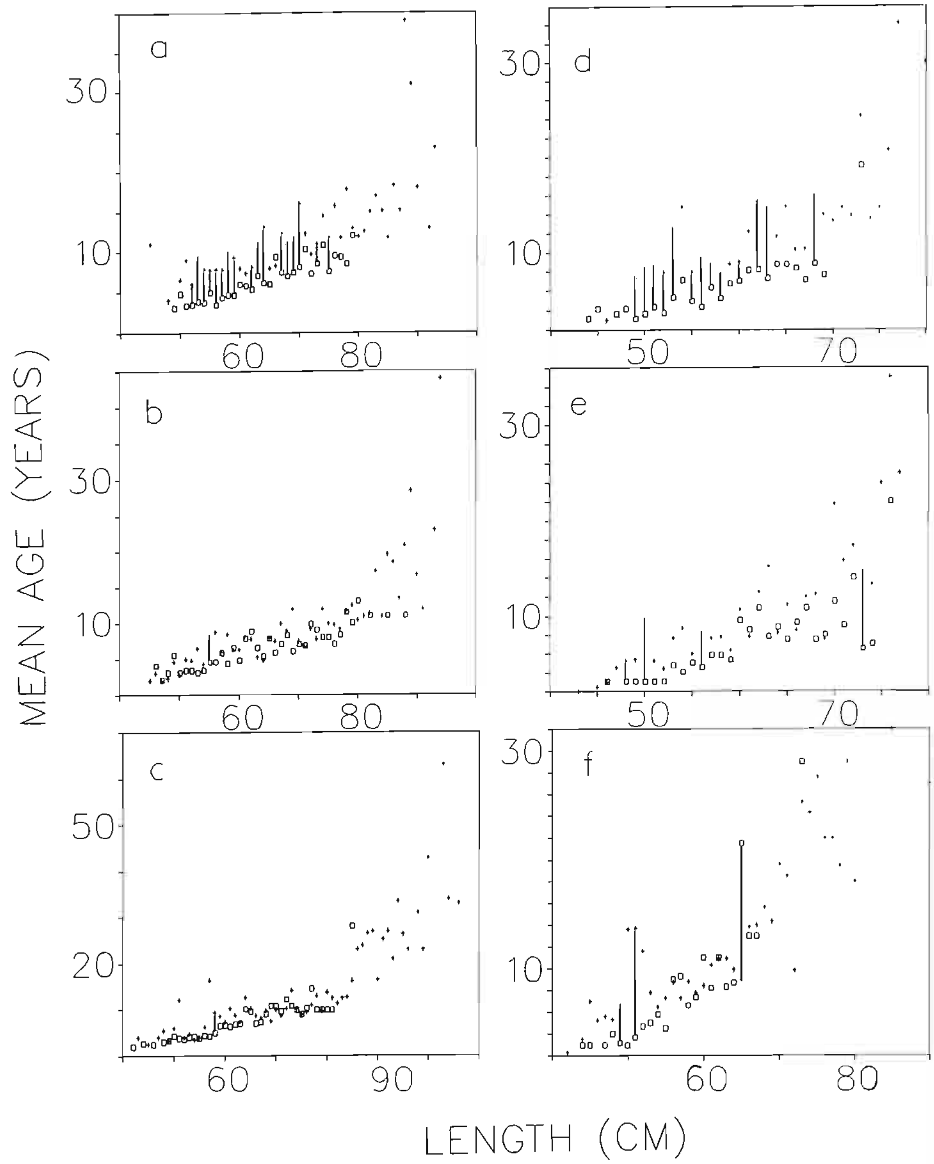

Figure 5

Sablefish mean age at length (cm) for the shelf (□) and slope (+): (a) Shumagin, (b) Kodiak, and (c) Southeastern females; (d) Shumagin, (e) Kodiak, and (f) Southeastern males. A vertical line indicates that mean length differed significantly ($P=0.05$) for the shelf and slope.

ally small compared to values of t_0 from other areas in this study (Table 1) as well as previous studies (Lai, 1985; McDevitt, 1990). The unusual t_0 values appear to result from the small sample size of fish <4 years old (Fig. 3c, d) and the lack of curvature in the shape described by the data points for these two areas (Fig. 4d, f).

Lai (1985) tested for depth differences in the age-length relationship, but did not find significant differences by depth as in this study, possibly because he compared depth strata (100–400 m and 600–1000 m) different from ours (100–200 m and 400–1,000 m). Further, the age ranges were similar in the two depths in Lai's study, whereas our shallow stratum contained younger and smaller fish than the deeper stratum. The difference between 100–200 m and 400–1,000 m may have been masked by Lai's pooling depths from 100 to 400 m. Alternatively, the disagreement between the studies may reflect changes in population structure between the sampling times for Lai's study (1982, 1983) and our study (1987, 1989). However, sablefish are long-lived compared to the time interval involved, so one would expect the depth differences to be similar.

Initially, we expected one growth model to fit all areas, at least for slope fish, because sablefish are highly migratory (Heifetz and Fujioka, 1991), implying substantial mixing of the population. The slope fish are more likely to have similar age–length relationships among areas because their ages encompass a wide range and older fish have had more time for extensive movement. As suspected, the age–length relationships generally were similar on the slope; for males, they did not differ significantly between areas; and for females, they did not differ significantly between Shumagin and Kodiak or between Kodiak and Southeastern areas.

On the shelf, all age–length relationships differed for females, and all but Shumagin and Kodiak differed for males, suggesting that grouping may occur within the population of migrating fish. Young sablefish on the shelf are in the age interval when growth is fastest, and thus environmental effects on their growth rates may be apparent. If fish are grouped within a highly migratory population, then environmental effects would appear as differences between growth in the areas. The differences in growth may be masked for fish on the slope: they are older, grow much more slowly, and have had time to mix.

Juvenile sablefish live near shore, whereas adults primarily inhabit the outer coastal waters of the upper continental slope (generally depths 200–1,000 m). This study provides some information on offshore movement because sampling was stratified by depth. The observation that mean size at age often was greater for the slope than for the shelf (Fig. 4) can be explained if, given age, smaller fish tend to be on the shelf and larger fish tend to be on the slope. This pattern implies that faster-growing fish in an age group are in deeper water. The observation that mean age at size usually was greater for the slope (Fig. 5) can be explained if, given size, younger fish tend to be on the shelf and older fish tend to be on the slope. This pattern implies that older fish at a given size are in deeper water.

One explanation of these patterns is that sexual maturation triggers directed movement to deeper water, and the probability of maturation increases with age and size. If true, an older fish of a given size is more likely to have matured and moved to the slope than a younger fish, and a larger fish of a given age is more likely to have matured and moved to the slope than a smaller fish, as was observed. An ontogenetic change other than maturation may trigger directed movement to deep water. Lactate dehydrogenase is pressure-insensitive in longspine thornyhead, *Sebastolobus altivelis*, and is an adaptation to deep water (Siebenaller and Somero, 1978). Sablefish may possess a deepwater adaptation that develops ontogenetically.

Another explanation of these patterns is that fish who reach the slope grow faster than fish who remain on the shelf. This explanation, however, does not account for why the mean age at length is greater on the slope. This explanation also seems unlikely because of the lower productivity of the slope.

A third explanation of these patterns does not require directed movement to deeper water by sablefish and therefore is more parsimonious: random movement of fish from shallow to deep water, where they remain. If individual fish move randomly on the shelf, they eventually encounter the slope by chance, for the slope is a finite distance from the nearshore areas where the juveniles live, and sablefish have been shown to travel long distances (Heifetz and Fujioka, 1991). The fish tend to be older on the slope because it takes time for individuals to randomly encounter the slope. At a given length, an older fish is more likely to have encountered the slope than a younger fish. Once there, fish remain on the slope. If, in addition, movement rate is positively correlated to fish size (i.e., if big fish swim faster than small fish), then larger fish at a given age will tend to be in deeper water because they have a greater chance of encountering the slope within a prescribed time. Thus the differences in the age–length relationship by depth can be explained by individual fish moving randomly from nearshore to offshore, where they remain, and by faster-growing fish moving more quickly.

Literature Cited

Beamish, R. J., and D. E. Chilton.
1982. Preliminary evaluation of a method to determine the age of sablefish (*Anoplopoma fimbria*). Can. J. Fish. Aquat. Sci. 39:277–287.

Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11:355–374.

Kastelle, C. R.
1991. Radioisotope age validation and an estimate of natural mortality from the gonad to somatic weight index for sablefish (*Anoplopoma fimbria*). M.S. thesis, Univ. Washington, Seattle.

Kimura, D. K.
1980. Likelihood methods for the von Bertalanffy growth curve. Fish. Bull. 77:765–775.

Kimura, D. K., and S. Chikuni.
1987. Mixtures of empirical distributions: an iterative application of the age–length key. Biometrics 43:23–35.

Lai, H.-L.
1985. Evaluation and validation of age determination for sablefish, pollock, Pacific cod and yellowfin sole; optimum sampling design using age–length key; and implications of aging variability in pollock. Ph.D. dissert., Univ. Washington, Seattle, 426 p.

McDevitt, S. A.
1990. Growth analysis of sablefish (*Anoplopoma fimbria*) from mark-recapture data from the northeast Pacific. M.S. thesis, Univ. Washington, Seattle, 87 p.

McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters off western Canada. *In* Proceedings of the International Sablefish Symposium, p. 59–80. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

Ricker, W. E.
1975. Computation and interpretation of biological statistics of fish populations. Fish. Res. Board Can. Bull. 191, 382 p.

Sasaki, T.
1985. Studies on the sablefish resources in the North Pacific Ocean. Bull. Far Seas Fish. Res. Lab. (Shimizu) 22, 108 p.

Seber, G. A. F.
1982. The estimation of animal abundance and related parameters, 2nd ed. Charles Griffin, London, 654 p.

Siebenaller, J., and G. N. Somero.
1978. Pressure-adaptive differences in lactate dehydrogenases of congeneric fishes living at different depths. Science 201:255–257.

Wilderbuer, T. K. (ed.).
1989. Condition of groundfish resources of the Gulf of Alaska in 1988. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-165.

Feeding Habits of Sablefish, *Anoplopoma fimbria*, off the Coast of Oregon and California

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ABSTRACT

The stomach contents of 1,868 sablefish, *Anoplopoma fimbria*, were examined from nine bottom trawl cruises between 1987 and 1992. The sablefish were found to be highly piscivorous. Their diet varied with length: the smallest sablefish ate mostly fish and small crustaceans, and the largest sablefish ate fish and cephalopods. Smaller sablefish took more prey that originated in midwater; larger sablefish foraged predominately on the benthos. The size of the prey increased with an increase in sablefish length. As noted in existing literature, change in diet with length coincided with a size–depth relationship in which smaller sablefish were found in shallow water, and larger fish occurred at varying depths, except in the shallowest areas. Geographic differences were evident: sablefish in the south consumed more midwater prey than those in the north.

Introduction

Sablefish from trawl landings off the U.S. west coast are typically caught with a mixture of other species including Dover sole, *Microstomus pacificus*, and thornyheads, *Sebastolobus* spp. This complex accounts for approximately 40% of groundfish landings, excluding Pacific whiting, *Merluccius productus*. Sablefish ranked second in landings of this complex (after Dover sole) and are third in overall trawl landings (after Pacific whiting and Dover sole; Pacific Fishery Management Council[1]). Landings have decreased in the last ten years, mostly because of management constraints.

Despite their importance in commercial landings, little has been published about the trophic ecology of sablefish. Sablefish are carnivores, feeding primarily on fishes (Grinols and Gill, 1968; Cailliet et al., 1988). Top predators play an important role within the community by controlling species composition and abundance (Regier et al., 1979). Since sablefish have an estimated biomass of 152,323 t (Methot[2]), their predation is likely to have indirect effects that cascade down through the system. Therefore, we examined sablefish feeding and its implications for trophic interactions and management.

Methods

Sablefish stomach samples were collected on nine bottom trawl cruises from 1987 to 1992. Cruises were con-

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[1] Pacific Fishery Management Council. 1992. Status of the Pacific coast groundfish fishery through 1992 and recommended acceptable biological catches for 1993. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland OR, 80 p.

[2] Methot, R. D. 1993. Assessment of the west coast sablefish stock in 1994. *In* Appendices to the status of Pacific Coast groundfish fishery through 1993 and recommended acceptable biological catches for 1994, Appendix B, 31 p. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland, OR 97201.

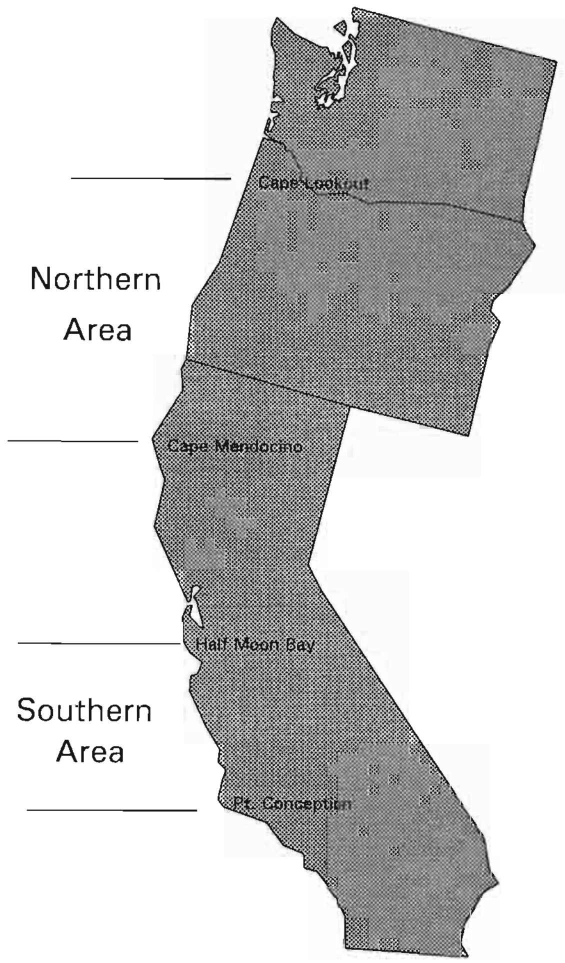

Figure 1
Map of the survey area showing northern (from 45°23' to 40°32'N) and southern (37°31' to 34°31'N) areas.

ducted off the coast of Oregon and California, in two areas: northern (Cape Mendocino, CA, to Cape Lookout, OR) and southern (Pt. Conception, CA, to Half Moon Bay, CA; Fig. 1). All cruises took place in fall or winter. Trawl stations were placed on fixed tracklines stratified into six depth strata: 183–366, 367–549, 550–732, 733–914, 915–1,097, and 1,098–1,280 m (100–199, 200–299, 300–399, 400–499, 500–599, and 600–699 fm). Stations were randomly placed within the depth strata. A total of 286 trawls were made (190 in the northern area and 96 in the southern area). Trawls lasted 30 minutes at depth for depths shallower than 732 m, and one hour for depths 732 m and deeper.

Catch sampling and processing followed procedures outlined by Smith and Bakkala (1982). Up to 15 fish were selected from any one trawl for stomach samples; only non-empty stomachs were used. Fish were selected to cover the entire length range found in the trawl sample.

In the laboratory, total volume was determined for each stomach. Prey from stomach samples were identified to the lowest taxon possible and enumerated. When possible, prey lengths (mm) were measured (standard length for fish, carapace length for crustaceans, mantle length for cephalopods, and the longest body diameter for the remaining taxa). The relative volume for each taxonomic group in a stomach was calculated. Frequency of occurrence was determined for each prey item individually and grouped by taxon; it was defined as the number of stomachs with that specific prey item (or taxon) divided by the total number of stomachs. Mean number of prey was calculated for each prey item individually and grouped by taxon. Prey species were classified by habitat (whether they spent greater than 50% of their time in the water column or on the bottom). An index of relative importance (IRI) was computed for each taxon (Pinkas, 1971) by multiplying percent frequency of occurrence by the sum of percent by relative volume and percent by number. Horn's index of overlap was calculated with the IRI data to compare sablefish diet from the north and south areas (Krebs, 1989). Sufficiency of sample size was shown by plotting the cumulative number of prey taxa against the number of stomachs examined (Cailliet et al., 1988).

Size analysis of sablefish feeding was conducted by pooling sablefish into length classes. To analyze general patterns in sablefish diet with size, we used the following length classes: less than 300, 300–399, 400–499, 500–599, 600–699, and more than 699 mm FL. For simplicity, we refer to these length classes by their midpoint value (e.g., 400–499 mm as 450 mm). For the studies of diet change with depth for same-sized fish, and of prey habitat versus size, we used smaller length classes with a range of 50 mm (e.g., 550–599 mm) to give sharper definition to trends with size.

We used regressions and correlations to give a sense of scale to increasing or decreasing trends in the following comparisons: diet measures (percent frequency of occurrence, percent diet volume, and mean number per sablefish) versus length classes of sablefish, and versus depth of capture; size of individuals in a prey taxon versus sablefish length; sablefish length versus depth of capture; and prey habitat versus sablefish length. We examined heterogeneity of slopes to detect differences in trends for sablefish length and depth between the north and south areas.

Results

Overall Diet

Fishes were the major prey of all sablefish combined, accounting for more than 75% of diet volume, occurring in greater than 63% of the sablefish sampled, and having a high IRI value of 4,911.6 (Table 1). Of the identifiable prey fish, scorpaenids—*Sebastolobus alascanus*, *S. altivelis*, and various species of *Sebastes*—accounted for the largest portion of the percent diet volume, highest IRI, and highest frequency of occurrence. A complex of midwater fishes including Pacific whiting, myctophids, and bathylagids ranked second in percent diet volume, IRI, and frequency of occurrence. Within this midwater complex, Pacific whiting accounted for 82.4% of the diet volume, had the highest IRI, and made up nearly half the total number of midwater fish eaten. Pacific whiting had a frequency of occurrence of 4.6%, again about half of all midwater fish. Unidentifiable fish made up a large portion of fish prey, accounting for almost one quarter of the diet volume and occurring in over 40% of the sablefish stomachs. Two adult sablefish each ate a single sablefish.

Invertebrates accounted for a much smaller diet volume than fish, about one quarter of the IRI, and were present at lower frequencies. Cephalopods—mainly squids (Teuthoidea)—were the dominant invertebrate prey. Squids constituted 7.4% of diet volume, were found in 9.8% of the sablefish, and had the highest IRI of all invertebrates. Heteropods—*Carinaria* spp.—were the next most abundant prey, present in 9.5% of all sablefish. Another prominent gelatinous prey was thaliaceans, present in over 6% of the sablefish. Of the remaining invertebrate prey, shrimps (natantian decapods)—most abundantly *Sergestes similis*—crabs (reptantian decapods)—most abundantly *Chionoecetes tanneri*—and small crustaceans, including mysids, gammarid amphipods, and euphausiids, were common components of the diet.

Some major differences were found between the diets of sablefish taken in the south and those from the north. The Horn's index of overlap of 0.36 indicates low similarity between sablefish diets in these two areas. Large gelatinous prey (heteropods and thaliaceans) were more important in the southern diet (Table 2, 3). Heteropods had a higher frequency of occurrence in the south (26.2% vs. 0.3% in the north), percent diet volume (14.5% vs. 0.03%), average number per sablefish (0.2 vs. 0.01), and IRI (386.7—the highest of any prey group in the south—vs. <0.1). Thaliaceans also had a higher frequency of occurrence in the south (13.5% vs. 2.9% in the north), percent diet volume (9.6% vs. 0.9%), and IRI (130.7 vs. 3.1), whereas the average number per sablefish was similar in the south (0.1) and north (0.2). Fish showed the opposite trend: in the south they were lower in percent occurrence (52.3% vs. 74.2% in the north), percent diet volume (51.0% vs. 80.4%), and IRI (122.5 vs. 6,072.9). Sablefish ate similar numbers of fish in both the south (1.6) and the north (1.5).

Cumulative prey curves for all fish and for fish from the northern or southern regions showed that adequate samples were taken in each analysis (Fig. 2, 3).

Change in Diet with Fish Size and Depth

Diet, characterized as percent frequency of occurrence in all guts within a length class, varied with increasing sablefish length, and length increased with depth. However, this change in diet composition with depth occurred only for a few prey groups.

Diet Change with Length—The composition of the sablefish diet changed with length (Fig. 4–6). Fish were the

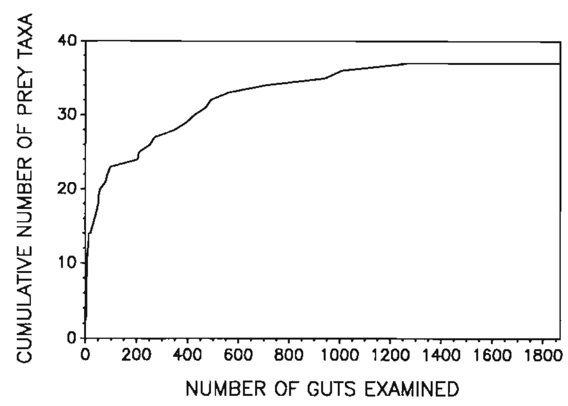

Figure 2
Cumulative number of prey taxa by the number of sablefish stomachs examined, for all sablefish.

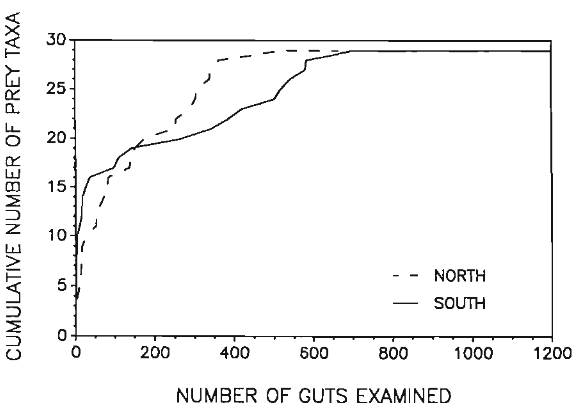

Figure 3
Cumulative number of prey taxa by the number of sablefish stomachs examined, for sablefish from the northern area (dashed line) and southern area (solid line).

Table 1

Average diet of all sablefish, *Anoplopoma fimbria*, captured from California and Oregon, 1987–92 (N = 1,868 sablefish).

Prey	Number per sablefish	% Diet volume	Avg size of prey	FO[1] (%)	IRI[2]	Habitat[3]
Pisces (all)	1.500	76.45	116.99	63.01	4,911.6	
Benthic Pisces	0.177	40.94	164.30	16.32	1,623.4	B
Myxinidae	0.007	1.18	204.00	0.64	0.8	B
Eptatretus deani	0.002	0.41	209.00	0.16	0.1	B
E. stoutii	0.002	0.72	365.00	0.21	0.2	B
Myxinidae egg case	0.003	0.04	37.50	0.21	<0.1	B
Petromyzonidae	0.001	0.01	200.00	0.05	<0.1	B
Chondrichthyes	0.005	0.70	275.00	0.48	0.3	U
Chondrichthyes unid.	0.002	0.03	0.00	0.16	<0.1	U
Apristurus brunneus	0.001	0.05	150.00	0.05	<0.1	B
Scyliorhinid egg case	0.001	0.00	0.00	0.05	<0.1	B
Squalus acanthias	0.002	0.35	400.00	0.16	0.1	U
Rajidae	0.001	0.27	0.00	0.05	<0.1	B
Chimaeridae						
Hydrolagus colliei	0.001	0.27	0.00	0.05	<0.1	B
Pleuronectiformes	0.004	0.61	158.60	0.37	0.2	B
Pleuronectiformes unid.	0.001	0.03	0.00	0.05	<0.1	B
Embassichthys bathybius	0.001	0.00	58.00	0.05	<0.1	B
Lyopsetta exilis	0.002	0.27	158.33	0.16	<0.1	B
Microstomus pacificus	0.001	0.31	260.00	0.11	<0.1	B
Macrouridae	0.001	0.46	190.00	0.11	0.1	B
Albatrossia pectoralis	0.001	0.30	190.00	0.05	<0.1	B
Coryphaenoides acrolepis	0.001	0.16	0.00	0.05	<0.1	B
Alepocephalidae						
Alepocephalus tenebrosus	0.002	0.81	173.33	0.16	0.1	B
Anoplopomatidae						
Anoplopoma fimbria	0.001	0.39	0.00	0.11	<0.1	B
Liparididae						
Careproctus melanurus	0.001	0.31	140.00	0.11	<0.1	B
Cottidae	0.001	0.00	25.00	0.11	<0.1	B
Scorpaenidae	0.149	35.39	120.06	13.70	486.9	B
Scorpaenidae unid.	0.001	0.05	105.00	0.11	<0.1	B
Sebastes alutus	0.002	0.86	175.00	0.16	0.1	B
S. caurinus	0.001	0.12	130.00	0.05	<0.1	B
S. crameri	0.002	0.45	192.50	0.11	<0.1	B
S. diploproa	0.001	0.16	150.00	0.05	<0.1	B
S. jordani	0.002	0.78	116.67	0.16	0.1	B
S. spp.	0.003	0.53	110.00	0.32	0.2	B
Sebastolobus alascanus	0.004	1.41	153.71	0.43	0.6	B
S. altivelis	0.132	30.20	117.64	12.10	367.0	B
S. spp.	0.002	0.82	110.00	0.21	0.2	B

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[1] FO = frequency of occurence.

[2] IRI = index of relative importance.

[3] U = undetermined; B = benthic; WC = water column.

Table 1 (continued)

Prey	Number per sablefish	% Diet volume	Avg size of prey	FO[1] (%)	IRI[2]	Habitat[3]
Zoarcidae	0.005	0.82	123.75	0.48	0.4	B
Zoarcidae unid.	0.003	0.19	101.00	0.27	0.1	B
Bothrocara remigerum	0.001	0.24	310.00	0.05	<0.1	B
Lycodes diapterus	0.001	0.32	80.00	0.11	<0.1	B
L. pacifica	0.001	0.07	95.00	0.05	<0.1	B
Midwater Pisces	0.085	13.48	123.05	8.24	111.8	WC
Merlucciidae						
Merluccius productus	0.047	11.11	169.27	4.55	50.8	WC
Bathylagidae	0.008	1.08	112.69	0.80	0.9	WC
Bathylagidae unid.	0.006	0.50	111.67	0.59	0.3	WC
Bathylagus pacificus	0.002	0.58	136.67	0.16	0.1	WC
Leuroglossus stilbius	0.001	0.00	50.00	0.05	<0.1	WC
Chauliodontidae						
Chauliodus macouni	0.004	0.48	176.67	0.43	0.2	WC
Clupeidae	0.001	0.16	120.00	0.05	<0.1	WC
Engraulididae						
Engraulis mordax	0.001	0.00	25.00	0.05	<0.1	WC
Malacosteidae						
Tactostoma macropus	0.001	0.19	220.00	0.11	<0.1	WC
Nemichthyidae	0.001	0.05	440.00	0.11	<0.1	WC
Nemichthyidae unid.	0.001	0.03	440.00	0.05	<0.1	WC
Nemichthys scolopaceus	0.001	0.01	0.00	0.05	<0.1	WC
Scomberesocidae						
Cololabis saira	0.005	0.07	115.00	0.43	<0.1	WC
Myctophidae	0.018	0.35	74.45	1.77	0.7	WC
Myctophidae	0.013	0.05	61.46	1.23	0.1	WC
Lampanyctus ritteri	0.002	0.26	126.25	0.21	0.1	WC
Stenobrachius leucopsarus	0.002	0.04	57.50	0.16	<0.1	WC
Tarletonbeania crenularis	0.002	0.00	70.00	0.16	<0.1	WC
Pisces misc.	1.238	22.02	83.50	41.33	961.3	U
Pisces unid. (entire animal)	0.238	19.52	109.68	23.82	470.6	U
Pisces bones	0.196	2.28	176.67	16.06	39.8	U
Pisces scales	0.027	0.00	0.00	0.64	<0.1	U
Demersal Pisces egg	0.536	0.09	8.32	0.75	0.5	U
Pisces egg case	0.236	0.13	21.50	0.27	0.1	U
Pisces larvae	0.005	0.01	20.40	0.37	<0.1	U
Algae	0.003	0.02	0.00	0.27	<0.1	B
Invertebrata	3.967	23.15	55.72	50.91	1,380.5	U
Porifera	0.001	0.01	0.00	0.11	<0.1	B

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Table 1 (continued)

Prey	Number per sablefish	% Diet volume	Avg size of prey	FO[1] (%)	IRI[2]	Habitat[3]
Hydrozoa	0.001	0.03	0.00	0.05	<0.1	WC
Scyphozoa	0.001	0.00	0.00	0.11	<0.1	WC
Anthozoa	0.005	0.08	72.50	0.37	<0.1	B
Nemertea	0.001	0.00	80.00	0.05	<0.1	B
Polychaeta	0.027	0.06	64.06	1.71	0.1	B
Polychaeta unid.	0.008	0.01	41.25	0.64	<0.1	B
Polychaeta, pelagic	0.001	0.00	110.00	0.11	<0.1	WC
Polychaeta, sedentary	0.001	0.00	90.00	0.05	<0.1	B
Polychaeta tubes	0.001	0.00	0.00	0.11	<0.1	B
Alciopidae	0.001	0.00	60.00	0.05	<0.1	B
Aphrodita spp.	0.005	0.03	64.17	0.43	<0.1	B
Flabelligeridae	0.002	0.00	33.00	0.05	<0.1	B
Glyceridae	0.009	0.03	77.50	0.27	<0.1	B
Gastropoda	0.021	0.49	21.60	1.77	0.9	B
Gastropoda unid.	0.005	0.02	32.00	0.43	<0.1	B
Gastropod egg capsule	0.002	0.18	0.00	0.21	<0.1	B
Amphissa versicolor	0.005	0.01	5.56	0.43	<0.1	B
A. spp.	0.008	0.05	7.81	0.43	<0.1	B
Neptunea priboloffensis	0.001	0.05	0.00	0.11	<0.1	B
Nudibranchia	0.002	0.19	88.00	0.16	<0.1	B
Heteropoda	0.149	4.02	94.15	9.53	39.7	WC
Carinaria japonica	0.020	0.65	63.29	1.18	0.8	WC
C. spp.	0.129	3.37	97.42	8.35	29.2	WC
Bivalvia	0.009	0.10	41.38	0.75	0.1	B
Bivalvia unid.	0.002	0.01	0.00	0.21	<0.1	B
Nuculana conceptionis	0.001	0.00	15.00	0.05	<0.1	B
Solemya spp.	0.006	0.10	0.01	0.48	0.1	B
Cephalopoda	0.185	11.20	86.67	17.56	199.9	U
Cephalopoda unid.	0.063	1.82	57.25	6.10	11.5	U
Octopoda	0.009	0.47	0.00	0.86	0.4	B
Octopoda unid.	0.007	0.47	0.00	0.64	0.3	B
Octopus spp.	0.002	0.00	0.00	0.21	<0.1	B
Teuthoidea	0.103	7.44	89.48	9.79	73.8	WC
Teuthoidea unid.	0.091	4.39	80.12	8.83	39.6	WC
Architeuthidae	0.001	0.48	0.00	0.11	0.1	WC
Galiteuthis spp.	0.001	0.03	200.00	0.05	<0.1	WC
Gonatopsis borealis	0.001	0.33	210.00	0.05	<0.1	WC
Gonatus spp.	0.001	0.00	0.00	0.05	<0.1	WC
Histioteuthis spp.	0.001	0.51	80.00	0.11	0.1	WC
Loligo opalescens	0.004	0.78	93.00	0.32	0.2	WC
Octopoteuthis spp.	0.001	0.29	57.50	0.11	<0.1	WC
Onychoteuthis spp.	0.002	0.60	106.67	0.16	0.1	WC
Vampyromorpha	0.011	1.50	95.00	1.12	2.6	B
Vampyroteuthis infernalis	0.011	1.50	95.00	1.12	2.6	B

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[1] FO = frequency of occurence.
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[3] U = undetermined; B = benthic; WC = water column.

Table 1 (continued)

Prey	Number per sablefish	% Diet volume	Avg size of prey	FO[1] (%)	IRI[2]	Habitat[3]
Small Crustacea	3.261	1.16	24.31	12.10	53.5	U
Crustacea unid.	0.035	0.11	0.00	3.64	0.5	U
Calanoida	0.001	0.00	4.00	0.11	<0.1	WC
Mysidacea	0.020	0.54	51.77	1.98	1.1	WC
Mysidacea unid.	0.002	0.00	13.00	0.16	<0.1	WC
Gnathophausia gigas	0.008	0.11	64.25	0.75	0.1	WC
G. spp.	0.010	0.44	61.40	1.02	0.5	WC
Siriella spp.	0.001	0.00	20.00	0.05	<0.1	WC
Cumacea	0.001	0.00	6.00	0.05	<0.1	B
Isopoda	0.004	0.00	15.20	0.32	<0.1	B
Isopoda unid.	0.003	0.00	18.00	0.27	<0.1	B
Cirolanidae	0.001	0.00	4.00	0.05	<0.1	B
Gammaridea	0.195	0.13	7.49	1.45	0.4	B
Gammaridea unid.	0.170	0.04	8.19	1.12	0.2	B
Gammaridae	0.001	0.01	0.00	0.05	<0.1	B
Lysianassidae	0.025	0.04	5.75	0.21	<0.1	B
Metaphoxus spp.	0.001	0.05	0.01	0.05	<0.1	B
Hyperiidea	0.004	0.01	10.50	0.21	<0.1	WC
Hyperiidea unid.	0.002	0.00	14.25	0.11	<0.1	WC
Hyperiidae	0.001	0.00	3.00	0.05	<0.1	WC
Scina spp.	0.001	0.00	0.00	0.05	<0.1	WC
Euphausiacea	3.001	0.37	17.97	4.93	16.6	WC
Euphausiacea unid.	0.093	0.01	14.67	1.82	0.2	WC
Euphausia pacifica	1.798	0.24	14.25	2.30	4.7	WC
Nematoscelis difficilis	0.002	0.00	20.67	0.16	<0.1	WC
Stylocheiron longicorne	0.001	0.00	12.00	0.05	<0.1	WC
Thysanoessa spinifera	1.107	0.12	23.00	0.75	0.9	WC
Reptantia	0.033	1.91	44.50	2.94	5.7	B
Reptantia unid.	0.011	0.57	22.50	0.75	0.4	B
Calocaris quinqueseriatus	0.001	0.01	0.00	0.05	<0.1	B
Callianassa goniophthalma	0.004	0.15	85.00	0.43	0.1	B
C. spp.	0.001	0.03	48.00	0.11	<0.1	B
Cancer spp. megalopa	0.001	0.00	4.00	0.05	<0.1	B
Chionoecetes tanneri	0.013	1.07	0.00	1.28	1.4	B
Paguridea	0.001	0.00	0.00	0.05	<0.1	B
Pagurus tanneri	0.001	0.00	0.00	0.05	<0.1	B
P. spp.	0.001	0.00	0.00	0.05	<0.1	B
Paralomis spp.	0.001	0.07	0.00	0.11	<0.1	B
Natantia	0.074	0.41	38.21	5.89	2.9	U
Natantia unid.	0.021	0.09	36.50	1.82	0.2	U
Eualus macrophthalmus	0.001	0.00	0.00	0.05	<0.1	WC
E. spp.	0.001	0.00	45.00	0.05	<0.1	WC
Palaemon ritteri	0.001	0.00	40.00	0.05	<0.1	B
Pandalus jordani	0.001	0.05	75.00	0.11	<0.1	B
P. spp.	0.002	0.00	70.00	0.11	<0.1	B
Pasiphaea pacifica	0.003	0.06	60.00	0.27	<0.1	WC
P. tarda	0.002	0.12	150.00	0.16	<0.1	WC
Sergestes similis	0.039	0.08	31.22	3.21	0.2	WC
Spirontocaris spp.	0.006	0.01	12.17	0.16	<0.1	WC
Sipunculida	0.001	0.00	0.01	0.11	<0.1	B

[1] FO = frequency of occurence.

[2] IRI = index of relative importance.

[3] U = undetermined; B = benthic; WC = water column.

Table 1 (continued)

Prey	Number per sablefish	% Diet volume	Avg size of prey	FO[1] (%)	IRI[2]	Habitat[3]
Echiura	0.006	0.02	0.01	0.54	<0.1	B
Asteroidea	0.002	0.02	18.00	0.21	<0.1	B
Ophiuroidea	0.012	0.02	0.01	0.80	<0.1	B
Ophiuroidea unid.	0.010	0.03	0.01	0.59	<0.1	B
Ophiopthalmus normani	0.002	0.01	0.01	0.21	<0.1	B
Echinoidea	0.007	0.02	0.00	0.70	<0.1	B
Holothuroidea	0.038	0.27	0.01	2.78	0.9	B
Holothuroidea unid.	0.009	0.07	0.01	0.75	0.1	B
Scotoplanes spp.	0.028	0.21	0.01	2.09	0.5	B
Ascidiacea	0.004	0.30	35.00	0.37	<0.1	B
Thaliacea	0.125	2.98	66.56	6.26	19.4	WC
Thaliacea unid.	0.058	0.69	55.71	2.84	2.1	WC
Iasis zonaria	0.002	0.01	36.00	0.16	<0.1	WC
Pyrosoma spp.	0.032	1.86	74.57	2.57	4.9	WC
Salpa maxima	0.002	0.00	37.50	0.16	<0.1	WC
S. spp.	0.021	0.09	65.00	0.54	0.1	WC
Thetys vagina	0.009	0.34	71.50	0.43	0.2	WC
Miscellaneous						
Eggs undet.	0.055	0.00	1.22	0.37	<0.1	U
Gravel	0.000	0.00	0.00	0.05	<0.1	B
Sand	0.005	0.04	0.00	0.70	<0.1	B
Tubes undet.	0.002	0.00	0.00	0.11	<0.1	B
Aves	0.006	0.05	0.00	0.27	<0.1	U

[1] FO = frequency of occurence.
[2] IRI = index of relative importance.
[3] U = undetermined; B = benthic; WC = water column.

most frequent prey category throughout all length classes, increasing significantly (slope=0.08%/mm; r^2=0.85; $F_{1,5}$= 23.3; p<0.01) from 45% in sablefish smaller than 300 mm to 75% in sablefish longer than 600 mm. Fish also represented the highest percent diet volume in each length class and increased significantly (slope=0.06%/mm; r^2=0.73; $F_{1,5}$=10.6; p=0.03) from 45% in the smallest length class to greater than 65% in the three largest length classes. Mean number of fish per stomach was low in the smallest length classes (0.45/fish) but higher in larger classes (but not a significant increase—p=0.14), with a peak of 2.7 fish/stomach in the 450-mm length class. Some fish prey species changed in abundance with sablefish length (rockfish and eelpouts decreased while thornyheads increased), although most species showed no change.

Small crustaceans were frequent in smaller sablefish stomachs up to the 350-mm length class, but less so in larger classes. Frequency of occurrence, percent diet volume, and mean number per sablefish all showed this pattern (Fig. 4–6). The peak mean numbers were more extreme than the other measures (Fig. 6); this peak stems largely from two hauls where the sablefish had fed primarily on *Euphausia pacifica.* Other than this feeding on euphausiids, no change in species composition of small crustaceans was noted as length changed.

Heteropods were frequent in the diet of smaller sablefish (at 350–450 mm), but less so in larger fish (Fig. 4–6).

Sablefish fed on different-sized prey as they grew. Thornyheads and cephalopods were significantly larger in the stomachs of larger sablefish. Thornyheads increased in size at a rate of 0.019 mm per 1.0 mm of sablefish length ($F_{1,220}$=13.7; p<0.01). For cephalopods, the rate of increase was 0.027 mm per mm of sablefish length ($F_{1,43}$=6.3; p<0.02). The size of heteropods in sablefish stomachs decreased with increasing sablefish

Table 2

Prey groups eaten by all sablefish from the southern area of the survey.

Prey group	Number	Number per sablefish	% Diet volume	FO[1] (%)	IRI[2]
Pisces	1,909	1.59	51.00	52.33	122.5
Algae	4	0.00	0.06	0.60	<0.1
Porifera	2	0.00	0.01	0.30	<0.1
Nemertea	1	0.00	0.01	0.15	<0.1
Polychaeta	40	0.03	0.42	3.61	1.6
Gastropoda	37	0.03	1.38	4.36	6.1
Heteropoda	275	0.23	14.53	26.20	386.7
Bivalvia	3	0.00	0.01	0.45	<0.1
Cephalopoda unid.	39	0.03	2.60	4.36	11.5
Octopoda	14	0.01	1.05	2.11	2.2
Teuthoidea	77	0.06	9.32	10.98	103.0
Copepoda	2	0.00	0.01	0.30	<0.1
Mysidacea	31	0.03	1.98	4.66	9.4
Cumacea	1	0.00	0.01	0.15	<0.1
Isopoda	5	0.00	0.02	0.60	<0.1
Gammaridea	67	0.06	0.14	2.56	0.5
Euphausiacea	2,080	1.73	0.45	5.86	12.8
Reptantia	32	0.03	3.53	3.91	13.9
Natantia	85	0.07	1.30	9.32	12.8
Sipunculida	2	0.00	0.08	0.30	<0.1
Echiura	7	0.01	0.10	0.90	0.1
Asteroidea	10	0.01	0.19	1.35	0.2
Echinoidea	7	0.01	0.08	1.05	0.1
Holothuroidea	6	0.00	0.26	0.90	<0.1
Ascidiacea	2	0.00	0.10	0.30	<0.1
Thaliacea	127	0.11	9.55	13.53	130.7
Eggs unid.	74	0.06	0.02	0.90	0.1
Tubes unid.	2	0.00	0.01	0.15	<0.1
Aves	1	0.00	0.01	0.15	<0.1

[1] FO = frequency of occurence.

[2] IRI = index of relative importance.

length, but the decrease was not significant at the 0.05 level ($F_{1,67}$=3.6; p=0.06).

Size–Depth Relationship—Sablefish length showed a significant, gradual increase as depth increased, with a high degree of scatter (Fig. 7; slope=0.32 mm/m; $F_{1,16,419}$=9,527; p<0.01; r^2=0.35). Typically, sablefish smaller than 400 mm were found in the shallowest depths (400 m or less). Two groups of small fish were collected at approximately 380 and 840 m. These represent small, pelagic individuals which were probably captured in midwater during either deployment or retrieval of the bottom trawl. The distribution for larger sablefish was not as evident, and they could be found throughout the entire range, except in the shallowest depths (less than 200 m). The distribution patterns were more pronounced in the south (slope=0.4 mm/m; $F_{1,1,545}$=2,241; p<0.01; r^2=0.59) than in the north (slope=0.3 mm/m; $F_{1,5,498}$=2,659; p<0.01; r^2=0.33). The rate of change of length with depth was different in the two areas (a test for heterogeneity of slopes showed a significant difference; depth*geographic area interaction: $F_{1,16,227}$=37.5; p<0.01).

Diet Change with Depth—The only prey groups whose occurrence had a significant relationship with depth over all fish sizes were thaliaceans, small crustaceans, cephalopods, and shrimps. Thaliaceans had a higher frequency of occurrence (slope=3.3%/m; r^2=0.33; $F_{1,13}$=6.3; p=0.03) with increasing depth. On the other hand, small crustaceans, cephalopods, and shrimps had a lower frequency of occurrence with increasing depth. Small crustaceans had a lower frequency of occurrence (slope=–1.4%/m; r^2=0.38; $F_{1,13}$=8.0; p=0.01) and a smaller mean number per sablefish (slope=–1.1 individuals/m; r^2=0.27; $F_{1,12}$=4.5; p=0.05) with an increase in depth. Cephalopods had a lower percent diet volume (slope=–0.01%/m; r^2=0.40; $F_{1,12}$=7.8; p=0.02) with an increase in depth. Shrimps had a significantly lower percent diet volume (slope=–2.4 %/m; r^2=0.32; $F_{1,12}$=5.9; p=0.03) with an increase in depth. Fish showed no

Table 3

Prey groups eaten by sablefish from the northern area of the survey.

Prey group	Number	Number per sablefish	% Diet volume	FO[1] (%)	IRI[2]
Pisces	964	1.45	80.45	74.15	6,072.9
Algae	4	0.01	0.86	0.33	0.3
Hydrozoa	1	0.00	0.09	0.08	<0.1
Scyphozoa	2	0.00	0.01	0.17	<0.1
Anthozoa	9	0.01	0.27	0.58	0.2
Polychaeta	10	0.02	0.08	0.67	0.1
Gastropoda	4	0.01	0.24	0.33	0.1
Heteropoda	5	0.01	0.03	0.33	<0.1
Bivalvia	13	0.02	0.36	0.91	0.3
Cephalopoda unid.	90	0.14	1.90	7.07	14.4
Octopoda	24	0.04	2.09	1.91	4.1
Teuthoidea	114	0.17	5.79	9.14	54.5
Mysidacea	6	0.01	0.09	0.50	0.1
Isopoda	2	0.00	0.01	0.17	<0.1
Gammaridea	306	0.46	0.28	1.16	0.9
Euphausiacea	3,526	5.30	1.15	4.66	30.1
Reptantia	29	0.04	1.48	2.41	3.7
Natantia	55	0.08	0.66	4.16	3.1
Echiura	4	0.01	0.08	0.33	<0.1
Asteroidea	17	0.03	0.09	0.83	0.1
Echinoidea	6	0.01	0.09	0.50	0.1
Holothuroidea	64	0.10	1.26	3.91	5.3
Ascidiacea	5	0.01	0.51	0.42	0.2
Thaliacea	106	0.16	0.89	2.91	3.1
Eggs unid.	30	0.05	0.01	0.08	<0.1
Sand	13	0.02	0.23	1.08	0.3
Gravel	1	0.00	0.01	0.08	<0.1
Tubes unid.	1	0.00	0.01	0.08	<0.1
Aves	11	0.02	0.38	0.33	0.1

[1] FO = frequency of occurence.

[2] IRI = index of relative importance.

significant trend as a group, but thornyheads demonstrated a significantly higher mean number per sablefish with increasing depth (slope=0.02 individuals/m; r^2=0.43; $F_{1,12}$=16.8; p=0.02).

Sablefish of the same size showed no change in diet composition with change in depth. For the four largest length classes (450–499, 500–549, 550–599, and 600–649 mm), frequency of occurrence showed large fluctuations, but no consistent trend with depth. See Figure 8 for an example (the 550–599-mm length class).

Prey Habitat

The prey in the sablefish stomachs came from both the water column and the benthos (Table 1). Major midwater prey consisted of heteropods, thaliaceans, squids, euphausiids, and midwater fishes, whereas major bottom prey consisted of gastropods, crabs, echinoderms, and bottom fishes. Overall, midwater prey occurred more frequently than benthic prey (76.7% and 51.8%, respectively). Of the 1,212 sablefish with prey that could be categorized by prey habitat, 1,041 (85.9%) had prey entirely from either the bottom or midwater habitat, and 171 (14.1%) had prey from both habitats. For sablefish with more than one prey item in their stomachs, mixed midwater and benthic feeding appeared in 31% (145 fish). Of the remaining 69% (325 fish) of sablefish with multiple prey items, approximately one third (110 fish) ate only benthic prey, and two thirds (215 fish) ate only midwater prey.

There was a significantly lower frequency of occurrence of midwater prey with increasing sablefish length (slope=–0.103%/mm; $F_{1,10}$=21.8; p<0.01), whereas benthic prey were more common with greater fish length (slope=0.01%/m; $F_{1,10}$=25.4; p<0.01; Fig. 9). The trend of decreased feeding on midwater prey with greater fish length was present for midwater fishes, squids, mysids, heteropods, and thaliaceans. Sablefish that fed on midwater prey averaged 484.2 mm long; sablefish that fed on benthic prey had a significantly greater average length of 520.3 mm (df=367; t=–8.8; p<0.01).

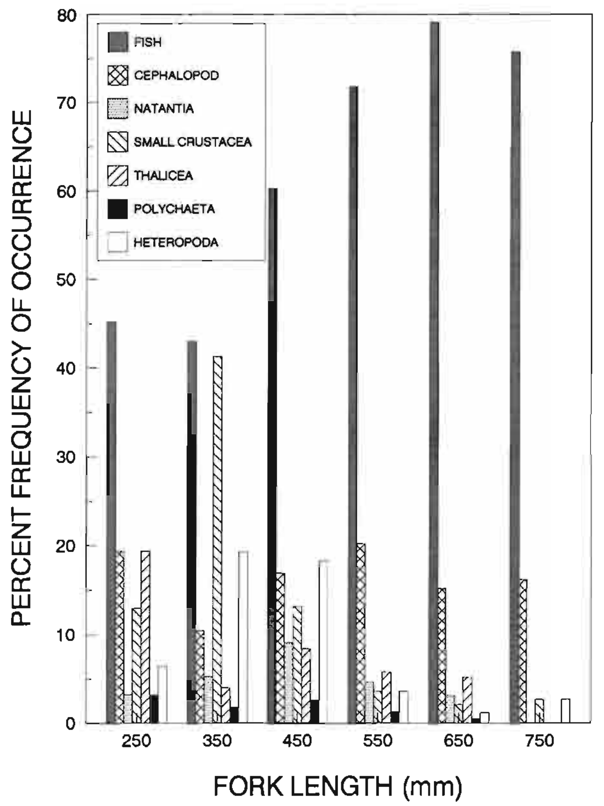

Figure 4

Percent frequency of occurrence of major prey categories by sablefish fork length, for all sablefish.

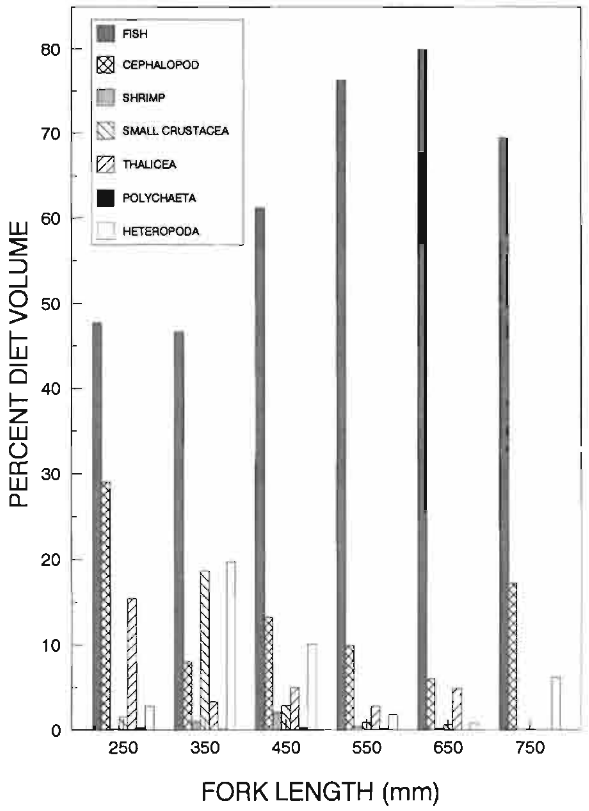

Figure 5

Percent diet volume of major prey categories by sablefish fork length, for all sablefish.

Sablefish from the south ate more midwater prey than fish from the north. In the south, the frequency of occurrence was 81.7% for midwater prey and only 33.9% for benthic prey. In the north, the frequency of occurrence was 32.8% for midwater prey, and 33.7% for benthic prey. This same trend emerged for percent diet volume: in the south it was 48.0% for midwater prey and 30.3% for bottom prey; in the north it was 26.2% for midwater and 40.5% for benthic prey. In both areas, the mean numbers of prey per sablefish were highest from the midwater prey category, because of the high numbers of euphausiids eaten.

Discussion

As sablefish increase in length, they change from a diet of small, midwater prey to large prey primarily from the benthos. The major prey of small sablefish are small crustaceans (mostly euphausiids, gammarid amphipods, and mysids), heteropods, and small fish (myctophids, deepsea smelts, etc.). Large, adult sablefish eat many different prey: fish, primarily thornyheads, are predominant, followed by cephalopods. Since there is little difference in the diets of sablefish of the same size over depth, the change in diet seems related to differences in size rather than depth. A similar change in diet with size was noted by Cailliet et al. (1988) off central California, and by Conway (1967) off southern California. However, Cailliet et al. (1988) observed that fishes were the principal prey for the largest length classes of sablefish, but that cephalopods were less important than euphausiids, amphipods, and decapod shrimps. McFarlane and Beamish (1983), working off the west coast of Canada, also found fish and cephalopods to be the two dominant prey groups, although no specific sablefish length classes were noted.

Sablefish feed on increasingly larger prey as they grow. This change in prey size is due both to change in predation tactics (mouth size, speed, etc.) with size and to the different habitats that sablefish inhabit as they mature. Conway (1967) observed a similar trend: two-year-old sablefish fed on small *Sebastolobus alascanus*, while older sablefish ate larger *S. alascanus*. This relationship has also been seen in species other than sablefish. Prince and Gotshall (1976) found that the size of

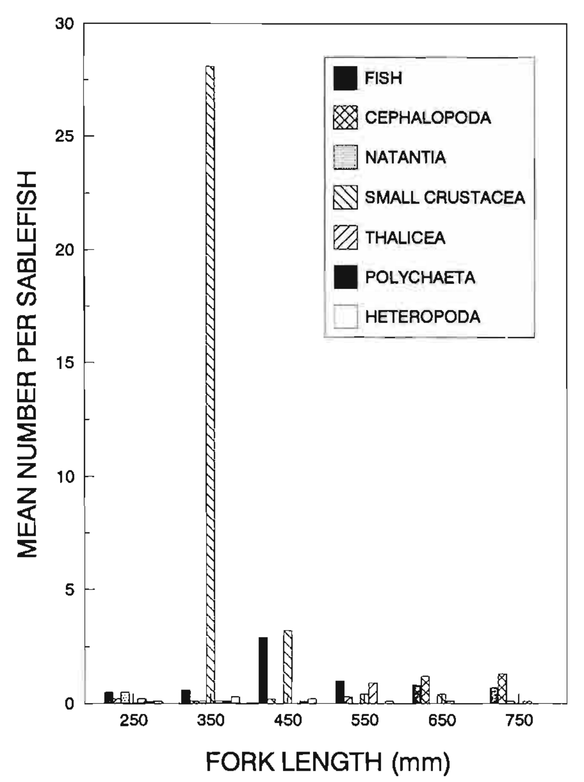

Figure 6
Average number per fish of major prey categories by sablefish fork length, for all sablefish.

prey for copper rockfish, *Sebastes caurinus*, increased with increasing fish size. In large leopard searobin, *Prionotus scitulus*, prey size increased with increasing fish length (Ross, 1978).

Sablefish show geographic differences in both diet and size distribution. Sablefish in the south feed more prominently on midwater prey than fish in the north. Sablefish in the southern area are smaller (Methot[3]) and have a more pronounced depth–size relationship. There may be some link between the smaller size in the south and the pelagic feeding mode, but the mechanism is not clear.

Different prey are taken in the two feeding modes—in midwater and on the benthos. This pattern may reflect the habitat that sablefish occupy at different life stages, possibly showing an ontogenetic transition from the pelagic juvenile stage to a benthic existence as adults. During this transition, sablefish reduce their midwater feeding and presumably their time in midwater, and become more strongly associated with bottom feeding. Although the time in midwater is reduced, sablefish are taken as bycatch in the midwater Pacific whiting fishery (Sampson et al., 1997). This gradual transition in feeding mode may help to explain

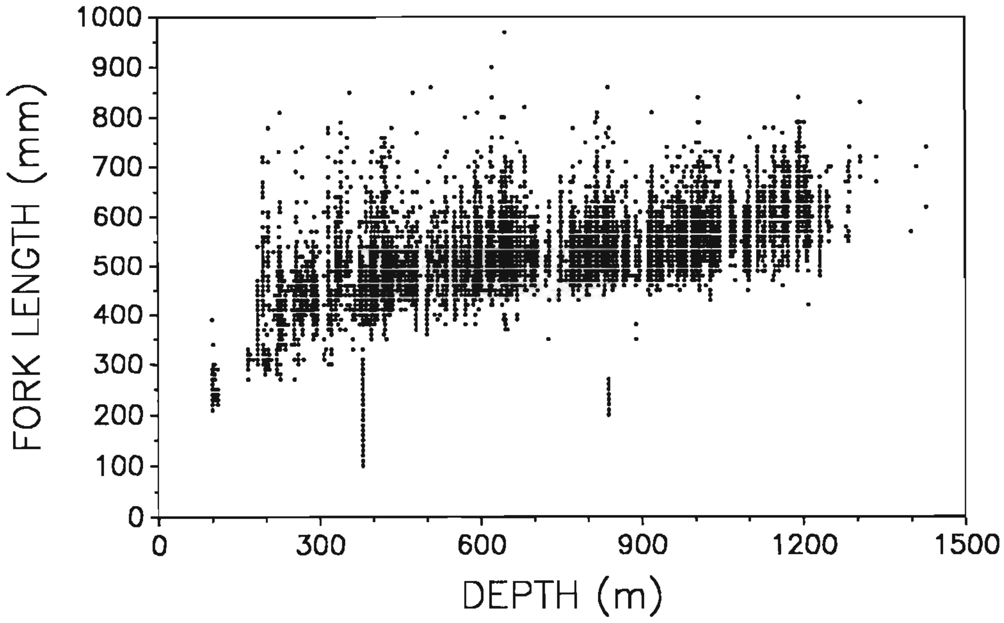

Figure 7
Fork length by depth of capture for all sablefish. The small individuals from approximately 380 m and 840 m are small pelagic fish which probably were collected in midwater.

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[3] Methot, R. D. 1992. Assessment of the west coast sablefish stock in 1992. *In* Appendices to the status of the Pacific coast groundfish fishery through 1992 and recommended acceptable biological catches for 1993, App. D, 96 p. Pac. Fish. Manage. Council, 2000 S.W. First Ave., Metro Center, Ste. 420, Portland, OR 97201.

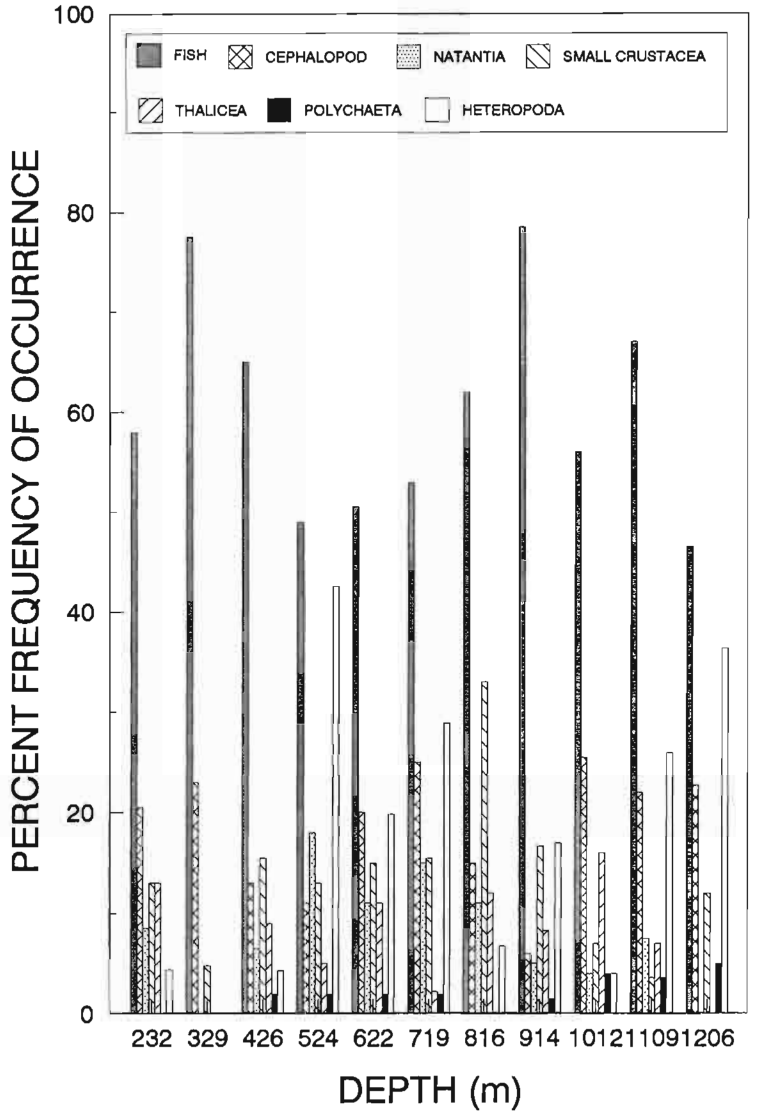

Figure 8
Percent frequency of occurrence of major prey categories by depth for sablefish from 550 to 599 mm in fork length.

why sablefish is one of the few species whose distribution extends from shallow water onto the slope.

The decline in midwater feeding with length, and thus in time spent in the water column, may result in a differential vulnerability to bottom trawl gear. Since, at any given time, a larger proportion of smaller fish would be feeding in midwater, bottom trawl estimates would be lower for smaller fish than for larger fish. It is difficult to assess from the data presented here how large an effect this trend would have, but the reduction in frequency of occurrence of midwater prey is substantial from the largest to the smallest length class. This trend is similar to that seen in differential vulnerability to trawl gear due to diel behavior reported in the northeastern Atlantic (Walsh, 1991; Engas and Soldal, 1992). The differential vulnerability of fish to the trawl would bias any trend of relative abundance from smaller to larger fish and therefore reduce apparent mortality.

Predatory fish play a dominant role in marine groundfish ecosystems, and changes in abundance of major piscivorous fish will cause a cascade of effects on these ecosystems (Bax, 1991). Attempts to incorporate these kinds of species interactions have been considered critical in heavily exploited ecosystems such as the North Sea, where consumption by fish, marine mammals, and seabirds are many times the amount taken by the fish-

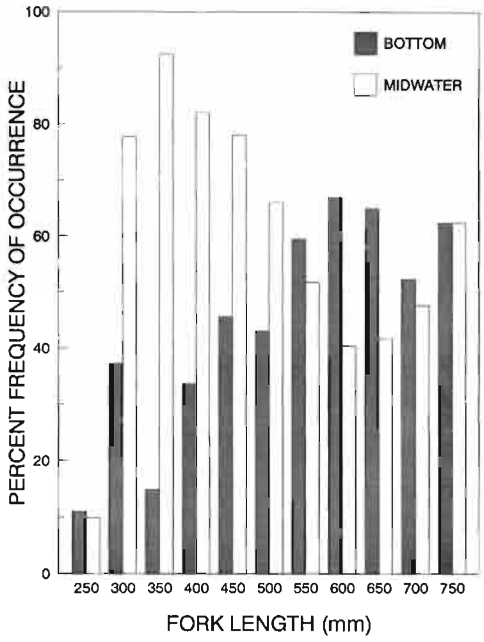

Figure 9
Percent frequency of occurrence of midwater and bottom prey, by sablefish fork length.

ery (Pope, 1991). This need has led to the development of multispecies virtual population analysis (MSVPA) where natural mortality consists primarily of abundances of major predators multiplied by their feeding rates on other harvested fish. The MSVPA assessments produce results that often contradict single-species assessments, and the question as to which of the contradictory predictions from single-species or MSVPA assessments is more accurate has not been resolved.

The combination of predator relations and the harvesting of sablefish and the two thornyhead species in the slope community presents the same situation that led to contradictory advice from single-species and MSVPA assessments in the North Sea. Sablefish and the two thornyhead species are harvested together, and sablefish are a major predator on the two species of thornyheads, particularly *S. altivelis*. Stock assessment of sablefish under the most optimistic conditions indicates that biomass has decreased to less than one half of 1971 levels (Methot[2]), and potentially the decrease could be much greater. Under the assumption of a MSVPA management regime, the reduced sablefish biomass would lead to a substantial reduction in natural mortality of *S. altivelis* and, to a lesser degree, *S. alascanus*, although the degree of reduction is impossible to predict, since it would be a function of a number of factors not known here, such as predation rate, digestion rate, etc. Thornyhead landings have increased ninefold in the same period as the sablefish decrease (Ianelli et al.[4]) and although there is a great deal of uncertainty associated with the assessment, *S. altivelis* is considered a lightly exploited stock, and *S. alascanus* is considered a highly exploited stock. If MSVPA assumptions become accepted, assessments of these two thornyhead species would change dramatically.

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Literature Cited

Bax, N. J.
1991. A comparison of the fish biomass flow to fish, fisheries, and mammals in six marine ecosystems. ICES Mar. Sci. Symp. 193:217–224.

Cailliet, G. M., E. K. Osada, and M. Moser.
1988. Ecological studies of sablefish in Monterey Bay. Calif. Fish Game 74(3):132–153.

Conway, J. B.
1967. Food relationships and general population biology of the sablefish, *Anoplopoma fimbria*, and Pacific hake, *Merluccius productus*. M.S. thesis, San Diego State College, San Diego, CA, 109 p.

Engas, A., and A. V. Soldal.
1992. Diurnal variations in bottom trawl catch rates of cod and haddock and their influence on abundance indices. ICES J. Mar. Sci. 49(1):89–95.

Grinols, R. B., and C. D. Gill.
1968. Feeding behavior of three oceanic fishes (*Oncorhynchus kisutch, Trachurus symmetricus*, and *Anoplopoma fimbria*) from the northeastern Pacific. J. Fish. Res. Board Can. 25:825–827.

Krebs, C. J.
1989. Ecological methodology. Harper Collins, New York, 654 p.

McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters off western Canada. *In* Proceedings of the International Sablefish Symposium, March 29–31, 1983, Anchorage, Alaska, p. 59–80. Alaska Sea Grant Rep. 83-8.

Pinkas, L.
1971. Food habits study. *In* L. Pinkas, M. S. Oliphant, and I. L. K. Iverson (eds.), Food habits of albacore, bluefin tuna,

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[4] Ianelli, J. N., R. Lauth, and L. D. Jacobson. 1994. Status of the thornyhead (*Sebastolobus* spp.) resource in 1994. *In* Appendices to the status of Pacific Coast groundfish fishery through 1994 and recommended acceptable biological catches for 1995, Appendix D, 58 p. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland, OR 97201.

and bonito in California waters, p. 5–10. Calif. Dep. Fish Game, Fish Bull. 152.

Pope, J. G.
1991. The ICES multispecies assessment working group: evolution, insights, and future problems. ICES Mar. Sci. Symp. 193:22–33.

Prince, E. D., and D. W. Gotshall.
1976. Food of the copper rockfish, *Sebastes caurinus* Richardson, associated with an artificial reef in south Humboldt Bay, California. Calif. Fish Game 62(4):274–285.

Regier, H. A., J. E. Paloheimo, and V. F. Gallucci.
1979. Factors that influence the abundance of large piscivorous fish. *In* R. H. Stroud (ed.), Predator–prey systems in fisheries management, p. 333–342. Sport Fishing Inst., Washington, D.C.

Ross, S. T.
1978. Trophic ontogeny of the leopard searobin, *Prionotus scitulus* (Pisces: Triglidae). Fish. Bull. 76(1):225–234.

Sampson, D., W. Barss, M. Saelens, and C. Wood.
1997. The bycatch of sablefish, *Anoplopoma fimbria,* in the Oregon whiting fishery. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 183–194. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Smith, G. B., and R. G. Bakkala.
1982. Demersal fish resources of the eastern Bering Sea: spring 1976. U.S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF-754, 129 p.

Walsh, S. J.
1991. Diel variation in availability and vulnerability of fish to a survey trawl. J. Appl. Ichthyology 7(3):147–159.

Influence of Ontogeny and Fishing Mortality on the Interpretation of Sablefish, *Anoplopoma fimbria*, Life History

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ABSTRACT

Synoptic trap surveys were conducted during 1989, 1990, and 1991 off the west coast of Canada to examine area- and depth-related differences in population parameters used to model the life history of sablefish. It was found that age composition, size at age, size at maturity, and age at maturity differed among depths and areas. Differences in most parameters with depth, and between sites north and west of Vancouver Island result from the interaction of sablefish ontogeny, varying temporal patterns of fishing effort, the width of available slope habitat, and the physical and biological oceanography of the fishery production domains of the two areas. Sablefish older than ten years were most abundant at depth and at southern sites, probably because of the interaction of ontogenetic dispersion and differential fishing mortality. Length at age declined with depth and increased with latitude. Plausible explanations for the variation in size at age by depth and area include fishery effects, biotic effects including abundance and food availability, and abiotic effects including temperature and oxygen. Length at maturity was similar over all areas in shallow depths and decreased with depth, a relationship that was more pronounced at southern sites. Age at maturity was lower for northern sites and shallow depths. A two-stage hierarchy of maturation is proposed, with length and age as primary and secondary stimuli, respectively. Implications to stock assessment are examined.

Introduction

Sablefish, *Anoplopoma fimbria*, is an economically important demersal species inhabiting the continental shelf and slope from Baja California to northern Japan. It has a long history of exploitation throughout its range, with landings recorded as early as 1913 from Canadian waters (Fig 1.; McFarlane and Beamish, 1983a). Canadian catches averaged 4,616 metric tons (t) over the period 1977–92. Combined trap, longline, and trawl fisheries landed 5,027 t in 1992.

In 1977, Canada assumed control of resources within its 200-nautical-mile Fishing Zone and initiated detailed studies of sablefish biology to support the stock assessments required for management of the developing fishery. These studies found substantial variation in most life-history parameters. For example, Beamish and Chilton (1982) and McFarlane and Beamish (1983b) noted considerable among-sample variation in sablefish size at age from the same general area, although the cause of the variation was not examined. A similar pattern of variation was noted in maturity estimates. Age and length at 50% maturity were estimated initially to be 5 y and 52 cm for males and 5 y and 58 cm for females (Mason et al., 1983). However, McFarlane and Beamish (1990) subsequently reported variation in estimated age and length at maturity. Their estimates of length at 50% maturity for females ranged from 51.7 to 54.0 cm, although those for males were less variable, ranging from 53.6 to 53.9 cm. Similarly, estimated age at 50% maturity ranged from 3.8 to 4.9 y for males and from 3.8 to 5.0 y for females. These estimates were based on samples from the commercial fishery.

Stock assessments conducted in recent years (Saunders and McFarlane, 1990, 1991, 1993) noted a juvenation of the commercial age composition over the period 1979–84, which coincided with a shift in the depth distribution of fishing effort. From 1977 through 1984, effort was directed at increasingly shallower depths (Fig. 2; Saunders and McFarlane, 1993). Since 1984, the age composition of the catch and the distribution of effort by depth have been relatively stable, although the amount of fishing in deeper water has gradually increased in the northern area. Saunders and McFarlane (1990) hypothesized that the cause of the juvenation could be either an effect of fishing mortality or an artifact of shifting effort patterns in conjunction with variable age composition among depths. We extend these hypotheses to include consideration of the effects of natural variation in growth rate and an ontogenic migration from shallow to deep water with age.

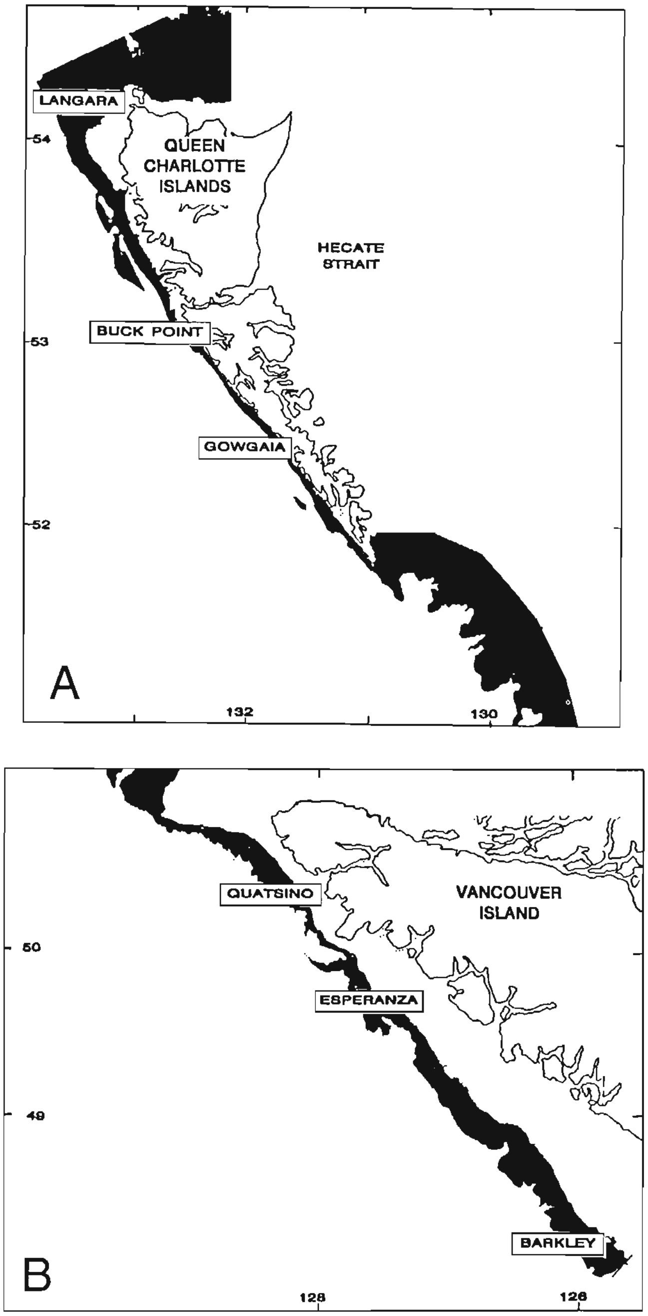

Figure 1
(A) Northern and (B) southern areas as defined in this study, showing sablefish survey trap-fishing stations and sablefish habitat (shaded) as indicated by bottom depths between 200 and 1,000 m.

In order to identify the best of these competing hypotheses for observed changes in age composition and variation in life-history parameters, we implemented a fishery-independent survey over the stock range. Our focus in this work is to describe the biological processes responsible for our observations, rather than to simply describe the data and attempt to account statistically for observed variation. We report the results of these area and depth investigations and provide evidence that the observed differences result from an interaction of ontogenetic processes and fishing mortality.

Materials and Methods

To examine the variation in age-specific parameters related to area and depth, sablefish were sampled during 1989–91 with longlined traps set at six standard stations coastwide, and within three discrete depth intervals at each station. The sampling was one component of a survey designed to index the abundance of sablefish. The stations were located in recognized commercial sablefish fishing areas and were spaced approximately 60 n.mi. apart (Fig. 1). The stations and related fishery data were divided into northern and southern areas along a boundary at approximately 51°15'N. This division was based on tagging evidence showing that the two areas draw recruitment from different portions of the shelf (McFarlane and Saunders, 1997).

At each station, we fished one string of gear consisting of 25 Korean conical traps attached to a 22-mm (7/8") polypropylene groundline at 45.8-m (25-fm) intervals. The traps were baited with 1 kg of frozen squid (*Loligo* spp.) suspended from the top of the trap in a fine-mesh bag. Target soak time was 24 h. Strings were set within three depth strata at each station: shallow, <350 fm (<640 m); midrange, 351–450 fm (641–824 m); and deep, >450 fm (>824 m). Fish from every second trap were sampled for fork length (mm), sex, maturity, and age.

Age was determined with Beamish and Chilton's (1982) criteria for interpreting burnt otolith cross-sections. Photographs of selected otoliths were used to examine the individual growth patterns of fish captured from shallow and deep strata. The photographic system consisted of a 35-mm camera attached to a Wild M8[1] dissecting microscope with fiber-optic lighting, and B/W T-max 100 ASA film. Maturity was assessed visually with the criteria of Weir et al. (1978).

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

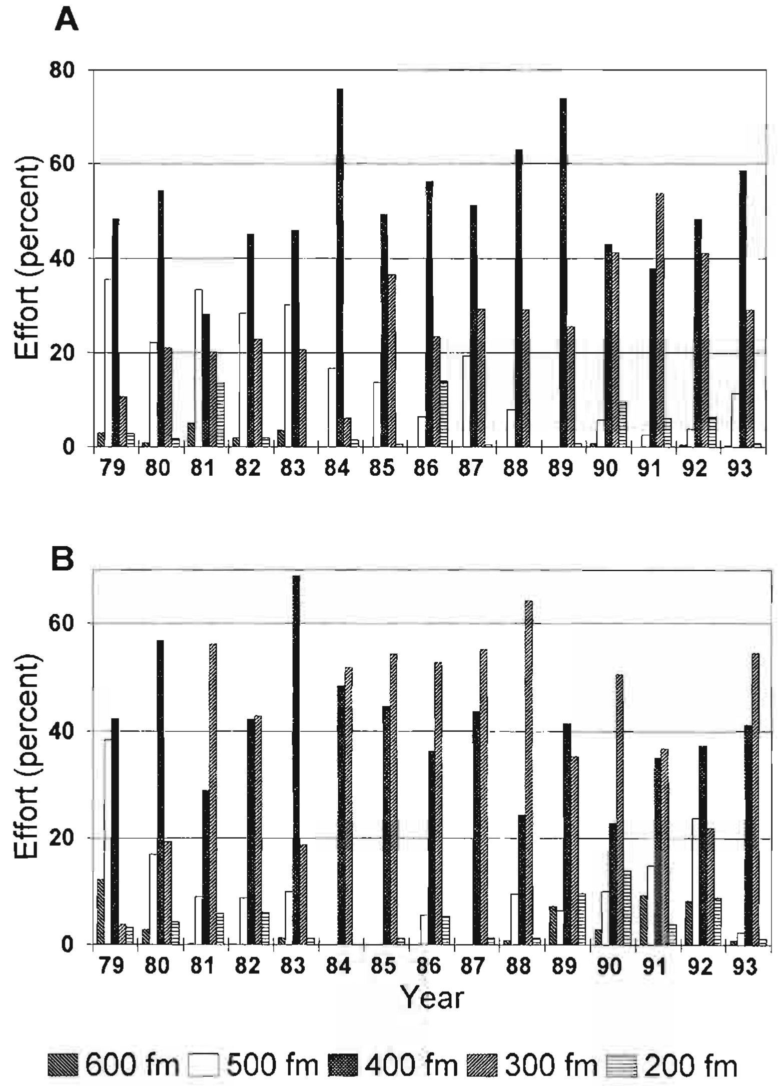

Figure 2

Distribution of sablefish trap effort for (A) northern and (B) southern areas by average depth (100-fm intervals), 1979–93.

Lengths and ages at maturity (L_{50}, A_{50}) were estimated as the 50% point on a logistic model of percent maturity as a function of length or age, where data were sufficient. Parameters of the logistic model were estimated by maximum likelihood (SYSTAT, 1992). Where data were insufficient for analytic estimation, first maturity was interpolated from observations.

Results

A total of 6,487 sablefish were aged from six stations and three depth strata (Table 1) sampled during 1989, 1990, and 1991. Ages from all surveys were pooled, since interannual differences in age distributions within areas and depths were minor. For example, Barkley-area age compositions from the three surveys over three depth strata are similar (Fig. 3). The only difference is that a mode of young fish present in the deep stratum in 1989 is absent from the 1990 and 1991 surveys.

Age and Growth

Age compositions at the six stations, for all years combined, were different among areas and depth strata (Fig. 4). At the southern stations (Barkley, Esperanza, and Quatsino) the proportion of older fish increased progressively from shallow to deep. Younger fish (<10 y) were present at all depths, although their abundance was much lower in deeper water, and the abundance of fish younger than 5 y, in particular, declined precipitously with depth. Fish older than 10 y did not occur in abundance until midrange depths and were dominant in the deep stratum. By comparison, age distributions from the northern stations (Gowgaia, Buck Pt., and Langara) were dominated by ages 1–10 y, and a reservoir of older fish was not apparent. Fish older than 10 y were present only occasionally, and primarily in the deep stratum, e.g., at Buck Pt.

Variation in other biological attributes was also depth dependent. The mean length at age (LAA) for both males and females decreased with depth, although the trend was less pronounced off the Queen Charlotte Islands. For example, plots of mean LAA by depth for the Quatsino and Langara stations (Fig. 5) show the mean length of females is above 70 cm for ages greater than 5 y in the shallow stratum, but below 70 cm in the deep stratum. Mean LAA averaged 7.2 and 5.1 cm larger in shallow strata than in deep for the Quatsino and Langara sites, respectively. Differences in mean LAA across depths are highly significant (p<0.01) in both areas. Sample sizes for northern stations reflect the lower abundance of males at these sites (Table 1).

Table 1

Numbers of sablefish aged by sex, station, and depth. Depth strata are: shallow, ≤350 fm (≤640 m); midrange, 351–450 fm (641–824 m); deep, >450 fm (>824 m).

	Depth stratum			
Station	Shallow	Midrange	Deep	Total
Males				
Barkley Canyon	235	277	186	698
Esperanza	134	256	146	536
Quatsino	262	138	307	707
Gowgaia	50	92	57	199
Buck Pt.	110	235	90	435
Langara	80	18	29	127
Total	871	1,016	815	2,702
Females				
Barkley Canyon	306	286	160	752
Esperanza	116	237	152	505
Quatsino	507	177	185	869
Gowgaia	183	275	208	666
Buck Pt.	324	164	122	610
Langara	280	32	71	383
Total	1,716	1,171	898	3,785
Total				
Barkley Canyon	541	563	346	1,450
Esperanza	250	493	298	1,041
Quatsino	769	315	492	1,576
Gowgaia	233	367	265	865
Buck Pt.	434	399	212	1,045
Langara	360	50	100	510
Total	2,587	2,187	1,713	6,487

Length at Maturity

Assessment of maturity for sablefish is hampered by the absence of immature fish in samples from most northern sampling stations (Fig 6.).

In concert with variation in growth and age composition, maturity schedules by length are also depth specific. Analysis of variance shows that, for both males and females, length at first maturity is significantly smaller (p<0.01) with greater depth. This difference with depth is greater for females than for males, and also greater for both sexes in the southern area than in the northern area (Fig. 7). For example, the range in female L_{50} across strata at Barkley (48–60 cm) is considerably greater than that off the west coast of the Queen Charlotte Islands (e.g., Buck Pt., 56–60 cm). Differences across strata are generally consistent in all areas, although variation in the estimated L_{50} for males in the middle stratum is apparent (Fig. 7). The estimation of differences at northern sites is hampered by the low number of immature animals observed in any but the shallow depth stratum.

Although the differences in L_{50} across strata are significant, a more notable feature of these data is the coherence of the L_{50} for females from shallow water, across areas. This coherence accounts in large measure for the lack of a significant area effect on the estimated L_{50} for females (p=0.08). Females sampled in middle and deep strata show strong latitudinal trends in L_{50}, whereas fish from the shallow stratum exhibit a uniform L_{50} (Fig. 7). For both the deeper strata, L_{50} increases from south to north. Mean size at maturity for females from deep samples ranged from as low as 48 cm at Barkley to 55+ cm off the west coast of the Queen Charlotte Islands. Male sablefish show significant variation (p<0.01) in length at maturity among areas, with fish maturing at larger sizes at the northern sites.

Age at Maturity

We do not yet have age estimates for all the fish for which length-at-maturity information was collected. Except for fish from the shallowest depth stratum, over 90% of sampled fish are mature at the northern sites. In areas where ages at maturity can be well determined, sablefish from deeper water mature at older ages than fish from shallower water (Fig. 8). Whereas shallow-stratum females matured at a mean age of approxi-

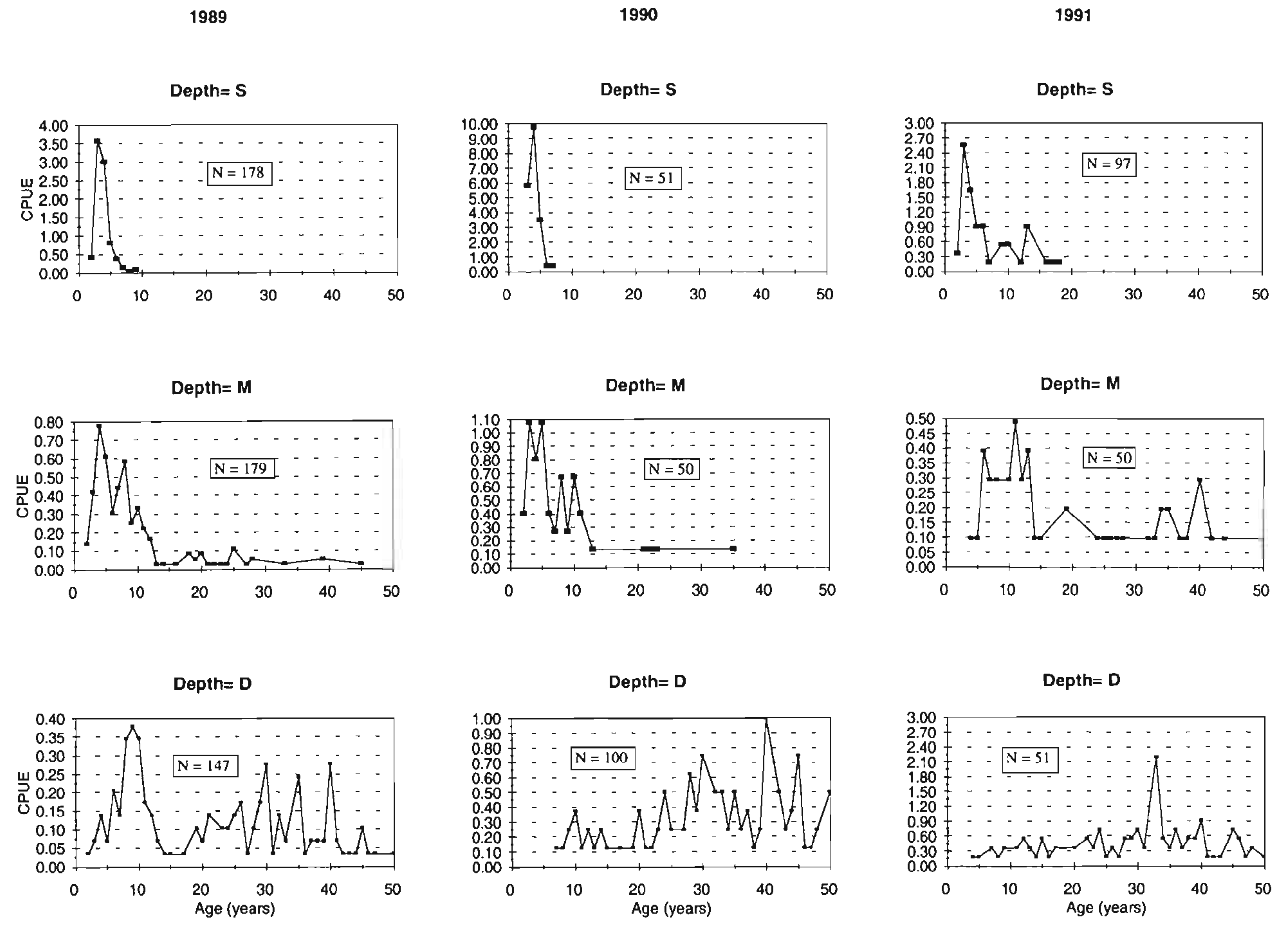

Figure 3

Abundance (CPUE) of sablefish age classes by survey and depth zone for the Barkley area. CPUE = number of fish per trap. Depth zones: S = shallow, M = midrange, and D = deep. Note variable y-axis scale.

mately 4.0 y (range 3.5–4.5 y), fish at the same localities from deeper water matured at a mean age of 4.4 y (3.0–5.5 y). Similarly, for male fish the estimated mean A_{50} was 2.7 y (range 2.5–3.0 y) in shallow water, and 3.3 y (range 3.0–4.0 y) in the deep stratum. When all areas are considered together, significant differences (p=0.02) in A_{50} among areas are evident, although the difficulties in obtaining precise estimates of A_{50} in the northern sites are noteworthy.

Discussion

Age Composition

In common with other demersal fish species, the age composition of sablefish off British Columbia is area and depth specific. The abundance of fish older than 10 y increases with depth, although this trend is less pronounced off the west coast of the Queen Charlotte Islands than off Vancouver Island. The depth differences are believed to result from the interaction of two dynamic processes—ontogenetic dispersion and fishing mortality. The differences in the expression of these processes between northern and southern areas are due to the effect of differences in available habitat.

Tagging studies have shown that juvenile sablefish frequent nearshore habitats and gradually migrate offshore, recruiting to the adult population at approximately 5 y (McFarlane and Beamish, 1983b; 1983c; Beamish and McFarlane, 1988; McFarlane and Saunders, 1997). These studies also show that most juvenile sablefish recruitment to northern offshore slope waters originates in Hecate Strait rather than in outside shelf waters. The progressive movement of juveniles into deeper water with increasing size has been noted in the shelf areas of Hecate Strait (Fargo et al., 1990) and off southern Vancouver Island (Tanasichuk, 1997). Our age-

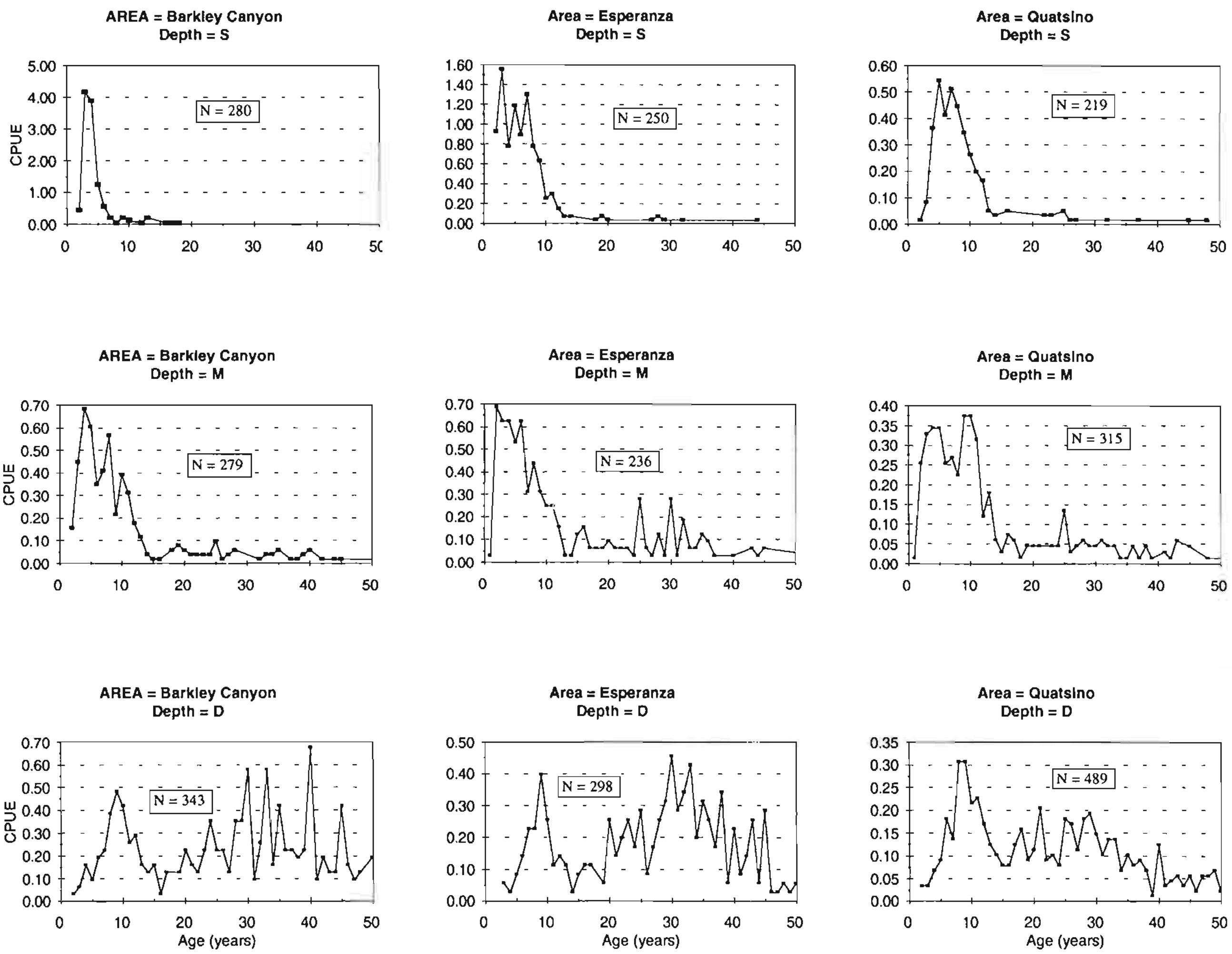

Figure 4

Abundance (CPUE) of sablefish age classes from surveys conducted from 1989 through 1991, by area and depth zone. CPUE = number of fish per trap. Depth zones: S = shallow, M = midrange, and D = deep. Note variable *y*-axis scale.

composition results indicate that this migration from shallow to deep continues as adults populate the shelf habitat. This clinal process is more pronounced off the west coast of Vancouver Island because the available habitat (200–1,000 m; Fig. 2) is geographically larger there, compared with the precipitous slope off the west coast of the Queen Charlotte Islands, where mixing of all age classes may occur more readily.

Historical differences in the temporal and spatial distribution of fishing effort also contribute to the observed patterns of age composition. The diminished abundance of older fish over all depths off the Queen Charlotte Islands could be the result of higher fishing rates in this area during the late 1960's and 1970's, as noted in the most recent stock assessment (Saunders et al., 1994).

Size at Age

Models of population dynamics used in stock assessment rely on parameters estimated from random samples. Parameter values are assumed to adequately describe the development of individual fish. Growth curves, for example, assume that pooled observations of size at age from a single sample in time can be used to describe and predict the growth trajectory of individual fish. In reality, the length-at-age curves derive from simultaneous observations of fish from many cohorts, each of which is growing on its own trajectory. Length at the time sampled can depend on genotype, past history (biotic and abiotic influences), and sampling biases arising from the selective nature of fisheries and fishing gear. The effects on the interpretation

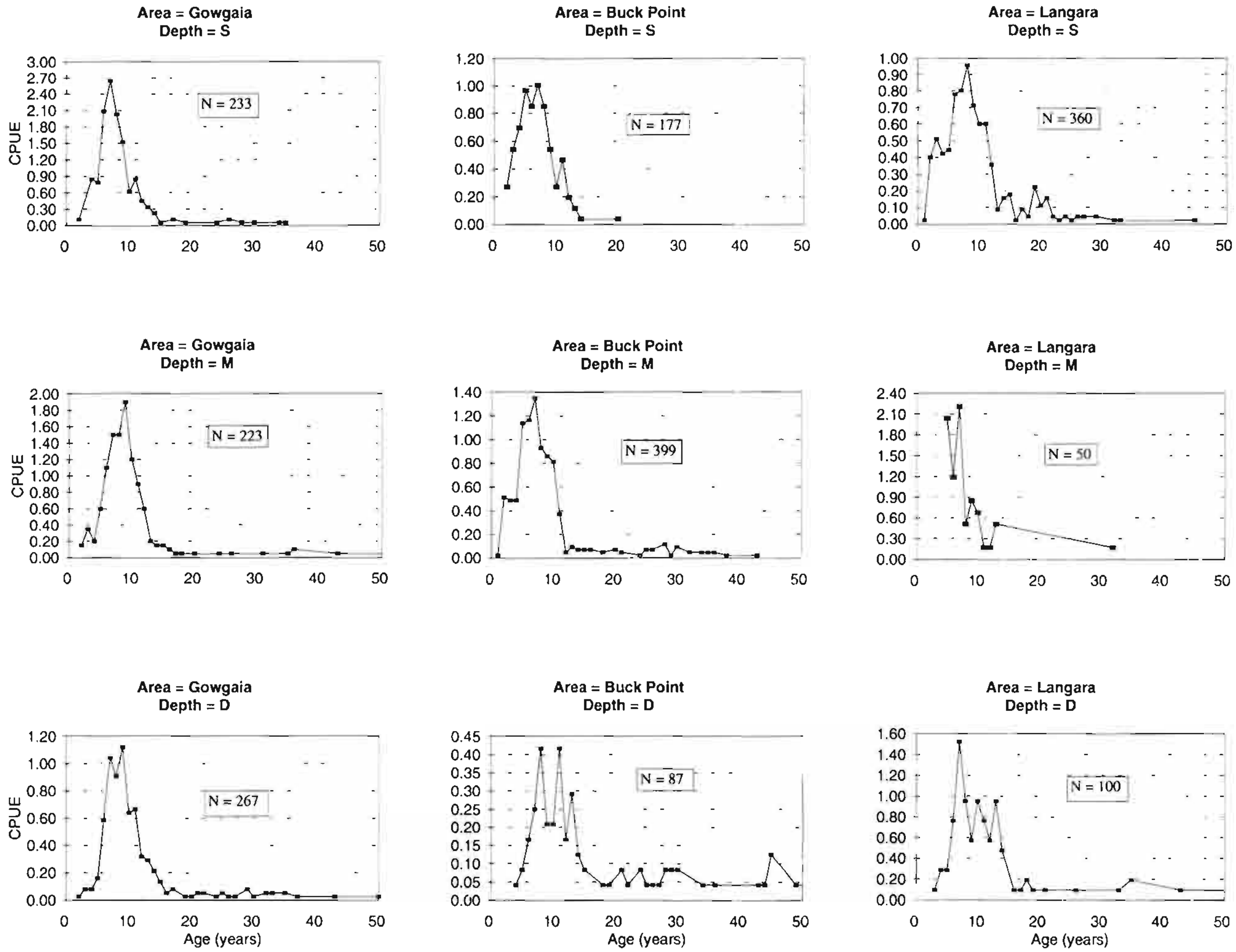

Figure 4 (continued)

of growth have been treated in detail by Mulligan and Leaman (1992).

Our results show significant variation in mean length at age and length at maturity among areas and depth strata. Similarly, Sigler et al. (1997) found variation in mean size at age and in age composition with latitude and depth in the Gulf of Alaska. Methot[2] found changes in age composition with depth and latitude but did not find any variation in mean size at age with depth from Washington to California. A number of competing, and in some cases confounding, hypotheses can be advanced to explain these observations. Some hypotheses invoke factors that influence growth rate, including the density-dependent effects of sablefish abundance and prey abundance. Alternatively, abiotic, genetic, or fishery-based factors can be suggested as root causes for the observed differences.

Sablefish inhabit a broad range of depths across the continental shelf and slope. The long history of the fishery means that we have few observations of distribution in what could be considered an undisturbed or natural state. But we do know that the concentration of fishing effort and removals from midrange depths is likely to distort the distribution of biomass, leading to lower biomass in this stratum and consequent density-dependent effects on growth. Surveys conducted in 1989–92 indicated higher average catch rates in the deep stratum (Saunders et al., 1994), which would be consistent with density-dependent effects in this stratum. Indeed, length at age is uniformly smaller in the deep stratum, although we note that the causes for variation in growth rate are manifold.

Growth rate in fish is sensitive to many abiotic factors. The decline in length at age observed with increas-

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[2] Methot, R. D. NW Fish. Sci. Cent., NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. Personal commun.

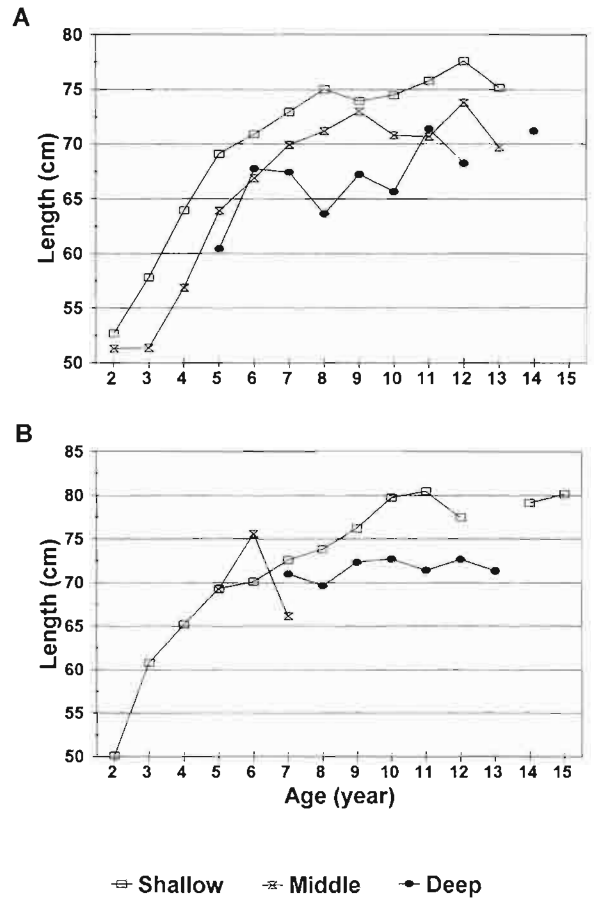

Figure 5
Mean length at age of female sablefish from (A) Quatsino and (B) Langara, by depth zone. Means are calculated only for ages with a sample size of more than five individuals.

ing depth could result from simple temperature effects, since bottom temperatures decrease with depth, and lower temperatures are known to depress both rate of food consumption and growth efficiency (Wootton, 1990). Differences among sites can also arise from latitudinal temperature effects. Our northern and southern stations fall within two distinct oceanographic domains (Ware and McFarlane, 1989), the Coastal Upwelling Domain and the Coastal Downwelling Domain. In summer, upwelling off the west coast of Vancouver Island brings cold, saline water from the deep onto the slope and shelf, a process not mirrored in northern waters (Thomson[3]), and which is consistent with observed differences in growth.

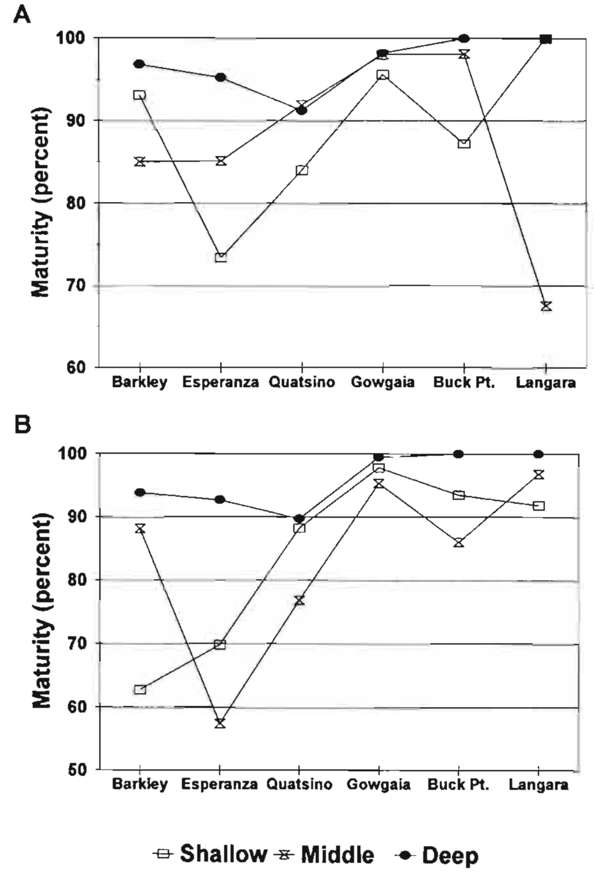

Figure 6
Percent maturity of (A) male and (B) female sablefish by area and depth stratum.

Area differences might also be examined in a genetic context. Although no genetic studies have been conducted on this species, genetic distinction requires spawning distributions that are mutually exclusive, with no mixing of the resulting progeny. Even with large population numbers, gene flow maintenance requires only a small number of migrants among units (Solbrig and Solbrig, 1979), a number well within observed mixing rates from our tagging studies. We note on this basis that genetically-based stock separation is unlikely, but this does not preclude the recognition of separate stocks for management purposes.

Similarly, a genetic basis for the bathymetric variation is possible. However, the fact that the distribution of spawning fish is continuous over the entire slope from 174 to 1,450 m (Mason et al., 1983) suggests a single stock. A genetic basis for observed variation must therefore advance a mechanism for segregation in the face of such continuous distribution. Potentially, the width of the slope could play a role. There is little

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[3] Thomson, R. Institute of Ocean Sciences, Fisheries and Oceans Canada, P.O. Box 6000, Sidney, B.C., V8L 4B2 Canada. Personal commun.

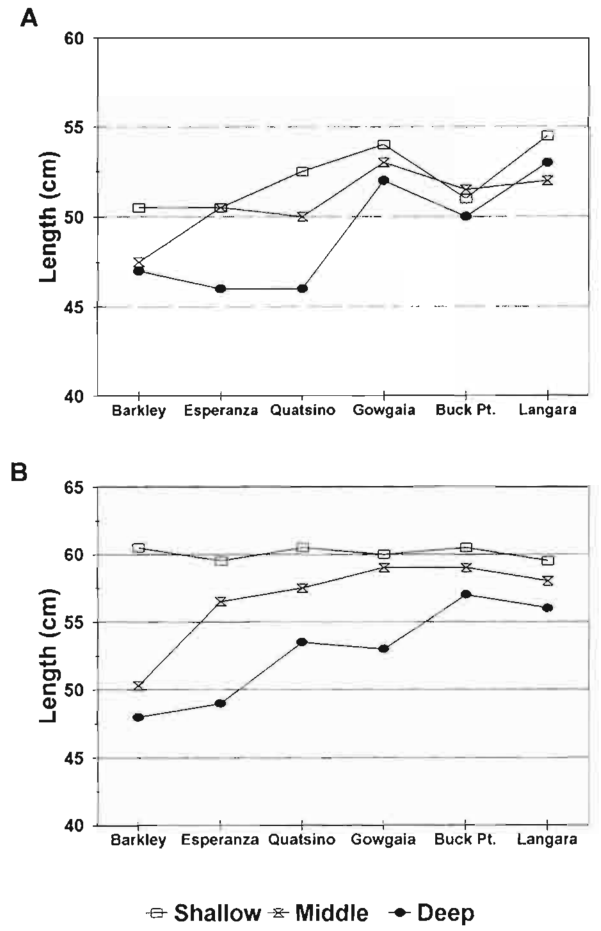

Figure 7
Length at 50% maturity for (A) male and (B) female sablefish by area and depth stratum.

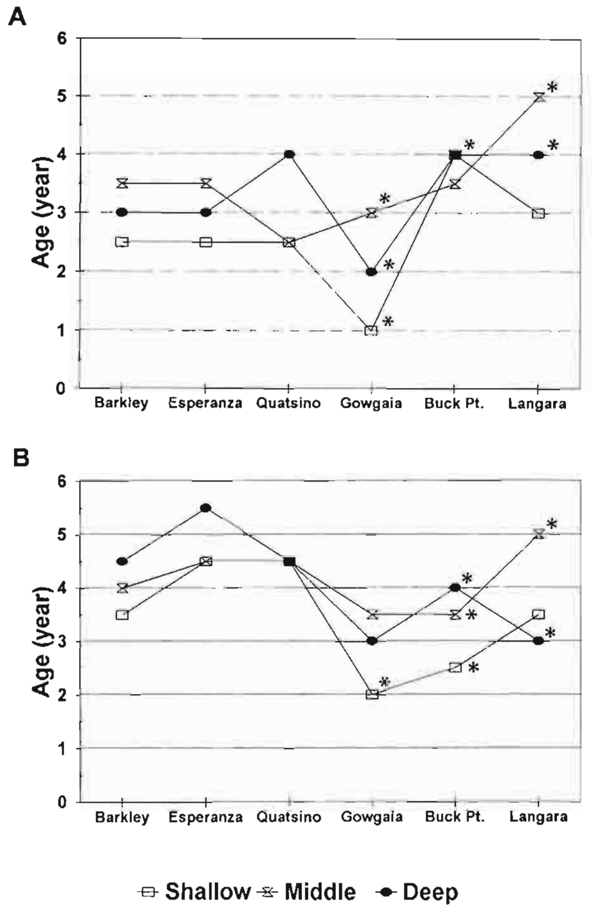

Figure 8
Age at 50% maturity for (A) male and (B) female sablefish by area and depth stratum. * represents observations with very small sample sizes and poor estimates of age at maturity (see also Fig. 6).

variation with depth in the northern area, where the slope is narrow and potential stock segregation is diminished during spawning. In the southern area, where the trend of declining size at age with depth is more pronounced, the slope area is widest and therefore imposes the greatest physical distance between slow- and fast-growing fish. These deep and shallow water components must be closed units—i.e., with no mixing—to perpetuate unique genotypes. However, tagging studies do not support such isolation. Laboratory studies of egg and larval development (Beamish and McFarland, 1992) showed that, due to the specific gravity of eggs and larvae and the depth distribution of water density off the coast of B.C., sablefish eggs must hatch in water deeper than 1,000 m. This requirement restricts the availability of suitable spawning habitat to a narrow coastal band and reduces the likelihood of genetic segregation.

Examination of annulus widths provides further evidence that the decline in growth with depth does not have a genetic basis. Photographs of broken and burnt sagittal otoliths in Figure 9 are from two male fish captured at the Barkley station. They are of comparable ages—33 and 36 years. The former was captured in the shallow stratum, the latter in the deep. At the time of capture, the shallow fish measured 65.1 cm; the deep fish 53.2 cm. On both otoliths the ninth annulus is marked. If we assume that the annular width is proportional to somatic growth, then the two fish had similar rates of growth until the ninth year. At that point the deep fish begins to show markedly lower otolith growth, in spite of its obviously similar growth capacity. We propose that the reduction in growth corresponds to the age at which the fish recruited to the deepwater environment, and that one or more nongenetic mechanisms are responsible for the reduced growth. It is thus possible that observed patterns of growth on sablefish otoliths could be used to infer movement among depth strata.

In summary, length at age is lower at depth and in southern sites. Plausible causes include density-dependent effects of varying abundance (both natural and fishery-induced); variation in abiotic factors (e.g., temperature); or even prey availability. Our examination indicates, however, that depth differences are unlikely to have a genetic basis.

Maturation Hierarchy

The low abundance of juveniles in northern waters renders a comprehensive discussion of maturation difficult. The ontogeny of sablefish in northern vs. southern waters explains the low numbers of immature fish off the west coast of the Queen Charlotte Islands. Whereas the prime area for juveniles off Vancouver Island is inshore and shallower than the adult distribution, most juvenile sablefish in northern waters are in the inside waters of Hecate Strait, rather than in the shallow waters of the narrow shelf off the west coast of the Queen Charlotte Islands. Tagging studies (Beamish and McFarlane, 1983; McFarlane and Saunders, 1997) show conclusively that juveniles recruit from Hecate Strait to the west coast of the Queen Charlotte Islands. Most fish have matured by the time they arrive in the fishery in this area.

Our study suggests a hierarchy of maturation stimuli for sablefish. Maturation of fish and other organisms is typically a mass-action phenomenon—i.e., it is mediated primarily by body size rather than age. The coherence in maturation of shallow female sablefish at an L_{50} of approximately 60 cm, across a broad geographic range, confirms such a size-based process. However, we have also shown that length at age varies greatly with both depth and latitude off British Columbia, and that sablefish from deeper water mature at significantly smaller sizes than those from shallower water. Although the upper limit of size at maturity for sablefish appears to be relatively fixed, the threshold size is apparently labile. Clearly, maturation of sablefish in deeper waters is governed by factors other than size.

In general, the influences of size and age are confounded in most analyses of maturation. This can be seen in the analytical framework of Richards et al. (1990), where age and size were shown to be jointly influential in lingcod maturity. The observations of age and size at maturity noted above suggest a hierarchy of size and age stimuli in the maturation of sablefish. Attainment of an appropriate size appears to be the primary stimulus. The attainment of these large sizes at maturity is associated with faster-growing fish from shallower water. The observations of maturation in smaller and older fish from midrange and deep waters indicate that if growth rates preclude the attainment of the threshold size for maturity within a specific time frame, fish will mature irrespective of size. For sablefish, our data indicate that the age ranges of 4.0–5.5 and 3.0–4.0 y represent such a secondary stimulus to maturation of deepwater females and males, respectively.

A two-stage maturation hierarchy is consistent with life-history theory, which predicts plasticity of maturation schedules in response to different environmental challenges (Stearns and Koella, 1986). Mayo et al. (1990) noted similar dual stimuli for maturation in Atlantic redfish.

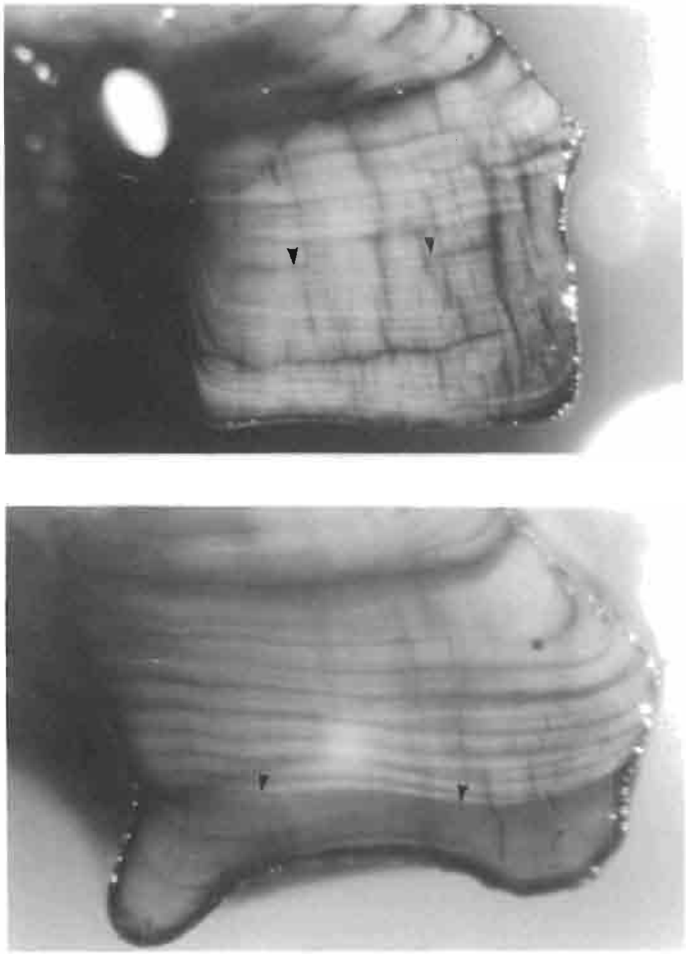

Figure 9

Burnt otolith cross sections from male sablefish of comparable ages captured from (top) shallow and (bottom) deep sets at Barkley. Arrows indicate the position of the ninth annulus on each cross section.

The type of hierarchy of stimuli observed for maturation in sablefish is required for optimization of reproductive effort against increasing mortality probability with age, a topic on which there is a rich literature (e.g., Charlesworth, 1980; Potts and Wootton, 1984; Clarke, 1987). In general, species follow a mixed evolutionary strategy in which optimal conditions for growth can be capitalized upon to enhance lifetime reproductive success, but age-mediated mechanisms will ensure that reproductive opportunities are not forgone within suboptimal growth trajectories. For sablefish, our data suggest a relatively fixed age-dependent maturity schedule which can be environmentally accelerated, but not delayed.

Summary and Implications for Stock Assessment

Our results have several implications for stock assessment and the estimation of yield from sablefish stocks. The bases for these implications are the ontogenetic behavior of the fish and its interactions with the spatial distribution of the fishery, and the productivity of the environments in which the sablefish live at different life stages. We have shown that the bathymetric and spatial distribution of the fishery, in conjunction with available habitat for sablefish, can yield fishery observations which are strongly biased compared with the total population. In addition, the biological characteristics observed in both research and commercial fishing reflect time-integrated processes of growth and selective fishing mortality. This highlights the importance of synoptic sampling surveys that cover the entire bathymetric and latitudinal range of the species.

Stock assessment models must begin to account for these selective processes, perhaps through the application of weighting algorithms that reflect the origin and history of the observed fish. For example, observed sizes at age might be weighted for depth and geographic origin of catch to account for potential biases associated with fishing patterns. Although such a consideration is not novel, the depth and geographic differences we have noted accentuate the need to bring these aspects into assessment models for sablefish. Historically, stock assessment has often assumed implicitly that fishery observations reflect general stock characteristics. We show that analysis of data from fisheries prosecuted primarily in shallow or deep water will provide over- and underestimates, respectively, of growth and productivity. Similarly, the estimation of relative cohort strengths through sequential population analyses can be affected by alterations in bathymetric fishing patterns, particularly if these patterns are progressive over time. Declines in relative abundance will be masked, and fishing mortality underestimated.

Of greater concern from an assessment perspective is the need to perceive stocks in a more detailed way. But greater complexity in stock structure is not desirable for fishery management because it makes monitoring more difficult and less precise. One of the major challenges facing biologists is the need to evaluate the effects of selective fisheries on long-term stock dynamics and to determine whether the biological complexities we note are important to sound management.

Acknowledgments

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Literature Cited

Beamish, R. J., and D. E. Chilton.
1982. Preliminary evaluation of a method to determine the age of sablefish (*Anoplopoma fimbria*). Can. J. Fish. Aquat. Sci. 39:277–287.

Beamish, R. J., and G. A. McFarlane.
1983. Summary of results of the Canadian sablefish tagging program. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, AK, p. 147–182. Alaska Sea Grant Rep. 83-3.
1988. Resident and dispersal behaviour of adult sablefish (*Anoplopoma fimbria*) in the slope waters off Canada's west coast. Can. J. Fish. Aquat. Sci. 45:152–164.

Charlesworth, B.
1980. Evolution in age-structured populations. Cambridge Univ. Press, Cambridge, 300 p.

Clarke, J.
1987. Temperature, latitude and reproductive effort. Mar. Ecol. Prog. Ser. 38:88–99.

Fargo, J., A. V. Tyler, and R. P. Foucher.
1990. Distribution of demersal fishes in Hecate Strait, British Columbia, based on systematic trawl surveys conducted from 1984–1987. Can. Tech. Rep. Fish. Aquat. Sci. 1,745, 115 p.

Mason, J. C., R. J. Beamish, and G. A. McFarlane.
1983. Sexual maturity, fecundity, spawning, and early life history of sablefish (*Anoplopoma fimbria*) in waters off the Pacific coast of Canada. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 137–140. Alaska Sea Grant Rep. 83-3.

Mayo, R. K., J. Burnett, T. D. Smith, and C. A. Muchant.
1990. Growth-maturation interactions of Acadian redfish (*Sebastes fasciatus* Storer) in the Gulf of Maine-Georges Bank region of the Northwest Atlantic. J. Cons. Int. Explor. Mer 46:287–305.

McFarlane, G. A., and R. J. Beamish.

1983a. Overview of the fishery and management strategy for sablefish (*Anoplopoma fimbria*) off the west coast of Canada. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 13–35. Alaska Sea Grant Rep. 83-3.

1983b. Biology of adult sablefish (*Anoplopoma fimbria*) in water off western Canada. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 59–80. Alaska Sea Grant Rep. 83-3.

1983c. Preliminary observations on the juvenile biology of sablefish (*Anoplopoma fimbria*) in waters off the west coast of Canada. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 119–136. Alaska Sea Grant Rep. 83-3.

1990. Effect of an external tag on growth of sablefish (*Anoplopoma fimbria*), and consequences to mortality and age at maturity. Can. J. Fish. Aquat. Sci. 47:1,551–1,557.

1992. Climatic influence linking copepod production with strong year classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 49:743–753.

McFarlane, G. A., and M. W. Saunders.

1997. Dispersion of juvenile sablefish, *Anoplopoma fimbria*, as indicated by tagging in Canadian waters. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 137–150. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Mulligan, T. J., and B. M. Leaman.

1992. Length-at-age analysis: can you get what you see? Can. J. Fish. Aquat. Sci. 49:632–643.

Potts, G. W., and R. J. Wootton (eds.).

1984. Fish reproduction: strategies and tactics. Academic Press, London, 410 p.

Richards, L. J., J. T. Schnute, and C. M. Hand.

1990. A multivariate maturity model with a comparative analysis of three lingcod (*Ophiodon elongatus*) stocks. Can. J. Fish. Aquat. Sci. 47:948–959.

Saunders, M. W., and G. A. McFarlane.

1990. Sablefish. *In* A. V. Tyler and J. Fargo (eds.), Groundfish stock assessments for the west coast of Canada in 1989 and recommended yield options for 1990, p. 127–149. Can. Tech. Rep. Fish. Aquat. Sci. 1,732, 343 p.

1991. Sablefish. *In* J. Fargo and B. M. Leaman (eds.), Groundfish stock assessments for the west coast of Canada in 1990 and recommended yield options for 1991, p. 117–136. Can. Tech. Rep. Fish. Aquat. Sci. 1,778, 320 p.

1993. Sablefish. *In* B. M. Leaman and M. Stocker (eds.), Groundfish stock assessments for the west coast of Canada in 1992 and recommended yield options for 1993, p. 132–162. Can. Tech. Rep. Fish. Aquat. Sci. 1,919, 407 p.

Saunders, M. W., G. A. McFarlane, M. Stocker, and B. M. Leaman.

1994. Sablefish. *In* M. Stocker (ed.), Groundfish stock assessments for the west coast of Canada in 1993 and recommended yield options for 1994. Can. Tech. Rep. Fish. Aquat. Sci. 1,975, 352 p.

Sigler, M. F., S. A. Lowe, and C. R. Kastelle.

1997. Area and depth differences in the age–length relationship of sablefish, *Anoplopoma fimbria*, in the Gulf of Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 55–63. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Solbrig, O. T., and D. J. Solbrig.

1979. Population biology and evolution. Addison-Wesley, Reading, Massachusetts, 468 p.

Stearns, S. C., and J. C. Koella.

1986. The evolution of phenotypic plasticity in life history traits: prediction of reaction norms for age and size at maturity. Evolution 40:833–913.

SYSTAT.

1992. SYSTAT for Windows, version 5. SYSTAT, Inc., Evanston, IL.

Tanasichuk, R. W.

1997. Diet of sablefish, *Anoplopoma fimbria*, from the southwest coast of Vancouver Island. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 93–97. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Ware, D. M., and G. A. McFarlane.

1989. Fisheries production domains in the Northeast Pacific Ocean. *In* R. J. Beamish and G. A. McFarlane (eds.), Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models, p. 359–379. Can. Spec. Publ. Fish. Aquat. Sci. 108.

Weir, K. R., R. J. Beamish, M. S. Smith, and J. R. Scarsbrook.

1978. Hake and pollock study, Strait of Georgia bottom trawl cruise, G. B. Reed February 25–March 13, 1975. Fish. Mar. Serv. Data Rep. 71, 53 p.

Wootton, R. J.

1990. Ecology of teleost fishes. Chapman and Hall, London, 404 p.

Diet of Sablefish, *Anoplopoma fimbria*, from the Southwest Coast of Vancouver Island

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ABSTRACT

I analyzed stomach content data for 2,479 sablefish, *Anoplopoma fimbria*, collected from continental shelf or slope locations along the southwest coast of Vancouver Island in August each year from 1985 through 1989. Euphausiids dominated the diet. Year and location had no significant effect on the importance of euphausiids and other invertebrates as food; however, the consumption of all invertebrates decreased as fish size increased. Pacific herring, *Clupea pallasi*, was the most important fish prey. The importance of herring and other fish as prey varied with year, location, and predator size. There was no effect of year, location, or size on the proportion of fish with empty stomachs.

Introduction

Waters off the southwest coast of Vancouver Island, including La Perouse Bank, are an extremely productive fishing area (Fig. 1). Commercial catches from the relatively small (10,000 km^2) bank region averaged 5.3 metric ton (t)/km^2/y over the last 30 years. This is about five times the average yield in the eastern Gulf of Alaska (Ware and McFarlane, 1989). Pacific hake, *Merluccius productus*, dominate the commercial catch. Their catch averaged 52,000 t between 1984 and 1989. Catches of sablefish, *Anoplopoma fimbria*, and other groundfish species were between 4,000 and 5,000 t annually over the same time.

Fisheries and Oceans Canada began an oceanographic study of the southwest coast of Vancouver Island in 1985. The goal was to investigate how the ocean affects fish production. The project has three parts: Physical oceanographers use mooring and oceanographic cast information to understand seasonal and interannual variations in circulation. Biological oceanographers monitor zooplankton abundance and community composition to see how they respond to such variations. Fisheries oceanography surveys document interannual variations in distribution and abundance of major fish species and predator–prey relationships.

The aim of the present study was to describe the diet of sablefish from stomach content data collected during the Fisheries and Oceans Canada fisheries oceanography surveys. I investigated the influence of year, fish size, and location on diet composition. Although sablefish is not a dominant species in the study area, it is a commercially valuable one. Information on sablefish diet and its variation enhances understanding of the trophic role this species plays, and also addresses factors that may influence sablefish growth and survival.

Materials and Methods

Sablefish were captured by commercial trawlers chartered for the Fisheries and Oceans Canada surveys. Bottom trawls were conducted during daylight each August between 1985 and 1990, in fishing subareas defined for the study (Fig. 1).

Routine biological and stomach-content information were collected from random subsamples from each tow. All fish were examined fresh and at sea. Fork length (cm) was measured, and sex, maturity, and stomach contents were recorded. Stomach contents were described by identifying each prey item to broad taxonomic group, visually estimating the volume (cc) of

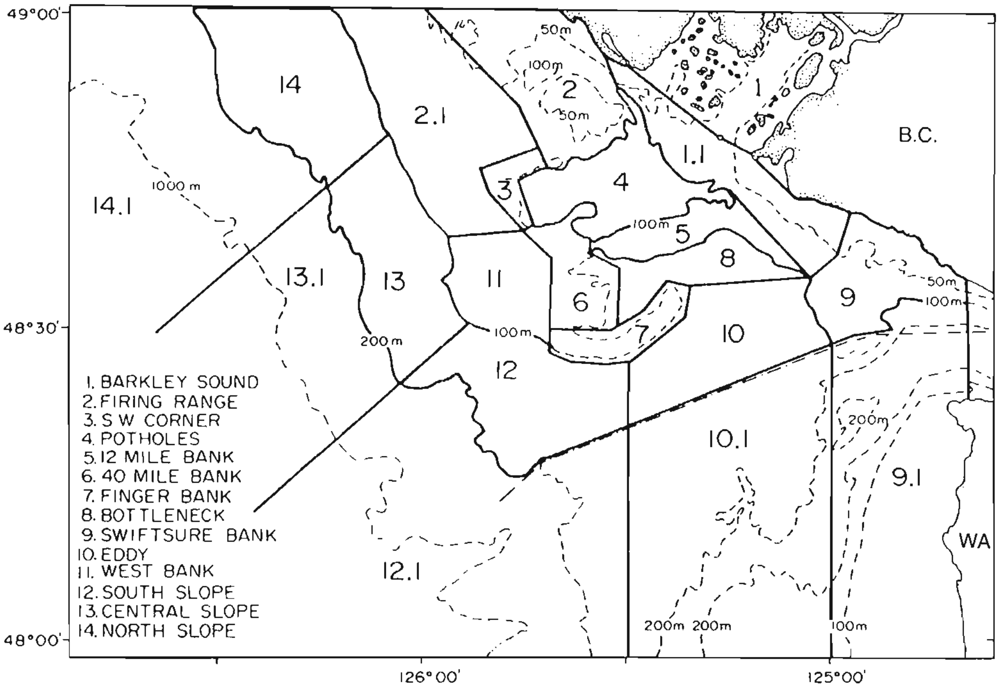

Figure 1

Fishing subareas defined for the Fisheries and Oceans Canada study of the southwest coast of Vancouver Island, B.C. The boundaries between subareas 9 and 9.1, 10 and 10.1, and 12 and 12.1 mark the Canada–U.S. fishing border between British Columbia and Washington.

each item, and then assigning a digestion code. Plastic syringes were used as guides for estimating prey volume. Digestion codes ranged from 1 (fresh) to 5 (fully digested). Standard length (mm) of ingested herring was measured. There was no evidence of regurgitation.

I restricted my analysis to locations where sablefish were caught consistently. These were nearshore around 100-m depth on and near 40 Mile and Finger Banks (subareas 6 and 7), and offshore on the continental slope at 150 m or deeper (subareas 12 and 12.1; Fig. 1). Sample sizes are given in Table 1. Data for 1990 were excluded because only 53 fish were caught that year in subarea 6, and none from other subareas.

Opinion varies about how to best describe fish diets. Volume or weight of prey can be misleading because the digestion rates of prey must be considered. Tanasichuk et al. (1991) estimated that Pacific hake and spiny dogfish, *Squalus acanthias*, digest euphausiids at least three times faster than they digest fish. However, sampling throughout the day should minimize the effect of differing digestion rates. Percent occurrence is immune to differences in prey digestibility, but can overemphasize the importance of small prey which may not contribute significantly to the amount of ingested material. I chose to describe the diet using the procedure outlined in Tanasichuk et al. (1991). I converted prey volume to weight as weight = 1.08 × volume. I calculated sablefish body weight (g) as $W = 0.0014L^{3.50}$ (McFarlane and Beamish, 1983), where L is fork length. Stomach contents were then expressed as a percentage of total body weight, which figure was used as a stomach fullness index.

I used 3-way factorial analyses of variance (Sokal and Rohlf, 1981) to test for significant effects of year, location, and fish size on the stomach fullness indices of dominant prey groups (euphausiids, other invertebrates, herring, and other fish). I tested the effect of size after assigning fish to 10-cm length classes. Index data were transformed with the arc sin transformation before analysis (Sokal and Rohlf, 1981). I used the Bonferroni t test to compare means. Statistical differences were insignificant if $p > 0.10$. The likelihood ratio chi-square test was used to compare sablefish size distributions.

I calculated the statistical power of these analyses using the procedures described by Cohen (1977). Statistical power evaluates how effectively an experimental design tested a null hypothesis that was not rejected. If power is high, then the null hypothesis is true. Otherwise, the null hypothesis cannot be accepted because experimental design was inadequate. I assumed a medium-sized effect for all tests, considering power less than 0.67 to be too low. All analyses had insufficient statistical power, which was most likely due to using the mean stomach-fullness index as the measure of feeding, reducing sample size to 1 for each combination of independent

Table 1

Mean stomach fullness indices of prey in sablefish from the southwest coast of Vancouver Island. Size is the midpoint of each 10-cm length class. Mt is the proportion of fish with empty stomachs.

	Bank						Slope					
Size	*n*	Herr.	Fish	Euph.	Invert.	Mt	*n*	Herr.	Fish	Euph.	Invert.	Mt
1985												
35	187	0	0.01	0.41	0.02	0.58	0	0	0	0	0	0
45	208	0	0.07	0.30	0.01	0.25	3	0	0	0.19	0	0.33
55	266	0.12	0.12	0.29	0.04	0.11	16	0	0	0.05	0	0.75
65	84	0.10	0.21	0.18	0.01	0.12	153	0	0.05	0.03	0.03	0.56
75	3	0	0.23	0.09	0	0	25	0	0.15	0.02	0.01	0.64
85	0	0	0	0	0	0	1	0	0	0	0	1.00
1986												
35	68	0	0.04	5.18	0	0.05	4	0	0	1.76	0.28	0
45	116	0	0.14	2.37	0.01	0.09	12	0	0.02	0.65	0.19	0.17
55	58	0.04	1.29	0.45	0.04	0.10	6	0	1.08	0.40	0	0.33
65	42	0	2.80	0.08	0	0.07	13	0	0.19	0.19	1.06	0.15
75	16	0	1.49	0.01	0.01	0.06	2	0	0	0.10	0	0.50
85	0	0	0	0	0	0	0	0	0	0	0	0
1987												
35	8	0	0	5.95	0	0.25	0	0	0	0	0	0
45	61	1.44	0.70	1.56	0.94	0.16	34	0.58	0.96	1.65	0.11	0.24
55	129	1.74	0.21	1.51	0.37	0.05	47	0.22	0.26	1.24	0.03	0.38
65	44	0.58	1.38	0.63	0.16	0.09	32	0.33	0.41	0.59	0.07	0.34
75	21	0.28	1.48	0.15	0.21	0.10	9	0	0.13	0.50	0	0.56
85	3	0	1.68	0	0	0.33	0	0	0	0	0	0
1988												
35	2	0	0	0	0	1.00	1	0	0	5.63	0	0
45	32	0.84	0.60	0.05	0.02	0.31	24	0	0.02	2.06	0	0.04
55	24	0.89	0.84	0.02	0	0.17	199	0.25	0.07	0.92	0	0.04
65	0	0	0	0	0	0	107	0.21	0.06	0.66	0	0.02
75	0	0	0	0	0	0	18	0.17	0.02	0.36	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0
1989												
35	0	0	0	0	0	0	0	0	0	0	0	0
45	31	0.02	0.02	5.02	0	0	14	0	0.03	2.27	0.02	0.07
55	109	0.54	0.03	2.32	0.03	0.02	158	0.71	0.21	0.83	0.01	0.08
65	14	0.01	0.01	1.15	0	0	66	0.17	0.12	0.31	0.03	0.11
75	5	0	0.78	0.12	0	0.40	4	0	0.02	0.08	0	0.25
85	0	0	0	0	0	0	0	0	0	0	0	0

effects; power drops drastically as sample size declines. In addition, sample collection during a fisheries survey rarely allows the highly controlled experimental design possible in the laboratory. This reduced the power of analyses for this study, as it likely does for the vast majority of fish-diet studies based on field sampling.

Results

Sablefish Size

Length-frequency histograms for the fish examined are shown in Fig. 2. Bank and slope fish averaged 50 ± 0.26 and 59 ± 0.25 cm (mean ± SE), respectively. Location had a significant ($p<0.0001$) influence on fish size.

Diet Composition

Sablefish consumed a variety of prey, including euphausiids, Pacific herring (*Clupea pallasi*), myctophids, Pacific hake, spiny dogfish, salmon, lingcod (*Ophiodon elongatus*), arrowtooth flounder (*Atheresthes stomais*), Pacific sand lance (*Ammodytes hexapterus*), rockfish, and other invertebrates. I calculated weighted mean stomach fullness indices (WMSFI) to determine the relative importance of each prey item. Mean stomach fullness indices were weighted by the number of fish in each year/location/size category. Euphausiids were the most important (WMSFI=0.95). Herring (WMSFI=0.30) was as important as all other fish species combined (WMSFI=0.27). Other invertebrates were least important (WMSFI=0.07).

Invertebrate Prey

Size affected the consumption of euphausiids ($p<0.001$) and other invertebrates ($p<0.05$) (Table 1). This was because invertebrates decrease in importance as predator size increases.

Fish as Prey

The MSFI of herring varied as a function of year ($p<0.001$), location ($p<0.10$), and fish size ($p<0.001$; Table 1). Herring was rare in 1985–86 and relatively abundant in 1987–89. Herring was more abundant in bank sablefish, and more common in sablefish between 40 and 80 cm (Fig. 3).

Table 2 gives the size composition of herring found in sablefish. Herring ranged from 13 to 25 cm long and averaged 20 cm. I found a significant ($p=0.07$) relationship between sablefish size and herring size. The functional regression equation (Ricker, 1973), calculated after pooling data over all years, was $H = 0.40 * S - 2.73$, where H is herring standard length (cm) and S is sablefish fork length (cm), with $R^2 = 0.04$.

The importance of other fish in the diet was also influenced by year ($p<0.01$), location ($p<0.01$), and size ($p<0.01$). Other fish occurred more frequently in 1986 and 1987, and in bank sablefish. Other fish entered the diet of sablefish longer than 40 cm.

Fish with Empty Stomachs

I found no effect of year, location, or fish size on the proportion of sablefish with empty stomachs. An average of 19%—weighted by the number of fish in each year/size/location category—of the sablefish had empty stomachs.

Discussion

Euphausiids dominate the diet of sablefish on the southwest coast of Vancouver Island, as they do the diets of hake and dogfish (Tanasichuk et al., 1991) and herring (Ware and Tanasichuk, unpubl. data) there. Shubnikov (1963), McFarlane and Beamish (1983), and Sasaki (1985) described diets of sablefish from the Bering Sea, Aleutian Islands, Gulf of Alaska, and northern British Columbia. All studies reported a variety of prey items ranging from benthic invertebrates to fish. The fish component of the diet reflected local species compositions. Shubnikov (1963) found that diet varied seasonally in the Bering Sea: sablefish fed mostly on fish in spring and autumn, and on ctenophores in summer.

I found a lower proportion of sablefish with empty stomachs (about 19%) than other studies reported. This could reflect feeding opportunity, as this area, especially La Perouse Bank, is extremely productive

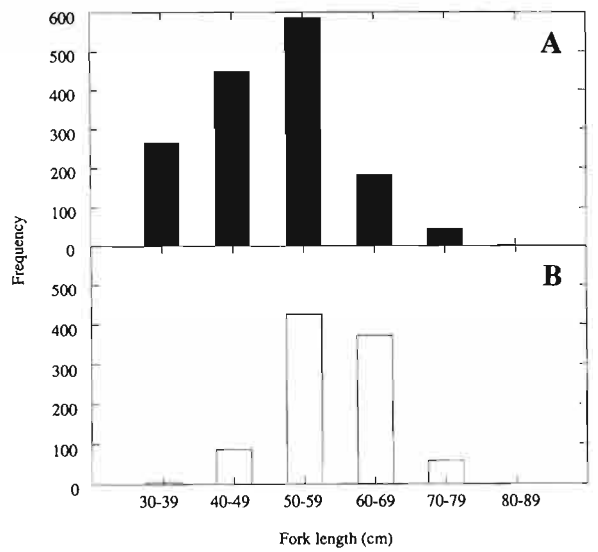

Figure 2
Length frequencies of sablefish trawled from (A) bank and (B) slope locations, 1985–89.

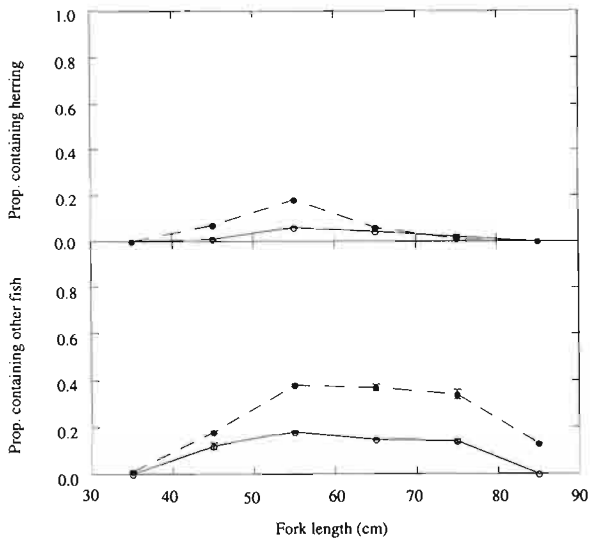

Figure 3
Proportions of sablefish containing herring and other fish, 1985–89. Dots indicate bank hauls and circles indicate slope hauls. Bars indicate 2 standard errors about the mean of the arcsin-transformed data.

biologically. Sasaki (1985) found that 25%–36% of sablefish trawled in the Bering Sea, Aleutians, and Gulf of Alaska did not contain food. Beamish et al. (1983, cited in McFarlane and Beamish, 1983) reported that 72% of the fish caught north of Vancouver Island had empty stomachs.

The frequency of occurrence of herring in sablefish stomachs from the southwest coast of Vancouver Island may reflect herring availability. Herring were rare in 1985 and 1986, when herring fisheries on the west coast of Vancouver Island and the Strait of Georgia were closed because of low stock abundance. Historic tagging statistics indicate that the herring fished in these locales feed in the La Perouse area over summer.

Our experience is that the proportion of predators containing fish increases with predator size to a point, and then decreases. The increase is probably due to the fact that fish become more important in the diet as predator size increases. I suggest that the apparent decrease is a simple sample-size effect, due to the difficulty of obtaining a representative sample of less-common large sablefish.

I am completing a detailed study of the population biology and productivity of euphausiids in Barkley Sound, within the study area. Preliminary results indicate that euphausiid biomass and productivity dropped by 75% after the 1992 and 1993 warm-water events, and that euphausiid populations show no signs of recovery. Biomass trends for Barkley Sound agree with those from synoptic zooplankton sampling data for the La Perouse area. This implies that euphausiid availability to sablefish has declined dramatically, which could have major implications for sablefish productivity given the importance of euphausiids as sablefish prey.

Table 2
Length frequencies of herring eaten by sablefish.

	Year					
Length (cm)	1985	1986	1987	1988	1989	Total
13	0	0	1	0	0	1
14	0	0	0	0	0	0
15	0	0	0	2	0	2
16	4	0	1	3	0	8
17	2	0	2	2	0	6
18	1	0	6	2	0	9
19	1	0	6	5	0	12
20	3	0	8	4	6	21
21	0	0	8	3	0	11
22	1	0	4	3	0	8
23	0	0	4	3	1	8
24	0	0	1	0	1	2
25	0	0	1	0	1	2
Unknown	10	1	2	16	43	72
Total	22	1	44	43	52	162

Acknowledgments

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Literature cited

Cohen, J.
1977. Statistical power analysis for the behavioral sciences. Academic Press, New York, 474 p.
McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters off western Canada. *In* B. Melteff, ed., Proceedings of the International Sablefish Symposium, Lowell Wakefield Fisheries Series. Alaska Sea Grant Rep. 83-8:59–93.
Ricker, W. E.
1973. Linear regressions in fisheries research. J. Fish. Res. Board Can. 30:409–434.
Sasaki, T.
1985. Studies on the sablefish resources of the North Pacific Ocean. Bull. Far Seas Fish. Res. Lab. 22:1–108.
Shubnikov, D. A.
1963. Data on the biology of sablefish of the Bering Sea. Transl. in Soviet fisheries investigations in the northeast Pacific, Part I, p. 287–296, by Israel Program Sci. Transl., 1968.
Sokal, R. R., and F. J. Rohlf.
1981. Biometry. 2nd ed. W. H. Freeman, San Francisco, 859 p.
Tanasichuk, R. W., D. M. Ware, W. Shaw, and G. A. McFarlane.
1991. Variations in the diet, daily ration and feeding periodicity of Pacific hake (*Merluccius productus*) and spiny dogfish (*Squalus acanthias*) off the lower west coast of Vancouver Island. Can. J. Fish. Aquat. Sci. 48:2,118–2,128.
Ware, D. M., and G. A. McFarlane.
1989. Fisheries production domains in the northeast Pacific Ocean. *In* R. J. Beamish and G. A. McFarlane (eds.), Effects of ocean variability on recruitment and evaluation of parameters used in stock assessment models, p. 359–379. Can. Spec. Publ. Fish. Aquat. Sci. 108.

Adaptive Radiation and Sablefish, *Anoplopoma fimbria*

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ABSTRACT

I develop an adaptive radiation hypothesis describing sablefish bathymetric stock structure and consisting of three statements: 1) juvenile sablefish occupy relatively shallow-water regions (<400 fm); 2) at some age near the onset of sexual maturity, adult sablefish migrate to a preferred bathymetric range and remain within that range for the remainder of their lifetime; 3) the cline in preferred depth for individual sablefish is maintained through a dynamic balance between physiological efficiency (determined by a large suite of genes), gene flow, and positive assortative mating (i.e., no reproductive migration). An important management implication of this hypothesis is that trends in catch per unit of effort (CPUE) from the commercial fishery may not reflect trends in overall stock abundance. CPUE's from the commercial fishery may overestimate stock abundance because fishing effort moves from shallow to deep water as the more readily accessible and higher-quality shallow-water portions of the stock become depleted. Thus observed relationships between mean age and depth may be artifacts of the varying application of size-selective fishing mortality with depth. The hypothesis offers an alternative to the ontogenetic hypothesis, which states that sablefish move deeper as they get older.

Introduction

The diversity of animals has fascinated people for ages. Darwin's *The Origin of Species* (1859) revolutionized our understanding of the origin of this diversity by refuting the concept of special creation and introducing the theory of evolution and its primary mechanism, natural selection. It has been recognized, however, that Darwin failed to adequately address the specific mechanisms of speciation, most notably, reproductive isolation (e.g., review by Sinclair, 1988). Stebbins (1950) summarized the problem as follows: "The processes responsible for evolutionary divergence may be entirely different in character and genetically independent of those which produce isolation mechanisms and consequently distinct species. . . . Descent with modification and the origin of species are essentially different processes."

Although the very definition of *species* remains controversial (e.g., review by Ereshefsky, 1992), many possible isolating mechanisms have been proposed, with those involving some form of geographic separation generally receiving the most attention (e.g., MacArthur and Wilson, 1967; Mayr, 1970; White, 1978). Geographic separation is an obvious isolating mechanism for many terrestrial non-fish and freshwater fish species. Cohen (1970) has noted that although freshwater covers only about 1% of the earth's surface, it contains about 41% of modern fish species. By contrast, salt water covers about 70% of the earth and contains only 58% of the species (the remaining 1% inhabit both fresh and salt water). Geographically isolated freshwater "islands in a sea of land" have undoubtedly played a major role in creating the relatively wider diversity of freshwater species. Isolating mechanisms in the marine environment, where there are few apparent geographical barriers to migration and dispersal, are more difficult to visualize. How does a single interbreeding population of marine fish diverge into two distinct species?

Understanding speciation mechanisms is of more than theoretical interest. Sinclair (1988) has suggested that unraveling the mysteries of speciation may improve fishery management by elucidating the factors controlling population abundance. He suggests that the general question of population regulation should be split into four components:

1. What determines the differences between species in population richness?
2. Why are the component populations of a particular species distributed in the observed geographical patterns?

3. What processes control the absolute abundance of the individual populations (or what controls their means)?
4. What processes control the temporal fluctuations in abundance of the individual populations (or what controls their variance)?

Most marine fish research and management, including that for sablefish, *Anoplopoma fimbria*, has focused on questions 3 and 4. Annual stock assessments are conducted to identify temporal trends in abundance, and correlations with environmental factors are computed to infer processes. But without adequate understanding of stock structure (i.e., the temporal and spatial distribution of populations), interpretation of assessments is problematic.

This paper addresses questions 1 and 2, particularly the bathymetric distribution of sablefish and its possible relationship to speciation processes. Sablefish is an excellent species for investigation of such issues because it is known to inhabit such broad geographic and bathymetric ranges. They are found along the edge of the continental shelf from Baja California to the Aleutian Islands and Hokkaido, Japan (Hart, 1973) and from the surface to depths of 2,740 m (Beamish et al., 1979). Sablefish are most abundant in the Gulf of Alaska and within the 400–1,000-m bathymetric range (Alverson et al., 1964; Hyamoto and Alton, 1965; Shippen[1]).

Two questions related to those posed by Sinclair (1988) arise: 1) In the region between California and Alaska, why are there at least 20 species within the genus *Sebastes*, but only a single species within the genus *Anoplopoma*? and 2) What isolation mechanisms created this extreme difference in species richness within genera? By seeking answers to these questions, I develop an alternative hypothesis concerning the bathymetric structure of sablefish stocks.

Most studies of sablefish stock structure have focused on delineating populations within their geographic ranges. Preliminary electrophoretic studies indicate that some genetic substructure may exist (Gharrett et al., 1983). Numerous tagging studies have been conducted to determine sablefish movements and delineate geographic stock structure (e.g., Holmberg and Jones, 1954; Beamish and McFarlane, 1983, 1988; Dark, 1983; McFarlane and Saunders, 1997; Rutecki and Varosi, 1997; Shaw[2]; Wespestad et al.[3]). In general, these studies indicate that 1) juvenile sablefish tend to migrate more than adults; 2) most adult sablefish remain within the same geographic region (i.e., within 200 km); and 3) some adult sablefish conduct extended migrations, occasionally up to 3,600 km. Beamish and McFarlane (1988) concluded that 1) "sablefish constitute one population throughout the range, and within this range most adults are resident," and 2) "because recruitment is irregular and most adults are resident, localized overfishing can occur even if exploitation rates are relatively low."

Sablefish management has generally reflected the Beamish and McFarlane view, in that separate stock assessments and harvest guidelines are prepared for different geographic regions. The associated mathematical models generally ignore the possibility of significant bathymetric stock structure (i.e., patterned bathymetric distribution of sablefish over time) and treat the stock within a geographic region as one homogeneous unit (e.g., Stocker and Saunders, 1997; Methot[4]). The tacit assumption is that within a given management unit both sablefish and fishing effort are more or less randomly distributed throughout the bathymetric range.

Historical data on the bathymetric distribution of sablefish are generally lacking. Only within the past 20 years has fishing technology permitted widespread exploitation of and research on sablefish throughout its bathymetric range. A few historical observations on diurnal and seasonal bathymetric migrations are available, however. Cox (1949) reported a seasonal migration to shallower water during the summer. Kulikov (1965) reported a diurnal migration to the surface during the day and a return to the bottom at night. More recently, Sullivan (1982) used a sonic tag to track the movements of a 54-cm male sablefish in La Jolla Canyon over a 44-h period. The fish migrated between 206 and 610 m, moving into shallow water at night and back into deeper water during the day.

The past decade has seen considerable work related to the bathymetric distribution of sablefish. Most of this work has focused on documenting intraspecific differences in life-history parameters correlated with depth. These findings are usually discussed within the context of general biology rather than stock structure, however. For example, this symposium places these subjects in the category of "Juvenile and Adult Biology," and, with

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[1] Shippen, H. H. 1972. Progress report on sablefish studies by the U. S. National Marine Fisheries Service 1971–1972. NWFC Proc. Rep. Northwest Fish. Cent., NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

[2] Shaw, F. R. 1986. Data report: an update of sablefish tagging studies in waters off the coasts of Washington, Oregon and California, through 1984. NWAFC Proc. Rep. 86-04, 35 p. Northwest and Alaska Fisheries Cent., NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

[3] Wespestad, V. G., K. Thorson, and S. Mizroch. 1978. Movement of sablefish (*Anoplopoma fimbria*) in the northeastern Pacific Ocean as determined by tagging experiments (1971–1977). NWAFC Proc. Rep., 54 p. plus appendices. Northwest and Alaska Fisheries Center, NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

[4] Methot, R. D. 1992. Assessment of the west coast sablefish stock in 1992. *In* Appendices to the status of the Pacific coast groundfish fishery through 1992 and recommended acceptable biological catches for 1993. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Avenue, Portland, OR 97201.

the exception of this paper, the "Stock Delineation and Movement" section contains papers dealing only with tagging studies. Thus relatively little attention has been paid to the possibility of bathymetric stock structure, despite a growing body of evidence that shallow- and deepwater sablefish appear to be "different." This evidence raises three questions analogous to those posed for geographic stock structure: Are most adult sablefish resident within a specific bathymetric zone? What is the pattern of recruitment to these bathymetric zones? Is localized depletion or overfishing possible within a bathymetric zone?

Controlling fishing effort within bathymetric zones is probably impractical. However, the existence of bathymetric structure may influence the interpretation of commercial catch and biological survey data used in stock assessments. For example, if fishing effort moves from shallow to deep water as fishing technology improves or as the more readily accessible shallow-water portions of the stock become depleted, long-term trends in catch per unit of effort (CPUE) from the commercial fishery may not reflect overall stock abundance. Also, observed life-history characteristics, such as the relationship between mean length or age and depth, may be artifacts of the varying application of size-selective fishing mortality with depth, as suggested by Saunders et al. (1997).

Some hypotheses regarding bathymetric stock structure have been proposed. Fujiwara and Hankin (1988) observed declining mean length and age at 50% sexual maturity with depth for sablefish off the coast of northern California. They proposed two hypotheses to explain these observations: 1) "sablefish may move to deeper waters at the onset of sexual maturity (for which size and age may vary considerably among individuals)," and 2) "distinct deep water and shallow water stocks may exist off northern California."

Sullivan (1982) noted that sablefish appear to have a deeper distribution at the southern end of their range, and tested the hypothesis that the geographic and bathymetric distribution of sablefish follows a pattern of tropical submergence, whereby fish living at lower latitudes move to greater depths following isotherms. Her experiments on thermal tolerance limits indicated that temperature per se was not forcing fish to live deeper as adults, and thus her results did not support the tropical submergence hypothesis.

A more common hypothesis is that sablefish move into deeper water as they get older (e.g., Hunter et al., 1989; Saunders et al., 1997; Methot[4]). Hunter et al. (1990) proposed the same hypothesis for Dover sole, *Microstomus pacificus*, a species that occupies the same general bathymetric range as sablefish. This ontogenetic hypothesis is based primarily on the observation that mean age of specimens collected from different depths tends to increase with depth. For example, using age-composition data collected from pot surveys along the Washington, Oregon, and California coasts, Methot[4] observed that 1) length at age is relatively similar in the three major depth zones; 2) age at length increases greatly in deeper water; 3) age composition at 150 fm includes no old sablefish; and 4) age composition deeper than 550 fm contains no young sablefish. He concluded that "the ontogenetic movement of sablefish into deeper water is related more to age than to size."

The ontogenetic hypothesis presents three difficulties. First, mean age (or mean length) at depth is typically not calculated separately for immature and mature fish (e.g., Hunter et al., 1989; Parks and Shaw, 1990; Methot[4]). As I demonstrate later, a much different pattern emerges when mean lengths for immature and mature fish are considered separately. Second, ageing methods often use depth of capture to "assist" in assigning ages to otoliths.[5] If age readers subscribe to the ontogenetic hypothesis and tend to assign older ages to otoliths from deeper-dwelling fish, analyzing mean age at depth involves circular reasoning. Third, there is empirical evidence from the early fishery (1917–18) that the virgin sablefish stock contained very large, and presumably old, fish in shallow water. Bell and Pruter (1954) report that average size of sablefish captured near Cape Flattery declined from 15–17 lb in 1917–18 to only 8 lb by 1952. Thus the absence of large, old fish in shallow water observed by Methot[4] may simply be the result of "fishing up" the shallow portion of the stock (i.e., changing the age structure toward younger fish by harvesting the older fish).

Hypotheses rarely gain full acceptance on the strength of observations alone: an underlying theory to explain the observations at both proximate and ultimate levels is generally required. Existing hypotheses regarding bathymetric stock structure are poorly developed. For example, the ontogenetic hypothesis for sablefish and Dover sole focuses on the proximate question: What determines the depth-preference range of an individual sablefish? It provides only a partially satisfactory answer: age. The hypothesis fails to describe the mechanistic details (i.e., stimulus-response system) of how age might be linked to depth preference. Do older fish move deeper because they prefer greater hydrostatic pressure, lower temperature, less food, less light, or do they just want to get farther from the juveniles? Further, the hypothesis does not address broader adaptation and evolutionary (ultimate) issues, such as identi-

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[5] Kastelle, C. Ageing Task, Natl. Mar. Fish. Serv., NOAA, 7600 Sand Point Way, N.E., Seattle WA 98115-0070. Personal commun.

fying the selective advantages of a life-history pattern that includes moving into deeper water with age. Does separation of juveniles and adults make more efficient use of food resources? Is recruitment better when eggs are spawned in deeper water?

The purpose of this paper is to initiate discussion and suggest research on these issues by developing an alternative hypothesis regarding the bathymetric structure of sablefish stocks. The hypothesis was motivated by previous research on two congeneric fishes (*Sebastolobus altivelis* and *S. alascanus,* commonly known as longspine and shortspine thornyheads, respectively), living at different depths but within the same general bathymetric range as sablefish. Siebenaller and Somero (1978) found that although these two species were electrophoretically indistinguishable, they appeared to have different muscle enzyme adaptations to hydrostatic pressure. The authors suggest that "hydrostatic pressure may play a major and heretofore unappreciated role in biochemical adaptation to the marine environment" and that "biochemical adaptations could be a significant factor in speciation events in the marine environment."

Since thornyheads occupy the same bathymetric range as sablefish, and are in fact managed by the Pacific Fishery Management Council as part of a multispecies deepwater complex that also includes sablefish and Dover sole, a reasonable question is: Are the observed differences between shallow- and deepwater sablefish also the result of enzyme adaptations to hydrostatic pressure? In previous work (Norris, 1989) I speculated that if they are, "sablefish may be in the initial stages of a population formation or speciation process."

In this paper I develop the hypothesis more fully. The underlying premise is that all species are constantly probing the margins of their habitats. Through genetic variation and natural selection they are adaptively radiating, at varying speeds, into new habitats, such as deeper bathymetric zones. Briefly, the adaptive radiation hypothesis consists of three statements: 1) juvenile sablefish occupy relatively shallow waters (<400 fm); 2) at some age near the onset of sexual maturity, adult sablefish migrate to a preferred bathymetric range and remain within that range for the remainder of their lifetime; 3) the cline in preferred depth of occurrence for individual sablefish is maintained through a dynamic balance between physiological efficiency (determined by a large suite of genes), gene flow, and positive assortative mating (i.e., no reproductive migration).

The paper is divided into six sections. First, I review what is known about sablefish growth and energetics, both in the wild and in controlled environments, and demonstrate that sablefish growth is extremely plastic (i.e., responsive to environmental conditions). This information provides the necessary background for interpreting the observed intraspecific differences correlated with depth, which are reviewed in the second section. There I argue that the differences are sufficiently great to conclude that individual sablefish occupy different bathymetric zones. The third section discusses a common characteristic of deep-dwelling teleost fishes—the "soft-textured condition"—which illustrates that the intraspecific sablefish differences are similar to interspecific differences between other shallow- and deep-living species. The fourth section develops the adaptive radiation hypothesis in detail. In the fifth section, I discuss both the ontogenetic and adaptive radiation hypotheses from two perspectives: proximate mechanisms and evolutionary significance. Finally, I draw conclusions and make recommendations for further research.

Sablefish Growth and Energetics

Sullivan and Smith (1982) conducted laboratory studies on sablefish captured at a depth of 468 m and found that sablefish fed a large ration (14% of wet body weight) every 7–10 d grow at rates two to three times greater than known growth rates for field fish. They also found that sablefish starved for 6 mo in the laboratory did not show signs of stress. Sullivan (1982) estimated that sablefish can tolerate food deprivation for up to 260 d under laboratory conditions, and found that sablefish utilize lipid stores in white muscle to tolerate food deprivation, followed by liver protein and lipid stores. Sullivan and Somero (1983) reported that starved sablefish under laboratory conditions had significantly higher water content and lower fat and protein content in muscle tissue than half- and full-ration fish. Furnell (1987) found evidence that "sablefish are able to allocate oxygen supply preferentially to locomoter muscles and suppress oxygen demand of digestion when active." Shenker and Olla (1986) reported that growth rates for small juvenile sablefish collected from the neuston off Oregon were highly dependent on ration size and prey type.

In preliminary mariculture studies, Kennedy (1974) reported growth rates of 0.11–0.15 kg/mo for pen-reared sablefish held off Nanaimo, B.C. Growth for larger fish (>2 kg) decreased dramatically when seawater temperature rose above 10°C, apparently due to lower ingestion rates; smaller sablefish (<2 kg) were less susceptible to decreased growth rates at high temperatures.

Later mariculture studies by McFarlane and Nagata (1988) demonstrated that sablefish growth rates vary widely between individuals and can be significantly affected by environmental factors (e.g., temperature, ration level, and food availability) during larval development. They found that sablefish raised on low ration levels during their first 10 months of life could not reach the same lengths as sablefish from the same cohort raised on high ration levels, even though ration levels for all treatment groups were maximized after 10 months. They also found that growth rates (about 0.13 kg/mo) for large juvenile and adult sablefish raised for a period of 24 mo were four to five times the rate for similar-sized wild fish. They concluded that sablefish "appear to have an adaptive physiology which is plastic enough to compensate for the changing metabolic needs associated with a variable food supply."

These laboratory and mariculture findings suggest that sablefish growth in length is not only quite plastic, but also that maximum length attained by any individual during juvenile and young adult stages (ages 3–12) may be strongly influenced by feeding success during the first year of life. The plastic nature of sablefish growth is reflected in the high variability of von Bertalanffy growth parameters estimated by different researchers (Fig. 1). Although some of the variability in these growth curves can be attributed to ageing errors, most studies on sablefish ageing methods conclude that the methods are relatively accurate up to ages 7 or 8 (e.g., Lai, 1985; Parks and Shaw, 1987). One observes, however, that even at these younger ages the predicted mean lengths at age are quite different (Fig. 1).

Most growth curves are determined by analyzing length-at-age data from a synthetic cohort composed of age classes from many separate true cohorts. If maximum attainable lengths for true cohorts are strongly influenced by environmental conditions during early life history, true cohorts may have different average growth functions. Thus growth-curve estimates from synthetic cohorts depend on the mixture of true cohort growth functions, especially for the younger ages (3–7).

Seasonal growth and sampling patterns may also influence estimated growth functions. For sablefish captured in depths less than 730 m (400 fm), Norris et al. (1987) estimated that mean raw fillet weight for 63-cm sablefish was 71 gm higher in October than in June, a 9.2% increase. Further analysis indicated that the observed increase was due primarily to increased skeletal muscle tissue rather than to increases in other somatic body parts (Norris, 1989).

Methot[6] examined length, age, and maturity data associated with depth from NMFS pot surveys in the area between northern California and Washington, and hypothesized that this region "contains a mixture of a morph with small maximum size, like that found south of San Francisco, and a large-maximum-size morph, such as that found in the Gulf of Alaska." In light of the extremely plastic nature of sablefish growth, as demonstrated by laboratory and mariculture studies, it seems that those observations could be equally well explained by regional differences in environmental conditions, both biological and physical.

I believe that the evidence more strongly supports the hypothesis that most of the growth variability observed in wild sablefish stocks is due to sampling variability and environmental conditions rather than to ageing errors or genotype. The fact that cultured sablefish can exhibit four to five times the growth rate of wild sablefish seems sufficient evidence to support this conclusion. The flip side is that observed phenotypic differences among sablefish captured from different geographic or bathymetric regions may indicate prolonged exposure to different environmental conditions. In the next section I review the observed morphological differences associated with depth for sablefish and draw conclusions about bathymetric distributions.

Phenotypic Characteristics Correlated with Depth

General Morphology

Norris (1989) reported that sablefish caught in deep water (>400 fm; 730 m) have darker external belly coloration, whiter raw fillet coloration despite external evidence of bruising, increased scale loss, thinner belly walls, and overall emaciated appearance. The differences in external coloration may be the result of temperature differences. Sullivan (1982) noticed that during temperature-tolerance tests, sablefish first responded to increased temperature with a bleaching of the ventral surface. Whiter raw fillet color may be due to lower hematocrits, as has been observed for other deepwater species (Blaxter et al., 1971).

Length–Weight Relationship

Klein (1985) noted a statistically significant difference in the length–weight relationship between sablefish caught by setnet gear and those caught by trap gear. Setnet fish, which were caught in relatively shallow water (90–150 fm; 160–275 m), had higher mean round weight for a given length than did the trap-caught fish, which were caught in deeper water (250–500 fm; 460–914 m). Since gear effects may have confounded the depth effects, these results are inconclusive.

To explore these differences further I compared length–weight relationships for shallow-water (< 350

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[6] Methot, R. D. 1993. Latitudinal and bathymetric patterns in sablefish growth and maturity off the U.S. west coast. Presented at the Intl. Symp. on the Biology and Management of Sablefish, April 13–15, 1993, Seattle, WA. NWFSC, NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

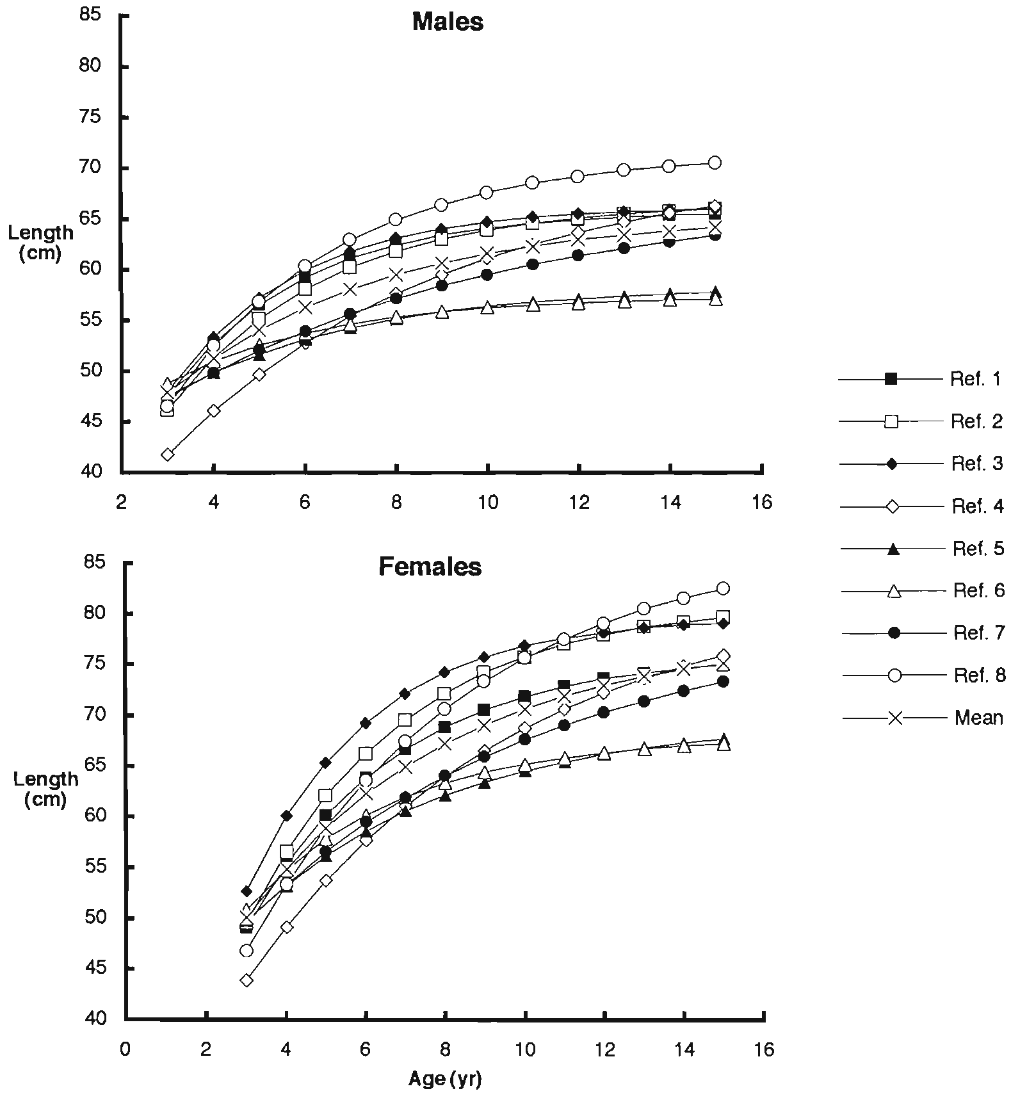

Figure 1

Eight sets of sablefish growth curves (male and female) taken from the literature. Refs. 1–3 are McFarlane and Beamish (1983); Ref. 4 is Klein (1985); Ref. 5 is McDevitt[1]; Refs. 6 and 7 are Parks and Shaw (1987); Ref. 8 is Maeda and Hankin (1983).

fm; 640 m) and deepwater (>350 fm; 640 m) sablefish captured during NMFS trap surveys in 1979, 1981, 1985, 1987, and 1989 off the coasts of Oregon and Washington. Off Oregon, shallow-water sablefish had greater round weight at a given length in all years except 1989, but the differences were statistically significant (95% level) only in 1979 (Fig. 2; Table 1). Off Washington, shallow-water sablefish had significantly greater round weight at a given length in all years (Fig. 3; Table 2).

Norris et al. (1987) found that for each 100 fm (183 m) of depth, mean raw fillet weight for 63-cm sablefish declined by about 5%. For example, 63-cm sablefish caught in 600 fm (1,100 m) averaged about 21% (170 gm) less raw fillet weight than sablefish of equal length caught in 200 fm (365 m). To put this difference in a temporal perspective, the mariculture studies by McFarlane and Nagata (1988) indicated that juvenile and adult sablefish fed a high-ration diet gained about

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[1] McDevitt, S. A. 1986. The status of the sablefish resource in waters off the U.S. west coast. *In* Status of the Pacific coast groundfish fishery through 1987 and recommended acceptable biological catches for 1988, p. B1–B32. Pacific Fishery Management Council, Metro Center, Suite 420, 2000 SW First Ave., Portland, OR 97201.

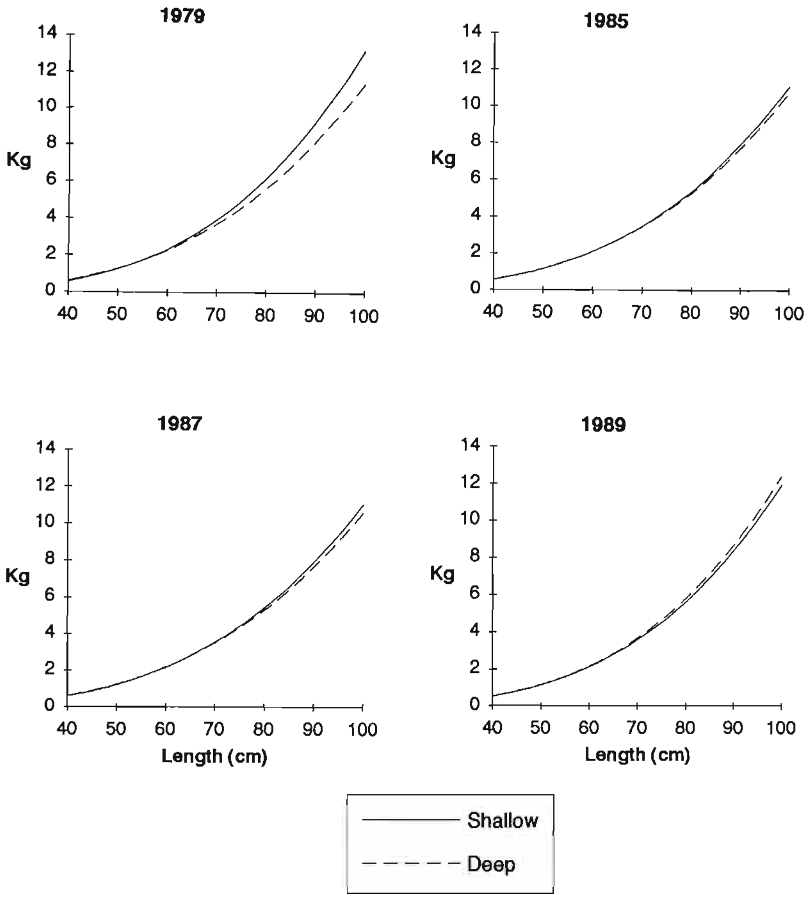

Figure 2
Length–weight relationships for shallow (<350 fm) and deep (>350 fm) sablefish captured during 1979, 1985, 1987, and 1989 by NMFS survey trap gear off the Oregon coast.

130 gm per month, which was about four to five times the growth rate of wild fish. Thus, for the average 63-cm sablefish living at 600 fm, it would take at least a month and a half to gain enough skeletal muscle weight to equal that of the average 63-cm shallow-water sablefish.

Table 1
Results of coincidence tests for length–weight relationships between shallow- and deepwater sablefish captured during NMFS trap surveys off the coast of Oregon.

Year	*N*	*F*	*p*
1979	1,079	13.35	0.000
1985	565	0.40	0.671
1987	508	1.50	0.224
1989	337	2.30	0.102

Mean Length and Age vs. Depth

Several studies document an increase in mean length with depth of capture (e.g., Hunter et al., 1989; Parks and Shaw, 1990; Methot[4]). But none of these studies computed separate relationships for immature and mature fish. I computed separate relationships for immature and mature sablefish captured during the NMFS trap surveys off the Oregon and Washington coasts using data from random samples (Fig. 4). For immature fish, mean length is fairly constant (48–53 cm) over the 150–450-fm (275–820-m) depth range (no immature fish were captured in waters deeper than 450 fm; 820 m). For mature fish, mean length vs. depth follows a V-shaped pattern, declining from about 62 cm at 150 fm (275 m) to a low of 55 cm at 450 fm (820 m) and then increasing back to 62 cm at 700 fm (1,280 m).

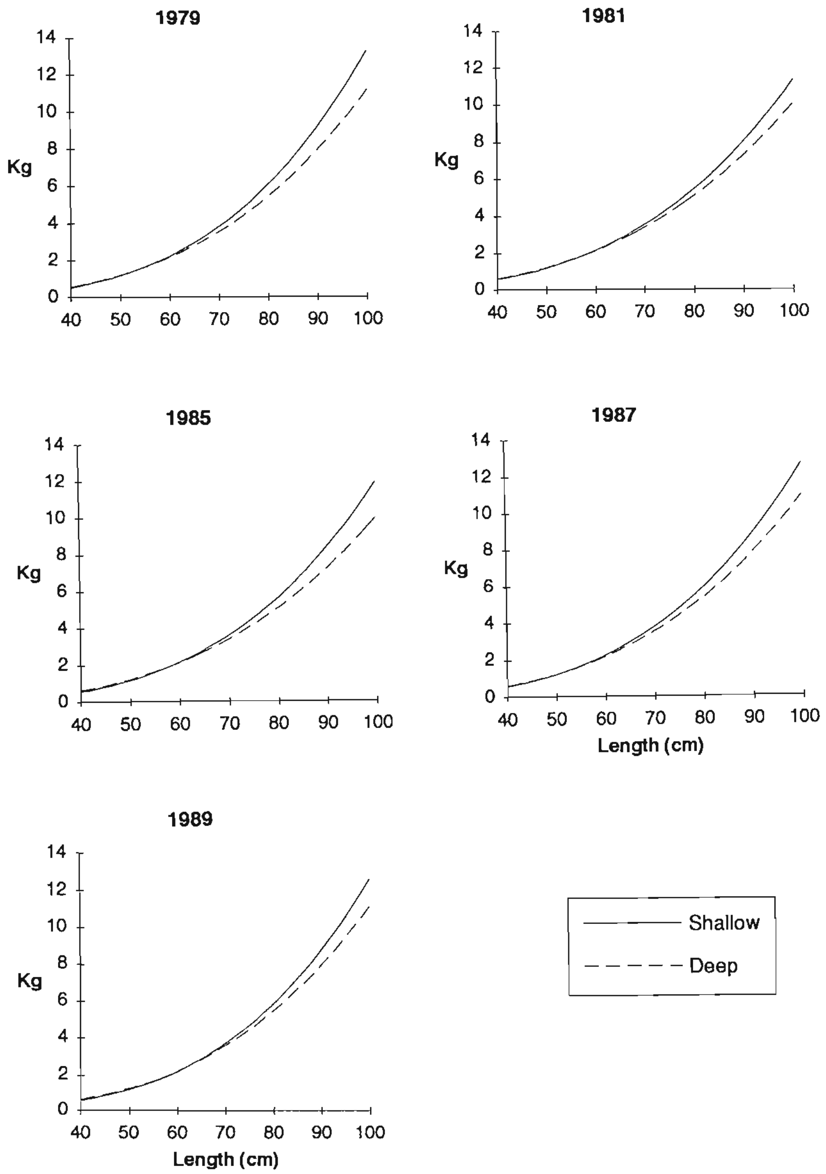

Figure 3
Length–weight relationships for shallow (<350 fm) and deep (>350 fm) sablefish captured during 1979, 1981, 1985, 1987, and 1989 by NMFS survey trap gear off the Washington coast.

I have found no published graphs of mean age vs. depth of capture. However, as mentioned earlier, several studies allude to increased mean age at depth (e.g., Hunter et al., 1989; Methot[4]).

Physiology

Gibbs and Somero (1990) measured the activity of Na^+-K^+-adenosine triphosphatase (Na^+- K^+-ATPase; the primary enzyme responsible for monovalent ion transfer) in the gills of several marine teleosts from different depths. They found that Na^+-K^+-ATPase activity decreased significantly with depth of capture. For sablefish, "Na^+-K^+-ATPase activities of shallow-occurring sablefish resembled those of other shallow-living species, whereas deeper-occurring individuals had much lower Na^+-K^+-ATPase activities which were similar to those of solely deep-living fishes."

Sullivan (1982) conducted temperature stress tests on sablefish and found that the upper acclimation tem-

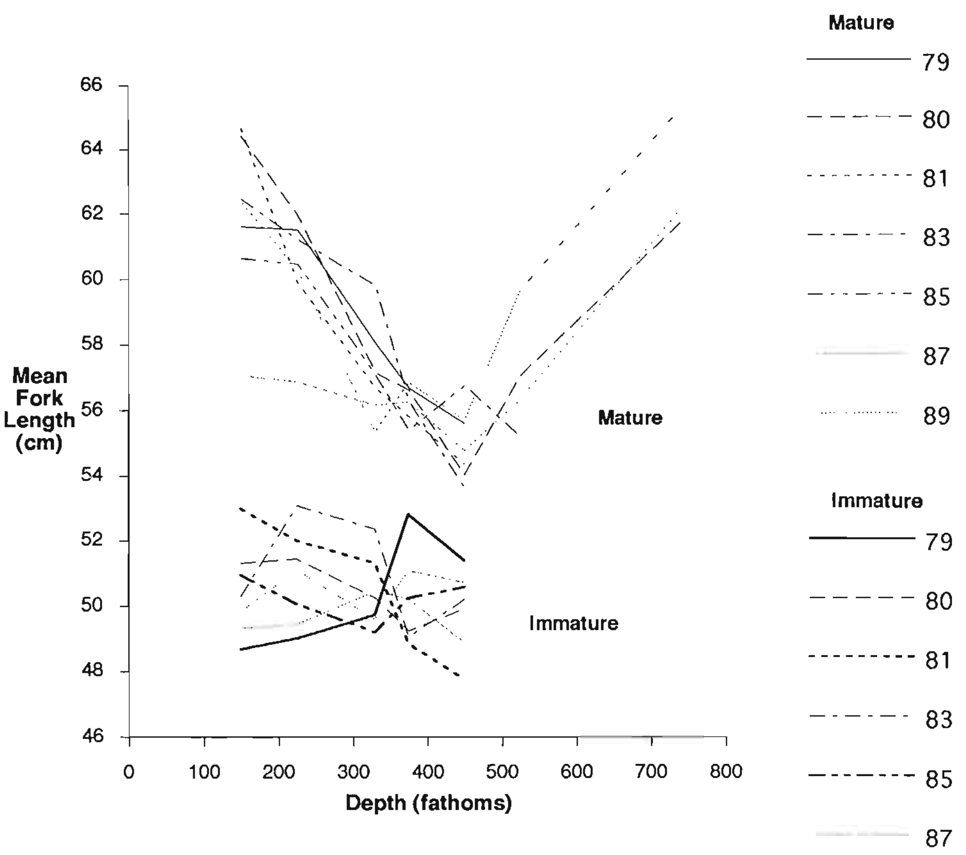

Figure 4
Mean fork lengths for mature and immature sablefish captured during NMFS trap surveys off the Washington and Oregon coasts from 1979 through 1989.

perature was about 18°C and that fish acclimated to 6°C died within 2 hr at 3°C, but lived indefinitely at 4°C. This apparent sensitivity to low temperature may be a critical factor in determining the maximum depth for sablefish.

Norris et al. (1987) reported that 24-h drip loss (free-drip water loss from a raw fillet sample within a 24-h period) increased significantly with depth of capture. For example, mean 24-h drip loss from sablefish captured in 200 fm (66 m) and 600 fm (1,097 m) was 6% and 24%, respectively.

Table 2
Results of coincidence tests for length–weight relationships between shallow- and deepwater sablefish captured during NMFS trap surveys off the coast of Washington.

Year	*N*	*F*	*p*
1979	965	10.45	0.000
1981	839	6.27	0.002
1985	688	31.60	0.000
1987	526	12.60	0.000
1989	463	14.07	0.000

Histology

Norris (1989) found that histological sections of muscle tissue from shallow-water sablefish were characterized by polygonally shaped muscle fibers with a large number of fat cells in between, whereas those from deepwater sablefish were characterized by spherical muscle fibers and an absence of fat cells. Muscle fibers from deepwater specimens appeared to be so severely hydrated that the cell walls were pulled away and the myofibrils were torn apart.

Summary

Shallow- and deepwater sablefish have significant differences in external morphology, mean weight at length, mean length and age at depth, physiological properties, and histological characteristics. Two important questions arise from these observations. First: To what extent are the observed intraspecific differences that are correlated with depth acquired or inherited? For example, differences in growth rate between shallow- and deepwater sablefish (or between sablefish from different geographic regions, for that matter) may be due to different environmental conditions or different genotypes. There is ample evidence that the habitats at the extremes of the most populated adult bathymetric range (150–1,300 m) differ both physically and biologically (Sullivan, 1982; Mason et al., 1983; Hunter et al., 1989). These factors may influence growth rate, and thus it is possible that occupying different bathymetric zones, or living under different environmental conditions in general, may result in the observed differences. A reviewer has suggested that the observed differences may simply be due to the ageing process.

A second question is: Are the observed differences great enough to suggest prolonged exposure to different environments? The only evidence linking observed differences with residence time is the finding that it would take the average (63-cm) deepwater sablefish at least a month and a half to gain enough skeletal muscle weight to equal that of the average (63-cm) shallow-water sablefish. Thus, it appears that deepwater sablefish cannot acquire the characteristics of shallow-water sablefish quickly, and vice versa—they must occupy the habitat for at least several months.

I conclude from this evidence that sablefish do not fully commingle throughout their bathymetric range. If this is true, the assumption of most stock-assessment and harvesting models—namely, that sablefish distribute themselves randomly over the continental slope and can be treated as a homogeneous unit—appears to be false. What is not so clear is: In what pattern and by what mechanisms do individual sablefish distribute themselves throughout the bathymetric range? The ontogenetic hypothesis states that sablefish move deeper as they get older, without suggesting the specific mechanisms. Before stating an alternative hypothesis, I discuss the "soft-textured condition" exhibited by sablefish and many other teleosts. The widespread occurrence of this condition provides a critical component of my hypothesis regarding sablefish bathymetric stock structure.

The Soft-textured Condition in Teleost Fishes

It has long been recognized that some commercially important species—most notably sablefish; American plaice, *Hippoglossoides platessoides*; and Dover sole—can have a "soft" or "jellied" condition which makes the fillets from such fish unmarketable. The fillets have been described as being "slimy," "jelly-like," "quivering," "glossy," and "opalescent" (Templeman and Andrews, 1956; Hendrickson et al., 1984; Patashnik et al.[7]). Chemical composition analyses have indicated that soft fish generally have higher water content and lower protein content than normal fish (Templeman and Andrews, 1956; Hendrickson et al., 1984; Patashnik et al.[7]). Other species exhibiting the soft-textured condition include winter flounder, *Pseudopleuronectes americanus* (Pearcy, 1961) and cabezon, *Scorpaenichthys marmoratus* (Lauth[8]). Some noncommercial species, such as those studied by Blaxter et al. (1971), also exhibit soft-textured characteristics. In similar work, Childress and Nygaard (1973) examined 37 species of midwater fishes off southern California and found a progressive increase in body water content with increasing depth, accompanied by decreases in protein, lipid, and skeletal ash content, especially for species without swim bladders.

Moisture content of skeletal muscle tissue may be related to both biological and environmental factors. Several authors have suggested that water content in muscle tissue increases as protein or fat is removed to meet the development needs of the gonads (Templeman and Andrews, 1956; Love, 1970; Bilinski et al., 1984). Sullivan and Somero (1983) found that starved sablefish under laboratory conditions had significantly higher water content and lower fat and protein content in muscle tissue than half- and full-ration fish. Seasonal effects may also be significant. Protein emaciation of the skeletal muscle tissue during the winter caused by the gonads having priority in the use of protein has been documented for American plaice (Templeman and Andrews, 1956; MacKinnon, 1972); Dover sole (Hendrickson et al., 1984); and English sole, *Parophrys retulus* (Dygert, 1985).

Haard (1987) suggested that the location of water within the muscle tissues (i.e., within cells or between cells) may be important in determining how that water affects the quality of the flesh. Templeman and Andrews (1956) suggested that drip-loss water from American plaice may be from between, rather than within, the muscle cells. Their conclusion is supported and generalized to other species by histological analyses of skeletal muscle tissues of American plaice (Templeman and Andrews, 1956), Dover sole (Fisher, 1985), and sablefish (Norris, 1989).

Norris (1989) selected sablefish specimens collected during mid-July to October from both depth strata that

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[7] Patashnik, M., H. Barnett, and J. Conrad. 1980. Soft sablefish (*Anoplopoma fimbria*) from the pot fishery off the Washington coast. Utilization Res. Div., NWAFC, NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. Unpubl. rep., 12 p.

[8] Lauth, Robert. Fish. Res. Inst., Box 357980, Univ. Washington, Seattle, WA 98105. Personal commun.

had a total moisture content of 69.0% to 77.0%. Totals of 103 specimens from the shallow stratum and 47 from the deep stratum satisfied this criterion. Mean total moisture percentages for these two subgroups were 72.1% and 73.2%, respectively. Two-sample *t*-tests indicated that deep samples had higher mean drip loss (18.6% vs. 11.3%) and lower smoked-fish yield (68.6% vs. 73.2%). These results support the hypotheses of Haard (1987) and Templeman and Andrews (1956) that the location of the water within the flesh (within or between muscle cells) may be more important in determining the quality characteristics than the amount of water.

Species exhibiting a soft-textured condition can be divided into two groups: 1) species for which soft texture is a seasonal condition correlated with spawning (e.g., American plaice, winter flounder, cabezon), and 2) species for which soft texture is a more permanent condition associated with depth—e.g., sablefish and Dover sole, species studied by Blaxter et al. (1971) and Childress and Nygaard (1973). The results of histological analyses on sablefish (Norris, 1989), American plaice (Templeman and Andrews, 1956), and Dover sole (Fisher, 1985), along with studies of the effects of starvation on moisture content (Sullivan, 1982; Sullivan and Somero, 1983) suggest that the soft-textured condition for both groups is caused by large, water-filled intercellular spaces resulting from protein or fat depletion in skeletal muscle tissues.

This hypothesis implies that soft texture is not a pathological condition, but rather a normal response to marginal environmental conditions (e.g., low food availability, low temperature, low oxygen) which may be either temporary (e.g., when the time of gonad maturation coincides with low food availability) or persistent (e.g., when a fish occupies a marginal habitat, such as the bathypelagic zone). The hypothesis has two important elements. First, it implies that the soft-textured condition is not related to hydrostatic pressure, and therefore explains how the condition can exist in both shallow- and deepwater species. Second, it implies that the soft-textured condition is reversible for some species.

No theories have been proposed to explain the adaptive significance of the soft-textured condition. However, two theories have been proposed to explain the correlation between high moisture content and depth. The first is that low-density body fluids/tissues function as an energy-efficient buoyancy control mechanism (Blaxter et al., 1971). The second is that low-density body fluids/tissues reduce the caloric content per unit weight, decrease the energy required per unit of growth, permit fish to grow to a larger size, and thereby make more prey items available (Childress and Nygaard, 1973). Both of these theories imply that increased moisture percentage increases the metabolic efficiency of the fish and thereby permits occupation of marginal habitats.

In Norris (1989) I proposed a third hypothesis: increased moisture content may be necessary to maintain hydrodynamic efficiency. It is possible that as muscle tissue is depleted it is replaced by water to maintain a relatively constant tissue volume within the skin. Fish skin has a limited amount of elasticity (Marshall, 1966) and performs critical biomechanical functions during locomotion (Wainwright et al., 1978; Wainwright, 1983). Wrinkled or baggy skin increases drag and reduces hydrodynamic performance (Hebrank, 1980). Increased moisture might be held between the individual muscle cells rather than within them because ionic patterns and levels must remain fairly constant within cells (Lutz, 1975). Haard (1987) has noted that the starvation situation in fish contrasts with that of mammals because in mammals there is no advantage to maintaining a constant body form during periods of starvation. In mammals, the added weight of any water retained to maintain external body form would impose a significantly greater cost than permitting the skin to hang loosely around the frame.

The Adaptive Radiation Hypothesis

To this point I have presented evidence supporting four statements: 1) sablefish morphology is strongly influenced by environmental conditions; 2) observed intraspecific morphological differences associated with depth are consistent with predictions from laboratory and mariculture studies (e.g., starved laboratory sablefish have characteristics similar to those of sablefish from deep water where food availability is thought to be low); 3) observed intraspecific morphological differences associated with depth are sufficiently large to conclude that individual sablefish occupy different depth ranges for extended periods of time; and 4) the physiological characteristics of deepwater sablefish are similar to those of many other deepwater species. To incorporate these statements into a common theory of sablefish stock structure, I return to a question posed in the introduction: How does a single interbreeding population of marine fishes diverge into two distinct species?

Siebenaller and Somero (1978) hypothesized that "successful colonization of deeper regions by a population may be attendant on the acquisition of pressure-adaptive changes in enzymatic properties. Such biochemical adaptations could be a significant factor in speciation events in the marine environment." Note that their hypothesis could be generalized to read ". . . the acquisition of any characteristic improving survival in deeper water." This type of speciation is referred to as clinal speciation. White (1978) describes clines as "geographic gradients in phenotypic characters that are generally assumed to be adaptive to some geographic regularity of the environment . . . The clinal mode of speciation is based on the idea that 'steps' in a cline become gradually steeper until an adaptive discontinuity is reached."

One can envision the speciation process in marine fishes proceeding as follows. Competition for limited resources forces poorer competitors to the margins of the habitat, such as deeper water. Genetic variation provides individuals better suited for survival at greater depths. If there is no spawning migration, assortative mating develops in which individuals adapted for specific depth zones reproduce with one another. The mature population develops a cline in characters associated with preferred depth zones, and the process continues until individuals at the extremes of the cline are reproductively isolated. Once isolation is established, speciation can proceed.

A full discussion of clinal speciation is beyond the scope of this paper. But from my cursory review of the literature, I draw three conclusions: 1) clinal speciation has been observed in the wild (e.g., see review by White, 1978); 2) clinal speciation has been demonstrated mathematically with a simple model of clines with coadaptive modifiers (Endler, 1977); and 3) the specific mechanisms differentiating clinal speciation and relatively static polymorphism within marine populations are poorly understood (e.g., Wilson and Hessler, 1987). Results from Endler (1977) suggest that clinal speciation occurs when the adaptive significance of the characteristic is large and gene flow is low.

Clines and clinal speciation are relevant to the bathymetric distribution of sablefish in demonstrating the possibility that geographic gradients in phenotypic characters (e.g., the soft-textured condition) may be adaptive to some geographic regularity of the environment, such as the physical factors associated with depth (e.g., pressure, temperature, salinity, oxygen, and light). From these observations I derive the adaptive radiation hypothesis, which consists of three statements:

1. Juvenile sablefish occupy shallow-water (<400 fm) regions.
2. At some age (perhaps the onset of sexual maturity) adult sablefish migrate to a preferred bathymetric range (to which they are adapted) and remain within that range for the remainder of their lifetime.
3. The cline in preferred mean depth for individual sablefish is maintained through a dynamic balance between physiological efficiency (determined by a large suite of genes), gene flow, and positive assortative mating (i.e., no reproductive migration).

This hypothesis is consistent with Beamish and McFarlane (1983) in describing sablefish as one population, with the additional comment that there exists large variability within that population. It assumes that the highly migratory behavior of some sablefish permits significant gene flow and inhibits complete reproductive isolation and further speciation. In the next section I discuss the hypothesis in relation to the ontogenetic hypothesis.

Discussion

Proximate Mechanisms

At the mechanistic level, one would like to know: What stimulus-response systems determine the bathymetric distribution of an individual sablefish throughout its lifetime? The ontogenetic hypothesis proposes age; the adaptive radiation hypothesis proposes an unspecified suite of physiological adaptations. Thus, at the proximate level, the hypotheses differ primarily in the timing and duration of the migration to deeper water. Under the adaptive radiation hypothesis, individual fish move relatively quickly (at most a few years); under the ontogenetic hypothesis, individual fish move gradually throughout their lifetime. Without further research, it is impossible to determine which hypothesis is more correct, or if a combination of both is more plausible.

The two hypotheses have different implications for management. If the bathymetric distribution of fishing effort is fairly constant over time, the ontogenetic hypothesis implies a gauntlet-type fishery through which fish move as they get older. Those that survive the gauntlet and reach depths below which there is little fishing effort have little fishing mortality. Thus, older fish should have lower fishing mortality. Under the adaptive radiation hypothesis, fishing mortality is highest on fish of all adult ages living within the bathymetric zone of greatest fishing effort. It is possible that relatively young adult sablefish preferring bathymetric zones outside those of concentrated fishing effort can have low fishing mortality.

Evolutionary Significance

The differences between the two hypotheses are perhaps more interesting from an evolutionary perspective. What evolutionary mechanism would favor each hypothesis? What are the selective advantages of each pattern of movement? As a basis for discussion, I first review the Member/Vagrant hypothesis proposed by Sinclair (1988), which comprises three statements:

1. Population *pattern* and *richness* are functions of the number and location of geographic settings within which the species' life cycle is capable of closure.

2. *Absolute abundance* is scaled according to the size of the geographic area in which there is closure of the life cycle of the free-crossing population.
3. *Temporal variability* in abundance is a function of the intergenerational losses of individuals (vagrancy and mortality) from the distributional area that ensures membership within a given population.

An important feature of this hypothesis is that "a population can lose members either by spatial or by energetics processes." Sinclair (1988) describes the significance of these two types of processes:

> In this conceptualization the energetics, or food-chain, processes lead to intraspecific competition for resources. Such competition generates selection for a certain class of adaptations associated with food-chain events. The spatial processes generated by the constraints of free-crossing in sexually reproducing animals result in relational events (membership, vagrancy), which generate what can be defined as life-cycle selection.

Sinclair's comments suggest that the ontogenetic hypothesis describing the bathymetric distribution of sablefish is more closely aligned to spatial processes and life-cycle selection than to energetics processes. That is, moving gradually into deeper water puts fish in the right place at the right time. Perhaps eggs spawned at certain depths have greater probability for life-cycle closure, given long-term current and weather patterns.

By contrast, the adaptive radiation hypothesis is more closely aligned with energetics processes. Competition for limited resources may force poorer competitors to the margins of the habitat. Those that have the best physiological adaptations survive and reproduce at the margins. The result is adaptive radiation into deeper habitats without speciation. If fishing mortality is confined to narrow bathymetric regions, localized depletion would be most likely under the adaptive radiation hypothesis.

Summary and Recommendations

I have presented evidence supporting the hypothesis that individual sablefish occupy different bathymetric regions for considerable periods of time. The strength of this support is in the observation that intraspecific phenotypic differences correlated with depth of capture are too great to be caused by short-term migrations between habitats. I hypothesized that the intraspecific differences observed for sablefish may be the result of adaptive radiation into deeper water. This hypothesis states that individual sablefish move to a preferred bathymetric range during a short time period around the age of sexual maturity and then remain in that range for the rest of their lives. I discussed the similarities with and differences from the ontogenetic hypothesis, and concluded that it was not possible at this time to distinguish between the two hypotheses.

Many interesting questions remain:

- In the early fishery, how old were the large fish caught in shallow water?
- Is the cline in age an artifact of harvest history, or does it represent the age structure in the virgin stock?
- How broad is the bathymetric distribution of individual sablefish?
- What is the mean and variance for the bathymetric range of individual sablefish?
- Do sablefish alter their typical bathymetric distribution during the spawning season?
- What is the likelihood of reproductive isolation for individuals living at the extremes of the bathymetric range for the stock?
- Does assortative mating occur?
- Are the physiological differences between deep- and shallow-water sablefish acquired characteristics, or are they inherited?
- Will deepwater sablefish have the same physiological characteristics as shallow-water sablefish after rearing in aquaria with high-ration feeding?
- If the physiological differences are acquired simply by occupying a different habitat (e.g., higher pressure, lower food availability), what are the advantages of occupying that habitat?
- In more general terms, what are the selective pressures for adaptive radiation into the deep ocean?

The above questions suggest several areas of future research that will enhance our understanding of sablefish stock structure. Sonic tagging studies would help determine the daily migration patterns of individual sablefish captured at different depths. Electrophoretic and mitochondrial DNA analyses on sablefish from different depths may help determine possible genetic associations or divergence. Physiology studies, similar to those employed by Siebenaller and Somero (1978) and Gibbs and Somero (1990), may help determine which characteristics are acquired and which are inherited. For example, comparing enzyme activity rates under hydrostatic pressure for sablefish captured at different depths and acclimated to low pressure for several months in aquaria would indicate whether or not such rates are fixed (suggesting an inherited trait) or variable (suggesting an acquired trait). Modeling studies to examine the behavior of life-history parameters (e.g., mean length and age at depth) under different biological hypotheses (adaptive radiation vs. ontogenetic) and different harvesting scenarios (uniform fishing pressure at all depths vs. increased fishing effort in deep water over time) may also be helpful in understanding landing and survey data. And finally, experiments to determine if ageing biases are created by using depth-of-capture information to age sablefish would make age-at-depth data more usable.

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Literature Cited

Alverson, D. L., A. T. Pruter, and L. L. Ronholt.
1964. A study of demersal fishes and fisheries of the northeastern Pacific Ocean. H. R. MacMillan Lectures in Fisheries, Univ. British Columbia, Inst. Fish., Vancouver, B.C., Canada, 190 p.

Beamish, R. J., C. Houle, C. Wood, and R. Scarsbrook.
1979. A summary of sablefish tagging and exploratory trapping studies conducted during 1978 by the Pacific Biological Station. Can. Data Rep. Fish. Aquat. Sci. 162, 113 p.

Beamish, R. J., and G. A. McFarlane.
1983. Summary of results of the Canadian sablefish tagging program. *In* Proceedings of the Lowell Wakefield International Sablefish Symposium, p. 147–184. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.
1988. Resident and dispersal behaviour of adult sablefish (*Anoplopoma fimbria*) in the slope waters off Canada's west coast. Can. J. Fish. Aquat. Sci. 45:152–164.

Bell, F. H., and A. T. Pruter.
1954. The Washington and Oregon sablefish fishery. Pac. Mar. Fish. Comm. Bull. 3:39–56.

Bilinski, E., R. E. E. Jonas, M. D. Peters, and E. M. Choromanski.
1984. Effects of sexual maturation on the quality of Coho salmon (*Oncorhynchus kisutch*) flesh. Can. Inst. Food Sci. Technol. J. 17(4):271–273.

Blaxter, J. H. S., C. S. Wardle, and B. L. Roberts.
1971. Aspects of the circulatory physiology and muscle systems of deep-sea fish. J. Mar. Biol. Ass. UK 51:991–1006.

Childress, J. J., and M. H. Nygaard.
1973. The chemical composition of midwater fishes as a function of depth of occurrence off southern California. Deep-Sea Res. 20:1093–1109.

Cohen, D. M.
1970. How many recent fishes are there? Proc. Calif. Acad. Sci. 37(17):341–346.

Cox, K.
1949. Sablefish. *In* The commercial fish catch of California for the year 1947 with an historical review 1916–1947. Calif. Dep. Fish Game Fish. Bull. 74:120–122.

Dark, T. A.
1983. Movement of tagged sablefish released at abundance index sites off southeastern Alaska, Washington, Oregon, and California during 1978–81. *In* Proceedings of the Lowell Wakefield International Sablefish Symposium, p. 143–146. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

Darwin, C.
1859. The origin of species. 1st ed. Penguin English Library, 1982, 476 p.

Dygert, P. H.
1985. An analysis of variability in the reproduction and growth of commercial marine fishes including considerations for some applied uses. Ph.D. dissert., Univ. Washington, Seattle, 275 p.

Endler, J. A.
1977. Geographic variation, speciation, and clines. Princeton Univ. Press, Princeton, NJ, 246 p.

Ereshefsky, M. (ed.)
1992. The units of evolution: essays on the nature of species. MIT Press, Cambridge, MA, 405 p.

Fisher, R. A.
1985. Histology and ultrastructure of the jellied condition of Dover sole, *Microstomus pacificus* (Lockington). *In* Proceedings of the Fifth European Conference of Ichthyologists, Stockholm, p. 345–350.

Fujiwara, S., and D. G. Hankin.
1988. Sex ratio, spawning period, and size and age at maturity of sablefish *Anoplopoma fimbria* off northern California. Nippon Suisan Gakkaishi (formerly Bull. Jpn. Soc. Sci. Fish.) 54(8):1,333–1,338.

Furnell, D. J.
1987. Partitioning of locomotor and feeding metabolism in sablefish (*Anoplopoma fimbria*). Can. J. Zool. 65(3):486–489.

Gharrett, A. J., L. N. Wishard, and M. A. Thomason.
1983. Progress in the study of the biochemical genetics of sablefish. *In* Proceedings of the Lowell Wakefield International Sablefish Symposium, p. 143–146. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

Gibbs, A., and G. N. Somero.
1990. Na^+-K^+-adenosine triphosphatase activities in gills of marine teleost fishes: changes with depth, size and locomotory activity level. Mar. Biol. 106:315–321.

Haard, N. F.
1987. Protein and non-protein nitrogen constituents in jellied American plaice, *Hippoglossoides platessoides.* Can. Inst. Food Sci. Technol. J. 20(2):98–101.

Hart, J. L.
1973. Pacific fishes of Canada. Fish. Res. Board Can. Bull. 180, 740 p.

Hebrank, M. R.
1980. Mechanical properties and locomotion function of eel skin. Biol. Bull. 158:58–68.

Hendrickson, G. L., R. A. Fritzsche, and H. M. Puckett.
1984. Ecology and possible causes of the "jellied' condition in Dover sole, *Microstomus pacificus.* Humboldt State Univ., Calif. Sea Grant bi-annual report, 1982–1984, R-CSG-CP-020, p. 129–130.

Holmberg, E. K., and W. G. Jones.
1954. Results of sablefish tagging experiments in Washington, Oregon, and California. Pac. Mar. Fish. Comm. Bull. 3:103–119.

Hunter, J. R., J. L. Butler, C. A. Kimbrell, and E. A. Lynn.
1990. Bathymetric patterns in size, age, sexual maturity, water content, and caloric density of Dover sole, *Microstomus pacificus.* Calif. Coop. Oceanic Fish. Invest. Rep. 31:132–144.

Hunter, J. R., B. J. Macewicz, and C. A. Kimbrell.
1989. Fecundity and other aspects of the reproduction of

sablefish, *Anoplopoma fimbria*, in central California waters. Calif. Coop. Oceanic Fish. Invest. Rep. 30:61–72.

Hyamoto, H., and M. S. Alton.
1965. Distribution, abundance and size of sablefish found in deep water off the mouth of the Columbia River. Comm. Fish. Rev. 27(2):1–8.

Kennedy, W. A.
1974. Sablefish culture—final report. Fish. Res. Board Can. Tech. Rep. 452, 15 p.

Klein, S. J.
1985. Selectivity of trawl, trap, longline, and set-net gears to sablefish, *Anoplopoma fimbria.* M.S. thesis, Univ. Washington, Seattle, 84 p.

Kulikov, M. Y.
1965. Vertical distribution of sablefish (*Anoplopoma fimbria* Pallas) on the Bering Sea continental slope. Tr. Vses. Nauchno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 58 (Izv. Tikhookean. Nauchno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 53):165–170. [In Russ.] Transl. in Soviet fisheries investigations in the northeast Pacific, Part IV, p. 157–161, by Israel Program Sci. Transl., 1968. Avail. Nat. Tech. Inf. Serv., Springfield, VA as TT 67-51206.

Lai, H. L.
1985. Evaluation and validation of age determination for sablefish, pollock, Pacific cod and yellowfin sole; optimum sampling design using age–length key; and implications of ageing variability on pollock. Ph.D. dissert., Univ. Washington, Seattle, 425 p.

Love, R. M.
1970. The chemical biology of fishes. Academic Press, London, 547 p.

Lutz, P. L.
1975. Adaptive and evolutionary aspects of the ionic content of fishes. Copeia 2:369–373.

MacArthur, R. H., and E. O. Wilson.
1967. The theory of island biogeography. Princeton Univ. Press.

MacKinnon, J. C.
1972. Summer storage of energy and its use for winter metabolism and gonad maturation in American plaice (*Hippoglossoides platessoides*). J. Fish. Res. Board Can. 29:1,749-1,759.

Maeda, R., and D. Hankin.
1983. Age and growth of sablefish landed in Eureka, California: a comparison of conventional surface age assignments with sectioned otolith assignments. *In* Proceedings of the Lowell Wakefield International Sablefish Symposium, p. 81–94. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

Marshall, N. B.
1966. The life of fishes. Universe Books, New York, 402 p.

Mason, J. C., R. J. Beamish, and G. A. McFarlane.
1983. Sexual maturity, fecundity, spawning, and early life history of sablefish (*Anoplopoma fimbria*) off the Pacific coast of Canada. Can. J. Fish. Aquat. Sci. 40:2126-2134.

Mayr, E.
1970. Populations, species, and evolution. Harvard Univ. Press.

McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters off western Canada. *In* Proceedings of the Lowell Wakefield International Sablefish Symposium, p. 59–80. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

McFarlane, G. A., and W. D. Nagata.
1988. Overview of sablefish mariculture and its potential for industry. *In* Proceedings of the Fourth Alaska Aquaculture Conference, Sitka, Alaska. Alaska Sea Grant Rep. 88-4.

McFarlane, G. A., and M. W. Saunders.
1997. Dispersion of juvenile sablefish, *Anoplopoma fimbria,* as indicated by tagging in Canadian waters. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 137–150. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Norris, J. G.
1989. Comparative analysis of harvesting strategies for sablefish stocks off the coasts of Washington, Oregon, and California. Ph. D. dissert., Univ. Wash., Seattle, 236 p.

Norris, J. G., J. Rowley, and S. B. Mathews.
1987. Analysis of four factors affecting the sablefish soft fish problem. Fish. Res. Inst., Univ. Washington, Seattle, FRI-UW 8715, 32 p.

Parks, N. B., and F. R. Shaw.
1987. Changes in relative abundance and size composition of sablefish in coastal waters of Washington and Oregon, 1979–85. NOAA Tech. Memo. NMFS F/NWC-124, 41 p.
1990. Changes in relative abundance and size composition of sablefish in coastal waters of Washington and Oregon, 1979–1989. NOAA Tech. Memo. NMFS F/NWC-188, 38 p.

Pearcy, W. G.
1961. Seasonal changes in osmotic pressure of flounder soma. Science 134:193–194.

Rutecki, T. L., and E. R. Varosi.
1997. Migrations of juvenile sablefish, *Anoplopoma fimbria,* in southeast Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 123–130. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Saunders, M. W., B. M. Leaman, and G. A. McFarlane.
1997. Influence of ontogeny and fishing mortality on the interpretation of sablefish, *Anoplopoma fimbria,* life history. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 81–92. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Shenker, J. M., and B. L. Olla.
1986. Laboratory feeding and growth of juvenile sablefish, *Anoplopoma fimbria.* Can. J. Fish. Aquat. Sci. 43:930–937.

Siebenaller, J., and G. N. Somero.
1978. Pressure-adaptive differences in lactate dehydrogenases of congeneric fishes living at different depths. Science 201:255–257.

Sinclair, M.
1988. Marine populations: an essay on population regulation. Univ. Washington Press, Seattle, 252 p.

Stebbins, G. L.
1950. Variation and evolution in plants. Columbia Univ. Press, New York.

Stocker, M., and M. W. Saunders.
1997. Utility of an age- and sex-structured model for sablefish, *Anoplopoma fimbria,* stock assessment off the west coast of Canada. *In* M. Wilkins and M. Saunders (eds), Biology and management of sablefish, *Anoplopoma fimbria,* p. 207–213. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Sullivan, K. M.
1982. The bioenergetics of the sablefish (*Anoplopoma fimbria*) occurring off southern California and energy allocation during low-frequency feeding in deep-living benthopelagic fishes. Ph.D. dissert., Univ. of California, San Diego, 237 p.

Sullivan, K. M., and K. L. Smith Jr.
1982. Energetics of sablefish, *Anoplopoma fimbria,* under laboratory conditions. Can. J. Fish. Aquat. Sci. 39:1,012–1,020.

Sullivan, K. M., and G. N. Somero.
1983. Size- and diet-related variations in enzymic activity and tissue composition in the sablefish, *Anoplopoma fimbria.* Biol. Bull. 164:315–326.

Templeman, W., and G. L. Andrews.
1956. Jellied condition in the American plaice, *Hippoglossoides platt-essoides* (Fabricus). J. Fish. Res. Board Can. 13(2):147–182.

Wainright, S. A.
1983. To bend a fish. *In* P. W. Webb and D. Weihs (eds.), Fish biomechanics, p. 68–91. Praeger, New York, 398 p.

Wainwright, S. A., F. Vosburgh, and J. H. Hebrank.
1978. Shark skin: function in locomotion. Science 202: 747–749.

White, M. J. D.
1978. Modes of speciation. W. H. Freeman, San Francisco, CA, 455 p.

Wilson, G. D., and R. R. Hessler.
1987. Speciation in the deep sea. Ann. Rev. Ecol. Syst. 18:185–207.

Movements of Tagged Sablefish, *Anoplopoma fimbria*, Released in the Eastern Gulf of Alaska

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ABSTRACT

During 1983–91, 67,000 adult sablefish, *Anoplopoma fimbria*, were tagged and released by the National Marine Fisheries Service in six areas within the eastern Gulf of Alaska (EGOA). Over half of the tagged fish were released in Chatham Strait, an area of intense fishing and high sablefish abundance. As of September 1992, 3,649 fish had been recovered. Over three-fourths of all tags were recovered in the EGOA, most of them in or adjacent to the original release area. Chatham Strait, with its high density of mature fish and low rate of tag recovery outside the EGOA, appears to have a high proportion of nonmigrating fish. Of the fish recovered outside the EGOA, more small fish (<57 cm FL when tagged) moved north and westward, and more large fish (>66 cm FL when tagged) moved south and eastward. Size composition of fish recovered in southern and eastern areas changed over time; recovery rates of fish tagged when small increased for fish recaptured after three years at liberty, indicating the return of westward migrants.

Introduction

The Gulf of Alaska supports a valuable commercial fishery for sablefish, *Anoplopoma fimbria*, which is currently managed by regulatory areas and harvest quotas set by the North Pacific Fishery Management Council (NPFMC). Several tagging studies have shown sablefish to be highly migratory for at least a portion of their life cycle (Bracken, 1982; Sasaki, 1985; Beamish and McFarlane, 1988; Fujioka et al., 1988). Heifetz and Fujioka (1991) studied the movement dynamics of sablefish in the northeastern Pacific Ocean and concluded that migration affects the number of harvestable sablefish in an area. Analysis of tag data is the primary method used to study sablefish movements.

Some of the most concentrated and intense fishing for sablefish takes place in the eastern Gulf of Alaska (EGOA). During 1983–91, the National Marine Fisheries Service (NMFS) tagged and released 67,000 adult sablefish in the EGOA. By September 1992, 3,649 of these fish had been recovered, with recovery locations ranging from California to the Bering Sea. This report summarizes the resulting data in terms of general patterns of movement outside and within the EGOA. Movement patterns of tagged juvenile sablefish are summarized in Rutecki and Varosi (1997).

Methods

Sablefish data included in this report are for fish tagged and released at exploitable size—>40 cm fork length (FL)—in the EGOA from 1983 through 1991. Recoveries of tagged fish were analyzed by release and recovery areas, size at release, and recovery patterns over time.

Fish were tagged by the NMFS Auke Bay Laboratory and other agencies, such as the Alaska Department of Fish and Game. Recoveries of tagged fish released in the EGOA during the Japan–U.S. cooperative longline survey are also included. The methods of Sasaki (1985) were used to tag the fish, which were recaptured mostly by commercial fishing operations in the areas of the northeast Pacific Ocean shown in Figure 1.

For analysis, the EGOA was divided into six release areas (Fig. 2). The inside waters of southeast Alaska include Clarence Strait and Chatham Strait; the outer

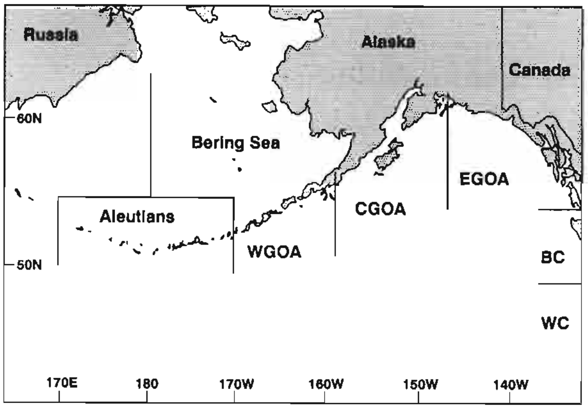

Figure 1
Northeast Pacific Ocean, British Columbia, and the West Coast of the United States, showing North Pacific Fishery Management Council regulatory areas. WC = West Coast; BC = British Columbia; EGOA = eastern Gulf of Alaska; CGOA = central Gulf of Alaska; WGOA = western Gulf of Alaska.

coastal waters were divided into the Southern Outside, Ommaney, Northern Outside, and Yakutat areas. The Ommaney area, although smaller than the others, was separated because of its strategic location at the entrance to Chatham Strait, an area of high sablefish abundance and an intensive fishery. The sixth area, Yakutat, extends from 137° to 147°W. Over half the tagged sablefish releases (hereafter referred to as "releases") were made in Chatham Strait.

Results of other studies have indicated differences in direction and extent of movement among different sizes of sablefish (Bracken, 1982; Fujioka et al., 1988). In general, small fish tend to move north or west from their release sites. Large fish tagged in the western areas of the Gulf of Alaska tend to move south and eastward, whereas large fish tagged in southern and eastern areas tend to remain close to the area of release. The three size categories of sablefish analyzed in our study were the same as those of Heifetz and Fujioka (1991): <57 cm FL (small), 57–66 cm FL (medium), and >66 cm FL (large). These size categories refer to size at release; accurate size at recovery is usually not available.

The size composition of releases from each area varied (Table 1). Clarence was the only area where most releases were small; other release areas had mostly medium fish (Southern and Northern Outside and Yakutat) or approximately equal numbers of medium and large fish and relatively few small fish (Chatham and Ommaney).

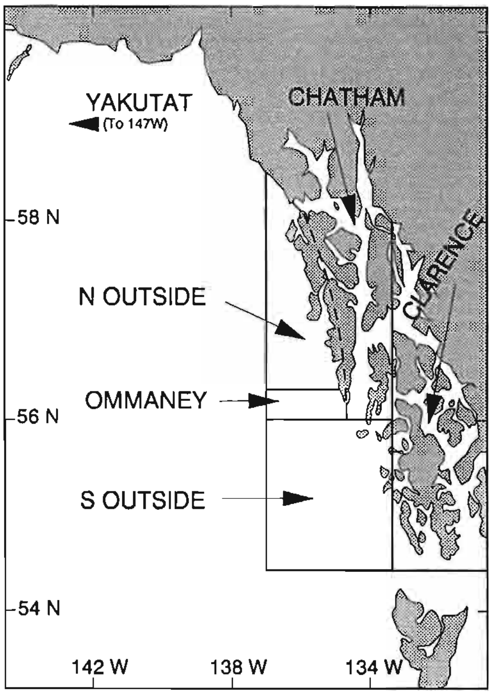

Figure 2
The six release areas for sablefish tagged in the eastern Gulf of Alaska.

Table 1
Numbers of tagged sablefish released, by fish size and area of the eastern Gulf of Alaska, 1983–91.

	Size[a]			
Release area	Small	Medium	Large	Total
Clarence	2,600	1,216	694	4,510
Chatham	3,562	16,113	15,136	34,811
S. Outside	1,811	3,532	947	6,290
Ommaney	331	1,069	1,182	2,582
N. Outside	1,721	4,536	2,343	8,600
Yakutat	3,070	5,103	2,034	10,207
Total	13,095	31,569	22,336	67,000

[a] Small is <57 cm FL; medium is 57–66 cm FL; large is >66 cm FL.

Recoveries of tagged fish (hereafter referred to as "recoveries") are expressed as percentages or, where appropriate, as rates of recovery, i.e., adjusted for release numbers (recoveries/1,000 releases). Adjustment of recoveries to the number of releases yields estimates of recoveries that would have been obtained if the same number of fish had been released from each area. Recoveries were not adjusted for reporting rates or level of fishing effort within an area.

For our analysis, we assigned recoveries to one of four areas. Data from the few (seven) recoveries from California, Oregon, and Washington were combined with those of British Columbia (BC). Bering Sea and Aleutian Island recoveries were combined with those of the western Gulf of Alaska (WGOA). The other two

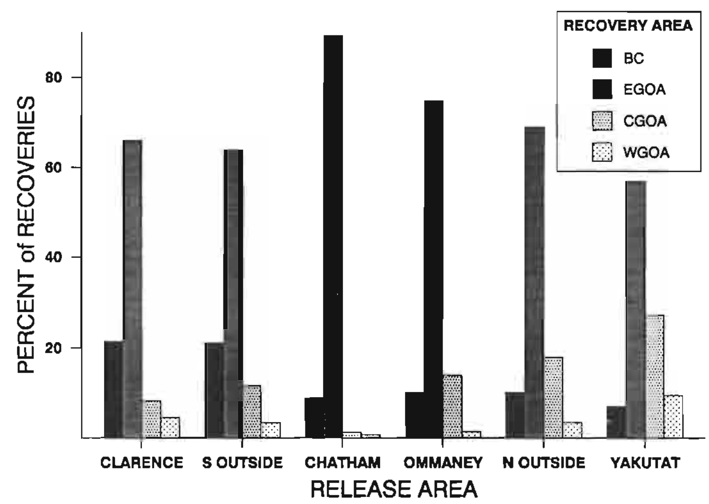

Figure 3

Recoveries of tagged sablefish (percentage) by release area in the eastern Gulf of Alaska. BC = British Columbia; EGOA = eastern Gulf of Alaska; CGOA = central Gulf of Alaska; WGOA = western Gulf of Alaska.

recovery areas are the EGOA and the central Gulf of Alaska (CGOA).

Results

Recoveries

Most recoveries from all six release areas were made in the EGOA (Fig. 3). The recovery patterns observed for the two southernmost release areas, Clarence and Southern Outside, were similar: over 20% of the recoveries in the adjacent BC area, about 65% in the EGOA, and the remainder in the CGOA and WGOA. Less than 10% of the recoveries of the other release areas were made in BC.

Nearly 90% of the recovered Chatham releases were in the EGOA, and <2% occurred in the CGOA or WGOA (Fig. 3). Percentage of recoveries made in the EGOA declined from south to north for the four northernmost release areas: Chatham releases (89%), Ommaney (75%), Northern Outside (67%), and Yakutat (57%). Conversely, the percentage of recoveries in the CGOA and WGOA increased from the southern to the northern release areas.

The rates of recovery in each of the four recovery areas are shown by release area in Figure 4. More BC recoveries were released in the two southernmost areas (Clarence and Southern Outside) than in the northern areas. EGOA recoveries were relatively high from all release areas, but highest from Chatham and Ommaney. In contrast, recoveries in the CGOA and WGOA were notably few from Chatham, and were highest from the northern (Northern Outside and Yakutat) releases.

Recoveries by Size

Recovery rates for all three sizes of fish were highest in the EGOA, except that slightly more small fish from Yakutat were recovered in the CGOA.

Small fish (i.e., release size <57 cm) from all release areas were recovered in all areas, except that no small Chatham fish were recovered in the WGOA and few in the CGOA (Fig. 5).

Medium fish from the Clarence or Ommaney areas were not recovered in the WGOA, and few from Clarence or Chatham were recovered in the CGOA. Most recoveries of medium fish in BC came from the Clarence and Southern Outside release areas. Most medium fish recovered in the CGOA originated from Ommaney, Northern Outside, and Yakutat; most in the WGOA originated from Yakutat.

No large fish from Clarence or Ommaney and few from the other release areas were recovered in the WGOA. Appreciable numbers of CGOA recoveries of large fish originated from the Ommaney, Northern Outside, and Yakutat areas, but there were few or none from Clarence, Southern Outside, and Chatham. In BC, recoveries of large fish were highest from Clarence and Southern Outside.

The proportions of the three size categories recovered in BC and the EGOA were similar to the overall release composition: a low percentage of small fish, a high percentage of medium fish, and an intermediate percentage of large fish (Fig. 6). CGOA and WGOA recoveries were mostly small and medium fish.

Recoveries by Size over Time

Size composition of recoveries in each recovery area changed over time (Fig. 7). BC and EGOA recoveries were mostly medium and large fish for the intervals up to four years after release. The proportion of small fish recovered remained low up to three years after release, increased for fish recovered between three and four years after release, and increased again for fish at liberty more than four years. These increases may represent migrating mature fish returning from the westward areas, fully recruited to the fishery.

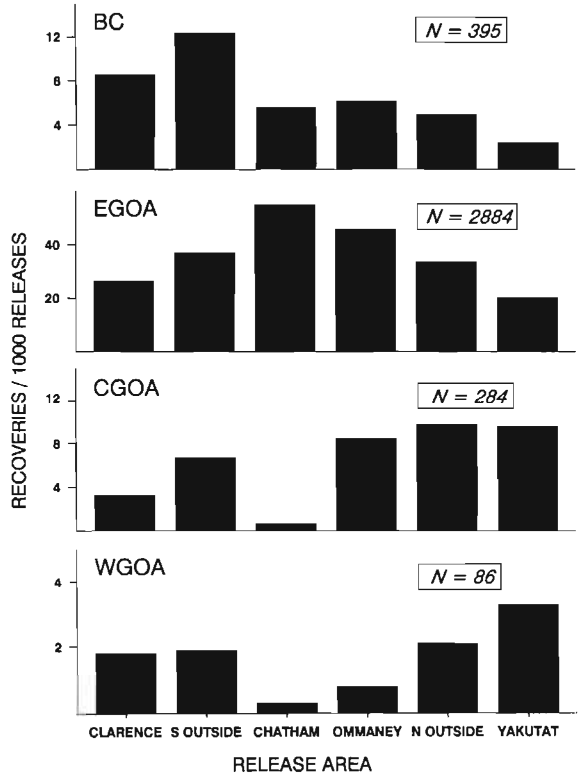

Figure 4

Recovery rates (recoveries/1,000 releases) of tagged sablefish in four recovery areas of the northeastern Pacific Ocean, by release area. BC = British Columbia; EGOA = eastern Gulf of Alaska; CGOA = central Gulf of Alaska; WGOA = western Gulf of Alaska. *N* is the actual number of recoveries made in an area.

Fish at liberty less than six months were not recovered in the CGOA or WGOA (Fig. 7), probably because of a combination of the travel time required and a lack or slowdown of fishing effort in winter. Most releases were made during summer and early fall. Small and medium fish made up 75%–80% of the recoveries in the CGOA and 85%–90% of those in the WGOA.

Movement within the EGOA

Over three-fourths of all recoveries were made in the EGOA. Most recoveries in an area originated within that area or in an immediately adjoining area (Table 2). Recoveries of Ommaney releases differed from those of the other release areas in that only about one-third were recovered within the Ommaney area, probably because of the relatively small size of the Ommaney area and its location at the intersection of the Northern Outside, Southern Outside, and Chatham areas. Also, 22% of the recoveries of Ommaney releases were made in Chatham, but only 2% of the recoveries of Chatham releases were made in the Ommaney area.

The distribution of releases and recoveries by size-at-release category within the EGOA is shown in Figure 8. The recoveries of small fish within Chatham were disproportionate to the releases: although only one-fourth of the total small fish releases were from Chatham, about one-half of the EGOA recoveries of small fish were made in Chatham. The Southern Outside and Ommaney areas also show slightly elevated levels of recoveries of small fish, whereas Clarence and the two northern areas exhibited the opposite trend.

The recovery distribution of medium and large fish is similar to that of the small fish. This pattern suggests an influx of fish of all size groups into Chatham, Southern Outside, and Ommaney, and a corresponding outward movement from Clarence and the northern areas. Analysis of each area's recoveries by origin and duration of liberty after release, adjusted for fishing and reporting rates, is needed to clarify these observations.

Conclusions

Results of this study are consistent with those of other studies of sablefish movement within the northeastern Pacific: smaller fish tend to move north and west from their release sites, and large fish in the eastern area move less than other size groups. CGOA and WGOA recoveries were dominated by small and medium fish, whereas medium and large fish composed the greatest part of BC and EGOA recoveries. In our study, recoveries of fish released when small in BC and EGOA increased after three to four years, which may indicate the return of westward migrants.

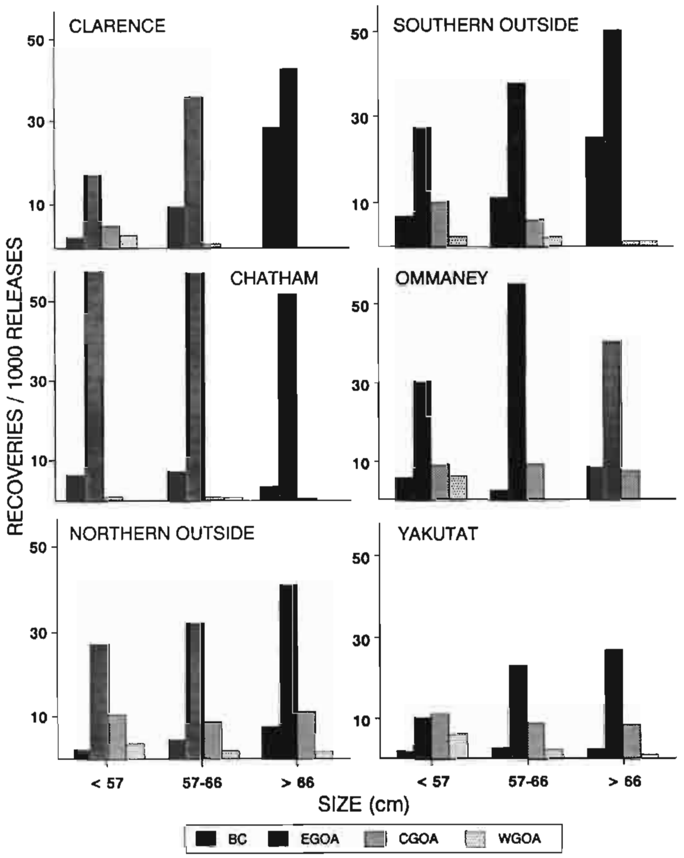

Figure 5

Recovery rates (recoveries/1,000 releases) of tagged sablefish by recovery area and size for each of the six release areas in the eastern Gulf of Alaska. BC = British Columbia; EGOA = eastern Gulf of Alaska; CGOA = central Gulf of Alaska; WGOA = western Gulf of Alaska.

Table 2

Percentage of tagged sablefish recoveries, by recovery area, for each of the six release areas in the eastern Gulf of Alaska. Columns sum to 100% of each release area's eastern gulf recoveries.

	Release area					
Recovery area	Clarence (%)	S Outside (%)	Chatham (%)	Ommaney (%)	N Outside (%)	Yakutat (%)
Clarence	**58**	3	<1	<1	<1	1
S Outside	35	**63**	4	13	7	3
Chatham	3	7	**89**	22	11	9
Ommaney	0	9	2	**31**	10	4
N Outside	1	8	3	15	**37**	20
Yakutat	3	10	2	19	35	**63**

Part of the EGOA population may be nonmigratory. Chatham Strait, with its high density of mature fish, and few released fish recovered in areas outside Chatham, appears to have a high proportion of nonmigrating fish. To verify this result, future analysis should account for how different fishing and reporting rates affect

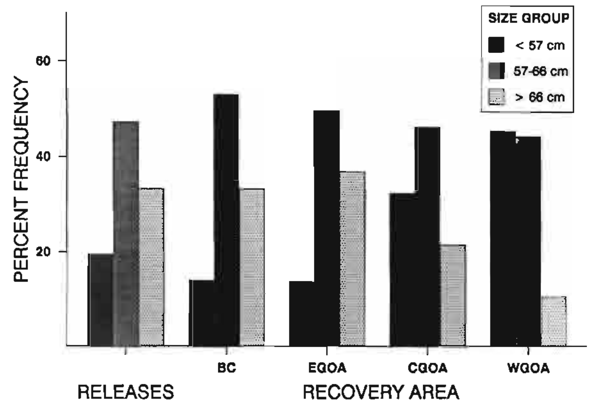

Figure 6
Percentages of small (<57 cm FL), medium (57–66 cm FL), and large (>66 cm FL) sablefish released in the eastern Gulf of Alaska and recovered from each recovery area in the northeastern Pacific Ocean. BC = British Columbia; EGOA = eastern Gulf of Alaska; CGOA = central Gulf of Alaska; WGOA = western Gulf of Alaska.

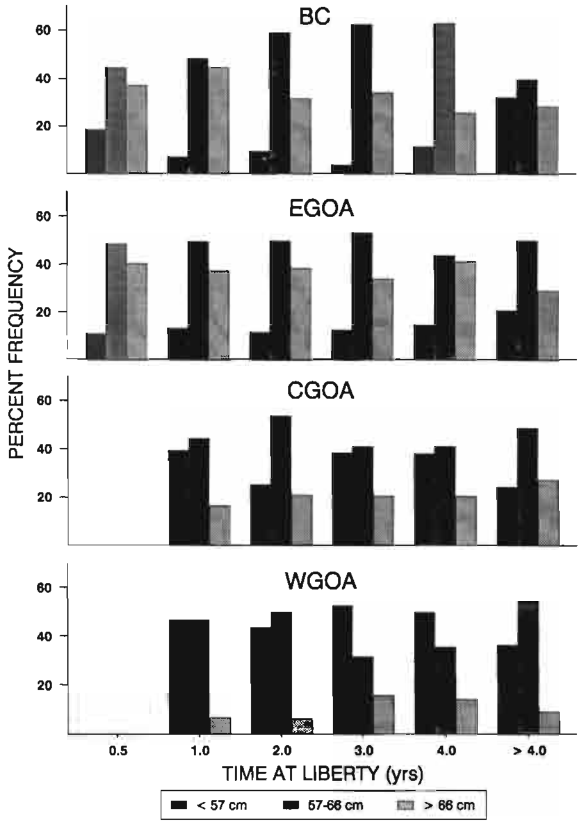

Figure 7
Recoveries (percentage) of tagged sablefish by size at release and by time at liberty after release for each of the four recovery areas in the northeastern Pacific Ocean. BC = British Columbia; EGOA = eastern Gulf of Alaska; CGOA = central Gulf of Alaska; WGOA = western Gulf of Alaska.

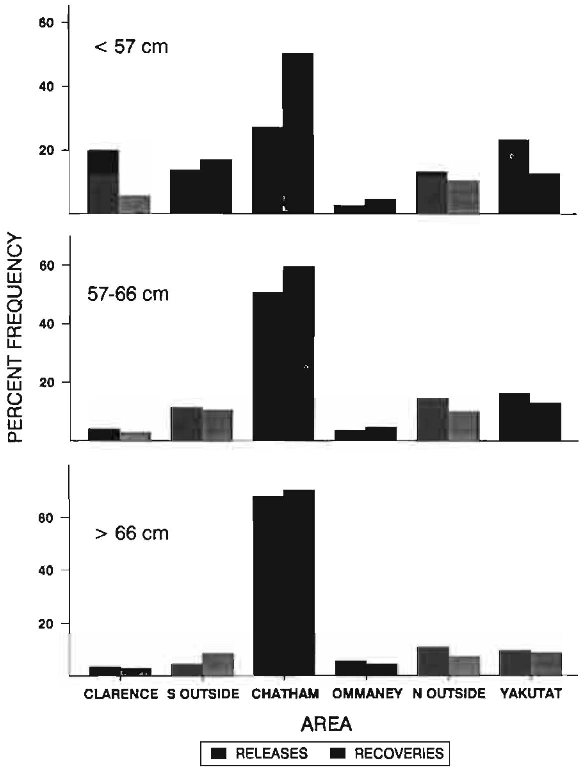

Figure 8
Releases and recoveries (percentage) of tagged sablefish by size at release for recoveries in the eastern Gulf of Alaska.

recovery rates of tagged fish (e.g., Heifetz and Fujioka, 1991). Reporting rates may have some area specificity. The EGOA and BC are thought to have higher tag-reporting rates than other areas (Beamish and McFarlane, 1988). Incorporating this information into future analyses would tend to decrease the proportion of nonmigratory fish in the EGOA and increase the proportion of westward migrants.

The advent of management by individual fishing quotas (IFQ's) should disperse fishing effort over time. Recoveries from different seasons may provide useful information on seasonal distribution and movement.

Acknowledgments

We gratefully acknowledge the many workers who helped tag sablefish, and the many fishermen, processors, and colleagues at the Alaska Department of Fish and Game and in Canada who returned tags. Contributions by J. Fujioka and suggestions by two anonymous referees improved the quality of this paper.

Literature Cited

Beamish, R. J., and G. A. McFarlane.
1988. Resident and dispersal behavior of adult sablefish (*Anoplopoma fimbria*) in the slope waters off Canada's west coast. Can. J. Fish. Aquat. Sci. 45:152–164.

Bracken, B. E.
1982. Sablefish (*Anoplopoma fimbria*) migration in the gulf of Alaska based on Gulf-wide tag recoveries, 1973–1981. Alaska Dep. Fish Game Info. Leafl. 199, 24 p. *Cited in* Heifetz and Fujioka (1991).

Fujioka, J. T., F. R. Shaw, G. A. McFarlane, T. Sasaki, and B. E. Bracken.
1988. Description and summary of the Canadian, Japanese, and U.S. joint data base of sablefish tag releases and recoveries during 1977–83. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-137, 34 p.

Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11:355–374.

Rutecki, T. R., and E. R. Varosi.
1997. Migrations of juvenile sablefish, *Anoplopoma fimbria,* in southeast Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 123–130. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Sasaki, T.
1985. Studies on the sablefish resources in the North Pacific Ocean. Bull. Far Seas Fish. Res. Lab. (Shimizu) 22, 108 p.

Migrations of Juvenile Sablefish, *Anoplopoma fimbria*, in Southeast Alaska

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ABSTRACT

From 1985 through 1991, approximately 20,000 juvenile sablefish, *Anoplopoma fimbria*, were caught, tagged, and released in the waters of southeast Alaska. Otolith analysis revealed that most were age 1, although some were age 0 or age 2. Of 818 recoveries, 220 provided sufficient information for analysis of migration patterns. Forty-six tags (21%) were recovered from the inland waters of southeast Alaska and 174 (79%) from outer coastal waters. Fish caught in outer coastal waters had moved in a westerly (counterclockwise) direction around the Gulf of Alaska; those recovered from inland waters had moved in a southerly direction within the Alexander Archipelago. Most juvenile sablefish migrated inshore during the summer of their first year (age 0) and to outer coastal waters in the fall of their second year (age 1). Few age-2 sablefish stayed in the inland waters of southeast Alaska.

Introduction

Sablefish, *Anoplopoma fimbria*, is a slow-growing, long-lived demersal fish of the continental slope of the North Pacific. Most commercially caught sablefish range in age from 4 to 35 years but can be as old as 70 (McFarlane and Beamish, 1983). The sablefish fishery is the third most economically important of Alaska's groundfish fisheries: ex-vessel landings of 22,000 t were worth about $58.3 million in 1991 (Kinoshita et. al, 1996). In Alaska, sablefish are caught primarily in the Gulf of Alaska (GOA) and in the inside waters of Chatham and Clarence Straits.

Sablefish juveniles (age 0 and age 1) are common, but rarely abundant, in the inland waters of southeast Alaska. In summer 1985, however, they were exceptionally abundant—as indicated by the catches of sport anglers and commercial salmon trollers—providing an opportunity to study their patterns of abundance, distribution, and migration. Surveys directed at monitoring abundance and at tagging juvenile sablefish were conducted from 1985 through 1991.

In this paper we summarize information on the onshore movement and migration of juvenile sablefish in the GOA based on recoveries of juveniles tagged during 1985–89 and recovered during 1985–91. This study adds to knowledge about the life history of sablefish in Alaska and provides information about the migration of juveniles as well as information that will be used for future age validation and studies of age at recruitment. Because movement plays an important role in determining the number of sablefish available for harvest in an area (Heifetz and Fujioka, 1991), results from this study will also be used to develop appropriate harvest strategies for the waters off Alaska. Additional information from these surveys on distribution, relative abundance, and age and growth is presented by Rutecki and Varosi (1997).

Methods

Gear used to capture juvenile sablefish consisted of hand-jigging equipment (Rutecki and Meyers, 1992); basket and Korean-style pots (Clausen and Fujioka, 1988); trawls; longlines; and purse seines (Rutecki and Varosi, 1997). Hand-jigging proved to be the best capture method because it was the most consistent (Rutecki and Varosi, 1997) and resulted in lower fish mortality than pots when water temperatures were relatively low (Rutecki and Meyers, 1992). The National Oceanic and Atmospheric Administration research vessels *John N. Cobb* and *Murre II* were the primary sampling platforms used during the survey. Skiffs and the Auke Bay Laboratory float also were used as platforms for hand-jigging.

Tagging

Juvenile sablefish were caught and tagged at 11 of 74 sites sampled in southeast Alaska during the 1985–91 study (Rutecki and Varosi, 1997). Most tagging was opportunistic and was done when other research in the GOA was suspended because of adverse weather. An exception was tagging at St. John Baptist Bay (SJBB), which was sampled more often than any other site because of its accessibility and the consistent availability of juvenile sablefish (Fig. 1). The fish were caught throughout the water column in SJBB, where the bottom depth was 26–30 m.

Fish caught from the RV *John N. Cobb* and RV *Murre II* were placed immediately into 667-L tanks of flowing

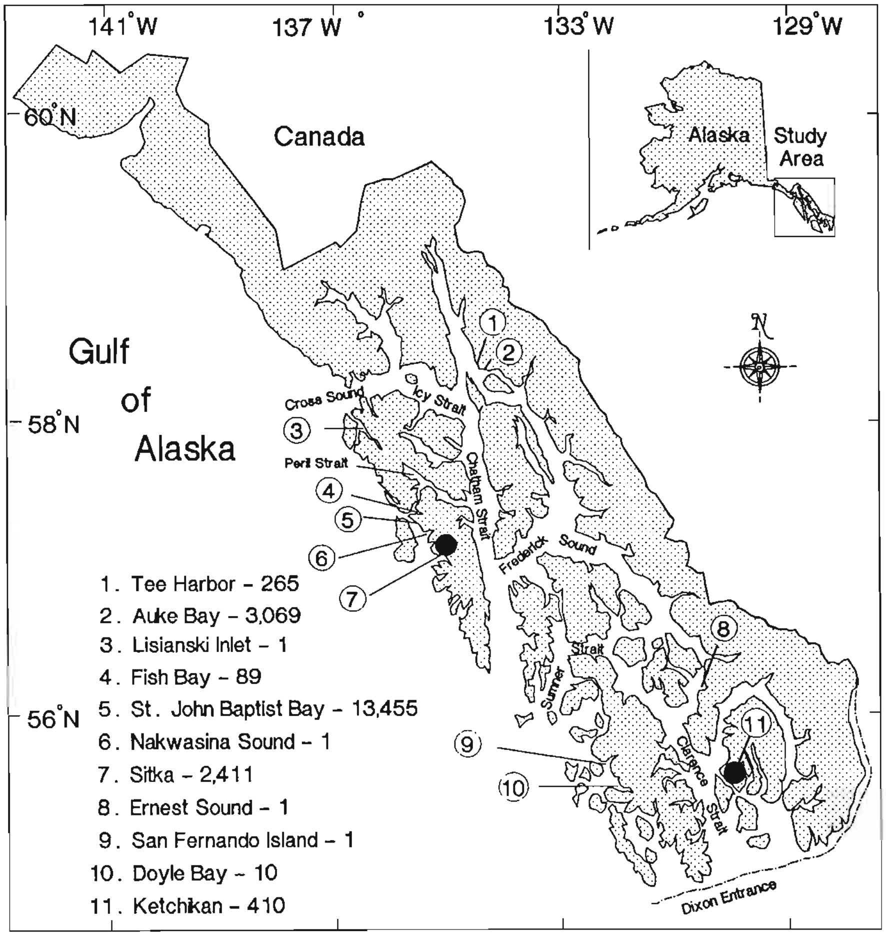

Figure 1

Locations (circled numbers) where juvenile sablefish were tagged and released in southeast Alaska, 1985–91. Numbers of fish tagged and released are given in the key to locations.

seawater. Fish caught from skiffs were put immediately into a plastic basket (1.5 m deep, 1.5 m diameter, 2-cm-mesh plastic webbing) submerged at the surface. The fish in the basket were transported to one of the research vessels, where they were put into the tanks before being tagged. Fish caught at the Auke Bay Laboratory float were held in plastic tubs (0.8 m deep × 1 m long × 0.8 m wide) filled with seawater. All fish were tagged and released within 2 h at the point of capture, except one group captured at SJBB and released near Sitka, Alaska, about 4 h after capture.

Fish were dipnetted from the live tanks and placed into a tagging cradle; anesthesia was not used. They were measured (fork length) to the nearest 0.5 cm, tagged with plastic Floy FD-68[1] anchor tags, and released. They swam directly toward the bottom and disappeared within seconds, indicating that any adverse effects from tagging were probably slight. During March and April of 1987, tagged juvenile sablefish caught by hand jigging and traps were held in tanks for observation of latent mortality (Rutecki and Meyers, 1992).

Data Analysis

To examine the migration of fish recruiting to the commercial fishery, we used data from the most reliable tag returns: those with a recovery location recorded to the nearest degree of latitude and longitude, and from fish at large 300 or more days. Shorter times were excluded because they provided little information on migration. For example, many of the fish excluded were released in Auke Bay and recovered a few days later by sport anglers nearby. The intent of this study was to look at the migrations of sablefish caught in the commercial fishery. Ages were assigned to fish based on their length and an age–length translation matrix (Rutecki and Varosi, 1997).

Results and Discussion

Releases

Nearly 20,000 juvenile sablefish were tagged and released during this study (Table 1). Based on length, most tagged sablefish were age 1, but some were age 0 or age 2 (Table 1). Tagged fish were released in the inland waters of southeast Alaska at 11 sites (Fig. 1). Most (99.6%) were released at five sites: SJBB (68.3%), Auke Bay (15.6%), Sitka (12.2%), Ketchikan (2.2%), and Tee Harbor (1.3%). Most sablefish were tagged at SJBB because juveniles were abundant there throughout most of the study. After 1986, juvenile sablefish were either not caught, or only a few were caught, at sites other than SJBB (Rutecki and Varosi, 1997).

Tagged fish were 20–52 cm long, with modes at 27 cm, 36 cm, and 45 cm (Fig. 2). The fish tagged and released at a given site in a given month and year were termed a "release group." The size of each release group was proportional to the number of fish caught at the same site in the same month and year. The release group with the largest size (41.4 cm mean length) was tagged in July 1986 at Sitka, where the fish were feeding on offal from fish-processing plants. These fish appeared to be exceptionally heavy for their length. Fish tagged near Ketchikan during August 1985 were also very heavy for their length as a result of feeding on fish offal. Although not weighed, the fish feeding on offal probably weighed approximately 1 kg. The smallest fish (23.8 cm mean length) tagged were caught at SJBB during October 1988. They were slender and averaged about 90 g. The relationship between length at release and percentage recovered is discussed later.

Recoveries

We used 220 of the 818 tags recovered for this study. Tagged sablefish were recovered in the following areas: Vancouver and Queen Charlotte Islands (4%); outer coastal waters of southeast Alaska (27%); inland waters of southeast Alaska (Chatham and Icy Straits 16%, Clarence Strait 4%); Yakutat (17%); Kodiak (18%); Chirikof (5%); Shumagin (6%); and the Bering Sea and Aleutian Islands (3%; Fig. 1, 3). These percentages show that recoveries of tagged fish were about equal in

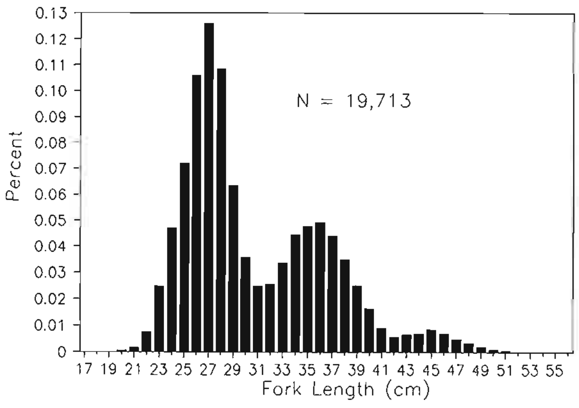

Figure 2

Length frequency histogram of all juvenile sablefish tagged in southeast Alaska, 1985–91.

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Table 1

Releases (1985–89) of juvenile sablefish tagged in southeast Alaska and recoveries (1985–91) of tags from the commercial fishery. Release sites shown in Figure 1.

	Releases				Recoveries	
Site	Date	Number	Mean length (cm)	Age (y)	Number	(%)
Tee Harbor	Jun 85	265	31.4	1	1	(0.38)
Auke Bay	Jul 85	1,687	31.3	1	23	(1.36)
	Aug 85	1,382	35.2	1	14	(1.01)
Lisianski Inlet	Aug 85	1	38.0	1	0	(0.00)
Fish Bay	Aug 85	35	34.0	1	2	(5.71)
	Jul 86	54	36.0	1, 2	1	(1.85)
Nakwasina Sound	Mar 87	1	28.0	1	0	(0.00)
St. John Baptist Bay	Aug 85	1,014	36.0	1	14	(1.38)
	Jul 86	154	41.3	1, 2	0	(0.00)
	Mar 87	6,667	26.8	1	60	(0.90)
	Apr 87	1,085	27.6	1	13	(1.20)
	Jun 87	82	27.8	1	0	(0.00)
	Aug 87	19	29.1	1	0	(0.00)
	Mar 88	641	26.2	1	2	(0.31)
	May 88	840	27.2	1	12	(1.43)
	Jun 88	659	28.1	1	7	(1.06)
	Oct 88	1,763	23.8	0, 1	1	(0.06)
	Jun 89	442	32.5	1	3	(0.68)
	Sep 89	89	36.8	1	0	(0.00)
Sitka	Aug 85	1,380	37.7	1	28	(2.03)
	Jul 86	969	41.4	1, 2	30	(3.10)
	Mar 87	62	26.5	1	1	(1.61)
San Fernando Island	Aug 85	1	39.1	1	0	(0.00)
Ernest Sound	May 87	1	24.5	1	0	(0.00)
Doyle Bay	Mar 88	10	29.4	1	1	(10.00)
Ketchikan	Aug 85	410	37.7	1	7	(1.71)
Total		19,713			220	(1.12)

inland and outside coastal waters of southeast Alaska (20% and 27%), and also in southeast Alaska (47%) and the remainder of the Gulf of Alaska and Bering Sea and Aleutian Islands areas (49%).

During the first few years of the study, most tagged fish were recovered close to release sites. As the study progressed, fish were caught farther from the release sites. For example, 12 of the 15 fish recovered during 1986 and 1987 were recovered from the eastern GOA one and two years after being tagged and released; no fish were recovered from the Aleutian area until 1990—five years after release (Table 2). The number of tagged fish recovered increased each year from 1986 to 1990 as the total number of fish tagged increased over time (Table 2); the recovery rate remained about the same.

Most (77%) fish recovered from the outer coastal waters had moved westward (counterclockwise) around the GOA (Fig. 4). Other studies have also described a westward movement of juvenile sablefish in the GOA. Heifetz and Fujioka (1991) quantified annual movement of tagged sablefish among regulatory areas and concluded that small (<57 cm) sablefish move westward along the continental slope. Bracken (1982) described the same direction of movement for small sablefish; he hypothesized that the eastern GOA is a pooling area for spawning adult sablefish and that the juveniles rear in shallow nearshore waters and migrate to deeper water in their third or fourth year. From there, most fish migrated westward before returning to southeast Alaska to spawn.

Of fish recovered from the Chatham Strait commercial fishery, 40% had been released at Auke Bay, 34% at SJBB, and 26% at Sitka. Fish tagged at these release sites could have migrated through inland waters to

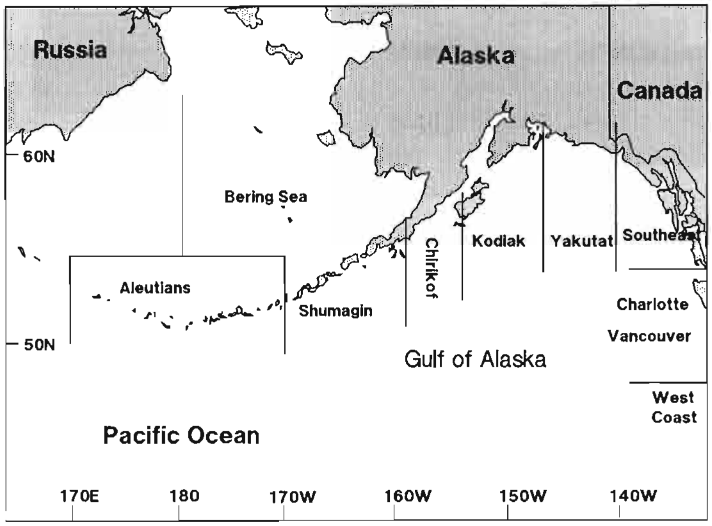

Figure 3
Areas where sablefish tagged as juveniles were recovered.

Table 2
Recoveries (1986–91) by year and area of tagged juvenile sablefish released in southeast Alaska, compared to total numbers released (1985–89).

	Number of fish recovered								
Area	1985	1986	1987	1988	1989	1990	1991	Total (%)	
Clarence	0	1	2	3	2	0	0	8	(4)
Chatham	0	1	1	3	12	8	11	36	(16)
Vancouver	0	0	0	0	2	0	0	2	(1)
Charlotte	0	0	0	2	0	0	5	7	(3)
Southeast	0	3	3	9	23	15	7	60	(27)
Yakutat	0	0	1	7	8	17	4	37	(17)
Kodiak	0	0	1	6	6	14	13	40	(18)
Chirikof	0	0	2	3	0	3	2	10	(5)
Shumagin	0	0	0	1	2	4	6	13	(6)
Aleutian	0	0	0	0	0	5	2	7	(3)
Total recoveries	0	5	10	34	55	66	50	220	(100)
Total tagged	0	6,175	1,177	7,927	3,903	531	0	19,713	

Chatham Strait and remained there, or migrated to the outer coastal waters before moving to Chatham Strait.

Fish tagged at Sitka and SJBB and recovered from the Chatham Strait fishery were recovered east of the release sites in inland waters. Fish tagged at Auke Bay and recovered in Chatham Strait showed a net migration to the southwest. Although the path these fish took from Auke Bay to reach Chatham Strait is unknown, they could have entered Chatham Strait through Icy Strait or Frederick Sound. From Sitka and SJBB, fish could have migrated through Peril Strait (Fig. 1) or to outer coastal waters before entering Chatham Strait. Regardless of migration route, sablefish that reared in coastal inlets of northern southeast Alaska contributed to the Chatham Strait fishery.

Most (75%) sablefish tagged as juveniles and recovered in the Clarence Strait fishery were tagged and released near Ketchikan; the remainder were released in Auke Bay (12.5%) and Sitka (12.5%). Fish released in Auke Bay and near Sitka were recovered in Clarence Strait southeast of the release sites. Fish released near Ketchikan were recovered in Clarence Strait (Fig. 1), west of the release site. Except for one fish recovered in British Columbia, all recoveries from the Ketchikan release group were made in the Clarence Strait area. The tag recoveries from Clarence Strait show that juvenile sablefish that rear in inlets throughout southeast Alaska contribute to the Clarence Strait fishery.

Although additional analysis will be done when more tags have been recovered, no relationship was apparent between size (fork length) at release, known distance traveled, and time at large (Table 3). Of the more than 1,600 age-0 fish tagged and released in SJBB, only one was recovered (Table 1). The low rate of return for the age-0 fish tagged in October may be due to a high rate of mortality. Those fish may have been too small to overwinter after being tagged. Rutecki and Meyers (1992) found a greater survival of hook-caught tagged juvenile sablefish in summer than in winter. Because of the low return rate for those fish, age-0 fish are no longer tagged. Return rates were greatest for release groups of larger age-1 (31–37 cm) and age-2 fish (Table 1). McFarlane and Beamish (1990) and Saunders et al. (1990) also observed lower recovery rates for smaller sablefish.

Table 3
Mean distance traveled and days at large for various size groups of tagged juvenile sablefish recovered during 1986–91.

Length (cm)	Distance traveled (km)	Days at large
17–31	540	1,085
32–41	555	1,346
42–55	392	1,158

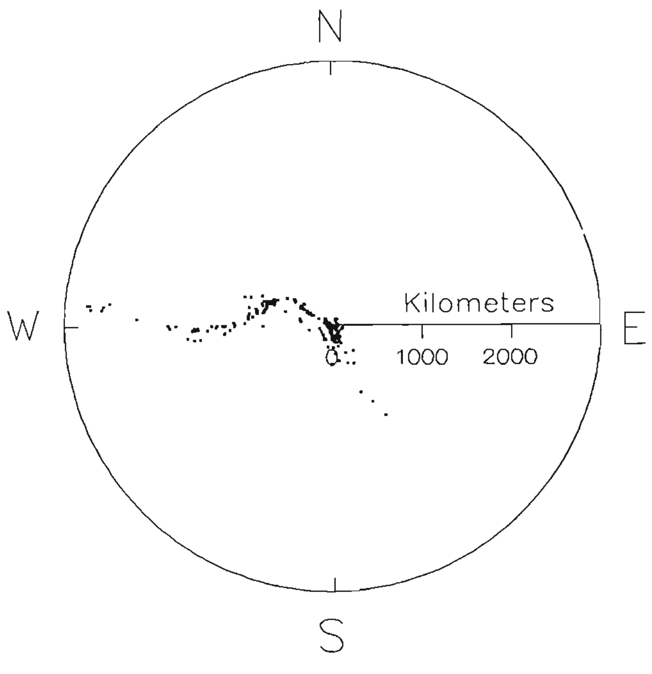

Figure 4
Distance and direction traveled by sablefish tagged as juveniles in southeast Alaska, 1985–89, and recovered in 1986–91. The central point 0 represents the site of release, and the black squares mark the sites of recovery of individual fish (*N*=220).

Onshore Movement

In British Columbia, sablefish spawn offshore about mid-February. Juvenile sablefish are commonly observed inshore and are habitually present in many major inlets, indicating that onshore movement is a feature of the life history of juvenile sablefish (McFarlane and Beamish, 1983). Kendall and Matarese (1987) describe the early life history of sablefish off the coasts of California, Washington, and Oregon, where pelagic eggs are spawned in winter near the edge of the continental shelf. The eggs float deeper than 200 m and probably require 2–3 weeks to develop. Shortly after hatching, larvae seem to swim to the surface and grow quickly (up to 2 mm per day) as part of the neuston during spring. Although not documented, spawning in southeast Alaska is assumed to also take place in outer coastal waters in winter. Wing (1997) noted that few, if any, sablefish larvae were collected inshore, but large numbers of larvae were collected far offshore (out to 220 km) during May. Migration shoreward is indicated by the juvenile sablefish (125–156 mm) caught during research cruises for salmon at various locations in July and August, from southern Chatham Strait to 46 km offshore (Table 4, Fig. 5). Wing (1985) found juvenile sablefish (100–170 mm) in the stomachs of salmon collected during August on the outer coast of southeast Alaska. The periodic abundance of small juvenile sablefish throughout the inland waters of southeast Alaska (as in 1985) also indicates that they migrate into the Alexander Archipelago from the GOA.

Changes in mean length of sablefish captured in SJBB have been used to determine the timing of juvenile onshore and offshore migration (Rutecki and Varosi, 1997). Sablefish captured in SJBB from July 1986 to October 1991 showed an annual pattern of increasing length until about September or October, when mean fork length decreased markedly, especially in 1990 (from 34 cm in July to 21 cm in September). According to Rutecki and Varosi

Table 4

Location and date of collection, type of gear used, and size of juvenile sablefish captured in southeast Alaska during salmon research cruises, 1983–84. Locations shown in Figure 5.

Location	Date	Gear type	*N*	Length (mm)
South Chatham Strait	Jul 83	Gill net	1	125
			4	130–139
			7	140–149
			5	150–156
Cape Ommaney 27.8 km offshore	Jul 84	Purse seine	5	83–95
Herbert Graves Is. area nearshore	Jul 84	Purse seine	1	
Graves Harbor 18.5 km offshore	Jul 84	Purse seine	1	
Lituya Bay 37 km offshore	Jul 84	Purse seine	2	115–140
Lituya Bay 18.5 km offshore	Jul 84	Purse seine	1	95
Inner Pt. Sophia	Jul 84	Purse seine	1	342
Cape Ommaney	Aug 84	Purse seine		
37 km offshore			166	100–170
46.3 km offshore			1	156
37 km offshore			2	110–119
			3	120–129
			4	130–139
			4	140–149
			3	150–159
			4	160–170
Cape Edgecumbe	Aug 84	Purse seine		
18.5 km offshore			1	115
Fish Bay	Aug 84	Purse seine	1	391
Graves Harbor	Aug 84	Purse seine		
9.3 km offshore			2	160–180
18.5 km offshore			1	190
37 km offshore			16	160–190
46.3 km offshore			16	131–175

(1997), this decreased mean length was due to immigration of the current year class from offshore to inland waters. By October, age-1 sablefish were absent from SJBB, which means that they emigrated from the bay about the same time age-0 sablefish immigrated into the bay.

Although the direction of migration of age-0 sablefish is shoreward, it is not known where the juveniles originate. Sablefish are known to spawn off British Columbia and are assumed to spawn off southeast Alaska in deep (>500 m) water (Wing, 1997). According to Wing (1993), pelagic sablefish eggs, which float deeper than 200 m, can be carried 15–30 km per day. Assuming a 3–4 week incubation period (Mason et al., 1983), hatching areas could be distant from spawning areas. For instance, eggs and larvae originating off British Columbia could be carried by rapid coastal currents, such as the Haida current, to Alaska waters. Off southeast Alaska, oceanographic currents such as the Sitka Eddy could carry eggs and larvae toward the coast. Or eggs and larvae could be carried north of southeast Alaska. Regardless of spawning and hatching locations, juvenile sablefish migrate shoreward in southeast Alaska and arrive in inland waters in autumn.

In conclusion, our study has provided information on the migration behavior of juvenile sablefish in southeast Alaska as they become available to the commercial fishery. This study is unique because all fish were tagged exclusively in nursery areas; most other studies have relied on fish tagged outside nursery areas (Bracken, 1982; McFarlane and Beamish, 1983). Further analyses are underway to determine the relation between release factors (i.e., site, age, size, and date) and recovery rates. Continuation of the tagging studies for juvenile sablefish will provide data for estimating the relation between age and availability to the commercial fishery. Estimates of age-specific availability are important parameters for assessing and managing sablefish in Alaskan waters (Sigler and Fujioka, 1993; Sigler[2]).

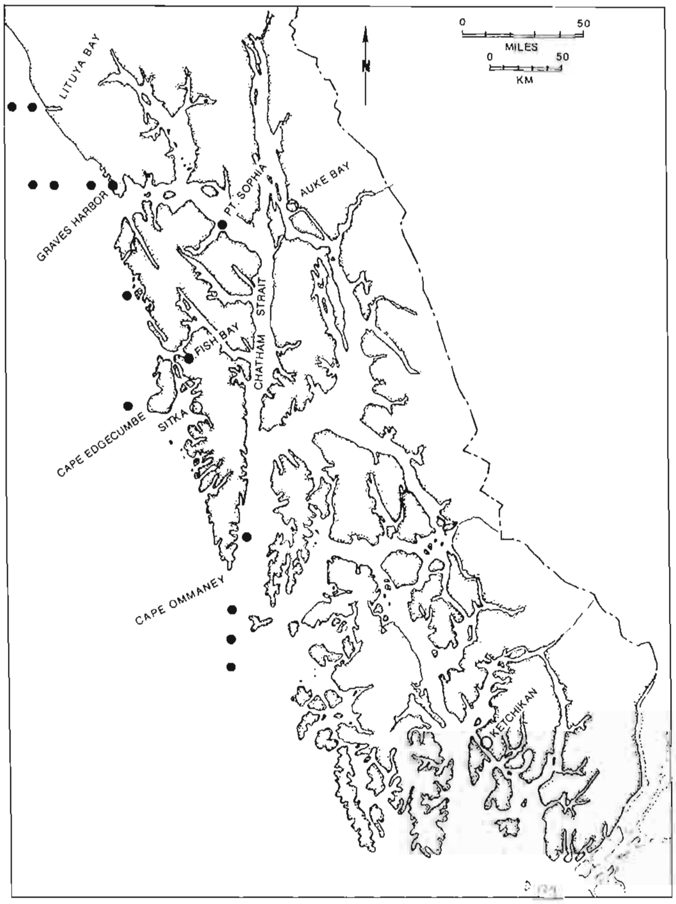

Figure 5
Locations (dots) where juvenile sablefish were caught during salmon research cruises, 1983–84.

Literature Cited

Bracken, B. E.
1982. Sablefish (*Anoplopoma fimbria*) migration in the Gulf of Alaska based on gulf-wide recoveries, 1973–1981. Alaska Dep. Fish Game Info. Leafl. 199, 24 p.

Clausen, D. M., and J. T. Fujioka.
1988. Relative abundance of sablefish in southeastern Alaska, based on trap indexing surveys, 1978–85. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-134, 57 p.

Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11:355–374.

Kendall, A. W., Jr., and A. C. Matarese.
1987. Biology of eggs, larvae, and epipelagic juveniles of sablefish, *Anoplopoma fimbria*, in relation to their potential use in management. Mar. Fish. Rev. 49(1):1–13.

Kinoshita, R. K., A. Greig, and J. M. Terry.
1996. Economic status of the groundfish fisheries off Alaska, 1994. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-62, 108 p.

Mason, J. C., R. J. Beamish, and G. A. McFarlane.
1983. Sexual maturity, fecundity, spawning, and early life history of sablefish (*Anoplopoma fimbria*) off the Pacific coast of Canada. Can. J. Fish. Aquat. Sci. 40:2,126–2,134.

McFarlane, G. A., and R. J. Beamish.
1983. Preliminary observations on the juvenile biology of sablefish (*Anoplopoma fimbria*) in waters off the west coast of Canada. *In* Proceedings of the Second International Sablefish Symposium, p. 119–135. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.
1990. Effect of an external tag on growth of sablefish (*Anoplopoma fimbria*), and consequences to mortality and age at maturity. Can. J. Fish. Aquat. Sci. 47:1,551–1,557.

Rutecki, T. L., and T. R. Meyers.
1992. Mortality of juvenile sablefish captured by hand-jigging and traps. N. Am. J. Fish. Manage. 12:836–837.

Rutecki, T. L., and E. R. Varosi.
1997. Distribution, age, and growth of juvenile sablefish, *Anoplopoma fimbria*, in southeast Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 45–54. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Saunders, M., G. A. McFarlane, and R. J. Beamish.
1990. Factors that affect the recapture of tagged sablefish off the west coast of Canada. Am. Fish. Soc. Symp. 7:708–713.

Sigler, M. F., and J. T. Fujioka.
1993. Harvest policies for sablefish in the Gulf of Alaska. *In* G. Krause, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II (eds.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, p. 7–19. Alaska Sea Grant 93-02.

Wing, B. L.
1985. Salmon stomach contents from the Alaska troll logbook program 1977–84. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-91, 43 p.
1993. Winter oceanographic conditions in the eastern Gulf of Alaska, January–February 1986. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-8, 53 p.
1997. Distribution of sablefish, *Anoplopoma fimbria*, larvae in the eastern Gulf of Alaska: neuston-net tows versus oblique tows. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 13–25. U.S. Dept. Commer., NOAA Tech. Rep. NMFS 130.

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[2] Sigler, M. F. 1994. An age-structured model on sablefish recruitment and biomass in Alaska. *In* Stock assessment and fishery evaluation report for the groundfish resources of Alaska as projected for 1995, Appendix E, p. 1–20. North Pacific Fishery Management Council, P.O. Box 103136, Anchorage, AK 99510.

Identification of Sablefish, *Anoplopoma fimbria* (Pallas, 1811), Stocks from Seamounts off the Canadian Pacific Coast Using Parasites as Biological Tags

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ABSTRACT

The parasites of sablefish, *Anoplopoma fimbria,* collected from three seamounts off Canada's west coast were investigated for their potential as biological tags. The distribution of several parasites was shown to be significantly different between seamounts, supporting the view that sablefish inhabiting seamounts are discrete stocks. Other data collected on the parasites of sablefish include new host and locality records, the relation between host age and infection, seasonal variation in parasite prevalence, and geographic distribution of the parasites. Of the nine identified species of parasites, three (*Genolinea laticauda, Gonocerca japonica,* and *Grillotia heptanchi*) had not been previously recorded in sablefish.

Introduction

In the process of developing a rational management strategy for sablefish, *Anoplopoma fimbria,* off Canada's west coast, the need arose for more detailed biological information, particularly with regard to stock delineation. Previous studies (Beamish and McFarlane, 1983, 1988), using tag-recovery information, reported that the population of sablefish inhabiting slope waters off Canada's west coast could be managed as a single unit, separate from sablefish in the United States zones to the north and south. Other attempts to differentiate between stocks of sablefish using genetic techniques have proved inconclusive (Gharrett et al., 1983).

The use of parasites as biological tags is a well-established technique for differentiating fish stocks. When parasites are restricted to a particular area, such as the shallow water over seamounts, by the environmental requirements of their intermediate hosts (e.g., molluscs, which are intermediate hosts for many trematodes), any movement of the host fish from that focus of infection can be detected. Fish from different localities can be separated because they carry different assemblages of parasites.

In an earlier study of sablefish parasites (Kabata and Whitaker, 1984) it was found that sablefish carry relatively few species, mostly helminth parasites in the digestive tract. Subsequently, Kabata et al. (1988) collected sablefish from a number of localities off the British Columbia coast to determine whether fish from the different areas could be distinguished on the basis of their parasites. Kabata et al. (1988) found that they could use the helminth parasites from the digestive tract to differentiate sablefish taken from two seamounts (Cobb and Union) from those collected on the continental slope. This suggested that sablefish stocks on seamounts were discrete and could, perhaps, be developed as localized fisheries.

The current study reexamined a previously sampled seamount to confirm earlier results, and expanded the number of seamounts sampled for biological tags. To this end, three seamounts were sampled in 1987 and 1988. The Union Seamount (Kabata et al., 1988) was revisited, and the Bowie and Dellwood Seamounts were sampled for the first time (Fig. 1).

Concurrently, in 1987, traditional tagging of sablefish was employed on the Bowie and Union Seamounts to allow a direct method of detecting sablefish movements.

Materials and Methods

Five samples from three seamounts off the British Columbia coast captured 246 sablefish: 49 from Dellwood

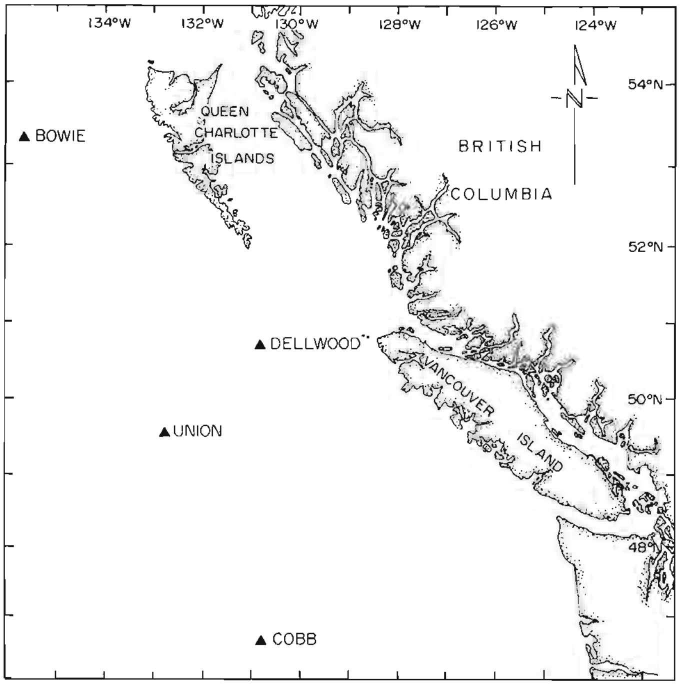

Figure 1
Locations of seamounts sampled for sablefish parasites.

(50°37'N, 130°42'W) in January 1987; a total of 120 from Bowie (53°18'N, 135°38'W) in February 1987 and September 1988; and a total of 77 from Union (49°35'N, 132°45'W) in July and September 1988 (Fig. 1). The samples from Bowie and Dellwood Seamounts were caught with traps which were fished for approximately 24 hours in depths of 585 m to 1,170 m. At Union Seamount, longlines were used in 318 to 1,155 m, also for 24 hours. At capture the fish were sampled for length and sex, and the otoliths were taken for later age determination. The viscera, including the gallbladder, of the fish selected for parasitological examination were removed, individually bagged, labeled, and frozen.

Following the examination protocols used by Kabata and Whitaker (1984) and Kabata et al. (1988), the viscera were thawed and the various organs separated. The contents of the stomach, caeca, and intestines were examined for trematodes with a dissection microscope at 9–75×. Scrapings and contents of the gall bladder were examined for Myxosporea under a compound microscope with phase contrast illumination at 160× and 320×. Parasites that could not be identified at the time of necropsy were preserved in acetoformolalcohol, then stained with Semichon's acetic carmine for later identification. Sablefish ages were estimated according to the methods of Beamish and Chilton (1982).

Prevalence data were examined with the chi-square test, and intensity differences with the Mann-Whitney and Kruskal-Wallis tests.

In addition, during February 1987 sablefish were captured, tagged, and released at both Bowie and Union Seamounts, in order to directly examine movement between seamounts. A Floy FD-68[1] anchor tag was applied according to the procedures described in Beamish and McFarlane (1988). We also examined recapture information for fish tagged by traditional methods and released off the west coasts of Vancouver Island and the Queen Charlotte Islands, and in Queen Charlotte Sound between 1977 and 1986, and subsequently recaptured during fishing operations on seamounts.

Results

Ten species of parasites were found, of which nine were identified (Table 1, 2). Four species were common to all five samples: the myxosporean *Ceratomyxa anoplopoma* from the gall bladder, and the trematodes *Fellodistomum breve*, *Lecithochirium exodicum*, and *Podocotyle atomon* from the digestive tract. Of the remaining five species, two—*Derogenes varicus* and *Lecithaster gibbosus*—are ubiquitous marine parasites that, along with the four species listed above, have been previously recorded from sablefish (Moser 1976, Kabata and Whitaker, 1984). The other three species—the hemiuroid trematodes *Genolinea laticauda* and *Gonocerca japonica* and the trypanorynch cestode *Grillotia heptanchi*—however, are recorded here in sablefish for the first time.

The data showed several significant differences in prevalence between the seamounts (Table 3) but no significant differences in the intensities of infection by any of the parasites. It is possible that this result was due to the small sample sizes.

The ages of the fish ranged from 3 to 40 years, with median ages of 7 or 8 years depending on the sample (Table 4). Only two samples, Bowie of September 1988 and the Dellwood sample, contained fish younger than 5 years. The September Bowie sample also contained the oldest fish (age 40). When parasite prevalences were combined by fish age class, only infections of *L. exodicum*, and perhaps *P. atomon*, were found to be age-related (Table 5).

Of the 229 fish both aged and sexed, 62% were male. Fish under age 5 composed 1.3% of the total (0.9% males and 0.4% females); fish of age 5–10 composed 74.3% (43.7% males and 30.6% females); fish of age 11–15 composed 9.2% (7.0% males and 2.2% females); and fish over age 15 composed 14.9% (10.5% males and 4.4% females). The prevalences of the four para-

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Table 1

Prevalence of parasites in sablefish collected from three British Columbia seamounts, 1987–88.

	Percentage of fish infected				
	Bowie		Union		Dellwood
Species	February 1987 (*N*=50)	September 1988 (*N*=70)	July 1988 (*N*=37)	September 1988 (*N*=40)	January 1987 (*N*=49)
Ceratomyxa anplopoma	14.0	17.1	37.8	27.5	24.5
Fellodistomum breve	24.0	12.8	16.2	20.0	28.6
Lecithochirium exodicum	22.0	11.4	13.5	15.0	18.4
Podocotyle atomon	4.0	1.4	8.1	5.0	10.2
Derogenes varicus	4.0	0.0	5.4	0.0	20.4
Genolinea laticauda[1]	0.0	1.4	13.5	7.5	0.0
Gonocerca japonica[1]	0.0	0.0	0.0	0.0	2.1
Lecithaster gibbosus	0.0	5.7	13.5	7.5	0.0
Grillotia heptanchi[1]	0.0	1.4	0.0	0.0	0.0
Unidentified trematode	8.0	1.4	10.8	0.0	2.0

[1] Species previously unreported in sablefish.

Table 2

Intensity of parasite occurrence in sablefish from three seamounts, 1987–88.

		Mean (range) number of parasites								
Date	Sample location	*Fellodistomum breve*	*Lecithochirium exodicum*	*Podocotyle atomon*	*Derogenes varicus*	*Genolinea laticauda*	*Gonocerca japonica*	*Lecithaster gibbosus*	*Grillotia heptanchi*	Unidentified
January 1987	Dellwood	2.6 (1–10)	3.4 (1–16)	1.0	2.0 (1–6)	0.0	2.0	0.0	0.0	3.0
Feburary 1987	Bowie	10.0 (1–48)	4.5 (1–14)	3.5 (1–6)	1.0	0.0	0.0	0.0	0.0	2.9 (1–4)
September 1988	Bowie	37.1 (1–478)	1.8 (1–6)	2.0	0.0	1.0	0.0	2.7 (1–7)	1.0	0.0
July 1988	Union	9.7 (1–29)	3.8 (1–7)	2.3 (1–4)	1.0	2.8 (1–8)	0.8	6.8 (2–15)	0.0	1.2 (1–2)
September 1988	Union	2.1 (1–7)	2.7 (1–6)	1.0	0.0	2.0 (1–3)	0.8	1.7 (1–3)	0.0	0.0

sites in all samples were similar for both sexes except for *P. atomon*: 3.4% of males were infected, and 7.1% of females.

Each of the nine parasite species identified is discussed below for its relevance as a stock delineator for sablefish.

Ceratomyxa anoplopoma—The site of infection of this myxosporean parasite is the gall bladder. Moser (1976) described *C. anoplopoma* in sablefish collected in California, but this is the first record in Canadian waters. Found in all five samples, *C. anoplopoma* was most preva-

Table 3

Chi-square analysis for differences in prevalence of parasites among seamounts. * Indicates significant difference (95% level).

Species	Bowie vs. Union	Union vs. Dellwood	Dellwood vs. Bowie
Ceratomyxa anoplopoma	*		
Derogenes varicus		*	*
Genolinea laticauda	*	*	
Lecithaster gibbosus	*	*	

lent in fish from Union Seamount and least prevalent in fish from Bowie Seamount. There was a significant difference in prevalence between these two seamounts (χ^2=7.48; df=1, $p<0.05$). There were no seasonal differences in prevalence (Table 1), and similar levels were seen in all age groups (Table 4).

Fellodistomum breve—Sablefish in all samples were infected with this trematode. Although there were no statistically significant differences (χ^2=1.90; df=2, $p \geq 0.05$) between the three seamounts, this parasite was more prevalent in the winter samples than in the summer samples (Table 1).

Lecithochirium exodicum—This trematode was also found in all samples of sablefish. The differences in prevalence between the seamounts were not significant (χ^2=0.69; df=2, $p \geq 0.05$). Like *F. breve*, *L. exodicum* was more prevalent in winter samples than in summer samples. It was the only one of the four common parasites that showed any definite trend related to increased age (Table 5).

Podocotyle atomon—This parasite was common to all samples. No statistically significant differences (χ^2=3.04; df=2, $p \geq 0.05$) were seen in prevalence between seamounts or seasons. Younger fish (age <5) showed a higher prevalence than older fish (Table 4) but this result, as well as an apparent difference in sex of hosts, may be due to the parasite's low prevalence.

Table 4
Range and median ages of fish in each seamount sample.
* One fish was not aged.

Sample	*N*	Range (y)	Median (y)
Dellwood, January 1987	49	3–31	8
Bowie, February 1987*	49	5–27	8
Bowie, September 1988	70	4–40	8
Union, July 1988	37	5–29	7
Union, September 1988	40	5–21	7

Genolinea laticauda—Prevalence of *G. laticauda* was significantly different in sablefish from Union Seamount and those from Bowie (χ^2=7.41; df=1,$p<0.05$) and Dellwood Seamounts (χ^2=5.44; df=1, $p<0.05$; Table 3).

Derogenes varicus—This is a frequent parasite of marine fishes. Its prevalence differed significantly between Dellwood and the Union (χ^2=11.02; df=1, $p<0.05$) and Bowie (χ^2=18.53; df=1, $p<0.05$) samples (Table 3). Although it was found at all three seamounts, it was not found in all fish. It was not found in either of the September samples taken at the Union and Bowie Seamounts. It was found in the July sample from Union and the February sample from Bowie (Table 1, 2).

Lecithaster gibbosus—This trematode is another frequent parasite of marine fishes. Its prevalence differed significantly between fish from Union and Bowie (χ^2=4.08; df=1, $p<0.05$) and from Union and Dellwood Seamounts (χ^2=5.44; df=1, $p<0.05$; Table 3).

Gonocerca japonica—Specimens were found in only one fish; it would appear to be an infrequent parasite of sablefish.

Grillotia heptanchi—A metacestode of this trypanorhynch cestode was found in the stomach of one sablefish.

In February 1987, 268 sablefish were tagged and released at Bowie and 379 at Union Seamount. Of the fish tagged and released at Bowie Seamount, 8 were recaptured between 1989 and 1992, all of them at Bowie. Of the fish tagged and released at Union Seamount, 9 were recaptured between 1989 and 1991, 8 at Union Seamount and 1 at Kodiak, Alaska.

Of the fish released in continental slope waters off Canada (west coast of Vancouver Island, west coast of Queen Charlotte Islands, Queen Charlotte Sound, and Hecate Strait) between 1977 and 1986 (Beamish and McFarlane, 1988; McFarlane and Saunders, 1997), 25

Table 5
Combined prevalence of the four common parasites by age group of fish.

Age group (y)	No. of fish	Prevalence (%)			
		Fellodistomum breve	*Lecithochirum exodicum*	*Podocotyle atomon*	*Ceratomyxa anoplopoma*
<5	10	0.0	10.0	20.0	20.0
5–10	178	22.5	12.4	4.5	23.6
11–15	22	18.2	22.7	9.1	13.6
>15	35	28.6	31.1	0.0	20.0

recaptures were made on seamounts between 1989 and 1992: 16 on Bowie Seamount, 5 on Union, 2 on Warwick, 1 on Dellwood, and 1 on Cobb.

All fish tagged and released in continental slope waters and later recovered at seamounts were tagged as juveniles. These fish ranged in length from 40 to 51 cm at time of tagging, corresponding to ages 3 and 4. None of the fish tagged as adults (>55 cm) were recovered from seamounts during the period of our study.

Discussion

The objectives of this study were to confirm the parasite tag results of Kabata et al. (1988), which suggested that stocks of sablefish on seamounts were discrete, and to determine if their results applied to other seamounts. The discreteness of seamount sablefish stocks would significantly affect the development of management strategies for these stocks. Specifically, could individual seamount stocks be fished without affecting sablefish inhabiting other seamounts, or the large, commercially important stock in the slope waters?

Of the nine species of parasites identified from the viscera of seamount sablefish, three—*G. laticauda, G. japonica,* and *G. heptanchi*—were previously unreported from sablefish. The infection rate from these species was low, and (with the possible exception of *G. laticauda,* which was more prevalent on one seamount) they cannot be regarded as frequent parasites of sablefish. Kabata et al. (1988) reported only three trematode species (*F. breve, L. exodicum,* and *D. varicus*) when they sampled the Union Seamount in September 1985, whereas we identified three additional trematodes at Union. But these species—*P. atomon, G. laticauda,* and *L. gibbosus*—showed prevalences of less than 10% in our September sample, which may explain why they were not observed earlier.

Our study indicated no relationship between sex of the host fish and prevalence of three of the four parasites common to all samples. *Podocotyle atomon* was found in female fish about twice as often as in male fish; however it occurred too infrequently to allow inferences about how the sex of the host affects parasite prevalence.

Life-span data have been reported for two of the parasites found in this study: *L. gibbosus* lives less than one year (2–9 mo) in its definitive host (Margolis and Boyce, 1969), and *D. varicus* can live over one year (8–15 mo; Meskal, 1967). However, the total age of these parasites—from egg through the first (mollusc) and second (crustacean) intermediate hosts to the definitive fish host—was not calculated. It is known that the cercaria of *L. gibbosus,* after being released from a snail and eaten by the copepod host, must develop for about three weeks before the resulting metacercaria is infective to fish (Køie, 1983).

Some parasite populations were associated with season. *F. breve* and *L. exodicum* were more prevalent in the winter samples; others—*L. gibbosus* and *G. laticauda*—were found only in summer samples. Because *L. gibbosus* has a life span of less than a year (Margolis and Boyce, 1969) the similar variation in seasonal prevalence observed for other parasites may indicate comparable life spans.

A correlation between host age and parasite prevalence or intensity is often seen in parasite studies. This may result from a change in diet as the host matures or from an accumulation of parasites over time. Of the four parasite species common to all samples, only *L. exodicum* showed any correlation with host age: its prevalence increased with the age of its host. Kabata et al. (1988) did not find a relation between the prevalence of any parasite, including *L. exodicum,* and fish age. However, their calculations combined fish from all samples, even those in which *L. exodicum* was not present, which may have obscured the relation seen in the current study. If, as suggested, *L. exodicum* has a life span of under one year, then the relation seen here between this species and host age would result from changes in the fish's diet rather than an accumulation with time. In contrast to the earlier study of Kabata et al. (1988), *Fellodistomum breve* was not identified here in any fish under age 5. This may be because we collected only a small number of fish from this age group.

Statistically significant differences were found between seamounts for several parasite species. The prevalences of both *L. gibbosus* and *G. laticauda* at Union Seamount were significantly different from those at Dellwood and Bowie Seamounts. But the Dellwood sample was taken in January, and these parasites were found only in the summer samples, so perhaps the Union–Dellwood differences for these species are not real. We believe that the results of the Union–Bowie comparisons are valid because summer samples were taken at both seamounts. Prevalence of the myxosporean parasite *C. anoplopoma* was statistically different between the Union and Bowie Seamounts, and there were no apparent seasonal or host-age differences between populations of this parasite. *D. varicus* was found in all seasons and with statistically different prevalences between the Dellwood sample and both the Union and Bowie samples. Therefore the prevalence of these species of parasites statistically separated ($p \geq 0.05\%$) the three seamounts. Fish from the Bowie and Union Seamounts could be differentiated on the basis of the prevalence of *C. anoplopoma, G. laticauda,* and *L. gibbosus.* The Dellwood Seamount could be differentiated from both the Bowie and Union Seamounts by the prevalence of *D. varicus.*

The prevalence of *Derogenes varicus* at these seamounts allows some speculation on the extent of any sablefish migration that may occur between the seamounts. *D. varicus* was found in samples collected in both winter and summer and was also found by Kabata et al. (1988)

in their winter and summer samples. From these observations and Meskal's (1967) findings on the parasite's life span, we conclude that this species is present in sablefish throughout the year. These data can be used for a preliminary analysis of the magnitude of possible exchange of sablefish between seamounts. The restricted distribution (Dellwood Seamount) and the life span (~1 year) of *D. varicus* indicate that any transit by sablefish between seamounts must require more than one year to complete. If there were frequent and rapid exchange between seamounts, the prevalence and intensity of *D. varicus* would be similar on all seamounts. But we found its prevalence and intensity at Bowie and Union Seamounts very low, implying that exchange between Dellwood and the other seamounts is slight.

The trematodes recovered from sablefish from the three seamounts corroborate the faunal differences seen by Kabata et al. (1988) between fish collected on seamounts and on the continental slope. In addition, the absence of fish under age 3 in this study confirms the previous work of Kabata et al. (1988), which suggested that movement of juveniles aged 3+ from the continental slope is the major source of recruitment to the seamounts. Tagging studies off the west coast of Canada support this hypothesis. Of the fish tagged and released on Bowie and Union Seamounts, all but one were recovered (up to five years after release) on the seamount on which they were released. In addition, sablefish tagged in continental slope waters and recovered on seamounts were all juveniles (age 3+, 4) at the time of tagging, corroborating the conclusion that recruitment to the seamounts results from the movement of juvenile fish. Once they become established on a particular seamount there is little evidence to suggest any major movement between seamounts.

The statistical differences that we found between the prevalences of *C. anoplopoma*, *L. gibbosus*, *G. laticauda*, and *D. varicus*, as well as the tagging data lead us to conclude that any exchange of sablefish between seamounts must be at a low level and over an extended time. Such movement would contribute little to the established biomass at any given seamount.

Although some small exchange may occur between seamounts, for purposes of the development of management strategies (which are modified annually), these stocks of sablefish can be considered discrete, both from other seamount stocks and from stocks along the continental slope.

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Literature Cited

Beamish, R. J., and D. E. Chilton.
1982. Preliminary evaluation of a method to determine the age of sablefish (*Anoplopoma fimbria*). Can. J. Fish. Aquat. Sci. 39:277–287.

Beamish, R. J., and G. A. McFarlane.
1983. Summary of results of the Canadian sablefish tagging program. *In* R. B. Meltoff (ed.), Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, AK, March 29–31, 1983, p. 59–80. Alaska Sea Grant Rep. 83-8.
1988. Resident and dispersal behaviour of sablefish in the slope waters of Canada's west coast. Can. J. Fish. Aquat. Sci. 45:152–164.

Gharrett, A. J., L. Wishard, and M. A. Thomason.
1983. Progress in the study of biochemical genetics of sablefish. *In* R. B. Metloff (ed.), Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, AK, March 29–31, 1983, p. 143–146. Alaska Sea Grant Rep. 83-8.

Kabata, Z., and D. J. Whitaker.
1984. Results of three investigations of the parasite fauna of several marine fishes of British Columbia. Can. Tech. Rep. Fish. Aquat. Sci., No. 1303.

Kabata, Z., G. A. McFarlane, and D. J. Whitaker.
1988. Trematoda of sablefish, *Anoplopoma fimbria* (Pallas, 1811), as possible biological tags for stock identification. Can. J. Zool. 66:195–200.

Køie, M.
1983. Digenetic trematodes from *Limanda* (L.) (Osteichthyes, Pleuronectidae) from Danish and adjacent waters, with special reference to their life-histories. Ophelia 22(2): 201–228.

Margolis, L., and N. P. Boyce.
1969. Life span, maturation, and growth of two Hemiurid trematodes, *Tubulovesicula lindbergi* and *Lecithaster gibbosus*, in Pacific salmon (Genus *Oncorhynchus*). J. Fish. Res. Board Can. 26:893–907.

McFarlane, G. A., and M. W. Saunders.
1997. Dispersion of juvenile sablefish as indicated by tagging in Canadian waters. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 137–150. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Meskal, F. H.
1967. Seasonal fluctuation in the population of two common trematode species from the stomach of the cod. Sarsia 26:13–20.

Moser, M.
1976. *Ceratomyxa anoplopoma* sp. n. (Protozoa, Myxosporida) from the sablefish *Anoplopoma fimbria*. Can. J. Zool. 54:1405–1406.

Dispersion of Juvenile Sablefish, *Anoplopoma fimbria*, as Indicated by Tagging in Canadian Waters

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ABSTRACT

A total of 72,296 juvenile sablefish, *Anoplopoma fimbria*, were tagged and released off the west coast of Canada between 1979 and 1987. As of December 31, 1992, 2,992 (4.1%) had been recaptured. Movement of juveniles from the northern (Queen Charlotte Sound/Hecate Strait and the west coast of the Queen Charlotte Islands) and southern (west coast of Vancouver Island) areas differed, when standardized for differences in recovery effort (exploitation rate). Over 60% of juvenile fish tagged in Queen Charlotte Sound/Hecate Strait from 1979 to 1981 (predominantly the 1977 year class) moved north of the tagging area into U.S. waters in the Gulf of Alaska. When corrected for unreported recaptures, this percentage increases to approximately 75% recaptured in the Gulf of Alaska. Fish tagged in the same area from 1982 to 1985 also showed a tendency to move northward, but the percentage recovered in U.S. waters (Gulf of Alaska) averaged approximately 20% (35% when corrected for unreported recaptures). The majority of juveniles tagged and released off the west coast of the Queen Charlotte Islands from 1983 to 1985 also moved into the Gulf of Alaska. In contrast, juvenile fish tagged and released off the west coast of Vancouver Island from 1983 to 1985 and in 1987 tended to remain near the release area. Of the fish that moved out of the area, approximately equal numbers moved to the north and south of the release area.

Introduction

From 1979 to 1987, juvenile (≤55 cm FL) sablefish, *Anoplopoma fimbria*, were tagged and released off the west coast of Canada to examine migration (recruitment) patterns. Other studies have reported a tendency of juvenile sablefish to move northward (Beamish and McFarlane, 1983, 1988; Bracken, 1983; Dark, 1983; Heifetz and Fujioka, 1991). In particular, a preliminary analysis of juveniles tagged in Canadian waters (Beamish and McFarlane, 1983) showed that the majority of juveniles tagged in Queen Charlotte Sound and Hecate Strait in 1979 and 1980 (predominantly the 1977 year class) moved northward, and the majority of these fish (60% to 70%) were recovered in the Gulf of Alaska (Figure 1). Beamish and McFarlane suggested that this area must be regarded as an important nursery area for sablefish recruiting to the United States fishery—just how important depends on the contribution of nursery areas off Alaska itself and how consistent this pattern remains. This study was continued in 1981 and 1983 to include tagging areas off the west coasts of the Queen Charlotte Islands and Vancouver Island in order to determine whether the northward movement of juveniles was consistent over a number of years and areas, and particularly whether movement into Alaskan waters was a general feature of juvenile movement.

In this paper we examine the movement of juvenile sablefish tagged in three areas (the west coast of Vancouver Island, the west coast of Queen Charlotte Islands, and Queen Charlotte Sound/Hecate Strait) between 1979 and 1987 and discuss the implications for management of the resource.

Materials and Methods

Fishing Methods

Juveniles were captured with trawl nets in Hecate Strait and Queen Charlotte Sound in 1979, 1980, and 1981. All other juveniles were captured with Korean-style coni-

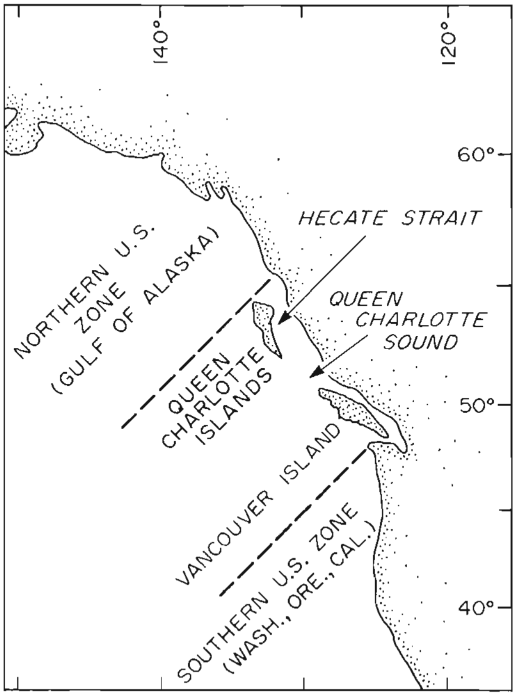

Figure 1
Major areas referred to in this study. Hecate Strait and shallow waters in Queen Charlotte Sound are sometimes referred to as "inside waters." Deeper waters in Queen Charlotte Sound, and areas off the west coast of the Queen Charlotte Islands, off Vancouver Island, and off the northern and southern coast of the United States are considered "outside" waters.

cal traps. Traps were baited with frozen herring and squid. Traps were set on bottom in strings of 15–60 at average depths of 300–500 m for approximately 24 hrs.

Tagging and Recapture

A Floy FD-68[1] anchor tag was applied according to procedures described in Beamish et al. (1979) and Beamish and McFarlane (1988). On the fishing vessel, fish were transferred directly into holding tanks with a continuous supply of seawater. Most fish were measured for fork length, tagged, and released immediately. Initially, fish were anaesthetized with MS 222 (ethyl aminobenzoate methane sulfonate), but its use was discontinued after several cruises when it was found that fish could be handled easily without anaesthetic.

Most tagged fish were recaptured in commercial sablefish fisheries that used traps and longline gear. The remainder were caught in trawl nets. As part of the recovery procedure, letters describing the tagging experiment and offering a reward were sent to Canadian and international fishermen. Fishermen were asked to return the whole fish and were compensated for all reasonable expenses. Recovered tagged sablefish were measured for fork length, examined for sex and maturity, and sampled for otoliths.

Comparisons of Recaptures Among Areas and Years

Tag recaptures were recorded for the four major areas in Figure 1 in the following categories: closer than or equal to 50 km, 50 to 200 km, and farther than 200 km from the release area. Recoveries were standardized between the Canadian and United States zones according to the procedures outlined in Beamish and McFarlane (1988). We used the relationship of average catch per biomass in the appropriate United States zone (north or south) compared with the average catch per biomass in the Canadian zone for each year from 1979 to 1992:

$$\text{Conversion factor} = \frac{\text{Catch}_{\text{Can}}}{\text{Biomass}_{\text{Can}}} \times \frac{\text{Biomass}_{\text{US}}}{\text{Catch}_{\text{US}}}.$$

This conversion factor approximately standardizes tag recoveries on the basis of the exploitation rate in an area. Canadian and United States catches were obtained from the Pacific Coast Fisheries Information Network (PacFIN) database on March 4, 1993. An average biomass in the Canadian zone of 53 kt was used over all years. This value is taken from Saunders and McFarlane (1993) and is the average of estimates of exploitable biomass in the Canadian zone based on trap surveys conducted in 1989 and 1991. The time series (1979–92) of biomass in the southern United States zone was taken from Methot and Hightower's[2] catch-at-age estimates of biomass. The 1989 biomass estimate was assumed to be appropriate for 1990–92. A biomass of 268 kt was used for the United States northern zone for all years. This was the mean of exploitable biomass estimates from surveys conducted in 1984 and 1987.[3]

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

[2] Methot, R. D., and J. Hightower. 1989. Status of the Washington-Oregon-California sablefish stock in 1989. *In* Status of the Pacific Coast groundfish fishery through 1989 and recommended acceptable biological catches for 1990. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 SW First Ave., Portland, OR 97201.

[3] Fujioka, J. 1989. Sablefish. *In* T. K. Wilderbuer (compiler), Condition of groundfish resources of the Gulf of Alaska in 1989. Alaska Fish. Sci. Center, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070.

The number and percentage of recoveries of juveniles moving out of the Canadian zone is also affected by nonreporting of recoveries in other zones. We examined this factor for Gulf of Alaska recoveries using Bracken's (1983) estimate of nonreporting. We did not incorporate estimates of tag loss, natural mortality, or differential recapture rates by size at release. We assume that these rates will be similar for all releases and will not overly influence our interpretation of juvenile movement.

Results

A total of 72,296 juvenile sablefish were tagged and released off the west coast of Canada between 1979 and 1987 (Table 1, Fig. 2). As of December 31, 1992, 2,991 tagged fish (4.1%) were recaptured. Recovery percentages varied among release areas and tagging cruises (Table 1), ranging from 0% to 10.3%. The extremes of this range came from areas where few fish had been released or from areas that are not fished extensively (Strait of Georgia). If these extremes are removed, recovery percentages ranged from 2.0% to 9.2%. Recoveries were made in continental slope waters along the entire west coast of North America from California through the Gulf of Alaska and into the Bering Sea (Fig. 3). Distributions of recoveries were similar among release years for northern release areas (Fig. 4, 5, 6), but differed among years for southern release areas (Fig. 7).

Queen Charlotte Sound/Hecate Strait Releases

From 1979 to 1984, a total of 50,169 juveniles were tagged and released in the inside waters of Queen Charlotte Sound and Hecate Strait (Table 1). As of December 31, 1992, a total of 1,653 (3.3%) fish had been recaptured. Of these, recovery information was collected for 1,546 (93.5%) fish. Two hundred ninety-one (18.8%) were recaptured within 50 km of the release area, 221 (14.3%) between 50 and 200 km, and 1,034 (66.9%) farther than 200 km from the release area (Table 2).

For most release years, fish were initially recaptured within 50 km of the release areas (Table 2). For example, fish tagged in 1979 and 1980 were predominantly from the 1977 year class (McFarlane and Beamish, 1990). During 1980, as age 3+ fish, most were recaptured within 50

Table 1

Releases and recaptures of tagged juvenile (≤ 55 cm) sablefish tagged and released in 1979–87.

Release area[1]	Release date	Number released	Number recaptured															
			79	80	81	82	83	84	85	86	87	88	89	90	91	92	Total	(%)
HEC/QCS	Oct/Nov 1979	25,253	16	140	68	78	49	38	36	43	33	15	20	17	10	8	571	(2.3)
	Oct 1980	10,686	—	6	59	59	52	26	31	41	25	18	23	18	14	8	380	(3.6)
	Aug 1981	11,437	—	—	39	127	80	53	46	50	28	26	22	27	6	8	512	(4.5)
	Oct/Nov 1982	271	—	—	—	0	9	8	4	4	0	1	1	1	0	0	28	(10.3)
	Apr/May 1984	2,522	—	—	—	—	—	41	25	49	10	15	9	7	4	2	162	(6.4)
	Total	50,169	16	146	166	264	190	166	142	187	96	75	75	70	34	26	1,653	(3.3)
WCQI	Nov/Dec 1983	3,883	—	—	—	—	0	28	14	17	14	8	12	7	3	0	103	(2.7)
	May 1984	4,914	—	—	—	—	—	141	85	55	25	12	7	13	11	9	358	(7.3)
	Mar/Apr 1985	2,914	—	—	—	—	—	—	46	83	30	12	17	12	12	9	221	(7.6)
	Total	11,711	—	—	—	—	0	169	145	155	69	32	36	32	26	18	682	(5.8)
WCVI	Nov/Dec 1983	3,824	—	—	—	—	0	66	21	33	10	11	6	4	0	0	151	(3.9)
	Apr 1984	111	—	—	—	—	—	0	0	0	0	0	0	0	0	0	0	(0)
	Apr/Jun 1985	5,259	—	—	—	—	—	—	66	266	41	51	24	25	3	5	481	(9.1)
	Mar 1987	1,099	—	—	—	—	—	—	—	—	3	7	6	3	2	1	22	(2.0)
	Total	10,293	—	—	—	—	0	66	87	299	54	69	36	32	5	6	654	(6.4)
Strait of Georgia	1984	123	—	—	—	—	—	0	0	1	0	0	0	0	0	0	1	(0.8)
Grand total		72,296															2,990	(4.1)

[1] HEC/QCS = Hecate Strait/Queen Charlotte Sound
WCQI = west coast of Queen Charlotte Islands
WCVI = west coast of Vancouver Island

km of the release area in Queen Charlotte Sound and Hecate Strait. During 1981 and 1982, an increasing percentage were recaptured in offshore waters farther than 200 km from the release site (Table 2). This pattern of recoveries continued throughout the period of the study.

A similar pattern occurred for fish tagged in 1981, which presumably also included a large percentage of the 1977 year class. For fish released in 1982, the pattern was the same initially, but because of the small number of releases (271) and recoveries (28), no trend was evident.

The general recovery pattern for 1984 releases was similar to the 1979 to 1981 releases, but, the percentage of fish recaptured farther than 200 km was lower, and the percentage of fish captured within 50 km of the release area, was higher.

For fish released in 1979, 1980, and 1981, predominantly the 1977 year class, between 52% and 68% (standardized) were recaptured in the United States zones. Of these, 98% were recovered off Alaska (Fig. 8). If recoveries made within 50 km of the release area (i.e., the juvenile rearing areas of Hecate Strait) are removed, between 60% and 76% were recovered in the United States zones (Fig. 9), of which 98% were in Alaskan waters. The majority of remaining recaptures (18% to 32%) were from the Canadian Charlotte region (west

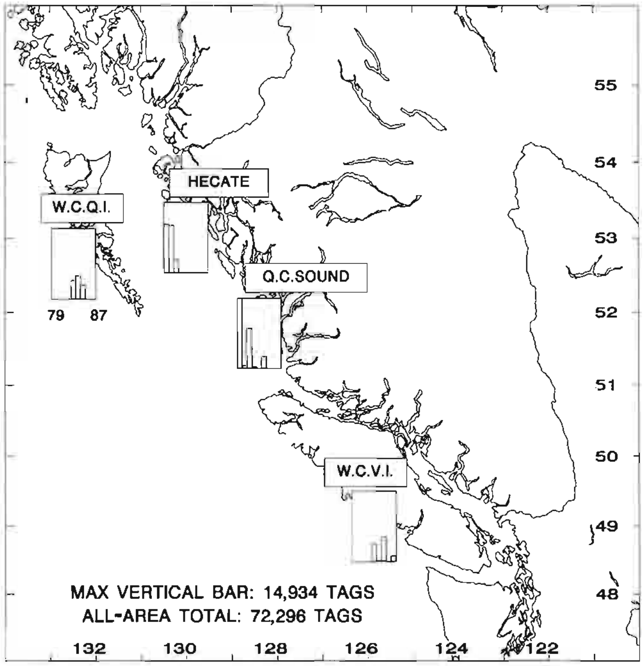

Figure 2

Tagging areas in waters off the west coast of Canada where juvenile sablefish were released from 1979 to 1987. Number of fish released in each year is shown for each area.

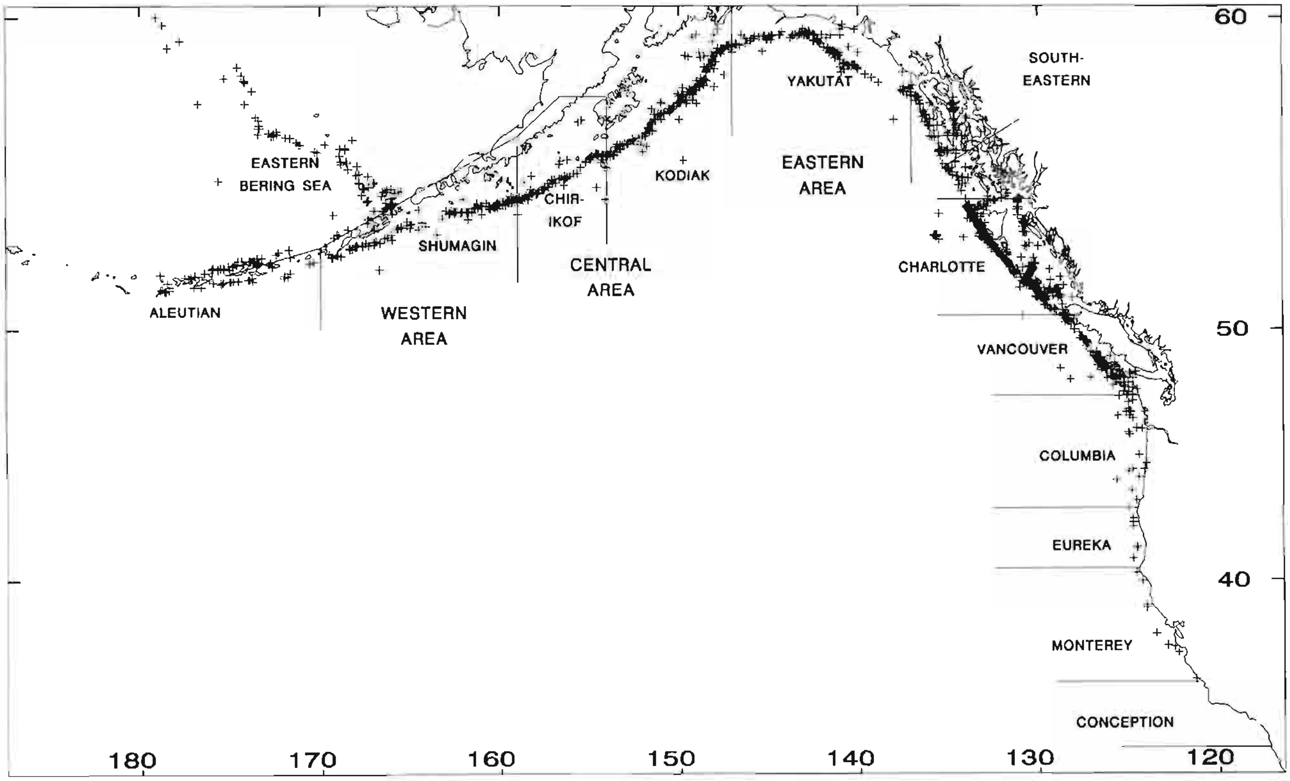

Figure 3

Recoveries, as of December 1992, of sablefish tagged as juveniles and released off the west coast of Canada from 1979 to 1987.

coast of Queen Charlotte Islands and deeper waters of Queen Charlotte Sound). Fish tagged and released in 1982 and 1984 (1979–81 year classes) also moved predominantly northward (Fig. 10), but the majority (60% to 66%) were recaptured off the Queen Charlotte Islands, and only 20% from 1982 releases and 18% from 1984 releases were recovered in waters off Alaska.

By using Bracken's (1983) figure of 70% nonreporting in waters off Alaska to correct these recovery percentages, we see that between 72% and 83% of fish tagged and released from 1979 to 1981, and between 28% and 40% of fish released in 1982 and 1984 were recovered in waters off Alaska. However, there is evidence (Bracken[4]) that the percentage of non-reporting was substantially lower after the mid-1980's, so these percentages adjusted for nonreporting would be high.

West Coast Queen Charlotte Island Releases

From 1983 to 1985, a total of 11,711 juveniles were tagged and released off the west coast of the Queen Charlotte Islands (Table 1). Release length data indicate that the fish were from the 1979 to 1983 year classes. As of December 31, 1992, 682 (5.8%) had been

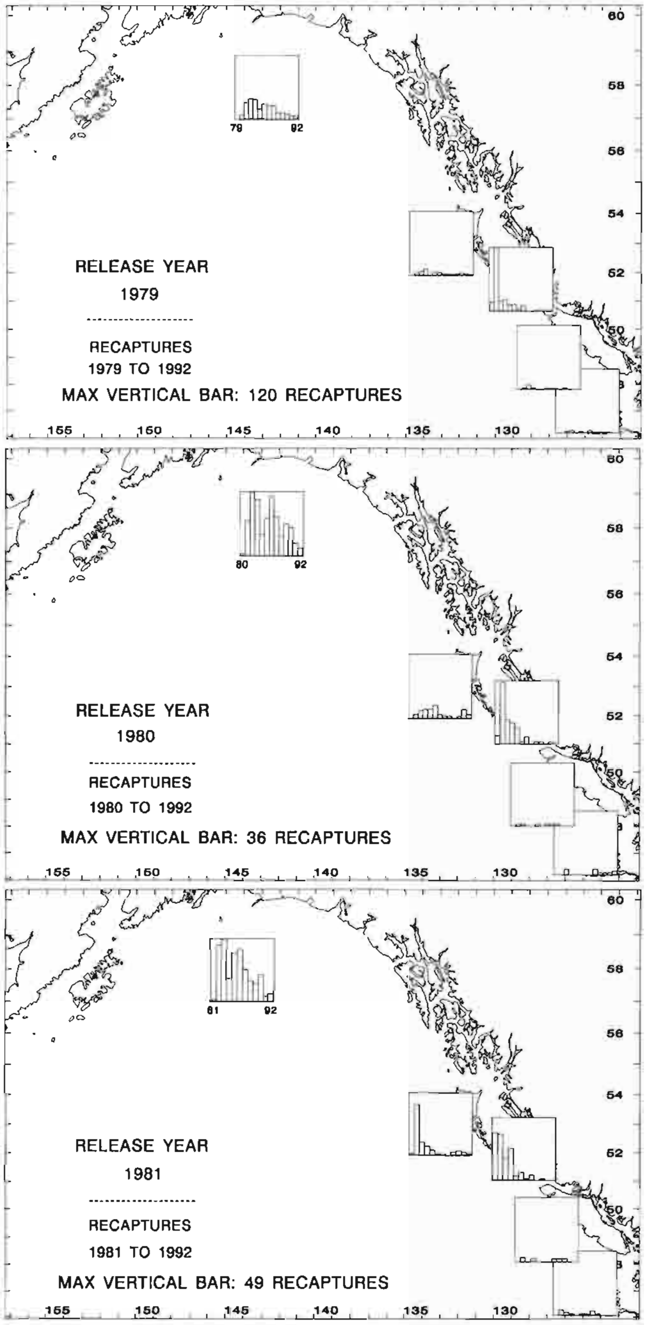

Figure 4

Recoveries, as of December 1992, of sablefish tagged as juveniles and released in Hecate Strait or Queen Charlotte Sound in 1979, 1980, and 1981.

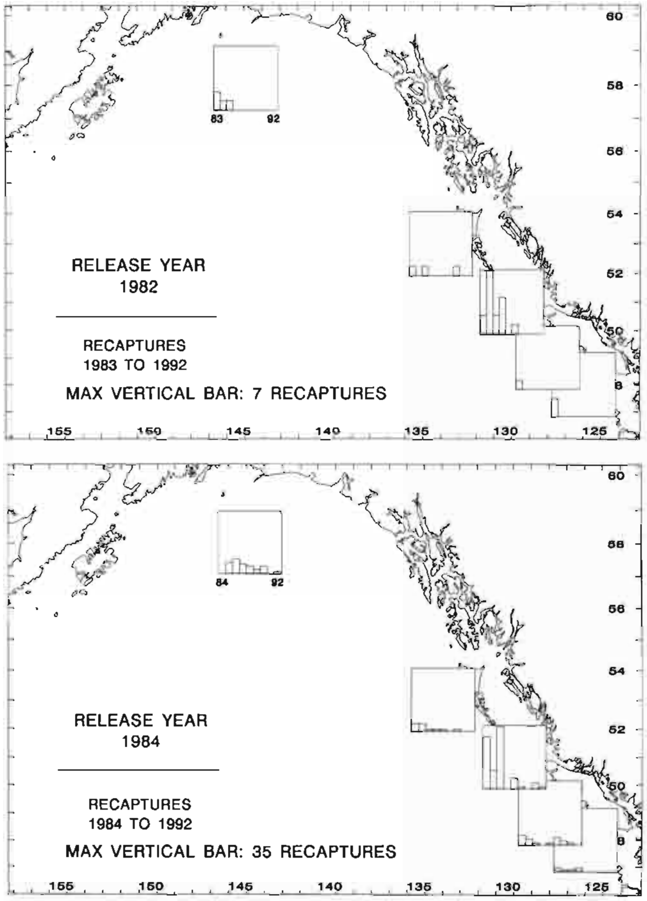

Figure 5

Recoveries, as of December 1992, of sablefish tagged as juveniles and released in Queen Charlotte Sound in 1982 and 1984.

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[4] Bracken, B. Alaska Dept. of Fish and Game, P.O. Box 667, Petersburg, AK 99833-0667. Personal commun.

recaptured, and recovery information was collected for 634 (93%). Of these, 242 (38.2%) were recaptured within 50 km; 108 (17.1%) from 50 to 200 km; and 284 (44.8%) farther than 200 km from the release area (Table 3). As with recoveries from the Queen Charlotte Sound/Hecate Strait releases, the percentage of fish recaptured farther than 200 km increased during the first 2 years after release (Table 3). This pattern continued throughout the study. For fish released in 1985, the percentages recovered within 50 km and farther than 200 km were similar.

There was a trend for juveniles released in this area to be recaptured north of the release area (Fig. 11). Approximately 86% of fish tagged and released in 1983

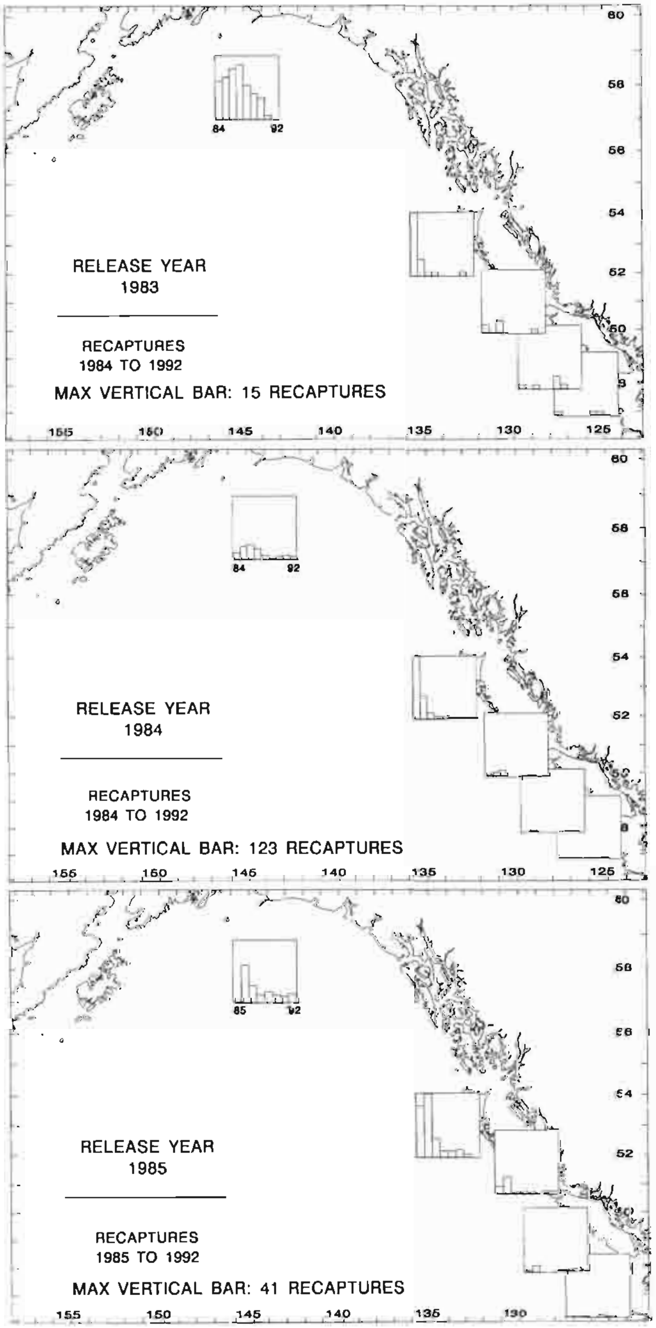

Figure 6

Recoveries, as of December 1992, of sablefish tagged as juveniles and released off the west coast of the Queen Charlotte Islands from 1983 to 1985.

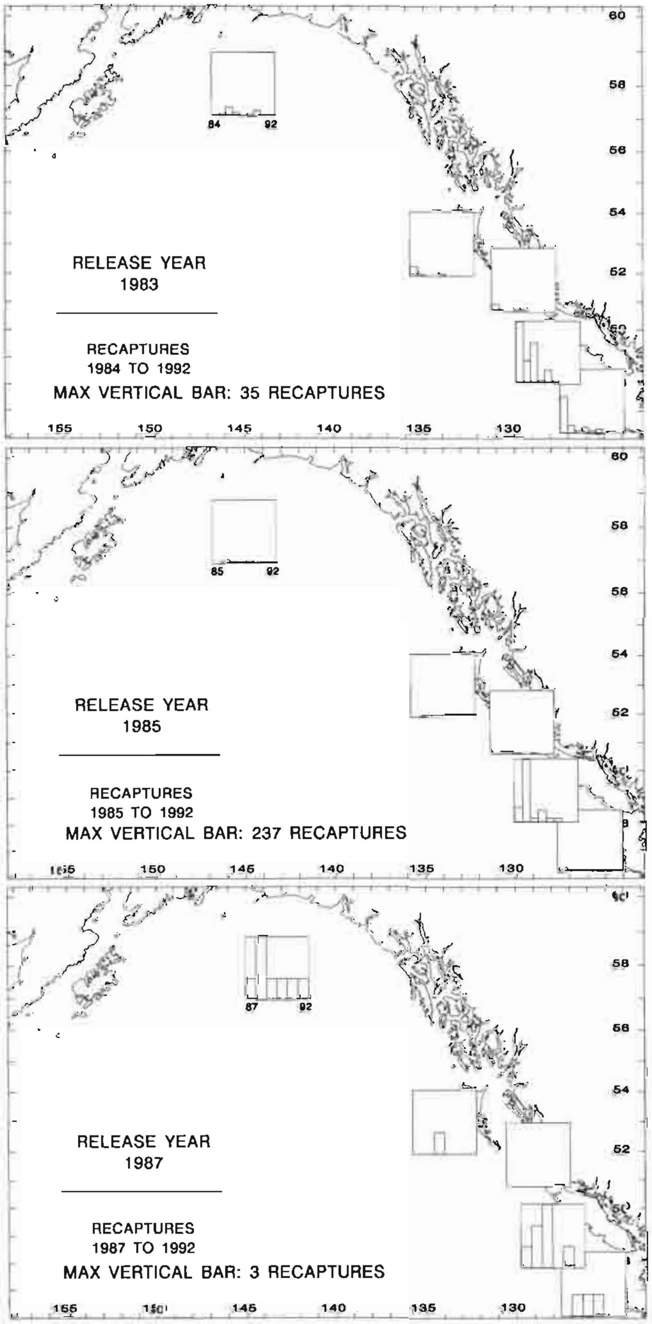

Figure 7

Recoveries, as of December 1992, of sablefish tagged as juveniles and released off the west coast of Vancouver Island in 1983, 1985, and 1987.

Table 2

Recoveries of tagged juvenile sablefish released from the combined Hecate Strait/Queen Charlotte Sound regions (1979–81) and Queen Charlotte Sound (1982 and 1984) by recapture year and distance traveled from release area. Recovery numbers have not been standardized for exploitation rate or unreported recaptures.

Release year	Recapture year	Total recoveries (with recovery info)	Recoveries by distance traveled (%)		
			<50km	50–200km	>200
Hecate Strait/Queen Charlotte Sound					
1979	1979	16 (16)	16 (100)	0 (0)	0 (0)
	1980	140 (133)	70 (53)	49 (37)	14 (11)
	1981	68 (65)	7 (11)	13 (20)	45 (69)
	1982	78 (74)	4 (5)	14 (19)	56 (76)
	1983	49 (48)	0 (0)	8 (16)	40 (83)
	1984	38 (36)	1 (3)	7 (19)	28 (78)
	1985	36 (34)	0 (0)	1 (3)	33 (97)
	1986	43 (36)	0 (0)	5 (14)	31 (86)
	1987	33 (29)	0 (0)	1 (4)	28 (97)
	1988	15 (13)	0 (0)	1 (8)	12 (92)
	1989	20 (20)	4 (20)	1 (5)	15 (75)
	1990	17 (17)	3 (18)	1 (6)	13 (77)
	1991	10 (10)	2 (20)	1 (10)	7 (70)
	1992	8 (8)	3 (38)	1 (13)	4 (50)
1980	1980	6 (6)	1 (17)	4 (67)	1 (17)
	1981	59 (58)	21 (36)	14 (24)	23 (40)
	1982	59 (57)	7 (12)	6 (11)	44 (77)
	1983	52 (44)	1 (2)	9 (21)	34 (77)
	1984	26 (25)	0 (0)	1 (4)	24 (96)
	1985	31 (30)	0 (0)	0 (0)	30 (100)
	1986	41 (40)	0 (0)	0 (0)	40 (100)
	1987	25 (23)	1 (4)	0 (0)	22 (96)
	1988	18 (14)	2 (14)	1 (7)	11 (79)
	1989	23 (22)	2 (9)	1 (5)	19 (86)
	1990	18 (18)	1 (6)	1 (6)	16 (89)
	1991	14 (14)	1 (7)	3 (21)	10 (71)
	1992	8 (8)	0 (0)	0 (0)	8 (100)
1981	1981	39 (39)	35 (90)	2 (5)	2 (5)
	1982	127 (123)	18 (15)	12 (10)	93 (76)
	1983	80 (74)	3 (4)	12 (16)	59 (80)
	1984	53 (49)	2 (4)	12 (25)	35 (71)
	1985	46 (41)	0 (0)	2 (5)	39 (95)
	1986	50 (46)	0 (0)	3 (7)	43 (94)
	1987	28 (27)	0 (0)	1 (4)	26 (96)
	1988	26 (20)	1 (5)	3 (15)	16 (80)
	1989	22 (20)	3 (15)	0 (0)	17 (85)
	1990	27 (27)	1 (4)	1 (4)	25 (93)
	1991	6 (6)	1 (17)	0 (0)	5 (83)
	1992	8 (8)	2 (25)	0 (0)	6 (75)
Queen Charlotte Sound					
1982	1983	9 (8)	2 (25)	1 (13)	5 (63)
	1984	8 (8)	7 (88)	0 (0)	1 (13)
	1985	4 (4)	1 (25)	1 (25)	2 (50)
	1986	4 (3)	2 (66)	1 (33)	0 (0)
	1987	0 (0)	0 (0)	0 (0)	0 (0)
	1988	1 (1)	0 (0)	1 (100)	0 (0)
	1989	1 (0)	0 (0)	0 (0)	0 (0)
	1990	1 (1)	0 (0)	0 (0)	1 (100)
1984	1984	41 (40)	26 (65)	7 (18)	7 (18)
	1985	25 (23)	7 (30)	6 (26)	10 (44)
	1986	49 (40)	20 (50)	7 (18)	13 (33)
	1987	10 (6)	0 (0)	0 (0)	6 (100)
	1988	15 (14)	5 (36)	3 (21)	6 (43)
	1989	9 (8)	3 (38)	2 (25)	3 (38)
	1990	7 (6)	1 (17)	0 (0)	5 (83)
	1991	4 (4)	3 (75)	1 (25)	0 (0)
	1992	2 (2)	1 (50)	0 (0)	1 (50)
Total		1,653 (1,546)	291 (19)	221 (14)	1,034 (67)

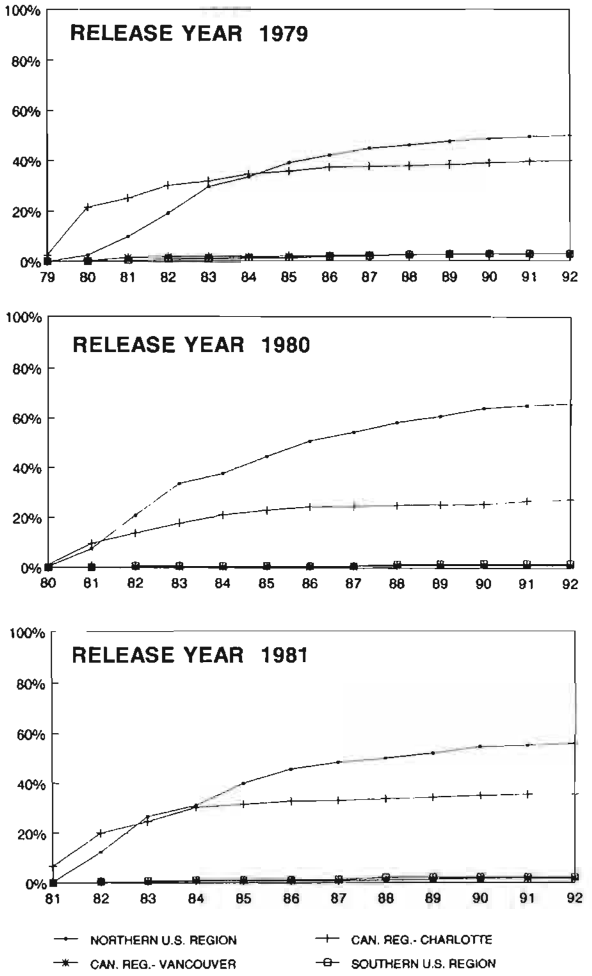

Figure 8

Cumulative standardized recoveries for releases in Queen Charlotte Sound and Hecate Strait in 1979, 1980, and 1981. All recoveries from Hecate Strait nursery areas are included. Recovery percentages not corrected for unreported recaptures.

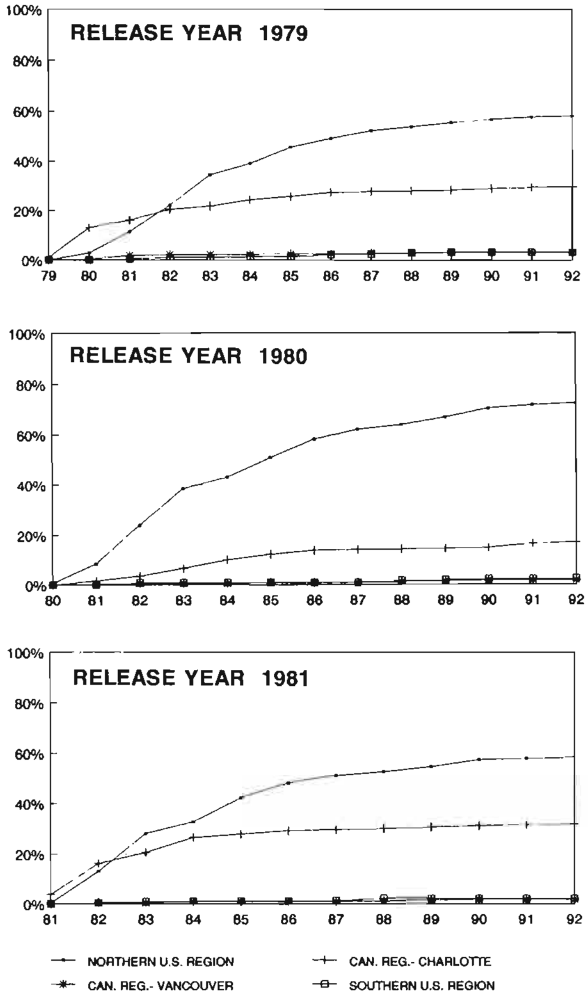

Figure 9

Cumulative standardized recoveries for releases in Queen Charlotte Sound and Hecate Strait in 1979, 1980, and 1981. Recoveries from Hecate Strait nursery areas are not included. Recovery percentages not corrected for unreported recaptures.

were recovered north of the release area—58% in waters off Alaska and 28% off the west coast of the Queen Charlotte Islands. Fish tagged and released in 1984 and 1985 also tended to move north, but only 28% of the 1984 releases and 21% of the 1985 releases were recovered in northern United States waters (off Alaska). When adjusted for nonreporting (Bracken, 1983) 70%, 31%, and 38% were recovered from Alaskan waters for the 1983, 1984, and 1985 releases.

West Coast Vancouver Island Releases

Between 1983 and 1987, a total of 10,293 juvenile sablefish were tagged and released off the west coast of Vancouver Island (Table 1). Release length data indicate that these fish were predominantly from the 1980–1986 year classes. As of December 31, 1992, 654 (6.4%) had been recaptured, and recovery information was collected for 586 (89.6%). Of these, 404 (68.9%) were recaptured within 50 km; 71 (12.1%) from 50 to 200 km; and 111 (18.9%) farther than 200 km (Table 4).

As in other areas, most recoveries were initially made within 50 km of the release area. However, except for 1987 releases, the percentage of recoveries made within 50 km of the release area remained higher throughout the study than it did for releases off the west coast of the Queen Charlotte Islands and in Hecate Strait/Queen Charlotte Sound. Recoveries from 1987 releases at dis-

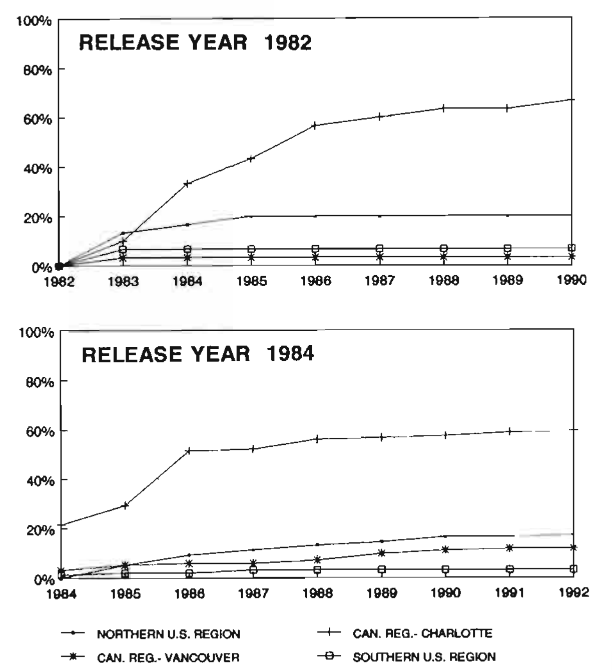

Figure 10
Cumulative standardized recoveries for releases in Queen Charlotte Sound in 1982 and 1984. Recovery percentages not corrected for unreported recaptures.

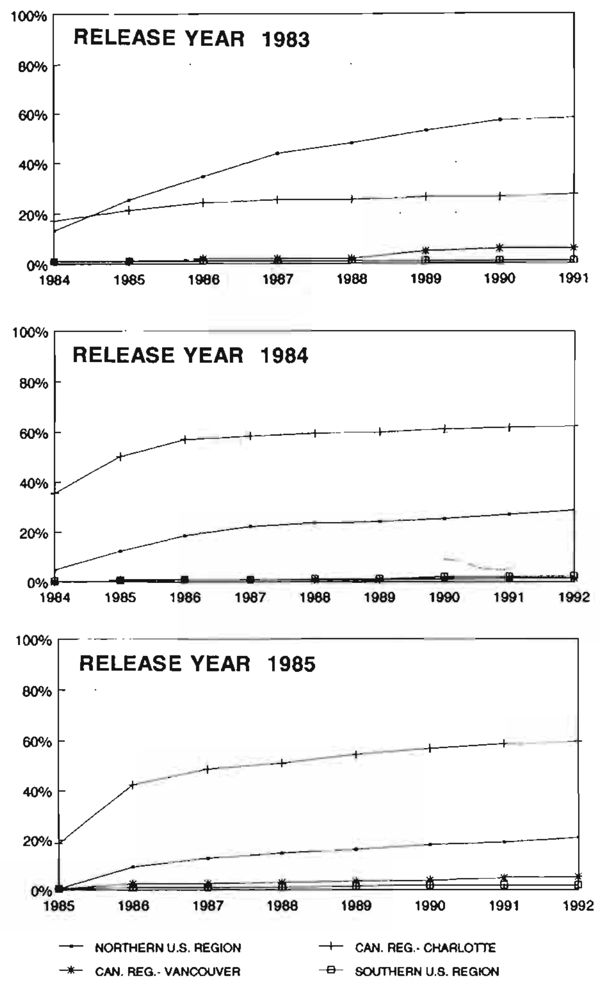

Figure 11
Cumulative standardized recoveries for releases off the west coast of the Queen Charlotte Islands in 1983, 1984, and 1985. Recovery percentages not corrected for unreported recaptures.

tances greater than 200 km were similar to those in other release areas.

In contrast to recaptures of Queen Charlotte Sound/ Hecate Strait and west coast of Queen Charlotte Island releases, juveniles released off the west coast of Vancouver Island tended to be recovered closer to and south of the release area (Figure 12). Between 55% and 85% were recovered off the west coast of Vancouver Island, and in 1983 and 1987 approximately 20% of recoveries were from United States waters from Washington to California. Recoveries north of Vancouver Island accounted for approximately 20% to 25% of total recoveries, approximately equally divided between the west coast of the Queen Charlotte Islands and northern United States waters (off Alaska) for 1983 and 1985 releases. Twenty percent of recoveries from 1987 releases were made in northern United States waters (off Alaska). As in other areas, these percentages in northern waters would be higher if adjusted for nonreporting.

Recaptures in Relation to Length at Release

In general, an increasing percentage of juveniles were recaptured with increasing length at release for all release years (Table 5). In all cases fish between 51 and 55 cm at time of release were recovered at a substantially higher rate than fish of other sizes. Fish released in 1984 and 1985 that were smaller than 40 cm at the time of tagging were recovered at rates higher than those for similar-sized fish released in other years, and higher than those for fish between 41 and 50 cm at time of release for all release years. However, during these two cruises, only a few fish were tagged in this category (107 in 1984; 22 in 1985), and recovery percentages do not indicate true values.

Discussion

Previous studies (Beamish and McFarlane, 1983, 1988; Bracken, 1983; Dark, 1983; Heifetz and Fujioka, 1991)

Table 3

Recoveries of tagged juvenile sablefish released off the west coast of the Queen Charlotte Islands by recapture year and distance traveled from release area. Recovery numbers have not been standardized for exploitation rate or unreported recaptures.

			Recoveries by distance traveled (%)		
Release year	Recapture year	Total recoveries (with recovery info)	<50km	50–200km	>200
1983	1984	28 (27)	8 (30)	7 (26)	12 (44)
	1985	14 (13)	3 (23)	1 (8)	9 (69)
	1986	17 (17)	1 (6)	1 (6)	15 (88)
	1987	14 (14)	0 (0)	1 (7)	13 (93)
	1988	8 (7)	1 (14)	0 (0)	6 (86)
	1989	12 (12)	2 (17)	1 (8)	9 (75)
	1990	7 (6)	1 (17)	0 (0)	5 (83)
	1991	3 (3)	0 (0)	1 (33)	2 (67)
1984	1984	141 (139)	90 (65)	37 (27)	12 (9)
	1985	85 (75)	36 (48)	10 (13)	29 (39)
	1986	55 (49)	6 (12)	7 (14)	36 (74)
	1987	25 (25)	3 (12)	2 (8)	20 (80)
	1988	12 (11)	2 (18)	1 (9)	8 (73)
	1989	7 (5)	1 (20)	1 (20)	3 (60)
	1990	13 (12)	3 (25)	3 (25)	6 (50)
	1991	11 (11)	3 (27)	0 (0)	8 (73)
	1992	9 (9)	2 (22)	1 (11)	6 (67)
1985	1985	46 (38)	15 (40)	16 (42)	7 (18)
	1986	83 (77)	32 (42)	10 (13)	35 (45)
	1987	30 (24)	11 (46)	1 (4)	12 (50)
	1988	12 (12)	4 (33)	1 (8)	7 (58)
	1989	17 (15)	6 (40)	1 (7)	8 (53)
	1990	12 (12)	4 (33)	2 (17)	6 (50)
	1991	12 (12)	6 (50)	1 (8)	5 (42)
	1992	9 (9)	2 (22)	2 (22)	5 (56)
Total		682 (634)	242 (38)	108 (17)	284 (45)

reported a tendency for juvenile sablefish to move in a northward direction (in the Gulf of Alaska, northwestward). With the exception of the study by Heifetz and Fujioka (1991), the small numbers of recaptured fish tagged as juveniles in these studies limited the usefulness of the information for development of management strategies.

The number of recaptured fish tagged as juveniles in this study (2,992 fish; 4.1%), although lower than reported for adults tagged off the west coast of Canada (Beamish and McFarlane, 1988) was large enough to allow us to examine the movement of juvenile fish from several year classes that were tagged in three major areas off Canada's west coast. Our main objectives were to determine the timing and area of recruitment of these fish to commercial fisheries. In particular, we wanted to determine whether the movement into Alaskan waters reported for the 1977 year class (Beamish and McFarlane, 1983) was consistent for other year classes and for fish tagged in other areas.

Timing of Recruitment

Using age determination of recaptures and incidental catches of juveniles in Hecate Strait trawl fisheries, Beamish and McFarlane (1983) and McFarlane and Beamish (1990) reported that juveniles of the 1977 year class (age 3+, 4) moved from inside (shallow) waters (Hecate Strait and shallow areas of Queen Charlotte Sound) to outside (deeper) waters in 1980–81. This pattern of recruitment was similar for other year classes in all areas (Table 2, 3). Tagged juveniles were initially recaptured close to the release site, and moved to deeper offshore waters both within the release zone and in other zones within 1 to 2 years of tagging (as indicated by length at release and distance moved). Although it was not possible to identify year classes specifically, and although most cruises tagged 2 or more year classes, which would not recruit simultaneously, it is apparent that most fish recruited to deeper waters at age 3+, 4 (based on size at release and years at liberty).

Table 4

Recoveries of tagged juvenile sablefish released off the west coast of Vancouver Island by recapture year and distance traveled from release area. Recoveries have not been standardized for exploitation rate or unreported recaptures.

Release year	Recapture year	Total recoveries (with recovery info)	Recoveries by distance traveled (%)		
			<50km	50–200km	>200
1983	1984	66 (62)	32 (52)	13 (21)	17 (27)
	1985	21 (18)	8 (44)	6 (33)	4 (22)
	1986	33 (28)	21 (75)	1 (4)	6 (21)
	1987	10 (7)	0 (0)	2 (29)	5 (71)
	1988	11 (11)	7 (64)	2 (18)	2 (18)
	1989	6 (3)	1 (33)	0 (0)	2 (67)
	1990	4 (4)	1 (25)	0 (0)	3 (75)
1985	1985	66 (59)	45 (76)	11 (19)	3 (5)
	1986	266 (247)	224 (91)	6 (2)	17 (7)
	1987	41 (25)	3 (12)	11 (44)	11 (44)
	1988	51 (48)	35 (73)	10 (21)	3 (6)
	1989	24 (23)	9 (39)	6 (26)	8 (35)
	1990	25 (24)	12 (50)	1 (4)	11 (46)
	1991	3 (3)	0 (0)	0 (0)	3 (100)
	1992	5 (5)	1 (20)	0 (0)	4 (80)
1987	1987	3 (1)	1 (100)	0 (0)	0 (0)
	1988	7 (7)	1 (14)	1 (14)	5 (71)
	1989	6 (6)	2 (33)	0 (0)	4 (67)
	1990	3 (2)	1 (50)	0 (0)	1 (50)
	1991	2 (2)	0 (0)	1 (50)	1 (50)
	1992	1 (1)	0 (0)	0 (0)	1 (100)
Total		654 (586)	404 (69)	71 (12)	111 (19)

Area of Recruitment

Overall, juvenile sablefish tagged and released in northern areas (Hecate Strait, Queen Charlotte Sound, and west coast of Queen Charlotte Islands) in all release years tended to move northward (Fig. 5, 6, 8–11). Juveniles from the 1977 year class showed strong movement into the Gulf of Alaska. Juveniles tagged in these areas from 1982 to 1985 also moved northward, but a lower percentage moved into northern United States waters. In particular, juveniles tagged off the west coast of the Queen Charlotte Islands moved northward and were recaptured at distances >200 km but still within northern Canadian waters.

A higher percentage of juvenile sablefish tagged off the west coast of Vancouver Island were recaptured closer to the release site. The majority of these fish recovered from all release years were recaptured off Vancouver Island (Fig. 7, 12). Movement out of the Vancouver region differed among release years. For example, for 1985 releases, almost all fish were recaptured off Vancouver Island, and approximately 6% were recaptured in each of the United States zones north and south of Canada. However, for 1987 releases, equal percentages of recaptures (20% in each area) were made in northern and southern United States waters, and for 1983 releases, more than twice the number of recoveries were made in the southern United States zone (20%) than in the northern zone (approximately 7%).

It is apparent that migratory behavior of juvenile sablefish differs between northern and southern Canadian tagging areas; the majority of juveniles tagged in northern areas in all years tend to move northward. Off Vancouver Island, there was much less movement out of the area. Of the juveniles that did move, approximately equal numbers moved north and south of the release area. Of fish moving into United States waters from Vancouver Island, a slightly higher percentage moved south.

The different recruitment patterns of juveniles tagged and released in northern and southern areas off the west coast of British Columbia may be linked to different oceanographic conditions associated with northeast Pacific production domains (Ware and McFarlane, 1989). Queen Charlotte Sound is considered a transition zone; fish to the south live in the coastal upwelling domain, and fish to the north live in the coastal downwelling domain.

Movement by Length at Release

Saunders et al. (1990) reported a significant relation between size at tagging and recapture percentage of tagged adults. Our study also showed a consistent and incremental relation between release size and recapture rate. McFarlane and Beamish (1990) examined recapture percentages by length at release for juveniles from the 1977 year class tagged in 1979 and 1980. In the release area, they did not find a significant difference in the recovery rates of fish released at lengths of 40–44 and 45–50 cm. But once the fish recruited to outside waters, there was a reduced recapture rate for the smaller size group. Because the reduced rate occurred after the fish moved offshore, away from the nursery area, McFarlane and Beamish believed the lower rate of recovery resulted from increased mortality due to predation. Our study corroborates previous reports, but the incremental relation is so consistent over all years and areas that we believe other factors must also be influencing the recovery percentages. It is unclear what these other factors might be.

Implications for Management

Beamish and McFarlane (1988) proposed that dispersal of adult fish is not a major contributor to the biomass of major fisheries. The major source of recruitment to any area is juveniles. In particular, strong year classes in 1941, 1953, 1958, and 1977 produced a large biomass of sablefish throughout its range, from the southern United States to the western Bering Sea.

Table 5

Recaptures of tagged juvenile sablefish by length at release.

Release year	Release length (cm)	Number released	Number recovered														Total recaptured[1]
			79	80	81	82	83	84	85	86	87	88	89	90	91	92	n (%)
1979	<40	2,316	1	12	2	4	2	3	1	4	1	2	0	0	0	1	33 (1.3)
	41–45	14,610	8	80	38	37	27	20	16	20	18	8	14	10	8	5	309 (2.1)
	46–50	7,764	6	42	22	30	19	14	16	17	14	5	6	7	2	2	202 (2.6)
	51–55	563	1	6	6	7	1	1	3	2	0	0	0	0	0	0	27 (4.8)
1980	<40	722		1	7	5	2	0	0	2	2	2	1	0	0	1	23 (3.1)
	41–45	1,446		1	9	8	10	2	6	6	1	0	3	2	0	1	49 (3.4)
	46–50	6,587		3	24	31	32	18	18	28	16	11	16	14	12	5	228 (3.5)
	51–55	1,931		1	19	15	8	6	6	5	6	5	3	2	2	1	79 (4.1)
1981	<40	755			3	6	5	1	2	1	1	1	0	0	0	0	20 (2.6)
	41–45	1,896			12	9	5	9	4	6	3	4	3	2	1	1	59 (3.1)
	46–50	4,678			6	36	32	13	16	18	15	9	11	9	4	6	175 (3.7)
	51–55	4,108			18	76	38	31	24	25	9	12	8	16	1	1	259 (6.3)
1982	46–50	55					0	0	2	0	0	0	0	1	0	0	3 (5.5)
	51–55	216					9	8	2	4	0	1	1	0	0	0	25 (11.6)
1983	41–45	425						0	0	1	0	0	0	0	0	0	1 (0.2)
	46–50	3,539						25	6	11	8	7	7	0	0	0	64 (1.8)
	51–55	3,743						69	28	38	16	12	11	9	3	0	186 (5.0)
1984	<40	107						0	0	5	0	0	0	0	2	1	8 (7.5)
	41–45	498						1	0	2	0	0	0	0	0	0	3 (0.6)
	46–50	2,266						16	17	17	13	6	3	3	3	3	81 (3.6)
	51–55	4,799						165	89	81	22	21	13	17	10	8	426 (8.9)
1985	<40	22							0	7	0	1	1	0	0	0	9 (7.7)
	41–45	655							6	8	2	1	2	6	1	0	26 (4.0)
	46–50	3,128							29	91	17	26	13	14	4	9	203 (6.5)
	51–55	4,368							77	243	52	35	25	17	10	5	464 (10.6)
1987	<40	962									2	4	5	3	1	1	16 (1.7)
	41–45	87									1	3	1	0	0	0	5 (5.8)
	46–50	50									0	0	0	0	1	0	1 (2.0)

[1] Six recaptured fish for which there was incomplete information are not included.

Our study clearly demonstrates that juveniles in the northern part of the Canadian zone recruit to fisheries north of their nursery areas. This phenomenon was consistent for all year classes examined. A large proportion of these northward-moving fish were recaptured in waters off Alaska. In particular, the movement of the majority of juveniles from large year classes (e.g., 1977) moving into northern United States waters can be considered a major contributor to fisheries in these areas. It is apparent that any fishery for juvenile sablefish conducted in the northern Canadian zone would affect subsequent recruitment to the fishery off Alaska, but would be particularly important in years following a strong year class.

The implications of a fishery for juveniles off Vancouver Island are less clear. The numbers of fish tagged in this area and recaptured in the United States zones both north and south of the release area are much lower than for northern release areas. Our study indicates that a fishery for juveniles in this area would have little effect on fisheries to the north. The effect on fisheries to the south of Vancouver Island may be greater. Twenty percent of recoveries of fish tagged in 1983 and 1987 were made in southern United States waters. At present there is little information on the migration patterns of juvenile sablefish tagged in southern United States waters. If they behave in a similar manner to those tagged off Vancouver Island, the contribution to fisheries off Canada would be small, and a fishery for smaller fish conducted in southern United States waters would not adversely affect Canadian fisheries. If, however, juveniles tagged in these waters displayed the same tendency for northward movement as fish tagged in northern Canadian waters, then this fishery would adversely affect the Canadian fishery off Vancouver Island. At present, there is no indication that this fishery is being affected by United States fisheries to the south. It is not possible to determine whether this phenomenon of less movement in southern Canadian and United States waters is consistent for all year classes, because few fish from the strong 1977 year class were tagged in southern areas. It is clear, however, that juvenile movement in all areas is dynamic and must be considered in our assessment of stocks and development of management strategies.

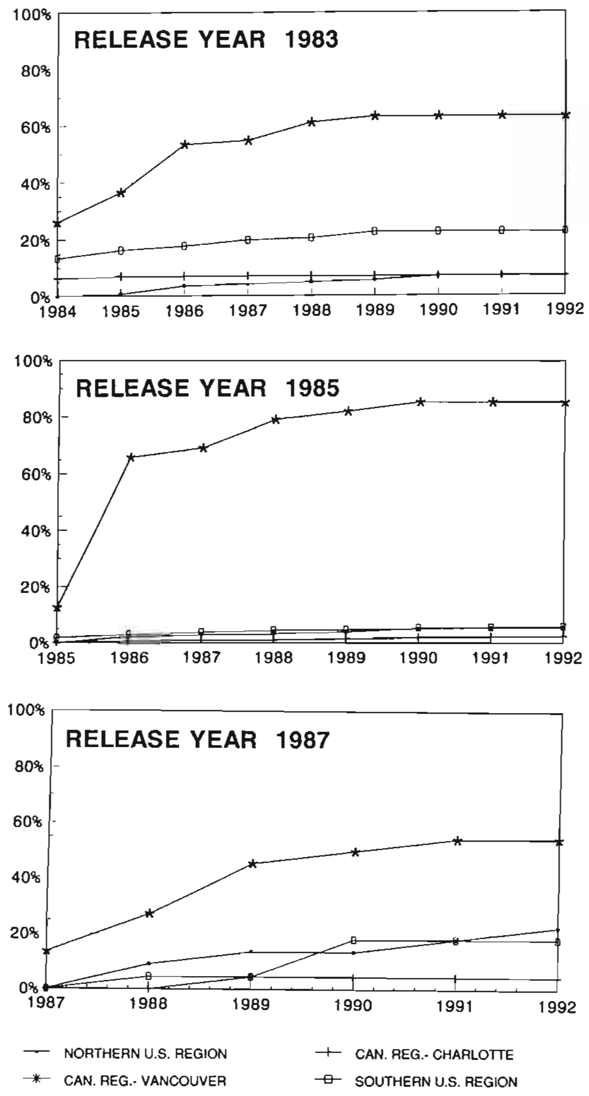

Figure 12

Cumulative standardized recoveries for releases off the west coast of Vancouver Island in 1983, 1985, and 1987. Recovery percentages not corrected for unreported recaptures.

Acknowledgments

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Literature Cited

Beamish, R. J., C. Houle, C. Wood, and R. Scarsbrook.
1979. A summary of sablefish tagging and exploratory trapping studies conducted during 1978 by the Pacific Biological Station. Can. J. Fish. Aquat. Sci. 162:113 p.

Beamish, R. J., and G. A. McFarlane.
1983. Summary of results of the Canadian sablefish tagging program. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 147–183. Alaska Sea Grant Rep. 83-8.

1988. Resident and dispersal behaviour of adult sablefish (*Anoplopoma fimbria*) in the slope waters off Canada's west coast. Can. J. Fish. Aquat. Sci. 45:152–164.

Bracken, B.
1983. Sablefish migration in the Gulf of Alaska based on tag recoveries. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 185–190. Alaska Sea Grant Rep. 83-8.

Dark, T. A.
1983. Movement of tagged sablefish released at abundance index sites off southeastern Alaska, Washington, Oregon and California during 1978–81. *In* Proceedings of the Second Lowell Wakefield Fisheries Symposium, Anchorage, Alaska, p. 191–207. Alaska Sea Grant Rep. 83-8.

Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11:355–374.

McFarlane, G. A., and R. J. Beamish.
1990. Effect of an external tag on growth of sablefish (*Anoplopoma fimbria*), and consequences to mortality and age at maturity. Can. J. Fish. Aquat. Sci. 47:1,551–1,557.

Saunders, M. W., and G. A. McFarlane.
1993. *In* B. M. Leaman and M. Stocker (eds.), 1993 groundfish stock assessments for the west coast of Canada in 1992 and recommended yield options for 1993. Can. Tech. Rep. Fish. Aquat. Sci. 1919, 407 p.

Saunders, M. W., G. A. McFarlane, and R. J. Beamish.
1990. Factors that affect the recapture of tagged sablefish off the west coast of Canada. Am. Fish. Soc. Symp. 7:708–713.

Ware, D. M., and G. A. McFarlane.
1989. Fisheries production domains in the Northeast Pacific Ocean. *In* R. J. Beamish and G. A. McFarlane (eds.), Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models, p. 359–379. Can. Spec. Publ. Fish. Aquat. Sci. 108.

Movement Patterns of Tagged Sablefish, *Anoplopoma fimbria,* Recovered on Seamounts in the Northeast Pacific Ocean and Gulf of Alaska

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ABSTRACT

Over 250,000 sablefish, *Anoplopoma fimbria,* were tagged and released off the U.S. West Coast, in the Gulf of Alaska and the Bering Sea, and in waters near the Aleutian Islands between 1971 and 1990. This paper describes the recovery of 95 tagged sablefish on seamounts in the Gulf of Alaska and northeastern Pacific Ocean since 1979 and indicates that many of these sablefish moved from coastal waters to the seamounts. These seamounts are located 110–330 km from the continental slope, with water depths between ranging from 2,900 to 5,300 m. Some of these fish had been free for nearly 20 years, and some were recaptured over 3,000 km from where they were tagged. These tagged sablefish recoveries support the hypothesis that sablefish populations of the Gulf of Alaska and northeast Pacific Ocean seamounts are maintained by fish moving from the slope region of the continental shelf.

Introduction

Sablefish, *Anoplopoma fimbria,* have been tagged and released in North Pacific waters by scientists from Japan, South Korea, Russia, Canada, and the United States since 1948 (Holmberg and Jones, 1954; Wespestad et al., 1983; Fujioka et al., 1988). A small number (99) of these releases were tagged on Gulf of Alaska seamounts.

Sablefish populations on the seamounts have become more important as fishing pressure has increased in recent years due to shrinking sablefish seasons and/or smaller trip limits within the U.S. Exclusive Economic Zone (Methot et al.[1]). Recovery of tagged sablefish from seamounts has therefore increased due to higher fishing effort there.

All the seamounts from which tagged sablefish have been recovered (Fig. 1) are separated from the continental slope by 110–330 km of water between 2,900 and nearly 5,300 m deep. Although the Bowie Seamount is relatively close to the British Columbia coastline (166 km), it too is separated from the continental shelf by 110 km of water with depths of at least 2,900 m.

The initial U.S. exploration of the nine Gulf of Alaska seamounts was performed in 1979 (Hughes, 1981). An earlier description of the topographical features of the Cobb seamount can be found in Birkeland (1971). Alton (1986) described the fish and crab populations of these seamounts and hypothesized that the sablefish inhabiting the summits of Gulf of Alaska seamounts are mature fish whose resident populations are maintained by fish straying from the slope region of the continental shelf. This paper describes the recovery of 95 tagged sablefish on Gulf of Alaska and northeastern Pacific Ocean seamounts (Fig. 1) since 1979, and supports the hypothesis that seamount sablefish populations are

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[1] Methot, R., R. Lauth, F. Shaw, and M. Wilkins. 1994. Assessment of the west coast sablefish stock in 1994. *In* Status of the Pacific coast groundfish fishery through 1994 and recommended acceptable biological catches for 1995. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland, OR 97201.

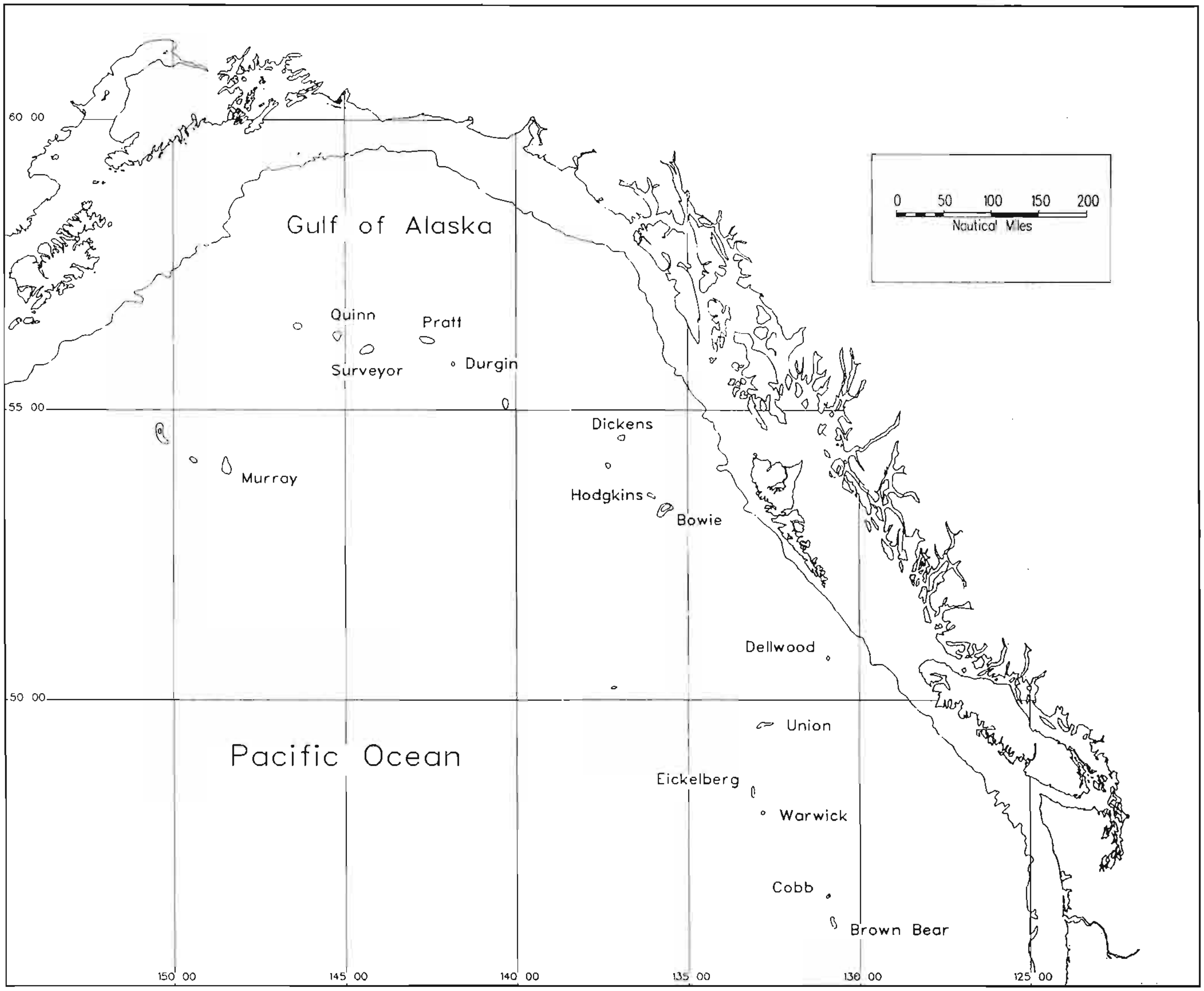

Figure 1

Seamounts in the Gulf of Alaska and northeastern Pacific Ocean on which tagged sablefish have been recovered.

maintained by fish moving from the slope region of the continental shelf.

Methods

Since 1971, over 250,000 sablefish have been released in the north Pacific Ocean and Bering Sea (Table 1). On the Washington, Oregon, and California coasts, most tagging occurred during the National Marine Fisheries Service (NMFS) sablefish abundance indexing surveys in which sablefish were captured with traps at 17 equally spaced sites (Parks and Shaw, 1990, 1994). Sablefish were tagged and released throughout the Gulf of Alaska and Bering Sea/Aleutian Islands areas during the Japan/U.S. cooperative longline surveys beginning in 1978 and continuing to the present. Approximately 42 sites were sampled annually in the Gulf of Alaska and another 74 sites were sampled in the Bering Sea/ Aleutian Islands area (Yoshimura and Sasaki[2]).

In all studies, the sablefish were put into "live" tanks filled with running seawater immediately after they were caught. Usually within 15 minutes of the completion of each haul, viable sablefish were measured, tagged, and released. Each fish was marked with a color-coded and

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[2] Yoshimura, T., and T. Sasaki. 1988. Preliminary report on Japan–U.S. joint longline survey by *Anyo maru No. 22* in 1987. Document submitted to the Annual Meeting of the International North Pacific Fisheries Commission, Tokyo, Japan, October 1988, 16 p. Fisheries Agency of Japan, Far Seas Fisheries Research Laboratory, 5-7-1, Orido, Shimizu 424, Japan.

Table 1
Numbers of sablefish tagged by area and 5-year period.

Area	1971–75	1976–80	1981–85	1986–90	All Years
Washington, Oregon, California	24,708	12,065	6,727	12,793	56,293
Gulf of Alaska	9,778	45,239	81,959	23,606	160,582
Gulf of Alaska seamounts		99			99
Bering Sea, Aleutian Islands	14	3,926	30,911	11,441	46,292
Total	34,500	61,329	119,597	47,840	263,266

numbered anchor tag implanted just below the first dorsal fin.

Since 1971, hat or cash rewards have been issued for nearly 17,000 sablefish tags returned to the NMFS, primarily from fishermen and fish processors in Alaska, British Columbia, and on the West Coast. Early in the reward program, $2.00 rewards were paid for all tags returned. As of January 1986, the reward was increased to $5.00 for tag returns with good recovery information and in 1991 a hat reward became an option. A description of the international tagging program and the Alaska Fisheries Science Center sablefish tag release and recovery files used in our analyses can be found in Fujioka at al. (1988).

Results

The general movement patterns of tagged sablefish recovered at various seamounts are shown in Figures 2 and 3, and individual fish data are provided in Table 2. Sablefish bearing Canadian tags have been recovered on Gulf of Alaska seamounts but are not included in this report.

Four tagged sablefish were recovered on the Brown Bear Seamount between 1990 and 1992. Two of these fish had been tagged in the Bering Sea, one each in 1984 and 1988, more than 2,850 km[3] from the recovery site. The third fish, recovered in 1991, had been tagged and released in the central Gulf of Alaska in 1983, a distance of 1,885 km. The fourth sablefish, recovered in 1992, had been released in Puget Sound in 1973, 615 km distant (Fig. 2, Table 2).

Four tagged sablefish were recovered on the Cobb Seamount by trap fishermen. Two recoveries were from fish tagged and released off the Washington coast between 1980 and 1981. A third fish, tagged off northern California, was recovered 907 km from the tagging site in 1991. The fourth sablefish, tagged in 1980 and recovered in 1992, was recovered 589 km from its southern Oregon tagging site (Fig. 2, Table 2).

Both of the tagged sablefish recovered on the Warwick Seamount in 1992 had been tagged and released 5 years earlier, one near the Aleutian Islands, a distance of 2,676 km, and the other off the northern Washington coast 560 km to the east.

The tagged sablefish recovered on the Eickelberg Seamount in 1992 had been tagged and released 8 years earlier near the western Aleutian Islands, 3,510 km away.

Four tagged sablefish were recovered on the Union Seamount by trap fishermen. Of these, one fish had been released in 1978 south of Unimak Pass (2,258 km); the second had been released in 1981 south of the Shumagin Islands (1,895 km); the third had been released in 1982 south of Kodiak Island (1,559 km); and the fourth had been released in 1987 off southeast Alaska (665 km) (Fig. 2, Table 2).

One tagged sablefish was recovered on the Dellwood Seamount in 1990. This fish had been tagged and released in 1985 near the western Aleutian Islands and had moved the greatest distance (3,611 km) of any of the seamount tag recoveries.

A sablefish tagged in the central Bering Sea in 1986 was later recovered on the Dickens Seamount in 1991, a displacement distance of 2,315 km.

Sasaki[4] reported the recovery of a tagged sablefish from the Pratt Seamount that had been tagged a year earlier at a longline station on the slope south of Unimak Pass. This fish had moved a distance of 1,461 km.

The single tagged sablefish recovered by a longline vessel on the Surveyor Seamount in 1992 had been tagged and released 2,079 km away, in the western Aleutian Islands, in 1987 (Fig. 2, Table 2).

A single tagged sablefish recovered on the Murray Seamount in 1992 had been tagged and released southeast of Kodiak Island in 1981, a distance of 391 km.

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[3] All distances referred to herein are great circle distances, defined as the length of the shorter arc of the great circle of the earch joining the release and recovery sites.

[4] Sasaki, T. 1980. An interim report on U.S.-Japan blackcod tagging experiments conducted in the Aleutian region and Gulf of Alaska in 1978 and 1979. Far Seas Fish. Res. Lab., Jpn. Fish. Agency, Shimizu, 13 p. [In Jpn.].

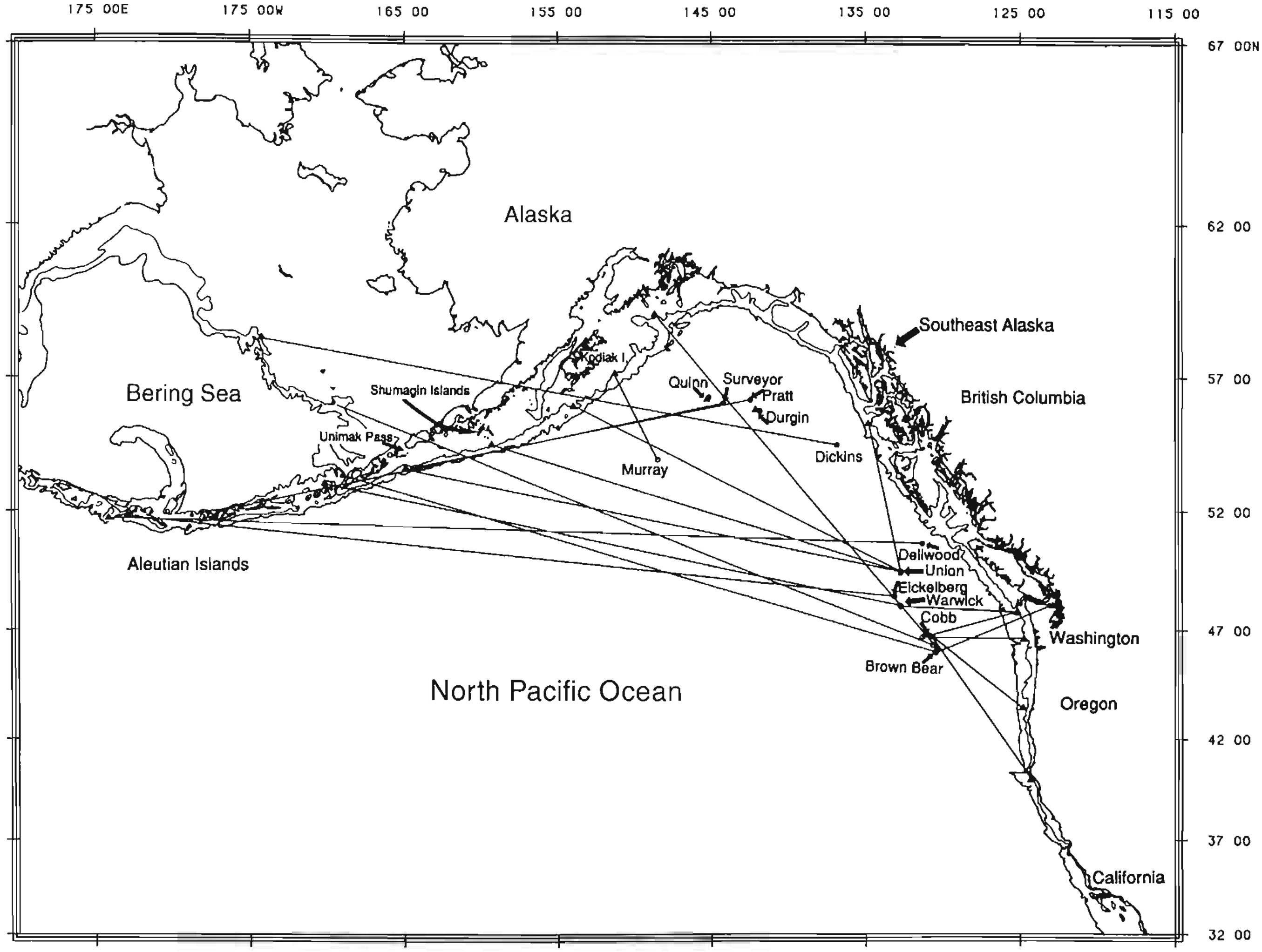

Figure 2

Movement patterns of tagged sablefish recovered on seamounts in the northeastern Pacific Ocean and Gulf of Alaska. ▲ indicates a release site. All movements are toward the seamounts.

A total of 70 tagged sablefish have been recovered from the Bowie Seamount (*n*=68) and nearby Hodgkins Seamount (*n*=2), the majority of which were recovered in 1990 (*n*=19), 1991 (*n*=20), and 1992 (*n*=12). Approximately one-half of these fish had been released off southeast Alaska, one had been tagged off southern Washington, and one off central California, with the remainder coming from the Gulf of Alaska, Bering Sea, and Aleutian Islands (Fig. 3, Table 2). For many of these sablefish, their release location in the Bering Sea and Aleutian Islands was 2,000–3,197 km from the Bowie Seamount. Two of these tagged sablefish had been at liberty for 17 and 19 years.

In 1979, NMFS captured and tagged 99 sablefish on Gulf of Alaska seamounts (Alton, 1986). None of these fish were recovered away from the seamounts. Of the 30 sablefish tagged on the Durgin Seamount, only three have been recovered. Two of the recoveries had been at large only 31 and 89 days; the third fish was captured 425 days after being released (Table 2). All three were caught by Japanese commercial longline vessels. Alton (1986) speculated that the high rate of tag recoveries (10%) and the presumed limited fishing effort expended to recover these fish suggests a small and localized population on the Durgin Seamount.

The two tagged sablefish recovered on the Quinn Seamount in 1986 had been released on the same seamount 7 years earlier. Both these fish were recaptured on the same day by a U.S. longline vessel within 7 km of their release location (Table 2).

Discussion

Alton (1986) hypothesized that sablefish populations on the seamounts are not self-contained and are dependent on continued immigration of adults from the con-

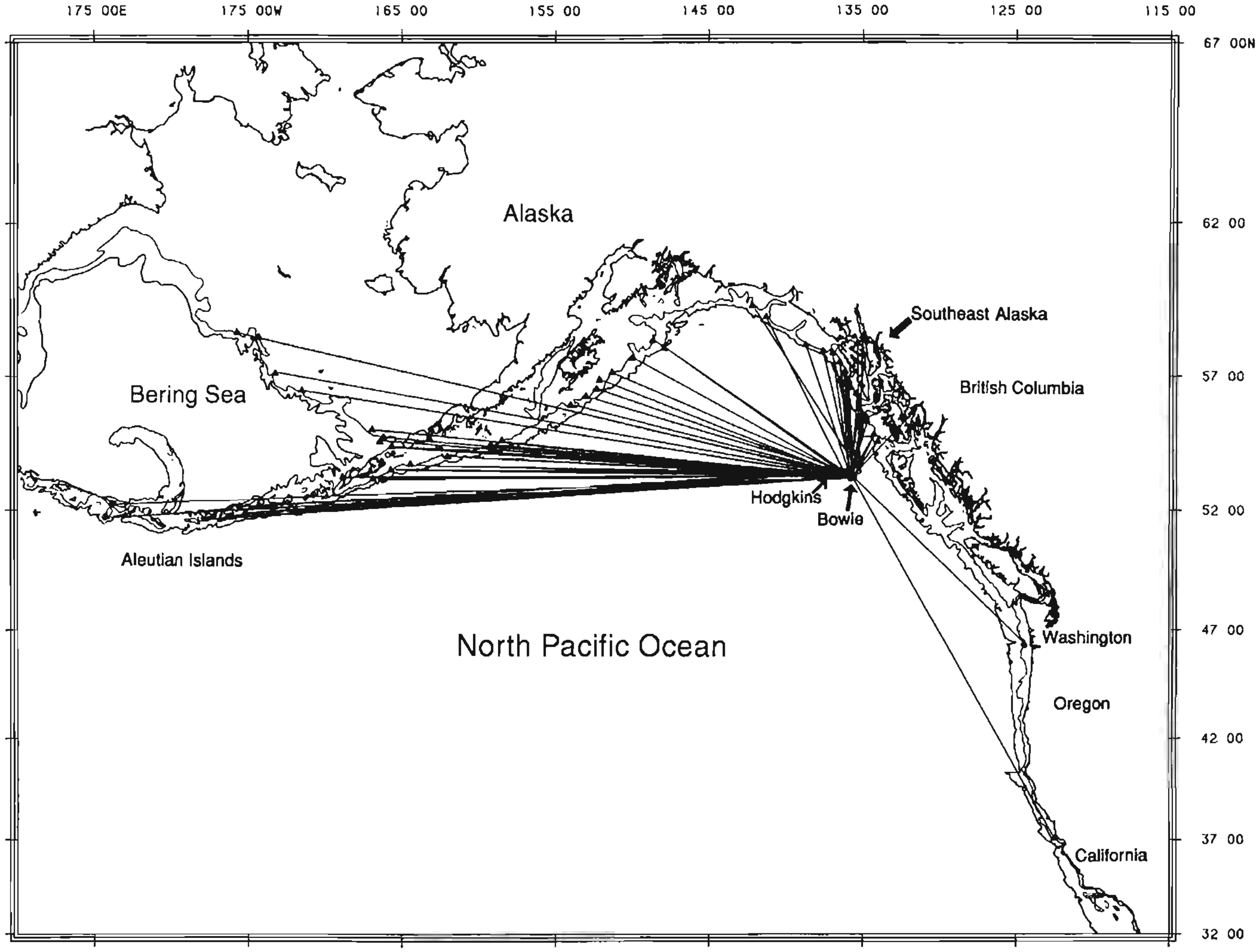

Figure 3
Movement patterns of tagged sablefish recovered on Bowie and Hodgkins seamounts in the northeastern Pacific Ocean. ▲ indicates a release site. All movements are toward the seamounts.

tinental slope. Since Beamish et al. (1979) reported catching moderate numbers of sablefish (3.6 per trap per 24 hours) off British Columbia in 1977 as deep as 2,740 m, we can conclude that this species is conceivably capable of traveling at great depths en route to offshore seamounts. Birkeland (1971), after scuba diving on the Cobb Seamount, noted that species with planktonic larvae (like sablefish) "seem to be characterized by successful recruitment" in the seamount habitat. He suggested, however, that planktonic larvae would tend to be swept away from the seamounts. Immigration to the seamount may explain the successful recruitment that Birkeland observed. The absence of juvenile sablefish on the seamounts and the demonstrated ability of tagged adult sablefish to swim from the continental slope to the seamounts (this paper) lend support to this hypothesis.

Funk and Bracken (1984) determined from their tagging experiments in southeast Alaska that sablefish less than 60 cm tended to move north and west once they reached offshore waters, while fish 60 cm and greater moved southeastward into British Columbia waters. Bracken (1982) reanalyzed Japanese and NMFS tag recovery data and found similar trends in direction of movement by size. Our data supports Bracken's findings, as all but a few of the tagged recoveries made on the Bowie, Hodgkins, Union, Dellwood, and Eickelberg Seamounts were sablefish larger than 60 cm, and all of these fish moved eastward or southward from where they were released.

In another study (Fujioka et. al., 1988), sablefish in Alaskan waters were shown to move much more than West Coast sablefish. Tag recoveries made on the seamounts confirm this pattern. Of the 79 recoveries made

Table 2
Tagged sablefish recovered on seamounts.

Seamount	Release area[1]	Release year	Recovery year	Days free	Recovery size (mm)	Distance moved[2] (km)	Recovery depth (m)	Recovery gear[3]	Growth (mm)	Sex
Brown Bear	BS	1984	1990	2,179	700	2,885	732	Trap	150	F
	AI	1988	1991	1,028	672	2,852	719	Trap	32	M
	WG	1983	1991	2,781	765	1,885	1,143	Trap	195	F
	WA	1973	1992	7,028		615	770			
Cobb	WA	1980	1990	3,549	602	439	457	Trap	52	M
	WA	1981	1990	3,174	630	500	549	Trap	40	M
	OR	1980	1992	4,319	605	589	928	Trap	65	M
	CA	1988	1991	1,047	600	907	448	Trap	110	F
Warwick	AI	1987	1992	1,828	694	2,676	1,125	Trap	54	F
	WA	1987	1992	1,739	568	560	824	Trap	58	M
Eickelberg	AI	1994	1992	2,942	741	3,510	1,050	Trap	61	M
Union	AI	1978	1990	4,360	689	2,258	549	Trap	29	M
	WG	1981	1990	3,263	849	1,895	300	Trap	209	F
	WG	1982	1992	3,542	731	1,599	732	Trap	141	F
	EG	1987	1990	1,019	606	665	274	Trap	–14	M
Dellwood	AI	1985	1990	1,866	731	3,611	600	Trap	61	F
Bowie	BS	1983	1987	1,352	530	2,398		Trap		
	BS	1983	1990	2,519	632	1,989		Trap	82	M
	BS	1983	1990	2,528	610	2,035	666	Trap	50	M
	BS	1983	1990	2,539	702	1,998	666	Trap	62	F
	BS	1984	1990	2,182	650	2,524	576	Trap	120	M
	BS	1985	1989	1,465		2,287	613	Trap		
	BS	1985	1990	1,808	707	2,030	695	Trap	–43	F
	BS	1985	1991	2,144	659	2,528	249	Trap	49	F
	BS	1986	1991	1,840	670	1,985	680	Trap	130	F
	BS	1986	1992	2,185	744	2,450	262	Trap	174	F
	BS	1987	1991	1,440	682	2,041	225	Trap	82	M
	AI	1980	1992	4,399	681	2,717	769	Trap	191	M
	AI	1981	1990	3,246	779	1,978		Trap	159	F
	AI	1982	1991	3,407	660	2,635	977	Trap	60	M
	AI	1982	1992	3,684	815	2,541	824	Trap	165	F
	AI	1983	1991	2,967	640	2,819	750	Trap	70	M
	AI	1983	1992	3,230	631	3,197	686	Trap	61	M
	AI	1984	1988	1,475	621	1,952	686	Trap	21	M
	AI	1984	1990	2,220	685	3,234	775	Trap	65	M
	AI	1985	1988	1,118	695	2,648	713	Trap	–5	M
	AI	1986	1988	682		2,063		Trap		
	AI	1986	1988	801	596	1,983		Trap	–24	M
	AI	1986	1991	1,841	660	1,959	900	Trap	80	M
	AI	1987	1992	1,901	690	2,191	992	Trap	130	F
	AI	1988	1991	1,107	616	2,665	432	Trap	–4	M
	WG	1980	1990	3,615	700	1,213	755	Trap	170	F
	WG	1981	1989	2,903		1,541	640	Trap		
	WG	1982	1988	2,160	692	1,900	1052	Trap	122	F
	WG	1982	1990	2,861	607	1,891	755	Trap	37	M
	WG	1982	1991	3,169	684	1,728	400	Trap	154	F
	WG	1982	1991	3,198	667	1,509	768	Trap	107	M
	WG	1982	1991	3,248	591	1,502	432	Trap	61	M
	WG	1983	1990	2,471	774	1,109		Trap	204	F
	WG	1983	1991	2,887		1,120	701	Trap		

continued

Table 2 (continued)

Seamount	Release area[1]	Release year	Recovery year	Days free	Recovery size (mm)	Distance moved[2] (km)	Recovery depth (m)	Recovery gear[3]	Growth (mm)	Sex
Bowie	WG	1985	1991	2,076	684	1,169	499	Trap	114	F
	WG	1987	1989	670	559	1,007	741	Trap	–1	M
	WG	1987	1991	1,435	630	978	750	Trap	40	M
	WG	1988	1990	669	594	976	666	Trap	–6	M
	WG	1988	1992	1,429	608	1,082	769	Trap	18	M
	EG	1972	1991	7,119	639	380	933	Trap	59	M
	EG	1979	1987	2,757		376		Trap		F
	EG	1979	1991	4,346	680	524	576	Trap	130	M
	EG	1979	1991	4,390	680	289	439	Trap	50	M
	EG	1979	1992	4,652	901	259	1,190	Trap	131	F
	EG	1979	1992	4,719	717	419	915	Trap	77	M
	EG	1980	1990	3,623	663	515	741	Trap	123	F
	EG	1981	1989	2,871		211	607	Trap		
	EG	1981	1990	3,241	525	478	666	Trap	35	M
	EG	1981	1990	3,282	620	244		Trap	120	M
	EG	1982	1988	2,144	653	470	768	Trap	13	M
	EG	1982	1990	2,831		252	746	Trap		
	EG	1982	1991	3,168	679	398	229	Trap	149	M
	EG	1982	1991	3,253	690	343	490	Trap	110	M
	EG	1982	1992	3,547	698	202	1,061	Trap	68	M
	EG	1982	1992	3,574	626	246	741	Trap	136	M
	EG	1982	1992	3,595	643	441	805	Trap	43	M
	EG	1983	1989	2,242		563	759	Trap		
	EG	1986	1989	1,018	634	724	741	Trap	–26	M
	EG	1986	1989	1,069	604	550	631	Trap	–16	M
	EG	1986	1990	1,393	669	398	777	Trap	19	
	EG	1986	1990	1,454	556	504	695	Trap	–4	
	EG	1987	1987	726		520	494	Trap		
	EG	1987	1988	296	620	430	713	Trap	–20	M
	EG	1987	1988	303	570	256	704	Trap	–10	M
	EG	1988	1989	316		782	686	Trap		
	EG	1988	1990	633	560	570	713	Trap	0	
	WA	1983	1990	2,492	653	1,109	503	Trap	173	M
	CA	1974	1991	6,023	681	2,069	450	Trap	311	F
Hodgkins	AI	1983	1991	3,048	673	2,493	1,080	Trap	123	F
	AI	1985	1992	2,598	680	2,620	860	Trap	40	F
Dickins	BS	1986	1991	1,793		2,315				
Durgin	SM	1979	1979	31	630	2	660	LL	20	
	SM	1979	1980	425	602	2	741	LL	–18	
	SM	1979	1979	89		0	680	LL		
Pratt	AI	1978	1979	374	640	1,461		LL	20	F
Surveyor	AI	1987	1992	1,835		2,079	549	LL		
Quinn	SM	1979	1986	2,553		7		LL		
	SM	1979	1986	2,553		7		LL		
Murray	WG	1981	1992	4,001	652	391	880	Trap	122	F

[1] AI = Aleutian Island; BS = Bering Sea; CA = California; EG = Eastern Gulf of Alaska; SM = seamount; WA = Washington; WG = Western Gulf of Alaska.

[2] Distances are great circle route distances between release and recovery sites.

[3] LL = Longline gear.

at Alaskan seamounts (north of 52% latitude), 77 had been released in Alaskan waters; of the 16 recoveries made at West Coast seamounts (south of 52° latitude), 10 had been released in Alaskan waters.

On the Bowie Seamount, where all the recoveries were by trap (Table 2), 68% of the sablefish longer than 60 cm FL were identified as males, in contrast to catches off Washington, Oregon, and California, where trap-caught sablefish longer than 60 cm FL were predominantly females.

Since few, if any, of the sablefish captured on the seamounts were small enough to be considered immature (Hughes, 1981), we believe there is little evidence of recruitment to the seamount sablefish populations from eggs produced by fish living there. Our study supports Alton's (1986) conclusion that sablefish inhabiting the summits of Gulf of Alaska seamounts are mature fish whose populations are maintained by fish moving from the slope region of the continental shelf. We found that relatively large numbers of tagged sablefish released on the continental shelf and slope are recovered on seamounts.

A factor not evaluated in our research was possible enhancement of resident recruitment by oceanographic conditions. An alternate hypothesis is that a seamount population is maintained by recruitment from the population itself. In many studies (Owens and Hogg, 1980; Perissinotto and Duncombe Rae, 1990; Dower et al., 1992), Taylor columns have been shown to exist over seamounts. These are oceanographic features that enhance primary production over seamounts by a combination of upwelling of deeper nutrient-rich water and entrapment into a localized area. The same processes that entrap and concentrate primary production over the seamount also entrap sablefish spawning products and larvae, enhancing the ability of resident sablefish to maintain populations on the seamounts. However, our research was not designed to monitor the possible effects of Taylor columns on larval recruitment.

Additional research would be helpful to verify the origin of sablefish populations on seamounts. Ichthyoplankton studies on seamounts would help determine whether sablefish larvae are spawned on and recruit to the seamounts. A survey designed to study juvenile sablefish populations on seamounts and to examine emigration away from seamounts by tagging sablefish in seamount populations would add to our understanding of the origins of these populations.

Literature Cited

Alton, Miles S.
1986. Fish and crab populations of Gulf of Alaska seamounts. *In* Richard N. Uchida, Sigeiti Hayasi, and George W. Boehlert (eds.), Environment and resources of seamounts in the North Pacific, p. 45–51. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 43.

Beamish, R. J., C. Houle, C. Wood, and R. Scarsbrook.
1979. A summary of sablefish tagging and exploratory trapping studies conducted during 1978 by the Pacific Biological Station. Can. Dep. Fish. Ocean. Data Rep. 162, 113 p.

Birkeland, Charles.
1971. Biological observations on Cobb Seamount. Northwest Sci. 45:193–199.

Bracken, B.E.
1982. Sablefish (*Anoplopoma fimbria*) migration in the Gulf of Alaska based on gulf-wide tag recoveries, 1973–1981. Alaska Dep. Fish Game Inf. Leafl. 199, 24 p.

Dower, J., H. Freeland, and K. Juniper.
1992. A strong biological response to oceanic flow past Cobb Seamount. Deep-Sea Res. 39:1139–1145.

Fujioka, J. T., F. R. Shaw, G. A. McFarlane, T. Sasaki, and B. E. Bracken.
1988. Description and summary of the Canadian, Japanese, and U.S. joint data base of sablefish tag releases and recoveries during 1977–83. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-137, 34 p.

Funk, F., and B. E. Bracken.
1984. Status of the Gulf of Alaska sablefish (*Anoplopoma fimbria*) resource in 1983. Alaska Dep. Fish Game Inf. Leafl. 235, 55 p.

Holmberg, E. K., and W. G. Jones.
1954. Results of sablefish tagging experiments in Washington, Oregon, and California. Pac. Mar. Fish. Comm. Bull. 3:103–119.

Hughes, S. E.
1981. Initial U.S. exploration of nine Gulf of Alaska seamounts and their associated fish and shellfish resources. Mar. Fish. Rev. 42(1):26–33.

Owens, W. B., and N. G. Hogg.
1980. Oceanic observations of stratified Taylor columns near a bump. Deep-Sea Res. 27:1029–1045.

Parks, N. B., and F. R. Shaw.
1990. Changes in relative abundance and size composition of sablefish in coastal waters of Washington and Oregon, 1979–89. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-188, 38 p.
1994. Relative abundance and size composition of sablefish (*Anoplopoma fimbria*) in the coastal waters of California and southern Oregon, 1984–1991. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-35, 38 p.

Perissinotto, R., and C. M. Duncombe Rae.
1990. Occurrence of anticyclonic eddies on the Prince Edward Plateau (Southern Ocean): effects on phytoplankton biomass and production. Deep-Sea Res. 37:777–793.

Wespestad, V. G., K. Thorson, and S. A. Mizroch.
1983. Movement of sablefish, *Anoplopoma fimbria*, in the northeastern Pacific Ocean as determined by tagging experiments (1971–80). Fish. Bull. 81:415–420.

Methods Used in the Determination of Acceptable Biological Catch for Alaskan Sablefish, *Anoplopoma fimbria*

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ABSTRACT

Sablefish off Alaska are managed by the North Pacific Fishery Management Council in three regions: the Gulf of Alaska, the Bering Sea, and the Aleutian Islands. Annual longline surveys of each area provide estimates of relative abundance which form the basis of the stock assessment. Survey abundances are incorporated into a single-stock, biomass-based model which estimates recruitment and projects future abundance. In the process, relative abundance estimates are converted to the absolute estimates ultimately required for catch recommendations. In addition to absolute biomass estimation, the appropriate fishing mortality rate applied to biomass forms the other key component of the acceptable biological catch (ABC) recommendation provided to fisheries managers. A variable exploitation-rate strategy is used for Alaskan sablefish. Under this approach, the fishing rate varies from zero to $F_{35\%}$ as current exploitable biomass varies from zero to a target level denoted $B_{35\%}$. Alternative methodologies being explored assume survey measurement error, use prior observations in determining current biomass, estimate absolute biomass independent of trawl survey biomass estimates, and are explicitly age-structured. This paper presents an overview of the stock assessment process leading to the ABC calculation, and discusses variability and uncertainty in the data and model assumptions in the framework of areas for future research.

Introduction

The distribution of sablefish, *Anoplopoma fimbria*, in North American waters ranges from northern Mexico through the Gulf of Alaska and along the Aleutian Islands chain and the edge of the continental slope in the eastern Bering Sea. Its range continues off the Siberian and Kamchatkan coasts of Russia to the northeastern coast of Japan. The sablefish resource is managed by discrete regions to distribute exploitation throughout its wide geographical range. There are two management areas in the Bering Sea/Aleutian Islands region: the eastern Bering Sea and the Aleutian Islands (Fig. 1). The Gulf of Alaska region is managed by Western, Central, and Eastern regulatory areas.

Catch History

The sablefish resource has been harvested by U.S. and Canadian fishermen since the early 1900's. Catches were relatively small and generally limited to areas near

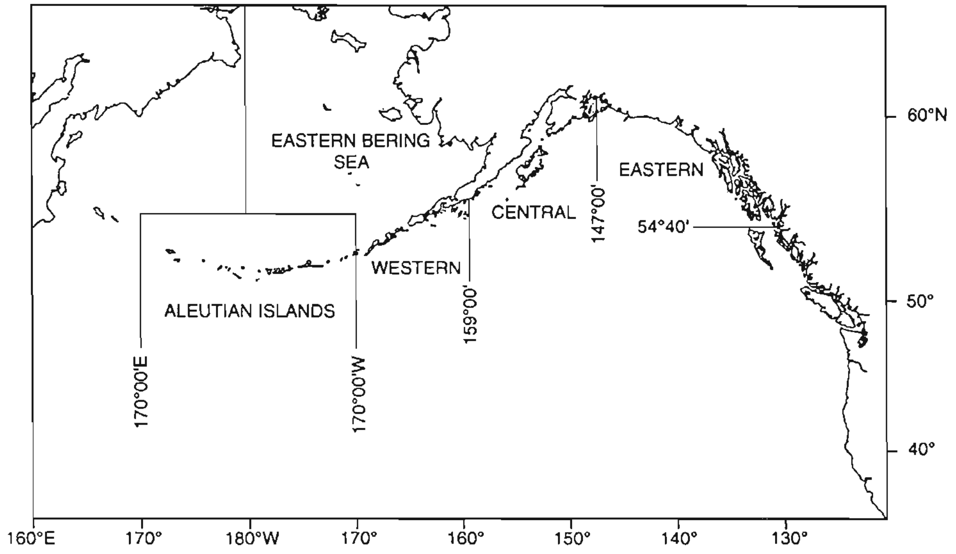

Figure 1
The northeast Pacific Ocean, showing sablefish management areas of the North Pacific Fishery Management Council.

fishing ports from California to southeast Alaska until Japanese longliners began operations in the eastern Bering Sea in 1958. The fishery rapidly expanded in this area, and catches peaked at about 26,000 metric tons (t) in 1962 (Table 1). As the fishing grounds in the eastern Bering Sea became dominated by expanding Japanese trawl fisheries, the longline fleet shifted to the Aleutian Islands and Gulf of Alaska. Catches in the Aleutian Islands region have been historically low. Aleutian Islands catches peaked at about 3,500 t in 1972 and at 3,800 t in 1987 (Table 1).

In the Gulf of Alaska, sablefish catches rapidly escalated during the mid-1960's after the Japanese longline fishery expanded into that area, and peaked at an all-nation catch of 37,500 t in 1972 (Table 1). Sablefish catches in the Gulf of Alaska declined to an average of about 28,000 t from 1973 to 1976. From 1974 through 1976 the Republic of Korea fishery, which was also developing in the Gulf of Alaska, harvested an average of about 3,000 t. Domestic harvests averaged about 1,300 t from 1973 through 1976.

The enactment of the Magnuson Fishery Conservation and Management Act led to significant restrictions on foreign fisheries beginning in 1977. This resulted in substantially reduced sablefish catches in all Alaskan waters (Table 1). In the Gulf of Alaska, declining stock abundance led to significant fishery restrictions from 1977 to 1985, and catches declined accordingly. Catches in the Gulf of Alaska from 1978 to 1983 averaged 9,000 t, then increased rapidly to about 30,000 t in 1988 due to exceptional recruitment, and slowly declined to about 23,000 t in 1994.

Catches in the eastern Bering Sea have remained relatively stable since 1977, reaching a peak of about 4,200 t in 1987; catches have since declined because of reduced stock levels and resultant lower annual fishing quotas. Catches in the Aleutian Islands region decreased after 1977, increased beginning in 1981 to an all-time high of 3,834 t in 1987, and subsequently declined to 1,546 t in 1992.

Resource Assessment Surveys

Japan–U.S. Cooperative Longline Survey

Japan and the United States conducted cooperative longline surveys in the Gulf of Alaska annually from 1978 to 1994 (the last year of operation). The survey was expanded to include the Aleutian Islands region in 1980 and the eastern Bering Sea in 1982. The main objectives of the survey were to determine the relative abundance and distribution of sablefish; Pacific cod, *Gadus macrocephalus*; and other groundfish taken with longline gear in the 101–1,000-m depth range.

Catches in numbers and weight, length frequencies, and sex determinations were recorded. Biological samples including extensive collections of sablefish otoliths for age determination were taken each year. Sablefish were tagged each year during the survey to determine migration patterns and rates of movement between management areas. Each year approximately 108 longline stations were surveyed: 34 stations in the eastern Bering Sea, 27 in the Aleutian Islands, and 47 in the Gulf of Alaska regions (Fig. 2). Station locations were explicitly specified, and an attempt was made to conduct the survey each year at the same stations. Some stations were shifted slightly to avoid gear conflicts with commercial vessels or because of weather or currents.

The catch data collected during the surveys are used to compute catch per unit of effort (CPUE) in numbers and kilograms of fish per skate of gear. These catch rates are then used to compute indices of population abundance: CPUE data are multiplied by the respective area of each depth stratum to obtain an index of relative population number (RPN) and an index of relative population weight (RPW). Precision of the survey indices is quite good: in the Gulf of Alaska, the standard error has been estimated at about 5% of the mean index (Sigler and Fujioka, 1988). Also, the effects of gear saturation on the survey longline catch rates have been found to be negligible over the range of observed catch rates (Sigler, 1993).

Relative population weights for the slope (201–1,000 m) increased through 1984 in response to a strong year class, and have since declined due to a lack of significant recruitment (Table 2).

Domestic Longline Survey

Since 1987 the Alaska Fisheries Science Center (AFSC) has conducted an annual longline survey (referred to as the domestic longline survey) designed to continue the time series of the Gulf of Alaska portion of the Japan–U.S. cooperative survey. The Japan–U.S. survey was discontinued after 1994. The AFSC's survey methods are similar to those of the Japan–U.S. survey; locations and methodology are described in Zenger (1997). In addition to sampling the continental slope habitat, the domestic survey also samples the major gully areas of the Gulf of Alaska. The domestic survey is being restructured to include the eastern Bering Sea and Aleutian Islands regions.

Relative population weights obtained by the two surveys in the Gulf of Alaska for depths 201–1,000 m show diverging trends in 1990 and 1992 (Fig. 3). The divergence in 1990 is attributed to gear differences, whereas in 1992 it seems to be caused by a lack of large fish in the domestic survey catch.[1] Work is under way to analyze and compare the performance of the two surveys and standardize the cooperative survey indices to the domestic survey indices (Kimura and Zenger[2]).

Table 1

Annual catches (t) of sablefish in the eastern Bering Sea (EBS), Aleutian Islands (AI), and Gulf of Alaska (GOA), 1956 to 1994.

Year	EBS	AI	GOA	Total
1956	—	—	1,391	1,391
1957	—	—	2,759	2,759
1958	6	—	797	803
1959	289	—	1,101	1,390
1960	1,861	—	2,142	4,003
1961	15,627	—	897	16,524
1962	25,989	—	731	26,720
1963	13,706	664	2,809	17,179
1964	3,545	1,541	2,457	7,543
1965	4,838	1,249	3,458	9,545
1966	9,505	1,341	5,178	16,024
1967	11,698	1,652	6,143	19,493
1968	14,374	1,673	15,049	31,096
1969	16,009	1,673	19,376	37,058
1970	11,737	1,248	25,145	38,130
1971	15,106	2,936	25,630	43,672
1972	12,758	3,531	37,502	53,791
1973	5,957	2,902	28,693	37,552
1974	4,258	2,477	28,335	35,070
1975	2,766	1,747	26,095	30,608
1976	2,923	1,659	27,733	32,315
1977	2,718	1,897	17,140	21,755
1978	1,192	821	8,886	10,899
1979	1,376	782	10,350	12,508
1980	2,206	274	8,542	11,022
1981	2,604	533	9,917	13,054
1982	3,211	927	8,556	12,694
1983	2,737	644	9,002	12,383
1984	2,327	998	10,230	13,555
1985	2,348	1,448	12,479	16,275
1986	3,518	3,028	21,614	28,160
1987	4,178	3,834	26,325	34,337
1988	3,193	3,415	29,903	36,511
1989	1,252	3,248	29,842	34,342
1990	2,255	2,206	26,600	31,061
1991	1,200	2,249	23,134	26,583
1992	558	1,546	23,376	25,480
1993	669	2,077	22,394	25,480
1994	699	1,742	22,807	25,248

Absolute Abundance

While the longline surveys provide a means to track relative abundance trends, they do not provide the estimates of absolute biomass ultimately needed for catch recommendations. In Alaskan waters, trawl survey abundance estimates are presumed to provide abso-

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[1] Zenger, H. Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle WA 98115-0070. Personal commun.

[2] Kimura, D. K., and H. H. Zenger. Standardizing sablefish (*Anoplopoma fimbria*) longline indices using comparative fishing data and logistic transformation. Alaska Fish. Sci. Cent., NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070. Unpubl. manuscr.

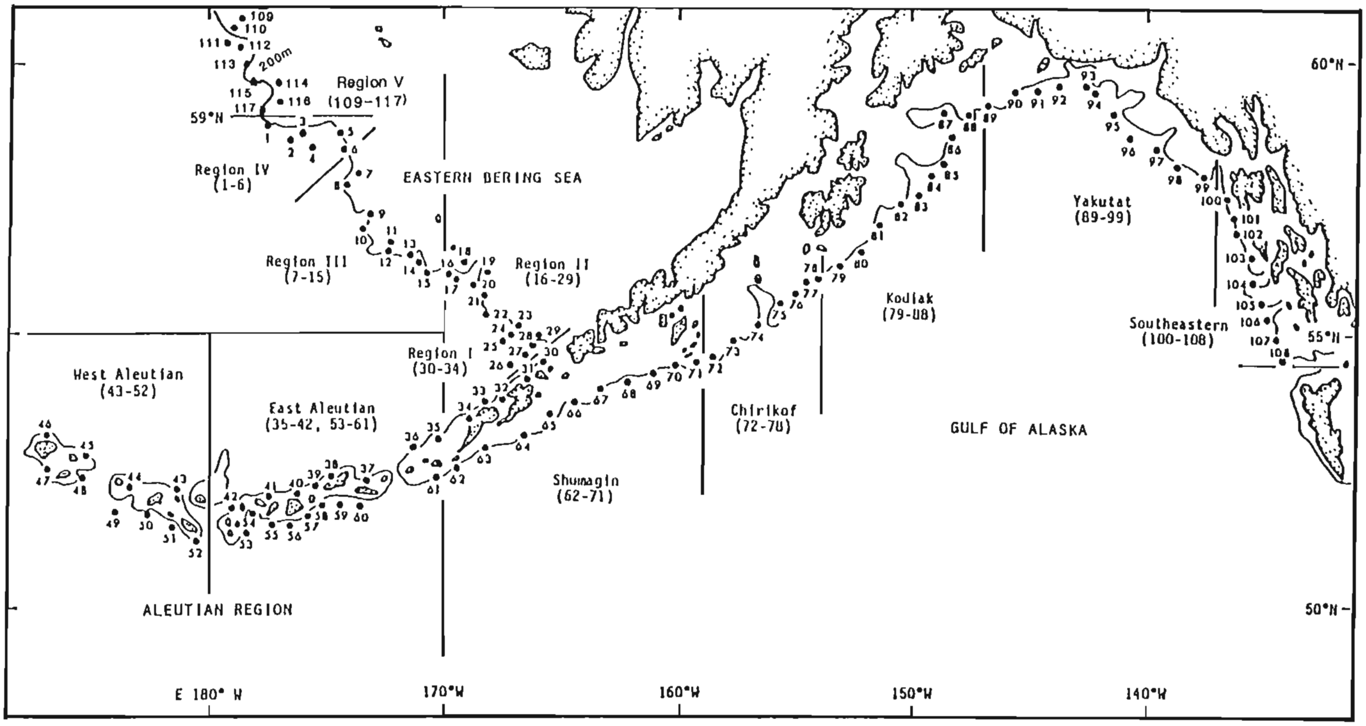

Figure 2
Station locations for the Japan–U.S. cooperative longline survey in the Gulf of Alaska, eastern Bering Sea, and Aleutian Islands.

lute estimates of biomass for groundfish species. Prior to 1990, estimates of sablefish exploitable biomass trends were obtained by scaling estimates of relative biomass indices from the longline survey (201–1,000-m RPW's) to estimates of absolute biomass (201–1,000-m) from trawl surveys conducted in the Gulf of Alaska, eastern Bering Sea, and Aleutian Islands regions. Because different net types were used in different areas and years, and because sampling variation was high, comparability between areas of the resulting estimates of exploitable biomass was questionable.

The best available data for determining an overall scaling factor until new models or methodologies can replace current methodology (which relies on abundance estimates from trawl surveys) is based on a comparative analysis of the 1984 trawl and longline surveys. The Japanese net used during the 1984 trawl survey appeared to be one of the most efficient, and coverage of the deeper depths was the most adequate of any survey. Rose (1986) provided size-specific ratios of trawl density estimates to longline survey CPUE. Applying these ratios to the longline index thus provides a method of estimating absolute biomass.

Current sablefish exploitable biomass has been computed since 1990 with the results obtained from Rose's (1986) study. Rose's (1986) size-specific trawl-to-longline CPUE ratios, applied to the size distribution estimated in the domestic longline survey (Zenger and Sigler, 1992), result in an average ratio of 141. Biomass in metric tons is estimated by multiplying the appropriate RPW by 0.141.

Stock Assessment Methodology

Stock Reduction Analysis

The stock assessment methodology currently applied to Alaskan sablefish utilizes a modification of the Schnute (1985) delay-difference equation in stock reduction

Table 2

Relative population weight indices from the Japan–U.S. cooperative longline surveys in the eastern Bering Sea (EBS), Aleutian Islands (AI), and Gulf of Alaska (GOA), 1979–94.

Year	EBS	AI	GOA
1979			651
1980		264	537
1981		264	671
1982	283	302	987
1983	321	359	953
1984	359	434	1,011
1985	547	566	1,456
1986	528	491	1,437
1987	208	491	1,370
1988	226	358	1,503
1989	345	476	1,356
1990	204	214	1,035
1991	93	203	1,025
1992	1,992	169	1,124
1993	34	177	1,106
1994	117	97	986

analysis (SRA; Kimura, 1985). The standard application of the delay-difference equation in SRA solves for biomass in year i (B_i) based on growth, survival, and recruitment parameters. This application was modified to track estimates of exploitable biomass (from the longline survey), and provide estimates of recruitment each year (R_i; Fujioka[3]). Thus the model assumes no survey measurement error and assigns all variability to recruitment variability.

The analysis assumes that all sources of population change can be accounted for by fishing, natural mortality, growth, and recruitment; however, the model occasionally computed negative recruitment when population decreases were greater than could be accounted for by natural mortality and reported catch. Estimated declines of such magnitude may result from unreported fishing mortality, underestimated natural mortality, an improper expansion of relative abundance to absolute abundance, random errors in relative abundance measurements, or emigration. Analysis of tag recovery data indicates that emigration is not insignificant. Fujioka et al. (1988) found that 25% of total tag recoveries occurred outside the area of release in the eastern Bering Sea, 67% in the Aleutian Islands, and 26% in the Gulf of Alaska region. Movement rates estimated by Heifetz and Fujioka (1991) indicate that each year 54% of large sablefish in the eastern Bering Sea and 30% of those in the Aleutian Islands regions move to the Gulf of Alaska.

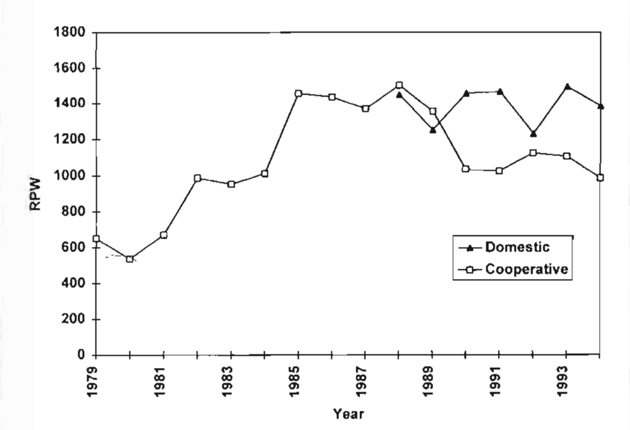

Figure 3

Relative population weights (RPW) from the Japan–U.S. cooperative and U.S. domestic longline surveys, 1979–94.

To alleviate some of the departures from the closed population assumption that occur in separate analyses, the Gulf of Alaska, eastern Bering Sea, and Aleutian Islands regions were combined into one model beginning with the 1990 ABC recommendation.

The analysis assumes a natural mortality rate (M) equal to 0.10; Kimura's (1985) parameterization of Schnute's (1985) growth parameters ρ equal to 0.882 and ω equal to 0.755; age at recruitment (K) equal to 5 years; and biomass equal to the RPW's scaled by 0.141 for all regions. This analysis was applied to the 1979–94 data (Fujioka[4]; Lowe[5]).

Recruitment Strengths and Relationships

Annual recruitment values $R(i)$ as estimated by the delay-difference equation varied greatly (including two years of negative recruitment despite the combined model) and averaged 34,000 t (Fig. 4). The recruitment time series is relatively short, and about one-third of the

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[3] Fujioka, J. T. 1989. Sablefish. *In* Stock assessment and fishery evaluation report for the 1990 Gulf of Alaska groundfish fishery. N. Pac. Fish. Manage. Council, P. O. Box 103136, Anchorage, AK 99510-2252.

[4] Fujioka, J. T. 1994. Sablefish. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1995. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510.

[5] Lowe, S. A. 1994. Sablefish. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions as projected for 1995. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510-2252.

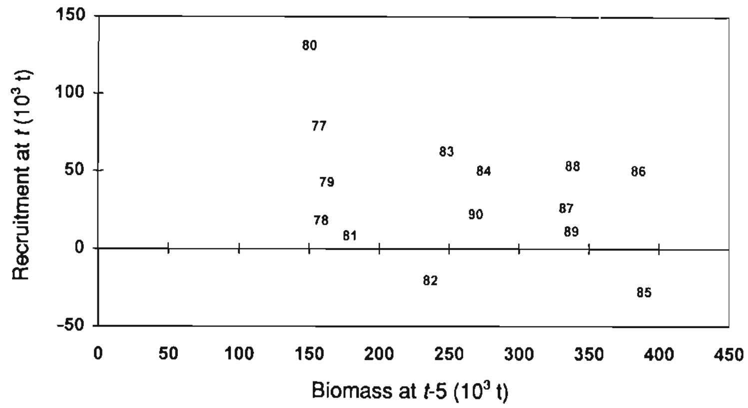

Figure 4
Estimated recruitment at time *t* plotted against stock biomass at time *t*–5 estimated by stock reduction analysis. Year classes are indicated.

(recruitment) data points are associated with stock biomass levels between 150,000 and 200,000 t.

Estimates of the two highest recruitments, in 1982 and 1985, correspond to the large 1977 and 1980 year classes observed during the juvenile stage. Although recruitment appears to decrease with biomass, a mechanism for such compensatory mortality has not been determined. The apparent trend (or lack of trend) is quite possibly a product of environmental factors (McFarlane and Beamish, 1992). Thus, while exceptionally large year classes are detectable during the juvenile stage prior to recruitment, sablefish recruitment is largely unpredictable.

Annual recruitment is a key variable needed to estimate the coming year's beginning biomass for the calculation of acceptable biological catch (ABC). Although the time series of estimated annual recruitment from the analysis includes two strong year classes (1977 and 1980), recent recruitment estimates have been variable but at a much lower level than the 1977 and 1980 year classes (Fig. 4). In the current model, biomass projections rely on an estimate of the average recruitment from the estimated time series, excluding recruitment from the 1977 and 1980 year classes. The 1995 biomass was estimated at 225,300 t for the Gulf of Alaska, eastern Bering Sea, and Aleutian Islands regions combined (Fig. 5).

To deal with the effect of stock-recruitment uncertainty on equilibrium yields and the fishing mortality rate associated with maximum sustainable yield (F_{MSY}), we have adopted exploitation strategies and fishing rate definitions that are considered robust over a range of groundfish spawner–recruit relationships and life-history parameters as an alternative to managing the population for maximum sustained yield (MSY) (Clark, 1991).

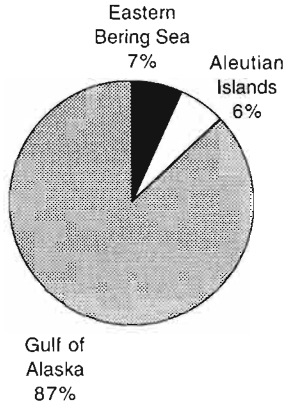

Figure 5
Sablefish exploitable biomass for 1995, by area, estimated by stock reduction analysis. Total estimated exploitable biomass for the combined areas is 225,300 t.

Fishing Rate and Biomass Reference Level

Previously, a constant exploitation rate associated with the fishing mortality rate equal to $F_{0.1}$ had been used for the ABC calculations. The $F_{0.1}$ policy is the fishing mortality rate that reduces the slope of the yield-per-recruit curve, as a function of fishing mortality, to 10% of its value at the origin (Gulland and Boerema, 1973). For an age of recruitment of 5 years, $F_{0.1}$ was estimated at 0.133 (exploitation rate=0.119).

Clark (1991) proposed two approaches to determining exploitation rates that provide a high yield at a low risk of overfishing when there is little knowledge of the yield curve (i.e., total yield as a function of fishing mortality) or the spawner–recruit relationship of the stock. One strategy is based on relative biomass, and the other is a fishing rate based on spawning biomass-per-recruit ratios. We use a combination of the two approaches in our ABC recommendations.

Clark (1991) showed that the fishing-rate strategy provided a sustainable yield nearly as high as the MSY, while maintaining the spawning biomass in the range of about 20%–60% of the unfished level for a stock with "typical groundfish" parameters. Based on Clark's (1991) analysis, the appropriate rate—denoted $F_{35\%}$—is the fishing mortality rate that when applied reduces the spawning biomass per recruit to 35% of the pristine level of spawning biomass per recruit. For sablefish, the $F_{35\%}$ fishing mortality rate is estimated to be 0.137 (exploitation rate = 0.122). This value is close to the $F_{0.1}$ value (0.133), but $F_{35\%}$ is preferable because it has the property of maintaining an appropriate level of spawning biomass per recruit.

Additionally, Clark (1991) demonstrated that even if the unfished spawning biomass was only a rough estimate, one could still obtain nearly the MSY by maintaining spawning biomass in the vicinity of 35%–40% of the estimated unfished level (denoted $B_{35\%}$). This relative biomass strategy was shown to be even more robust than the $F_{35\%}$ strategy (Clark, 1991). Unfished spawning biomass can be estimated by the product of the unfished spawning biomass-per-recruit value and the average estimates of recruitment. For sablefish, this results in a strategy of keeping biomass in the vicinity of 247,000 t for the combined regions.

Clark (1991) suggested that hybrid strategies could be developed to combine the advantages of the two above-mentioned approaches. Fujioka et al. (1997) show how one such hybrid strategy compared favorably to a constant exploitation strategy. Simulation models demonstrated that a variable-exploitation-rate policy was preferable to a constant-exploitation-rate policy in avoiding overfishing (Sigler and Fujioka, 1993; Fujioka[6]).

Alternative harvest strategies for sablefish were explored that accounted for uncertainty in recruitment and biomass estimates, and that determined the risk of the population falling below the lowest observed level. It was found that for a variety of recruitment scenarios, the risk that the sablefish population will fall below the lowest observed level is lessened in the long run by implementing a threshold or using a variable-exploitation-rate policy, with only modest decreases in average catch. A variable-exploitation-rate policy is preferable to a threshold policy, because adopting a threshold policy may require abrupt fishery closures if stocks fall below the threshold level, and because an appropriate threshold level is difficult to identify.

In addition, it seems reasonable that the current condition of the stock relative to a desirable level (or an undesirable level) should be a factor in determining the appropriate fishing rate. Employing a combination of the fishing rate and the $B_{35\%}$ relative reference point based on Clark's (1991) findings for typical groundfish, an adjustable fishing rate strategy is used in ABC recommendations for Alaskan sablefish management. Under this approach, the fishing rate can vary from zero to $F_{35\%}$ as current exploitable biomass varies from zero to $B_{35\%}$ (247,000 t). Annually, the current estimated exploitable biomass is evaluated relative to the reference level ($B_{35\%}$), and that proportion is applied to the $F_{35\%}$ rate to compute the recommended fishing mortality rate.

Although Clark's (1991) results are generalized for a wide range of groundfish life-history types and recruitment curves, Fujioka et al. (1997) showed that Clark's general results apply well to sablefish parameters as currently assumed.

The corresponding rate, equivalent to a 30% reduction in spawning stock biomass per recruit from pristine conditions ($F_{30\%}$), is $F = 0.166$. This value is currently used to compute the overfishing level for Alaskan sablefish.

Calculation of Acceptable Biological Catch

The ABC recommendations for Alaskan sablefish are computed by applying an exploitation rate to the estimated biomass projected by the SRA model. Thus the scaled absolute biomass estimates, the assumed biological parameters in the analysis, and the exploitation rate greatly affect the ABC estimation.

The recommended ABC for 1995 was obtained by first multiplying the $F_{35\%}$ fishing mortality rate (0.137) by the ratio of current biomass to $B_{35\%}$ ($B_{95}/B_{35\%} = 0.91$). This resulted in a fishing mortality rate of 0.125 with an associated exploitation rate of 0.12. This rate was applied to biomass projected to the beginning of 1995 using the combined Gulf of Alaska, eastern Bering Sea, and Aleutian Islands model, resulting in an ABC of 25,240 t for the combined regions.

Geographic Apportionment of Exploitation

Prior to the 1995 fishing season, annual sablefish quotas were apportioned to management areas approximately in proportion to the estimated relative abundance distribution from the most recent longline survey. With the implementation of area-specific individual transferable quotas (ITQ's) in 1995, the geographic apportionment of the quota will have greater implications for sablefish management and result in considerably more scrutiny of the areal apportionment recommendations.

Concerns about the optimal apportionment pattern for sablefish have been raised from a biological perspective as well. Heifetz et al. (1997) evaluated various spawning and recruitment conditions that determine an optimal allocation of the quota. Results indicated that in the absence of any strong areal differences in recruitment, growth, and survival, mixing rates are sufficiently high and exploitation rates sufficiently low that moderate variation in the biomass-based apportionment would not significantly change overall yield.

For the 1995 fishing season, a new apportionment scheme was presented; it used the current abundance distribution from the longline survey and the previous four years' distributions weighted approximately expo-

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[6] Fujioka, J. T. 1990. A comparison of five harvest policies applied to sablefish in Alaskan waters. Appendix III, Envir. assess./reg. impact report of amend. 21 to fish. mgmt. plan for groundfish of the Gulf of Alaska. Document submitted to the N. Pac. Fish. Manage. Council, Anchorage, AK. Available from the Alaska Fish. Sci. Cent., NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070.

nentially, with the highest weight given to the current year. The new method was recommended for apportionment among regions (eastern Bering Sea, Aleutian Islands, and Gulf of Alaska) and areas within the Gulf of Alaska. This approach is intended to provide consistency and to buffer rapid changes in apportionment due to annual variation in the estimated RPW distributions, but at the same time respond to changes in distribution.

The method of determining the weighting values for each year is derived from a simple Kalman filter model (Meinhold and Singpurwalla, 1983), which is dependent on the ratio of survey variability (measurement error) to total variability, including both measurement and process error. If survey variability is one-half of the total variability and the time series consists of five points, then the weighting is as follows :

Year	1	2	3	4	5
Weight	0.0625	0.0625	0.125	0.25	0.50

Discussion

Several of the key assumptions in the sablefish stock assessment that need futher research have been identified. Current research priorities focus on the procedure for estimating absolute biomass, improved model assumptions about error structure, and age-structured modeling. Assumptions in these areas directly and significantly affect the determination of ABC for Alaskan sablefish. Work is in progress to improve current methodologies and assumptions in these areas of stock assessment.

Surveys

The termination of the Japan–U.S. cooperative longline survey will affect our ability to adequately assess the stock and collect biological samples. The Gulf of Alaska will continue to be surveyed annually by the domestic survey, which has been in place since 1987, and the eastern Bering Sea and Aleutian Islands will be surveyed less than annually with an expanded domestic survey. Each year the cooperative survey also made extensive otolith collections and carried out large-scale tagging to determine migration patterns and movement rates. The loss of such data may be critical to sablefish assessment; the domestic survey shoud initiate biological collections and continue the tagging experiments.

Absolute Abundance

The scaling factor used to convert the relative indices of abundance to absolute estimates is at best a very rough estimate and dependent on trawl-survey estimates of biomass. There is a great deal of variability in the data available for computing trawl:longline catch ratios, which are then used to convert longline CPUE to absolute estimates of abundance. Sigler (1993) used an age-structured model along the lines of the stock synthesis model (Methot, 1990) to determine the types of information necessary for estimating absolute biomass. An estimate of biomass from a trawl survey was not necessary, but information on recruitment or selectivity was necessary to obtain relatively precise estimates of absolute biomass.

The current methodology for estimating absolute abundance assumes a catchability coefficient of 1.0 for trawl surveys. When this assumption is relaxed and additional information on selectivity or annual recruitment is used, alternative estimates of absolute biomass can be derived independent of trawl survey information. A second age-structured analysis (following Kimura, 1989, 1990) was completed to estimate values for absolute biomass from 1979–93 without using independent estimates of biomass from trawl surveys (Sigler, 1994). Pending review of this new methodology, the sablefish stock assessment will evolve to incorporate an age-structured model in the very near future.

Stock Assessment

The application of SRA as currently applied does not account for measurement error in the time series of survey and catch data. Nor is there an explicit recognition of process error. Estimates of abundance and recruitment thus assign all variability to recruitment. The current methodology also uses only the most recent survey results to estimate current abundance, ignoring prior observations. As pointed out by Pella,[7] failing to consider within-survey variability and annual changes in availability as well as measurement error in catch, biomass, and life-history-parameter estimates can lead to erroneous model results, such as negative estimates of recruitment.

Recently, the delay-difference equation has been applied to sablefish in two cases, addressing some of these shortcomings. Pella[7] used the Kalman filter to account for survey measurement error and recruitment variability in computing conditional estimates of annual abundance. New estimates of parameters of interest that are considered constant in the current assessment can be made, and the computations can be repeated until maximum likelihood estimates are obtained. One pa-

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[7] Pella, J. J. 1994. Kalman filtering of sablefish biomass indices via the Deriso equation: methodology and software. Alaska Fish. Sci. Cent., Auke Bay Laboratory, 11305 Glacier Highway, Juneau, AK 99801. Unpubl. manuscr.

rameter of interest, which relates the survey index to absolute abundance, suggests a much lower biomass than currently assumed. The range of estimated annual recruitment also does not reflect the relative magnitude of large year classes that are believed to have occurred. A second application by Kimura et al.,[8] also using the Kalman filter with the delay-difference equation, produced similar results. Work continues in these areas.

Key life-history parameters in the stock assessment which directly affect the ABC calculation include estimates of natural mortality rate, growth rates, and age-specific schedules of recruitment. The current assumed rate of natural mortality (0.1) is an average rate computed by the Alverson-Carney procedure using a range of maximum ages, and length-frequency mode separation techniques that tracked the strong 1977 year class (Funk and Bracken, 1984). Early catch-at-age work by Johnson and Quinn (1988), which used values of 0.1 and 0.2, found that a value of 0.1 provided better fits to survey data. However, it is also noted, on the basis of West Coast sablefish work (Methot et al.[9]), that the value may be lower than 0.1. Clark (1991) showed that although the optimal relative biomass ($B_{35\%}$) is quite robust, and the desired spawning biomass-per-recruit ratio for determining an appropriate fishing rate ($F_{35\%}$) is fairly robust, the actual fishing rate is quite sensitive to changes in M. For example, if $M = 0.20$ was used in the assessment, $F_{35\%}$ would increase approximately twofold from 0.14 to 0.28. Although assuming a value of 0.1 is reasonable, an updated evaluation and sensitivity analysis of the estimate is needed. Independent estimates of natural mortality are preferable to estimates from an age-structured model.

Work in the areas of age and growth is actively being pursued. Adult sablefish from Chatham Strait, Alaska, were tagged and injected with oxytetracycline for age validation. Otoliths from these fish have been collected and are awaiting analysis. Sablefish tagged as juveniles (ages 0–2) during 1984–91 throughout southeast Alaska and recovered during 1988–93 were used to examine ageing methods for sablefish. Otoliths from 52 of these fish have been aged; preliminary results show that the current sablefish ageing criteria are generally correct. Sablefish otoliths were also collected periodically from 500 fish from 1986 to 1992 during 8 months of the year. This collection was used to study otolith edge-type development to determine the time of year of annular deposition.

Recruitment

Determining the age-specific schedule of recruitment (selection) is a key input to the modeling process. The current methodology (SRA) assumes knife-edge recruitment at age 5. Clearly this is a simplifying assumption, and more realistic recruitment-at-age schedules hypothesized for the longline survey have been used in the age-structured models (Sigler[10]). Since fishery and longline survey gear selectivities are assumed to be equal, recruitment to the fishery and to the longline survey is assumed to be identical. However, independent estimates of the recruitment (selection) schedule for the fishery based on recoveries of fish tagged as juveniles showed recruitment at younger ages than presumed in the stock assessment models. These results are very preliminary, because the data used for estimation fully covered only two cohorts. Age at recruitment is a critical parameter in the stock assessment, and more data must be collected and evaluated.

Uncertainty about a recruitment relationship (or lack thereof) directly affects the ABC recommendation in at least three ways. Estimates of equilibrium yield and F_{MSY} are highly sensitive to the assumed spawner–recruit relationship; estimates of reference points that are percentages of unfished biomass (e.g., $B_{35\%}$) often assume some level of average long-term recruitment; and projections of biomass to the next fishing year are dependent on predicted annual recruitment levels. At this time uncertainty about the spawner–recruit relationship is somewhat compensated for by a robust harvest strategy. However, in order to progress toward predicting recruitment, research must first focus on egg and larval studies to determine spawning distributions in time and space. Presently we know general months and areas where sablefish larvae can be located, but large-scale egg and larval studies are needed to determine areas of successful spawning and recruitment. Incorporating uncertainty about recruitment is discussed below in the context of determining optimal exploitation rates.

The geographic distribution of recruitment may have important implications for sablefish management. If effective spawning distribution and levels of recruitment contributed by different areas can be determined, optimal exploitation strategies could be developed. It is unclear whether our current assumption that the stock actually benefits from uniform exploitation over areas is correct.

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[8] Kimura, D. K., J. W. Balsiger, and D. H. Ito. Kalman filtering the delay-difference equation: practical approaches and simulations. Alaska Fish. Sci. Cent., NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070. Unpubl. manuscr.

[9] Methot, R., R. Lauth, F. Shaw, and M. Wilkins. 1994. Assessment of the west coast sablefish stock in 1994. *In* Status of the Pacific Coast groundfish fishery through 1994 and recommended acceptable biological catches for 1995. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 SW First Ave., Portland, OR 97201.

[10] Sigler, M. F. 1994. An age-structured model of sablefish recruitment and biomass in Alaska, Appendix E. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1995. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99501-2252.

Fishing Rate and Biomass Reference Level

The current fishing rate for sablefish ($F_{35\%}$) is the fishing mortality rate that, when applied, reduces the spawning biomass per recruit to 35% of the unfished level. This rate, based solely on life-history parameters, is a surrogate for MSY, which is determined by density-dependent mechanisms rarely known. It is based on deterministic computations with a range of life-history parameters and spawner–recruit curves (Clark, 1991). In an updated analysis using stochastic trials, Clark (1993) found that random variation in recruitment resulted in slightly higher target levels of spawning biomass per recruit, and more so if recruitment deviations had a high serial correlation. For the levels of recruitment variability considered by Clark (1993), which are in the realm of those observed for Alaskan groundfish stocks, it appeared that optimal target levels of spawning biomass per recruit are clustered around 40%, as compared to the deterministic computations, which were clustered around 35%. Although Fujioka et al. (1997) showed that Clark's general deterministic results applied well to sablefish parameters, consideration of recruitment variability could suggest different fishing rates, as shown by Clark (1993). Exploration of how recruitment variation affects the determination of a fishing rate is an important next step.

Rivard and Maguire (1993) recommend models that analyze risk to account for uncertainties in the stock assessment as well as variability in recruitment. Along these lines, Lowe and Thompson (1993), Shelton et al. (1993), and Hollowed and Megrey (1993) evaluated harvest strategies, given recruitment stochasticity and uncertainty in the measurement of stock abundance, by simulating the dynamics of the stock and the assessment process upon which the harvest recommendations are made—i.e., by modeling both the true and the perceived populations. Sigler and Fujioka (1993) compared alternative harvest policies to the constant exploitation policy previously used for sablefish. Their risk criterion was defined as the lowest spawning biomass observed. The simulations included both survey measurement error and stochastic variable recruitment. An expansion of this type of modeling along the lines of the risk analyses described above would be useful for evaluating various objective functions and determining optimal fishing mortality rates.

Geographic Apportionment

Current recommendations for apportionment of the sablefish harvest use a simple Kalman filter model based on an assumption regarding the proportion of survey variability (measurement error) relative to total (system) variability. Research is needed to more precisely define the error structure and incorporate it in the stock assessment. Simulations and sensitivity analyses of assumptions about the error structure will not only allow us to refine the apportionment scheme, but will improve our estimates of absolute abundance and the fishing mortality rate, thereby directly affecting harvest recommendations.

The AFSC's Sablefish Working Group has formulated a Sablefish Research Plan to improve the Center's sablefish management recommendations and ability to deal with anticipated management questions. The plan is a comprehensive review of sablefish research, and covers past, current, and future studies. Research in the plan includes 1) directly observing sablefish density and behavior by using manned or remote submersible technology in conjunction with longline survey gear-performance experiments; 2) initiating effective sablefish egg and larval sampling to determine the geographic distribution of successful spawning; and 3) improving estimates of sablefish age composition and using age-structured models to refine estimates of natural mortality and annual recruitment. Work in the areas discussed in this paper continues, and as new methodologies and assumptions are adequately analyzed and reviewed, the sablefish stock assessment will evolve to incorporate new findings.

Literature Cited

Clark, W. G.
1991. Groundfish exploitation rates based on life history parameters. Can. J. Fish. Aquat. Sci. 48:734–750.
1993. The effect of recruitment variability on the choice of a target level of spawning biomass per recruit *In* B. Baxter (ed.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, p. 233–246. Alaska Sea Grant Rep. 93-02.

Fujioka, J. T., J. Heifetz, and M. F. Sigler.
1997. Choosing a harvest strategy for sablefish, *Anoplopoma fimbria,* based on uncertain life-history parameters. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 247–251. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Fujioka, J. T., F. R. Shaw, G. A. McFarlane, T. Sasaki, and B. E. Bracken.
1988. Description and summary of the Canadian, Japanese, and U.S. joint data base of sablefish tag releases and recoveries. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-137, 34 p.

Funk, F., and B. E. Bracken.
1984. Status of the Gulf of Alaska sablefish (*Anoplopoma fimbria*) resource in 1983. Alaska Dep. Fish Game Inf. Leafl. 235, 55 p.

Gulland, J. A., and L. K. Boerema.
1973. Scientific advice on catch levels. Fish. Bull. 71:325–335.

Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11(3–4):355–374.

Heifetz, J., J. T. Fujioka, and T. J. Quinn II.
1997. Geographic apportionment of sablefish, *Anoplopoma fimbria,* harvest in the northeastern Pacific Ocean. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 229–237. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Hollowed, A. B., and B. A. Megrey.
1993. Evaluation of risks associated with application of alternative harvest strategies for Gulf of Alaska pollock *In* B. Baxter (ed.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, p. 291–320. Alaska Sea Grant Rep. 93-02.

Johnson, S. L., and T. J. Quinn II.
1988. Catch-age analysis with auxiliary information of sablefish in the Gulf of Alaska. Center for Fish. and Ocean Sci., Univ. Alaska, Juneau, Publ. UAJ JCFOS 8803, 79 p.

Kimura, D. K.
1985. Changes to stock reduction analysis indicated by Schnute's general theory. Can. J. Fish. Aquat. Sci. 42:2,059–2,060.
1989. Variability, tuning, and simulation for the Doubleday-Deriso catch-at-age model. Can. J. Fish. Aquat. Sci. 46:941–949.
1990. Approaches to age-structured separable sequential population analysis. Can. J. Fish. Aquat. Sci. 47:2,364–2,374.

Lowe, S. A., and G. G. Thompson.
1993. Accounting for uncertainty in the development of exploitation strategies for the Atka mackerel resource of the Aleutian Islands. *In* B. Baxter (ed.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, p. 203–231. Alaska Sea Grant Rep. 93-02.

McFarlane, G. A., and R. J. Beamish.
1992. Climatic influence linking copepod production with strong yearclasses in sablefish, *Anoplopoma fimbria.* Can. J. Fish. Aquat. Sci. 49(4):743–753.

Meinhold, R. J., and N. D. Singpurwalla.
1983. Understanding the Kalman filter. Am. Statistician 37(2):123–127.

Methot, R. D.
1990. Synthesis model: an adaptable framework for analysis of diverse stock assessment data. Int. North Pac. Fish. Comm. Bull. 50:259–277.

Rivard, D., and J. J. Maguire.
1993. Reference points for fisheries management: the eastern Canadian experience. *In* S. J. Smith, J. J. Hunt, and D. Rivard (eds.), Risk evaluation and biological reference points for fisheries management. Can. Spec. Publ. Fish. Aquat. Sci. 120:31–58.

Rose, C. S.
1986. A comparison of catch rates of sablefish by bottom trawls and longlines. *In* R. L. Major (ed.), Condition of groundfish resources of the Gulf of Alaska region as assessed in 1985, p. 181–192. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-106.

Schnute, J.
1985. A general theory for analysis of catch and age data. Can. J. Fish. Aquat. Sci. 42:414–429.

Shelton, P. A., J. E. Carscadden, and J. M. Hoenig.
1993. Risk evaluation of the 10% harvest rate procedure for capelin in NAFO Division 31. *In* S. J. Smith, J. J. Hunt, and D. Rivard (eds.), Risk evaluation and biological reference points for fisheries management. Can. Spec. Publ. Fish. Aquat. Sci. 120:193–202.

Sigler, M.
1993. Stock assessment and management of sablefish *Anoplopoma fimbria* in the Gulf of Alaska. Ph.D. dissert., Univ. of Washington, Seattle, 188 p.

Sigler, M., and J. T. Fujioka.
1988. Evaluation of variability in sablefish abundance indices in the Gulf of Alaska using the bootstrap method. Fish. Bull. 86(3):445–452.
1993. A comparison of policies for harvesting sablefish (*Anoplopoma fimbria*) in the Gulf of Alaska. *In* B. Baxter (ed.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, p. 7–19. Alaska Sea Grant Rep. 93-02.

Zenger, H. H., Jr.
1997. Comparisons of sablefish, *Anoplopoma fimbria,* abundance indices estimated from two longline surveys. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 215–228. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Zenger, H. H., and M. Sigler.
1992. Relative abundance of Gulf of Alaska sablefish and other groundfish based on National Marine Fisheries Service longline surveys, 1988–90. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-216, 103 p.

Estimates of Sablefish, *Anoplopoma fimbria*, Abundance in the Gulf of Alaska Based on Depletion Experiments Using Longlines

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ABSTRACT

Two experiments, one in 1989 and the other in 1991, were conducted in Chatham Strait, southeastern Alaska, to estimate the biomass of sablefish in the Gulf of Alaska. Each year's study consisted of a Leslie-type depletion experiment. Compared to other Leslie studies, these experiments were unique because they were based on only one removal event and used a combination of research and commercial fishing. Research longline fishing was conducted in a study area in Chatham Strait before and after the area's 24-hr commercial fishery for sablefish. The decline in experimental catch rates after the fishery, together with the commercial catch, was used to estimate the population of the study area and to compute a catchability coefficient for sablefish. This coefficient was then applied to catch rates from an annual longline survey to estimate sablefish abundance in the Gulf of Alaska. The 1989 experiment resulted in an estimate of exploitable sablefish biomass of 54,863 t in the Gulf of Alaska. Although the estimate was relatively precise (coefficient of variation=26.5%), it appeared to be unreasonably low. This suggested that the experiment's assumptions of constant catchability may have been violated, either between Chatham Strait and the Gulf of Alaska, or before and after the commercial fishery. To further investigate some of these problems of catchability, the experiment was modified in 1991. The 1991 experiment, however, also yielded a Gulf of Alaska biomass estimate for sablefish that appeared to be too low. More information on sablefish, especially concerning their feeding behavior and vulnerability to longline gear, is needed to better interpret the results of both experiments.

Introduction

An accurate estimate of biomass is an important element in stock assessment for any marine species that is commercially exploited. Biomass is a highly desirable parameter in many stock assessment models. In recent years, stock reduction analysis (SRA) has been the model applied to sablefish, *Anoplopoma fimbria*, in Alaskan waters to assess condition of the stock and predict future trends.[1] Sablefish biomass estimates are used in SRA to scale the model so that catches can be based on biomass and recruitment.

The biomass estimates used in SRA, however, have been highly uncertain. The primary source of assessment information for sablefish in the Gulf of Alaska comes from longline surveys that have been conducted annually since 1979,[2] but these surveys only provide trends of relative abundance. Consequently, before 1990, estimates of absolute sablefish abundance were based on scaling the longline survey indices to results of

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[1] Fujioka, J. T. 1990. Sablefish. *In* Stock assessment and fishery evaluation report for the 1991 Gulf of Alaska groundfish fishery, p. 125–139. N. Pac. Fish. Manage. Council, P. O. Box 103136, Anchorage, AK 99510-2252.

[2] From 1979 to 1994, an annual cooperative longline survey was conducted by Japan and the United States in the Gulf of Alaska, Aleutian Islands, and eastern Bering Sea. Since 1988, a domestic longline survey has also been conducted in the Gulf of Alaska.

comprehensive trawl surveys of the Gulf of Alaska in 1984 and 1987 (Gulf of Alaska Groundfish Plan Team[3]). These trawl surveys are thought to have poorly estimated sablefish biomass, especially below 300 m, where much of the continental-slope habitat of sablefish could not be trawled with the survey's nets.

To obtain improved biomass estimates, a comparison of sablefish catch rates among various Alaskan trawl and longline surveys was undertaken (Fujioka[1]). From this comparison, it was concluded that results of a trawl–longline experiment conducted during the 1984 trawl survey (Rose, 1986) provided the best available data for converting longline survey indices to biomass. The experiment involved trawl hauls at certain stations that were also sampled in that year's longline survey. Using the results of this experiment, Fujioka[1] computed a conversion factor that related biomass to an index of abundance, relative population weight (RPW), in the longline survey. The product of the conversion factor (0.141) and the RPW yielded an estimate of biomass (t). Based on this conversion factor, annual estimates of sablefish exploitable biomass in the Gulf of Alaska ranged between 193,000 and 225,000 t during 1989–92 (Table 1). Although these estimates were considered the best available, they were still uncertain, as the conversion factor was derived from data collected years before in a single experiment of limited scope.

Because of the questionable biomass estimates in 1989 and the importance of these estimates to the SRA model, we conducted an experimental longline study in that year to obtain an alternative estimate of sablefish biomass. The study's objective was to compute a catchability coefficient for gear used in the domestic longline survey. This coefficient was used to convert survey catch rates to density (number of fish per unit area). The density estimate was then expanded over the total area of sablefish habitat in the Gulf of Alaska to yield an overall estimate of biomass. Additionally, we conducted a modified follow-up experiment in 1991 to improve the estimate of the catchability coefficient. Results of both experiments are reported here. Each experiment relied on a modified Leslie-type depletion methodology (Leslie and Davis, 1939, cited in Ricker, 1975). We also compare our experiments with other studies that used this method.

Table 1

Estimates of exploitable biomass of sablefish in the Gulf of Alaska used in the stock reduction analysis model, 1989–92. Corresponding values of commercial catch are also listed. Table is based on data from Zenger and Sigler, 1992; Fujioka[1]; and Sigler.[2]

Year	Exploitable biomass (t)	Commercial catch (t)
1989	197,878	29,842
1990	225,483	25,701
1991	231,222	19,580
1992	192,781	20,451

[1] Fujioka, J. T. 1992. Sablefish. *In* Stock assessment and fishery evaluation report for the 1993 Gulf of Alaska groundfish fishery, p. 4-1–4-17. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510-2252.

[2] Sigler, M. Feb. 1993. Auke Bay Lab., AFSC, 11305 Glacier Hwy., Juneau, AK 99801-8626. Personal commun.

1989 Experiment: Methods

The experiment was a cooperative effort between the National Marine Fisheries Service Auke Bay Laboratory (ABL) and the Alaska Department of Fish and Game (ADFG). It was conducted in a study area in Chatham Strait, southeastern Alaska, between 57°00' and 58°00'N latitude. These waters are under jurisdiction of the State of Alaska and correspond to ADFG statistical areas 345701 and 345731 (Fig. 1). Chatham Strait is a long fiord, generally deeper than 400 m, and provides excellent sablefish habitat.

Each September in recent years, Chatham Strait has been the site of a single, 24-h commercial longline fishery for sablefish. This intensive fishery, which in 1989 involved 64 vessels in the study area fishing an estimated total of 1.4 million hooks (Bracken[4]), results in a substantial removal of sablefish over a very short period of time. We used this fishery in the 1989 effort to obtain a population estimate for sablefish in the study area and an estimate of the catchability coefficient. A research vessel was used to determine catch per unit of effort (CPUE) before and after the fishery. If a significant decline was observed in sablefish CPUE after the fishery, this decline, together with the reported commercial catch, could be used to estimate population size in the study area. Given the population size, an estimate of the catchability coefficient for sablefish could then be computed. Since the fishing gear used in the experiment was identical to that in the domestic longline survey, the coefficient could also be applied to the survey results to yield an estimate of sablefish biomass in the Gulf of Alaska.

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[3] Gulf of Alaska Groundfish Plan Team. 1989. Sablefish. *In* Stock assessment and fishery evaluation report for the 1990 Gulf of Alaska groundfish fishery, p. 97–111. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510-2252.

[4] Bracken, B. Alaska Dep. Fish and Game, Commer. Fish. Manage. and Dev. Div., P. O. Box 667, Petersburg, AK 99833. Personal commun.

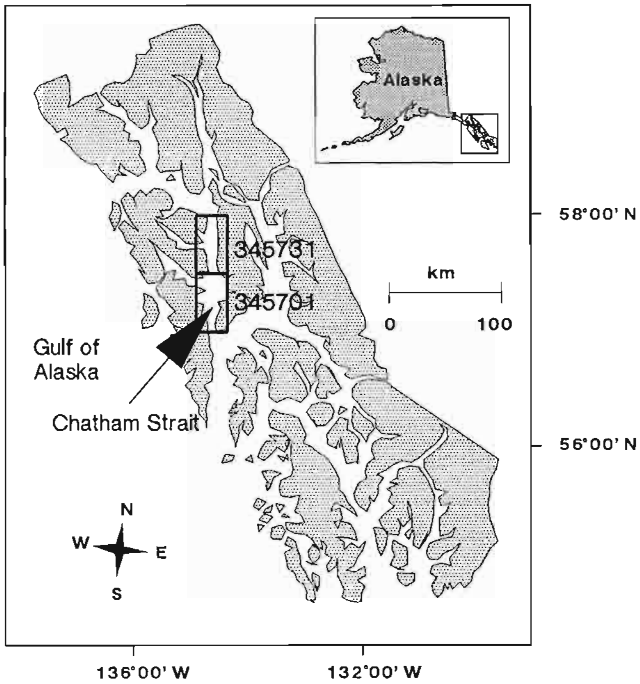

Figure 1
Location of the two Alaska Department of Fish and Game statistical areas (345731 and 345701) fished during sablefish population experiments in Chatham Strait, southeastern Alaska, in 1989 and 1991.

The methodology for determining population size in the study area was similar to that of Leslie and Davis (1939, cited in Ricker, 1975), in which repeated removals of individuals from a population cause a gradual decline in CPUE. The rate of this decline is used to estimate the population at the beginning of the experiment. Our study was a modified version of Leslie and Davis's approach: there was only one large removal (the commercial catch) and two overall observations of capture rates (mean experimental CPUE before and after the fishery). In a typical Leslie-type experiment, the precision of the population estimate is determined by the number of removal episodes over time. Our experiment, however, was somewhat different: to obtain a precise estimate, we repeatedly measured CPUE, but for only two time periods: once before and once after the fishery.

The NOAA RV *Townsend Cromwell* was used to fish longlines in the study area at 33 stations before the commercial fishery and 22 stations after the fishery. The commercial fishery took place on 22–23 September; research fishing dates were 29 August–16 September and 24 September–4 October. Two randomly selected stations were fished each day. The vessel attempted to set and retrieve one longline at each selected station. If a station appeared to be unfishable (usually because of steep bottom topography on the edges of Chatham Strait), an adjoining or nearby fishable site was substituted.

Fishing gear and bait were identical to those used in the domestic longline survey of the Gulf of Alaska. A longline consisted of 15 100-m skates (sections of longline) tied together, with 45 hooks attached to each skate by gangions 38 cm long. Thus, 675 hooks were fished at each site. Hooks were spaced 2 m apart and were baited with chopped Atlantic squid, *Illex* sp. For a more detailed description of this gear, see Zenger et al. (1994). The longlines were generally set in the same direction as the tide and were fished for a soak time of ~4 h, measured from the time the last buoy was set until the first buoy was hauled. Fork lengths were recorded for all sablefish caught.

Values of sablefish CPUE were compared for the periods before and after the fishery. First, sablefish CPUE for each station was computed as the percentage of hooks that caught sablefish, including fish observed falling off the hooks during retrieval, and excluding all skates with more than five ineffective hooks (missing, broken, bent, or tangled). Based on these CPUE values by station, an overall mean CPUE was computed for each period, before and after the fishery. To test for the significance of any observed decline in mean CPUE after the fishery, a one-tailed t test of the difference of two means was used.

The sablefish population size and density in the study area were then estimated. Biomass for the study area was estimated with the formula

$$\hat{B} = \frac{C}{D} \tag{1}$$

where $\hat{B}$ is the original biomass before the fishery, C is the commercial catch in kg, and D is the proportionate decline in CPUE after the fishery. By dividing $\hat{B}$ by the mean weight per sablefish in the study area, we estimated the number of sablefish in the study area before the fishery ($\hat{N}$). Mean weight per sablefish was determined by applying a sablefish length–weight regression (Sasaki, 1985) for both sexes combined in the Gulf of Alaska to the length-frequency of sablefish caught during the experiment. Sablefish density ($\hat{r}$; number of fish per km^2) was then estimated by dividing $\hat{N}$ by the area of sablefish habitat within the study area. Sablefish habitat was defined to be all waters deeper than 320 m, and we estimated this habitat within the study area to be 929.5 km^2.

After determining $\hat{r}$ in the experiment, we estimated a catchability coefficient ($\hat{q}$) that relates CPUE and $\hat{r}$ for sablefish caught on the longline gear:

$$\hat{q} = \frac{\text{CPUE}}{\hat{r}}. \tag{2}$$

This equation assumes a linear relationship between CPUE and $\hat{r}$; e.g., if CPUE increases twofold, estimated density will also increase by a factor of 2. Given $\hat{q}$, density of sablefish in the Gulf of Alaska was estimated by dividing overall CPUE in the domestic longline survey in 1989 by $\hat{q}$. This density was then multiplied by the area of exploitable sablefish habitat in the gulf (43,159 km^2; Zenger and Sigler, 1992) to yield a gulfwide population estimate. Finally, biomass in the Gulf of Alaska was estimated from the product of this population estimate and the mean weight per sablefish in the survey.

Standard errors and 95% confidence intervals were estimated with the nonparametric bootstrap method (Efron and Tibshirani, 1986). For each bootstrap replicate, we constructed a new data set of CPUE values before and after the fishery by sampling with replacement from the observed CPUE values. Sample sizes were the same as in the original experiment. For each replicate, $\hat{q}$ and the corresponding biomass in the Gulf of Alaska were determined from Equations 1 and 2. This procedure was replicated 1,000 times. The standard deviations for $\hat{q}$ and biomass were calculated from the distribution of bootstrap replicates in the usual way. Standard deviation is an estimate of the standard error of a parameter, and the coefficient of variation (CV) was computed by dividing the standard error by the estimate. The 95% confidence interval (CI) was estimated from the interval between the lower and upper 2.5% of the bootstrap frequency distribution.

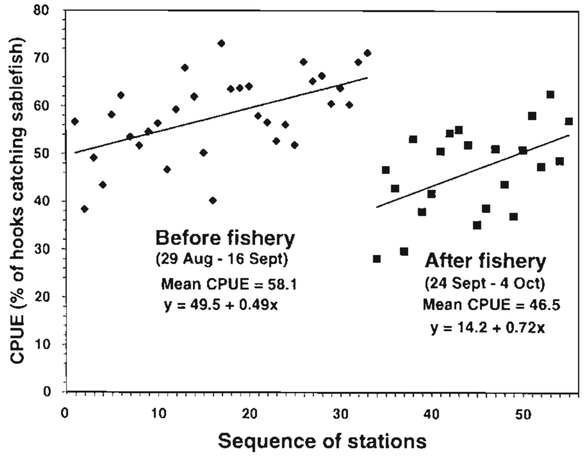

Figure 2
Sablefish catch per unit of effort (CPUE) at longline stations completed during the 1989 sablefish population experiment in Chatham Strait, southeastern Alaska. Each point represents the CPUE of one longline station.

1989 Experiment: Results

The mean experimental CPUE's for sablefish before and after the commercial fishery were 58.1% and 46.5%, respectively (Fig. 2). This relative decrease of 19.9% was highly significant (t test; df=53, p<0.001). Therefore, we were able to estimate sablefish biomass using the methods described in the previous section.

The computational results are summarized as follows. The 1989 commercial catch of sablefish in the study area was 661,142 kg round weight (Richardson[5]). Thus by using Equation 1, we estimated biomass in the area before the fishery to be 3,316,218 kg. Mean weight per sablefish in the experiment was 3.51 kg, so that $\hat{N}$ was computed to be 944,792 fish, and density was 1,016 fish/km^2. Hence by using Equation 2, we determined that the catchability coefficient for sablefish on the longline gear was 0.0571 (CV=21.2%; 95% CI=0.0336–0.0808). Gulfwide mean catch rate and weight of exploitable sablefish in the 1989 domestic longline survey were 20.56% and 3.53 kg/fish, respectively (computed from data in Zenger and Sigler, 1992). The computed catchability coefficient together with these survey data yields the following gulfwide estimates for sablefish in 1989: density, 358 fish/km^2; population size, 15,538,331 fish; and exploitable biomass, 54,863 t (CV=26.5%; 95% CI=38,789 – 93,363 t).

Applying the same catchability coefficient to other years of the domestic longline survey gives the following point estimates of sablefish biomass in the Gulf of Alaska: 1990, 61,967 t; 1991, 64,385 t; and 1992, 56,201 t.

1989 Experiment: Discussion

The study area's 19.9% decrease in sablefish abundance implies an unusually high annual exploitation rate for such a long-lived species. At this rate, it would be difficult for the fishery in Chatham Strait to remain sustainable. Patterns of sablefish migration in the Gulf of Alaska, however, may result in an annual movement of fish into Chatham Strait that replenishes the population. A recent study of sablefish tag returns (Maloney and Heifetz, 1997) supports this hypothesis: high rates of immigration, and correspondingly low rates of emigration, were found for Chatham Strait. Therefore, if we accept the 19.9% decrease as plausible, there is no reason to reject our biomass estimate for the study area. There are no alternative biomass estimates for Chatham Strait to compare with our results.

Our experiment's estimates of sablefish biomass for

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[5] Richardson, B. Alaska Dep. Fish and Game, Commer. Fish. Manage. and Dev. Div., P. O. Box 667, Petersburg, AK 99833. Personal commun.

the Gulf of Alaska are relatively precise, but they appear to be biased. Their precision is indicated by the relatively small CV of 26.5% for the 1989 data. The estimates, however, are unreasonably low. They are much lower than the previously mentioned biomass estimates derived from Rose's trawl–longline comparisons which are used in the SRA model. For example, the 1989 biomass from the trawl–longline comparisons is 197,878 t (Table 1)—greater than our point estimate by a factor >3.6. The commercial catch statistics also cast doubt on the validity of the experiment's biomass estimates. During 1989–92, the annual Gulf of Alaska commercial catch ranged from 29,842 to 19,580 t (Table 1). It is highly unlikely that biomass of only ~50,000–60,000 t during these years (our gulfwide biomass estimates) could have supported catches of this magnitude. A long-lived species such as sablefish could not sustain this level of exploitation without severely depleting the population, and there is no evidence of this kind of depletion from either the longline surveys or the commercial fishery.

To explain these results, it is important to note that our study was based on five major assumptions. Violation of any of these assumptions could result in biased estimates of catchability and biomass in either the study area or the Gulf of Alaska. The first four are requirements for any Leslie-type depletion experiment (Cowx, 1983): 1) the population in the study area must be closed, i.e., there must be no movement of fish into or out of the area; 2) natural mortality must be negligible during the experiment; 3) the depletion must result in a significant reduction of the population size; and 4) catchability must be constant throughout the experiment. Assumption 5 is related to 4 but is unique to our study: that sablefish catchability is the same in Chatham Strait as in offshore waters of the Gulf of Alaska.

Our experiment easily met assumptions 2 and 3. Given the long life expectancy of sablefish, natural mortality during the 37 days of the experiment was inconsequential, and we clearly found a significant reduction in the population as a result of the commercial fishery.

The experiment also appeared to fulfill the criterion for assumption 1, i.e., that of a closed population. Chatham Strait is a geographically confined area which restricts fish from moving in and out. To the east and west, it is bounded by land. To the north, suitable sablefish habitat extends for only ~45 km, and abundance of the fish progressively diminishes in this direction. This leaves only the south as a possible avenue for significant migration. In general, long-term tagging studies have shown that sablefish in Alaska undertake considerable migrations (Heifetz and Fujioka, 1991), but in Chatham Strait, as previously mentioned, most adult fish tend to remain after they have arrived. Unfortunately, there is no published information on short-term movements of sablefish, such as might occur during the period covered by our experiment. As a precursor to our experiment, in 1988 the short-term movement of sablefish near the northern boundary of the study area was determined by ultrasonic telemetry (Sigler and Fujioka[6]). Movements were tracked for up to 24 days. Generally, the distance traveled was relatively small; the maximum trackline for any one fish was only 43.2 km, and after an initial period of relatively swift movement, perhaps in reaction to the stress of tagging, daily travel averaged <1 km. Thus, migration was probably not an important factor in our 1989 experiment, and sablefish in the study area were likely a closed population for the duration of the experiment.

The assumption of constant catchability (4) as it relates to our experiment is more problematic. A possible violation of this assumption may partly explain the low biomass estimates computed from the study. As shown by Equations 1 and 2, if the observed decline in CPUE after the fishery was greater than the true decrease in abundance, biomass computed for the study area would be inaccurately low, leading to an overestimate of the catchability coefficient. Application of this biased catchability coefficient would result in underestimation of sablefish biomass in the Gulf of Alaska. Short-term declines in catchability, in which CPUE decreases at a faster rate than does abundance, are well documented in the longline fishery for Pacific halibut in Alaska and British Columbia (Quinn, 1987). Similarly, changes in catchability over time often introduce systematic errors into depletion-type estimates of population (Ricker, 1975). Frequently, the most vulnerable fish are caught first, after which CPUE declines faster than the true decline in abundance. A situation similar to this could have occurred in our study. At any given time, only a certain percentage of sablefish may be actively feeding, and these will be the individuals attracted to the longline. Thus many of these active feeders would be removed in the commercial fishery, and the postfishery experimental CPUE would decline substantially.

If the scenario in the previous paragraph were correct, we would expect CPUE after the fishery to increase with time, as other fish started to actively feed. Figure 2 shows this was indeed the case. However, CPUE before the fishery also showed an increasing trend with time. Linear regression analysis (Fig. 2) was used to determine the significance of these trends. CPUE was found to increase significantly with time both before and after the fishery ($p<0.001$ before the fishery and $p<0.02$ after the fishery). Because the slope of the re-

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[6] Sigler, M F., and J. T. Fujioka. 1989. Tracking short-term movements of sablefish using sonic telemetry. Available from N.M.F.S., Auke Bay Laboratory, 11305 Glacier Hwy., Juneau, AK 99801-8626. Unpubl. manuscr.

gression line after the fishery was somewhat greater than before the fishery, we postulated that catchability may have changed as more sablefish began to feed after the fishery. The slopes of the two lines, however, did not differ significantly (*F*-test for difference between two regression coefficients [Sokal and Rohlf, 1969]; $p>0.25$). Apparently the trend of increasing CPUE was consistent during both parts of the experiment.

The causes for this increase in CPUE during both parts of the experiment are uncertain. Fishing methods and gear were consistent throughout the experiment, and there was no reason to suspect a progressive change in fishing power of the research vessel. We also made sure that the selected stations were not fished in any particular order by geography or depth, which might cause a systematic bias in the results. Tidal cycle during the study was examined to determine whether tide affected CPUE; analysis of covariance, in which time was the variant and daily range in tide height was the covariant, showed tide had no influence on catch rates ($p=0.40$). Thus, after rejecting these possible causes, the only remaining explanation for the increasing CPUE is some temporal change in sablefish behavior which is presently unknown. An example of such a change would be a progressive increase in feeding activity during late summer–early autumn.

The validity of the final assumption in the experiment—that catchability of sablefish on the longline gear is equivalent in Chatham Strait and the Gulf of Alaska—is also difficult to prove. We attempted to minimize any differences in catchability between the two regions by fishing the same gear and following the same procedures as the longline survey. The possibility exists, however, that either sablefish behavior or the effectiveness of the longline gear was different in Chatham Strait. If so, one plausible explanation for the experimental results is that the population estimate for the study area was valid, but the corresponding estimate for the Gulf of Alaska was biased.

Competition for hooks between species is an obvious factor that might influence sablefish catchability in each area. In the experiment, such competition was of little consequence, as species other than sablefish accounted for just 13% of the catch. In the Gulf of Alaska longline survey, other species accounted for 45% of the catch in 1989, which suggests that competition could affect catches of sablefish. In a detailed analysis of the longline survey, however, Sigler (1993) concluded that competition for hooks is of little importance in determining sablefish catch rates. Consequently, if there were catchability differences between Chatham Strait and the Gulf of Alaska in 1989, the nature and extent of these differences are unknown.

Clearly, it would have been preferable to conduct the experiment in the Gulf of Alaska, since that was the area of concern for determining biomass. This would have circumvented any problems regarding catchability differences between Chatham Strait and the Gulf of Alaska. A Leslie-type experiment, however, was not feasible in the gulf for a number of reasons. First, there are no geographically isolated areas inhabited by sablefish that would be appropriate for a study site. Any site selected would likely violate the assumption of a closed population. Second, in the late 1980's, the sablefish fishery in the gulf began in early April and usually extended for several weeks. The fishery was less intense than in Chatham Strait, and there was no "instantaneous" large removal of fish that would be conducive to a depletion experiment. Third, because of the timing of the commercial fishery, much of the research fishing for an experiment would have had to occur in March. This would have created a major problem because the research vessel available for this project was not designed to withstand the rigors of winter fishing in Alaska.

1991 Experiment: Methods

Although results of the 1989 study were uncertain, the short and intensive commercial fishery for sablefish in Chatham Strait provided a unique opportunity to use a Leslie-type depletion experiment for estimating sablefish abundance. To further investigate the possible change in longline catchability which may have influenced the 1989 results, we modified the experimental design in 1991 in two ways.

First, trawling was added to the experiment to obtain alternative estimates of sablefish CPUE which would not be affected by feeding behavior. Second, experimental fishing was spread over a longer time than in 1989. The cruises in 1991 began in late July (~6 weeks before the commercial fishery) and ended in mid-October (~4 weeks after the fishery). Scheduling part of the experimental fishing substantially later than the commercial fishery was believed to be particularly important. This was to help determine whether the fishery caused a short-term reduction in CPUE by removing the most vulnerable fish. All the postfishery experimental fishing in 1989 was done in the 11 days immediately after the fishery, and this may not have been enough time for the catch rates to recover. Presumably, if sablefish CPUE is affected by short-term changes in vulnerability, fishing in October would yield a more valid, unbiased measure of postfishery CPUE.

The study area in 1991 was reduced to just one ADFG statistical area, 345731, in Chatham Strait between latitudes 57°30'N and 58°00'N (Fig. 1). The smaller area was necessary because the inclusion of trawling in the experiment did not allow as many longline stations to be fished as in 1989. Also, fewer vessel days were allocated to the study in 1991. Therefore, to keep the density of longline stations comparable to that in 1989, we diminished the size of the study area. Sablefish habitat within this study area was estimated to be 468.2 km^2.

The NOAA RV *John N. Cobb* was used for the 1991 experiment. Fishing was divided into four discrete cruises: Cruise 1, 30 July–7 August and Cruise 2, 4–9 September (before the commercial fishery); and Cruise 3, 21–26 September and Cruise 4, 13–18 October (afterward). The commercial fishery took place on 16–17 September.

A 400-mesh eastern otter trawl was used for all trawl operations. This nylon net measured 21.6 m along the headrope and 28.6 m along the footrope. No roller gear was used on the footrope, and the codend liner consisted of 3.2-cm-stretched mesh nylon. A pair of double 54.9-m dandylines connected the net to a pair of steel "V" doors (1.5 m × 2.1 m, 386 kg each).

Random selection of trawl sites was not possible because most of the bottom within the study area was too rugged for trawling. Consequently, we chose three trawl indexing sites in localities known to be trawlable (Fig. 3). Each site measured 6.86 km^2 (2 n.mi.^{2}) and had a relatively smooth bottom of nearly uniform depth. During each cruise, we attempted to complete two successful trawl hauls at each indexing site, for a total of six hauls per cruise. Because of trawling difficulties, however, only five successful hauls were made during Cruises 1, 2, and 4. Standard duration of trawl hauls was 15 minutes, measured from the time the net reached bottom and started fishing ("equilibrium") until the time of haulback. Accurate positions were taken at equilibrium and haulback to calculate distance fished over the bottom. CPUE was expressed as number of sablefish caught per distance (n.mi.) trawled.

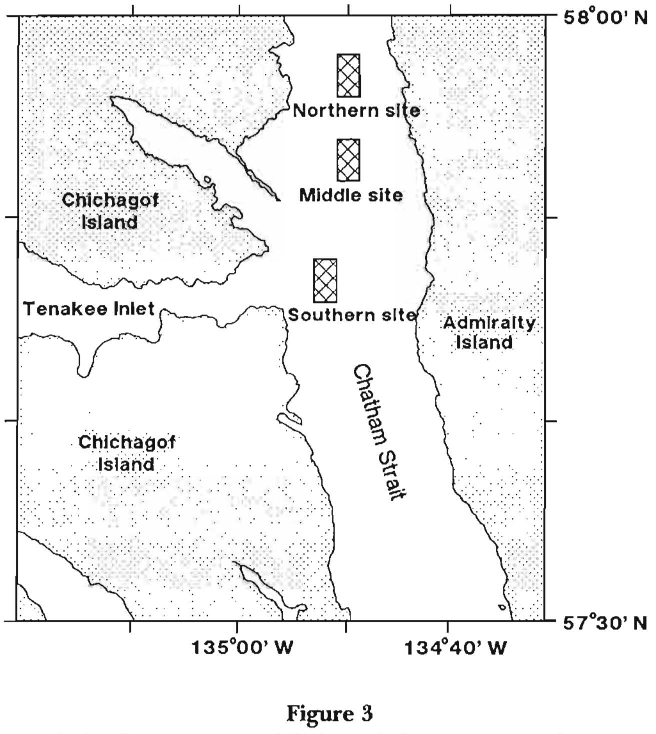

Figure 3

Alaska Department of Fish and Game statistical area 345731, Chatham Strait, southeastern Alaska, showing location of the three trawl indexing sites fished during the 1991 sablefish population experiment.

Trawl CPUE's before and after the fishery were compared with a three-factor, unweighted means, analysis of variance (Snedecor and Cochran, 1967). In this analysis, the cruises were nested within the periods before and after the fishery and were crossed with indexing sites.

A total of 15 longline stations was fished before the fishery, and 16 afterward. After the two cruises that preceded the fishery, it was apparent that the longline catch rates were much more variable than in 1989. This raised concern that the data might be too imprecise to detect a significant change in CPUE after the fishery. To reduce this variability, we elected to replicate eight of the stations after the fishery (i.e., fish eight stations at the exact same positions as before the fishery). All other longlining procedures, including site selection, gear, and fishing operations, were identical to those in 1989.

To determine the significance of differences in longline CPUE before and after the fishery, we used a two-factor nested analysis of variance with unequal sample sizes (i.e., 15 stations before and 16 stations after the fishery; Sokal and Rohlf, 1969). In the analysis, each cruise was nested within the periods before and after the fishery. To analyze the replicate station data, a paired t test was used to test the significance of differences in CPUE before and after the fishery for the eight repeated stations. As in the 1989 experiment, the standard error and 95% CI of the catchability coefficient and biomass were determined by the nonparametric bootstrap method. In the case of the replicate station data, for each bootstrap replicate, a new dataset of CPUE values for the periods before and after the fishery was constructed by sampling with replacement from the eight pairs of observed CPUE values.

1991 Experiment: Results And Discussion

Trawling

There appeared to be a substantial decline in trawl CPUE after the fishery (Table 2). CPUE decreased 26.8% from 121.8 fish/n.mi. before the fishery to 89.2 fish/n.mi. after. This decline, however, was not statistically significant (analysis of variance; $p>0.25$); consequently, we did not use the trawl data to compute a population estimate for the study area.

The lack of significance was evidently caused by the large variability in catch rates between hauls. For example, after the commercial fishery, the CPUE at the southern indexing site ranged by a factor of 8, from ~11 fish/n.mi. (haul 40) to ~91 fish/n.mi. (haul 53). Some of this could be due to the inherent variability of trawl catches, but one problem encountered during trawling may have increased the variability. The *John N. Cobb* was not equipped with a netsounder, so there was no way to verify that the net was always in contact with the bottom during a haul. Because of the strong tidal currents in Chatham Strait, it was often necessary to let out all the available cable to ensure that the net would reach bottom. Nevertheless, on five hauls the net apparently either did not reach bottom or just briefly touched bottom, as shown by extremely sparse catches. We excluded these clearly unsuccessful hauls from our analysis. The failure of the net to reach bottom on these hauls, however, suggests that the net may not have been completely on bottom during all the "successful" hauls. If true, the catch rates of certain hauls may be considerably underestimated, and this would increase the variability of the trawl data.

Table 2

Sablefish catch per unit of effort (CPUE) in hauls successfully trawled during the 1991 sablefish population experiment in Chatham Strait, southeastern Alaska. CPUE is expressed as number of sablefish caught per n.mi. trawled.

Cruise no.	Indexing site[1]	CPUE
Before the commercial fishery		
1	M	111.6
1	M	161.4
1	S	138.8
1	S	151.7
1	N	143.1
2	N	124.6
2	M	69.2
2	S	50.0
2	M	54.1
2	N	213.3
Mean		121.8
After the commercial fishery		
3	N	207.5
3	M	58.9
3	S	11.4
3	S	53.8
3	M	138.3
3	N	103.3
4	M	50.6
4	S	91.4
4	S	64.6
4	M	55.3
4	N	146.2
Mean		89.2

[1] N = northern site; M = middle site; S = southern site.

Longlining

Mean sablefish CPUE for all the longline stations declined from 39.7% of hooks catching fish before the commercial fishery to 33.8% after the fishery (Fig. 4). According to our analysis of variance, however, this relative decrease of 14.9% was not significant ($p>0.50$). Differences in CPUE among cruises within each period (i.e., before and after the fishery) were also not significant ($p>0.10$). Therefore, as with the 1991 trawl data, the overall longline data in 1991 could not be used to estimate the sablefish population or a catchability coefficient for sablefish on the longline gear.

These results are very different from those of the 1989 longline experiment, which showed a significant change in CPUE after the fishery. Sablefish catch rates in 1991 varied more (compare Fig. 2 with Fig. 4), and abundance generally appeared to be more patchy than in 1989. This variability would make it difficult to detect a true change in the postfishery CPUE. The increased variability in 1991 was caused by a greater range in CPUE; in particular, relatively low CPUE values (<40% of hooks catching sablefish) were found at many more stations in 1991.

The 1991 longline experiment showed no trend of increased sablefish CPUE during the course of the study, such as that observed in 1989. The longline portion of

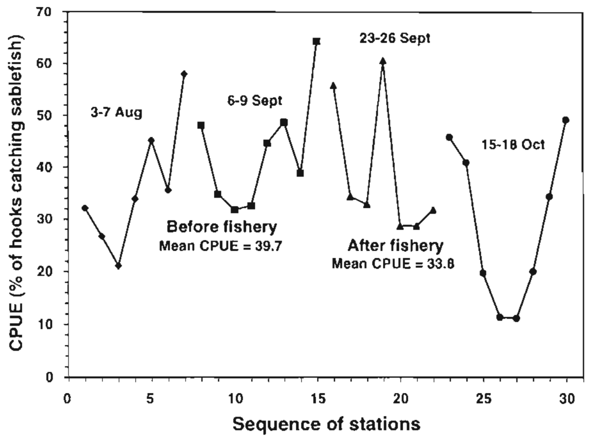

Figure 4

Sablefish catch per unit of effort (CPUE) at longline stations during the 1991 sablefish population experiment in Chatham Strait, southeastern Alaska. Each point represents the CPUE of one longline station.

each 1991 cruise, however, was only 4–5 days, and it is unlikely that trends would be detectable over this short span. Still, a progressive increase in sablefish CPUE during August and September 1991 would probably have been indicated by significant increases in the catch rates of the three cruises during this time.

The 1991 results also did not support the hypothesis that the most vulnerable sablefish may be removed by the fishery, thereby introducing bias into the postfishery catch rates. We scheduled the last cruise in the 1991 experiment (Cruise 4) in mid-October, about one month after the commercial fishery. If CPUE was temporarily depressed by removal of the most vulnerable fish, we would expect a rebound of CPUE by October as more of the remaining fish became vulnerable. This did not happen in the 1991 study. Mean CPUE for sablefish in Cruise 3, soon after the fishery, was 38.6%; instead of increasing in October during Cruise 4, mean CPUE declined to 29.0%. This difference was not significant (*t* test; $0.10<p<0.20$). These results do not exclude the possibility that vulnerability of individual fish may affect catch rates, but they indicate that, at least for 1991, such an effect could not be detected.

Mean sablefish CPUE at the eight replicate longline stations in 1991 decreased from 37.8% before the commercial fishery to 30.4% afterward (Table 3). This relative decline of 19.7% was significant (*t* test; df=7, $p<0.01$). Thus, a sablefish catchability coefficient and resultant biomass estimates were computed with these data.

The computational results are as follows: The reported 1991 commercial catch in statistical area 345731 was 166,596 kg round weight (Richardson[5]); biomass in this area before the fishery was estimated to be 845,775 kg. Given a mean weight of 3.51 kg/fish, this converts to 240,731 fish and 514 sablefish/km^2. The catchability coefficient ($\hat{q}$) for sablefish was then 0.0736 (CV=30.8%; 95% CI=0.0273–0.1152). Mean catch rate and weight of exploitable sablefish in the 1991 domestic longline survey were 24.33% and 3.50 kg, respectively (Sigler[7]). Thus, the estimated density of sablefish in the Gulf of Alaska was 331 fish/km^2. Finally, the 1991 estimated gulfwide population was 14,264,640 exploitable sablefish, and the corresponding biomass estimate was 49,967 t (CV=41.6%; 95% CI=31,925–134,517 t).

Table 3

Sablefish catch per unit of effort (CPUE) for paired longline stations fished during the 1991 sablefish population experiment in Chatham Strait, southeastern Alaska. CPUE is in percentage of hooks that caught sablefish.

	Original stations (before fishery)	Replicate stations (after fishery)
	21.1	11.1
	33.9	36.3
	45.2	34.3
	35.6	34.3
	58.0	45.8
	31.8	19.7
	32.5	32.8
	44.7	28.7
Mean	37.8	30.4

Like the results of the 1989 longline experiment, this biomass estimate seems too low. Our previous discussion of how the 1989 study apparently underestimated the biomass pertains equally to the 1991 results. Moreover, the estimated biomass of 49,967 t estimated from the 1991 experiment is even lower than the estimate of 64,385 t based on the 1989 study. This lower biomass in the 1991 study was due to the higher estimate of the catchability coefficient in that experiment ($\hat{q}$=0.0736 in 1991 vs. 0.0571 in 1989).

Comparisons with Other Leslie Studies

To better interpret our methodology and results, we compared our experiments with other Leslie-type depletion studies. A brief literature survey for the years since 1977 indicated at least 13 fishery studies that used the Leslie method (or its modifications) to estimate abundance (Table 4). Examination of these studies reveals several pertinent facts:

1) The design of our experiments was different from all the other studies because we used only one removal event (the 24-hr commercial fishery) each year. The methodologies of the other studies were based upon a more typical Leslie approach, in which multiple removals were used to determine a declining ratio of CPUE to cumulative catch. Linear regression analysis is usually appropriate for these latter procedures, in which q (catchability coefficient) is estimated as the absolute value of the regression line's slope, and B (initial biomass) is estimated by the x intercept. In addition, more recent, sophisticated models (e.g., Schnute, 1983) have been developed for multiple removal experiments to analytically evaluate problems of catchability. Because our experiments dealt with only a single removal, these newer techniques were not available to us.

2) Another unique aspect of our experiments was that they combined research and commercial fishing, which none of the other studies did. Our experiments used the massive fishing effort of the commercial fleet to carry out the removal, whereas research fishing pro-

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[7] Sigler, M. N.M.F.S., Auke Bay Lab, 11305 Glacier Hwy., Juneau, AK 99801-8626. Personal commun.

Table 4
Fishery studies published since 1977 that used a Leslie-type methodology to estimate abundance.

Study	Area	Species	Habitat
Rhodes et al., 1977	South Carolina	Clam	Estuary
Mahon, 1980	Poland/Ontario	Fish	Stream
Peterson et al., 1980	Nebraska	Fish	Lake
Cabraal and Wheaton, 1981	Maryland	Clam	Estuary
Havey et al., 1981	Maine	Fish	Lake
Methot and Botsford, 1982	California	Crab	Ocean
Schnute, 1983	New Brunswick	Fish	Stream
Polovina, 1986	W. Pacific	Fish	Ocean
Ralston, 1986	W. Pacific	Shrimp	Ocean
Mohn and Elner, 1987	Nova Scotia	Crab	Ocean
Clarke and Yoshimoto, 1990	Hawaiian Is.	Lobster	Ocean
Rosenberg et al., 1990	Falkland Is.	Squid	Ocean
Brodziak and Rosenberg, 1991	NW Atlantic	Squid	Ocean

vided the data on CPUE. In contrast, all the marine studies (estuary or ocean) in Table 4, except Polovina (1986) and Ralston (1986), relied totally on CPUE data from commercial fisheries to estimate abundance. (The Polovina and Ralston studies can be considered special cases, because both were conducted with the same research vessel in 1984 at isolated reefs.) As such, the other studies had varying degrees of difficulty in standardizing fishing effort. Because of these standardization problems, research fishing would clearly be preferred for a depletion experiment. In most marine situations, however, it is neither practical nor politically acceptable for a research program to remove a significant portion of a commercial species' population. Thus our experimental approach, which used both research and commercial fishing, has some merit. Given the right circumstances (a large removal by a commercial fishery over a short time), other depletion studies may be improved by adopting our method.

3) The study most analogous to ours was that of Clarke and Yoshimoto (1990). Based on a fairly straightforward application of the Leslie method, their study used CPUE from a commercial vessel to determine a population estimate for slipper lobsters, *Scyllarides squammosus*, in a small area in the northwestern Hawaiian Islands. This estimate was then expanded over the total area of appropriate habitat in the entire northwestern Hawaiian Islands. The authors concluded that the population estimate for the small area covered by the experiment was reasonable, but the extrapolated population estimate differed considerably from the existing estimates used in managing the fishery. These results are similar to ours, except for the fact that the expanded population numbers in the Hawaiian study were much higher than the existing numbers, whereas in our study they were much lower. The results of both studies indicate that when population estimates from depletion experiments are expanded beyond the area of the experiment, the investigator needs to interpret the expanded estimates with great caution.

Summary and Conclusions

The 1989 and 1991 experiments both successfully used the Leslie method to compute abundance estimates and catchability coefficients for sablefish in the Chatham Strait study areas. These experiments were different from other recent Leslie studies because they were based on just one removal and used a combination of research and commercial data. The validity of the abundance estimates for Chatham Strait is unknown, but there is nothing to indicate that they are not correct. When the computed catchability coefficients were applied to the Gulf of Alaska longline survey, however, the resultant gulfwide biomass estimates were unreasonably low, especially in comparison to recent commercial catches.

The low biomass estimates were probably caused by violations of the experiment's assumptions of constant catchability. These violations may have occurred in two ways: 1) sablefish catchability may have changed during the experiments, or 2) sablefish catchability in Chatham Strait may be different than in the Gulf of Alaska. If statement 1 were true and catchability decreased after the fishery in the experiments, then sablefish abundance in Chatham Strait would be underestimated. This would translate into low biomass estimates for the Gulf of Alaska. If statement 2 were correct, biomass and the catchability coefficient for the study areas in

Chatham Strait may be valid, but extrapolation of these results to the longline surveys would yield biased estimates of gulfwide biomass.

The reasons for these violations are uncertain, but they probably result from our relative lack of information on sablefish biology and behavior. In particular, changes in the feeding behavior of sablefish during the experiments, or in their attraction and vulnerability to longline gear, may have influenced the results. Until more is known about these aspects of sablefish behavior, we do not recommend any further depletion-type population studies that rely on changes in longline CPUE.

The follow-up studies in 1991 did not achieve their intended goal, which was to better explain and improve the results of the original 1989 experiment. The modifications added to the experimental design in 1991 (trawling, and extending the study over a longer time period) addressed possible problems of changing catchability which were identified in the 1989 study. High variability in sablefish CPUE, however, was a problem in both the trawl and longline portions of the 1991 studies. This led to a lack of significant change in sablefish CPUE in both the trawl and the overall longline portions of the experiment. Similarly, no detectable change in sablefish catchability was observed during the course of the experiment, which differed from the 1989 results.

Estimation of a valid catchability coefficient for longline-caught sablefish is still an important objective for improved stock assessment. Alternative approaches to computing a catchability coefficient should be examined. For example, direct enumeration of sablefish from a submersible, in conjunction with longlining, might provide a catchability coefficient which could be used to estimate sablefish biomass.

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Literature Cited

Brodziak, J. K. T., and A. A. Rosenberg.
1991. Assessment of squid fisheries in the northwest Atlantic. Int. Counc. Explor. Sea., Shellfish Committee, Copenhagen, 17 p.

Cabraal, R. A., and F. W. Wheaton.
1981. Estimating Maryland Chesapeake Bay oyster population using Leslie and DeLury equations. Trans. Am. Soc. Agric. Engin. 24(2):519–523.

Clarke, R. P., and S. S. Yoshimoto.
1990. Application of the Leslie method to commercial catch and effort of the slipper lobster, *Scyllarides squammosus,* fishery in the northwestern Hawaiian Islands. Mar. Fish. Rev. 52(2):1–7.

Cowx, I.G.
1983. Review of methods for estimating fish population size from survey removal data. Fish. Manage. 14(2): 67–82.

Efron, B., and R. Tibshirani.
1986. Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. Stat. Sci. 1:54–77.

Havey, K. A., D. O. Locke, and C. L. Smith.
1981. A comparison of four methods of estimating populations of hatchery-reared brook trout at Tomah Lake, Maine. N. Am. Fish. Manage. 1:186–192.

Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11:355–374.

Leslie, P. H., and D. H. S. Davis.
1939. An attempt to determine the absolute number of rats on a given area. J. Anim. Ecol. 8:94–113. *Cited in* Ricker (1975).

Mahon, R.
1980. Accuracy of catch-effort methods for estimating fish density and biomass in streams. Biol. Fish. 5(4):343–363.

Maloney, N. E., and J. Heifetz.
1997. Movements of tagged sablefish, *Anoplopoma fimbria,* released in the eastern Gulf of Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 115–121. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Methot, R. D., and L. W. Botsford.
1982. Estimated preseason abundance in the California Dungeness crab (*Cancer magister*) fisheries. Can. J. Fish. Aquat. Sci. 39:1,077–1,083.

Mohn, R. K., and R. W. Elner.
1987. A simulation of the Cape Breton snow crab, *Chionoecetes opilio,* fishery for testing the robustness of the Leslie method. Can. J. Fish. Aquat. Sci. 44:2,002–2,008.

Peterson, J., M. Taylor, and A. Hanson.
1980. Leslie population estimate for a large lake. Trans. Am. Fish. Soc. 109:329–331.

Polovina, J. J.
1986. A variable catchability version of the Leslie model with

application to an intensive fishing experiment on a multispecies stock. Fish. Bull. 84(2):423–428.

Quinn, T. J., II.
1987. Standardization of catch-per-unit-effort for short-term trends in catchability. Nat. Res. Modeling 1(2):279–296.

Ralston, S.
1986. An intensive fishing experiment for the caridean shrimp, *Heterocarpus laevigatus*, at Alamagan Island in the Mariana Archipelago. Fish. Bull. 84(4):927–934.

Rhodes, R. J., W. J. Keith, P. J. Eldridge, and V. G. Burrell Jr.
1977. An empirical evaluation of the Leslie-Delury method applied to estimating hard clam, *Mercenaria mercenaria*, abundance in the Santee River estuary, South Carolina. Proc. Natl. Shellfish. Assoc. 67:44–52.

Ricker, W. E.
1975. Computation and interpretation of biological statistics of fish populations. Can. Bull. Fish. Aquat. Sci. 191, 382 p.

Rose, C. S.
1986. A comparison of catch rates of sablefish by bottom trawls and longlines. *In* R. L. Major (ed.), Condition of groundfish resources of the Gulf of Alaska region as assessed in 1985, p. 297–304. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-106.

Rosenberg, A. A., G. P. Kirkwood, J. A. Crombie, and J. R. Beddington.
1990. The assessment of stocks of annual squid species. Fish. Res. 8:335–350.

Sasaki, T.
1985. Studies on the sablefish resources in the North Pacific Ocean. Bull. Far Seas Fish. Res. Lab. (Shimizu) 22, 108 p.

Schnute, J.
1983. A new approach to estimating populations by the removal method. Can. J. Fish. Aquat. Sci. 40:2,153–2,169.

Sigler, M.F.
1993. Stock assessment and management of sablefish *Anoplopoma fimbria* in the Gulf of Alaska. Ph.D. dissert., Univ. Washington, Seattle, 190 p.

Snedecor, G. W., and W. G. Cochran.
1967. Statistical methods, 6th ed. Iowa State Univ. Press, Ames, 593 p.

Sokal, R. R., and F. J. Rohlf.
1969. Biometry: the principles and practice of statistics in biological research. W. H. Freeman, San Francisco, 776 p.

Zenger, H. H., Jr., and M. F. Sigler.
1992. Relative abundance of Gulf of Alaska sablefish and other groundfish based on National Marine Fisheries Service longline surveys, 1988–90. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-216, 103 p.

Zenger, H. H., Jr., M. F. Sigler, and E. R. Varosi.
1994. Assessment of Gulf of Alaska sablefish and other groundfish species based on the 1988 National Marine Fisheries Service longline survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-39, 55 p.

The Bycatch of Sablefish, *Anoplopoma fimbria*, in the Oregon Whiting Fishery

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ABSTRACT

The fishery for Pacific whiting, *Merluccius productus*, has removed tremendous quantities of fish since the onset of the foreign fishery in 1966. Although this trawl fishery targets on midwater schools of whiting, other species are caught incidentally. This paper analyzes in detail the bycatches of sablefish, *Anoplopoma fimbria*, landed in 1992 by trawlers delivering whiting to onshore processing facilities in Oregon. From May through October, port agents examined 49% of all deliveries and recorded the bycatches of sablefish and other regulated species. About half of these deliveries included small sablefish, which ranged in length from 33 to 54 cm and weighed an average of about 0.9 kg. The distribution of sablefish landed per delivery was highly over-dispersed ($\bar{x}$=24.6, SD=106.9). In addition to the shoreside sampling, 15% of the whiting trips from Oregon ports also carried onboard agency observers who kept track of catches from the time they were brought on board until they were offloaded at the processing plants. About half of the whiting trips caught at least one sablefish, and on about half of the trips that caught sablefish, some sablefish was discarded at sea. When sablefish was discarded, it amounted to about one-quarter of the sablefish catch. For the entire season we estimate that the shoreside fishery in Oregon caught about 31,400 sablefish—about 0.35% of the estimated number of sablefish that recruit annually.

Introduction

In almost all fisheries the harvest process results in the incidental capture of nontargeted species. This problem of bycatch is particularly acute in trawl fisheries, where the relatively nonselective action of the nets captures whatever organisms are in their path. Although the midwater trawl fishery for Pacific whiting, *Merluccius productus*, off the Pacific coast of North America is better than most fisheries in taking reasonably pure catches, there is concern that this fishery, by its sheer magnitude, could have a substantial impact on other species that are caught incidentally.

Since the start of the international fishery for Pacific whiting in the mid-1960's, this fishery has removed 90,000–310,000 metric tons (t) of whiting annually (Dorn and Methot[1]), which represents the greatest single source of removals by any fishery in this geographic region. Other fish caught as bycatch in the whiting fishery include Pacific salmon, *Oncorhyncus* spp.;

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[1] Dorn, M. W., and R. D. Methot. 1992. Status of the coastal Pacific whiting resource in 1992. *In* Status of the Pacific Coast groundfish fishery through 1992 and recommended biological catches for 1993: stock assessment and fishery evaluation. Appendix A, 55 p. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland, OR 97201.

widow rockfish, *Sebastes entomelas*; yellowtail rockfish, *S. flavidus*; and sablefish, *Anoplopoma fimbria*.

The extent and effect of bycatches of prohibited species, particularly salmon, was a management concern in the international and joint venture fisheries for whiting that operated until 1990. In 1991, when the whiting fishery became exclusively domestic, the fleet of U.S. factory ships, in cooperation with the National Marine Fisheries Service (NMFS), established a voluntary bycatch observer program. Information from the whiting fishery was required to determine whether bycatch could be controlled by management restrictions such as prohibition of night fishing, area closures, or timing of the fishing season. Initially, the factory ships supplied observers as an extension to their arrangements for complying with the mandatory observer program of the North Pacific Fishery Management Council. Because significant landings were expected on shore in 1992, a comparable observer program was needed to monitor the whiting catches delivered to onshore processors.

In 1992, participating vessels, processors, and government agencies conducted a cooperative shoreside whiting observation program in Oregon. The government agencies involved in the program included the Pacific Fishery Management Council, NMFS, the Pacific States Marine Fisheries Commission (PSMFC), and the Oregon Department of Fish and Wildlife (ODFW). The program provided data on the bycatch of groundfish delivered to shore and on the bycatch discarded at sea. To be consistent with the overall observation rates on the offshore whiting factory ships, the shoreside whiting observer program attempted to monitor 20% at sea and 30% on shore of the shoreside deliveries of whiting. The data examined in this paper on the bycatch of sablefish in the Oregon whiting fishery were collected as part of the Oregon shoreside whiting observer program.

The objectives of the work presented here were to analyze the whiting fishery in detail to determine what factors influenced the amount and quality of the sablefish bycatch, and to estimate how much sablefish bycatch occurred as a result of the 1992 Oregon shoreside whiting fishery.

Materials and Methods

Observers were assigned to the major Oregon ports where Pacific whiting were delivered for onshore processing: Newport, on the central Oregon coast, and Astoria, to the north (Fig. 1). The official 1992 whiting season began on 15 April and ended on 30 October; the observation program was conducted from 1 May through 29 October.

At-sea observers were certified by NMFS and were supplied under contract by Pacific Observers, Inc. of Seattle, Washington. Shoreside observers were hired by PSMFC and trained and supervised by ODFW. The NMFS-certified observers monitored the catch and discard of species on participating vessels at sea, and also inspected the offloading of those same trips to determine total groundfish bycatch. The ODFW-trained observers monitored the offloading of additional whiting trips, which were not observed at sea, to estimate total bycatch from those landings.

Data Collection and Processing

Although whiting trips were not selected at random for observation, we believe that the data collected were representative nevertheless. At-sea observers were normally associated with a single processor and its vessels. They remained on a vessel for about one week and then rotated to another vessel. Through a rotation schedule we attempted to maintain similar observation rates on all participating vessels. Shoreside observers were usually responsible for monitoring deliveries at a single processor for at least one week at a time. Observations were scheduled to provide similar coverage for all participating vessels delivering to a plant.

Bycatches of groundfish, including sablefish, were determined by sorting, weighing, and counting fish by species. Weights were recorded to the nearest pound. Usually the entire landed bycatch was weighed, but when this was impractical, samples for average weight were taken at several times throughout the off-loading. For trips monitored at sea, the observers counted and weighed only those fish that were discarded; landings were monitored on shore.

For observed trips, usually all of the landed bycatch was counted during the off-loading process. But at one processing plant in Newport, when the off-loading exceeded an eight-hour shift, the observer was sometimes authorized to monitor only the first eight hours of off-loading and then extrapolate the data to the whole delivery. This occurred for 2 of the 40 deliveries observed at this plant.

As part of the regular groundfish sampling program, the ODFW port biologists collected the fishing logs from the vessels landing whiting in Oregon. These logs, maintained by the vessel captains in the Standard Trawl Logbook for Washington-Oregon-California, provided tow-by-tow data including date, time, location, bottom depth, fishing depth, speed, and approximate catch in pounds by species for most whiting landings in Oregon. However, the logs often did not report small amounts of incidental catches of species such as sablefish.

In addition to the observer data on sablefish bycatch and the corresponding logbook information on the location and circumstances of its capture, we examined the official landing receipts (fish tickets) which the processors completed and provided to ODFW and the

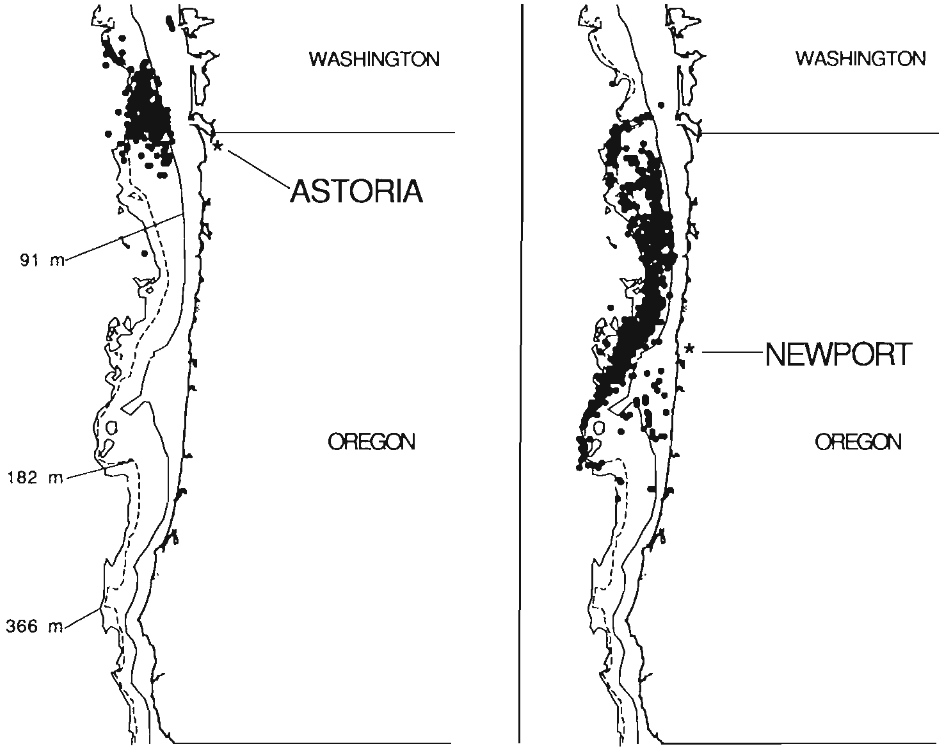

Figure 1
Locations of whiting tows made by boats landing in Astoria (left) and Newport (right) during the 1992 whiting season.

observer program. These fish tickets summarized each vessel's landings in pounds by species and provided a time series of fishing trips and landings of whiting.

As a preliminary step in data processing, we matched the observer data with the corresponding fish tickets to determine the whiting landings, and with the logbooks for detailed, tow-by-tow information. For most analyses we worked with all available data. However, in our analysis of factors contributing to sablefish bycatch, we excluded data from 51 of the 197 trips observed at sea. These trips had characteristics (e.g., location or time of day) that we considered to be ill-defined. They included trips with tows from more than one day or with more than one type of gear; trips with tow starting times separated by more than four hours or with tow starting locations separated by more than 0.1° of latitude or longitude; and trips with tow bottom depths or net depths that differed by more than 55 m (30 fm).

Statistical Analyses

In examining the sablefish bycatch data, we conducted various kinds of analyses using GLIM 3.77, a statistical program for fitting generalized linear models using maximum likelihood (Baker and Nelder, 1985). We used GLIM to 1) investigate which factors may have influenced the average fish weight of the landed sablefish bycatch, 2) compare the size of retained versus discarded sablefish, and 3) analyze the attributes of whiting trips that resulted in the capture and discard of sablefish.

For analyzing average fish weights we used standard linear models and assumed that errors in the dependent variables were independent normal random variates. For analyzing proportions, such as the proportion of trips that caught sablefish, we used logistic models and assumed that errors in the dependent variables were binomially distributed random variates. For analyzing the numbers of sablefish caught or landed we applied log-linear models and assumed that errors in the dependent variables were distributed as Poisson random variates.

To assess the statistical significance of different factors and factor combinations, we conducted forward-stepwise analyses (Draper and Smith, 1966) and examined the relative improvement in fit that occurred as we added factors to a model. GLIM uses a statistic called "deviance" to measure how well a statistical model fits observed data. If the model is correctly specified, the deviance, which is a linear function of the log likelihood, is approximately distributed as a chi-square random variable (McCullagh and Nelder, 1983).

To test for a significant interaction between factors A and B, for example, we would use GLIM to compute the deviance and degrees of freedom for the model A + B and for the model A + B + A·B, and we would calculate the ratio

$$F = \frac{\text{(Change in deviance)/(Change in degrees of freedom)}}{\text{(Deviance)/(Degrees of freedom)}}.$$

where the deviance and degrees of freedom in the denominator are from the more complete model (A + B + A·B). We would then compare this F ratio with the corresponding theoretical F distribution.

If the model is correctly specified and the random errors in the data are normally distributed, then the deviance is equivalent to the residual sums of squares in standard least-squares analysis, and the test statistic F, which is the ratio of two independent chi-square random variables, exactly follows the theoretical F distribution. If the random errors in the data are other than normally distributed, the F ratio only approximately follows the theoretical F distribution (McCullagh and Nelder, 1983).

Because the data were very unbalanced, with missing values for numerous combinations of factors, we were unable to conduct standard analyses that included all main effects and all possible interactions. Instead we used a forward-selection procedure in which we first examined the individual factors one at a time and determined which were significant ($P<5\%$). We then examined all pair-wise combinations from the set of the individually significant factors. We tested the interaction of two factors A and B only if both were individually significant and if A given B, and B given A were also both significant.

In our analysis of factors contributing to sablefish bycatch, we examined the significance of the following factors: port (Astoria or Newport); week (April 15–21 was week number one); boat; total hours of towing; weight of whiting landed; time of day (before 10:00, between 10:00 and 15:00, after 15:00); latitude (by half-degree); bottom depth (by 92-m [50-fm] intervals); net depth (by 92-m intervals); and net depth off the bottom (by 92-m intervals).

Estimation of Total Discard

To estimate sablefish bycatch for the entire shore-based whiting fishery in Oregon, we treated our sample data as if they had come from a stratified random survey, with independent random samples taken by port and week, and we used standard estimators for stratified samples (Jessen, 1978). For the ports and time periods covered by the sampling program we estimated the total bycatch using the formula

$$\text{Total} = \sum_i \sum_j (N_{i,j} \cdot \bar{x}_{i,j})$$

where $N_{i,j}$ is the number of whiting deliveries, and $\bar{x}_{i,j}$ is the observed average number of sablefish landed per delivery at the ith port during the jth week. The individual terms $(N \cdot \bar{x})$ are estimates of the total bycatch for each port–week stratum.

We estimated the standard error of the estimated total bycatch using the formula

$$\text{SE(total)} = \sqrt{\sum_i \sum_j \left[N_{i,j} \cdot \text{SE}(\bar{x}_{i,j})\right]^2}$$

where the standard error for a given stratum average was calculated with the formula

$$\text{SE}(\bar{x}) = \sqrt{(1 - n/N) \cdot \sum (x - \bar{x})^2 / \left[n \cdot (n-1)\right]}$$

with n equal to the number of sampled deliveries in the stratum and N equal to the total number of deliveries in the stratum. The individual terms $[N \cdot \text{SE}(\bar{x})]$ are the standard errors for the estimates of total bycatch for each port–week stratum.

We estimated the number of sablefish landed in deliveries not covered by the sampling program (i.e., landings at the start of the fishing season and at two small Oregon ports) by applying the overall season average number of sablefish per delivery.

Results

During the initial months of the 1992 shoreside whiting fishery (April through June), the catches were relatively small. They were taken primarily off the central Oregon coast and landed in Newport (Fig. 1, 2). As the season progressed, the vessels from Newport gradually moved northward. The vessels operating from Astoria fished almost exclusively in the region off the mouth of the Columbia River. The tow locations were generally concentrated along the 183-m (100-fm) isobath (Fig. 1). Other general characteristics of the trips observed at sea are summarized in Table 1.

During 1992, 48,950 t of whiting were landed in Oregon: 10,660 t in Astoria and 38,280 t in Newport

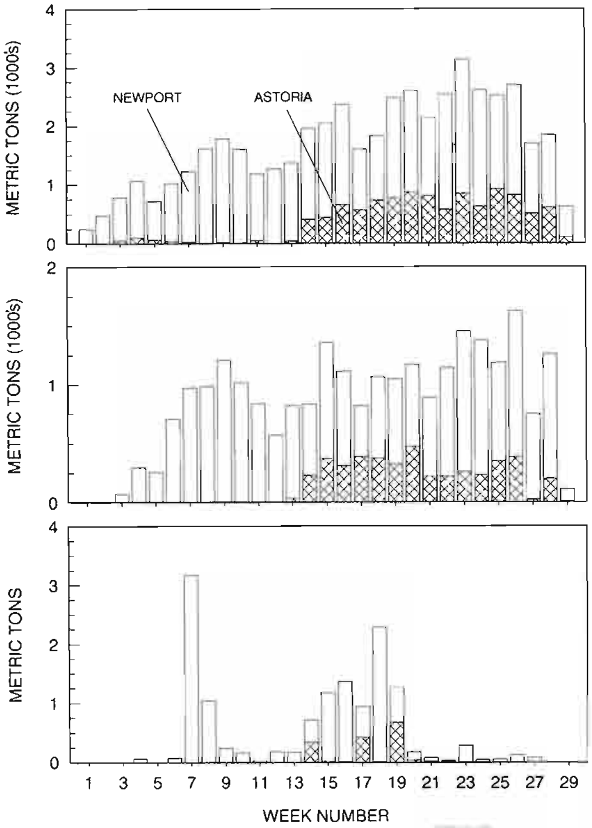

Figure 2

Weekly whiting landings during the 1992 whiting season (upper panel). Weekly whiting landings monitored by the observer program (middle panel). Weekly observed landings of sablefish bycatch in the shoreside deliveries of whiting (lower panel).

Table 1

Characteristics of whiting trips observed at sea.

Characteristic	Min	Max	Mean
Number of tows	1	6	1.6
Total hours of towing	0.2	9.7	2.6
Whiting landings (t)	7.8	75.1	37.5
Time of day (1st tow)	0415	1930	
Bottom depth (m)	101	731	214
Net depth (m)[1]	78	274	159

[1] There were 42 missing values.

Table 2

Fishing trips observed by the Oregon shoreside whiting sampling program in 1992.

Processor/ vessel	Total number of trips	Observed At sea Number	Observed At sea Percent	Observed On shore Number	Observed On shore Percent
Processor 1					
Vessel 1	129	18	14.0	52	40.3
Vessel 2	18	0	0.0	3	16.7
Vessel 3	97	18	18.6	25	25.8
Others	21	3	14.3	4	19.1
Processor 2					
Vessel 1	59	6	10.2	15	25.4
Vessel 2	49	4	8.2	14	28.6
Vessel 3	63	13	20.6	15	23.8
Processor 3					
Vessel 1	72	8	11.1	23	31.9
Vessel 2	70	10	14.3	18	25.7
Vessel 3	71	12	16.9	21	29.6
Vessel 4	75	11	14.7	25	33.3
Vessel 5	63	5	7.9	23	36.5
Others	5	0	0.0	0	0.0
Processor 4					
Vessel 1	65	11	16.9	22	33.9
Vessel 2	85	15	17.7	36	42.4
Vessel 3	103	18	17.5	48	46.6
Vessel 4	99	18	18.2	43	43.4
Vessel 5	92	17	18.5	39	42.4
Others	44	10	22.7	17	38.6
Grand total	1,221	197	16.1	443	36.3

(Fig. 2, upper panel). About half of these landings (4,440 t in Astoria and 20,500 t in Newport) were monitored by the shoreside whiting observer program (Fig. 2, middle panel). Of the 1,312 deliveries of whiting to Oregon processors (390 in Astoria and 916 in Newport), 15% were observed at sea and an additional 34% on shore. Some of the deliveries were made before the start of the monitoring program or included some whiting taken incidentally by groundfish vessels fishing with bottom trawls. Also, a few of the shoreside whiting vessels and processors did not participate in the observer program. The overall observation rate for the processors and vessels that did participate in the program was 16% at sea and 36% on shore (Table 2).

For the whiting trips that were observed, the total bycatch of sablefish was 13.8 t: 1.6 t in Astoria and 12.2 t in Newport. The landings of sablefish bycatch were irregular during the season (Fig. 2, lower panel). The amount of bycatch documented by the observer program was generally greater than that reported on the fish tickets. For example, total sablefish landings from the observed trips were almost as large as the total sablefish landings of 16.4 t reported on the fish tickets for all whiting trips. Because the groundfish bycatch had no market value and because of the importance of quickly removing the bycatch from the whiting to maintain high product quality and plant efficiency, some processors did not attempt to accurately account for the bycatch. This problem was generally resolved by the middle of August.

Analysis of Sablefish Average Size

Although the bycatch of sablefish in the whiting fishery was small in terms of weight, it was large in terms of numbers of fish. The sablefish that were caught were relatively small, averaging about 0.86 kg over the season (Fig. 3, upper panel). During certain weeks of the fishery the mean weight per sablefish was significantly different (P<5%) from the season average (Fig. 3, upper panel), and there were also significant differences in mean weight between sablefish landed by different vessels. However, mean sablefish weight did not vary significantly between fish landed in Astoria and in Newport, or between trips observed at sea and those observed only on shore, and it appeared to be independent of the size of both whiting and sablefish landings (Table 3).

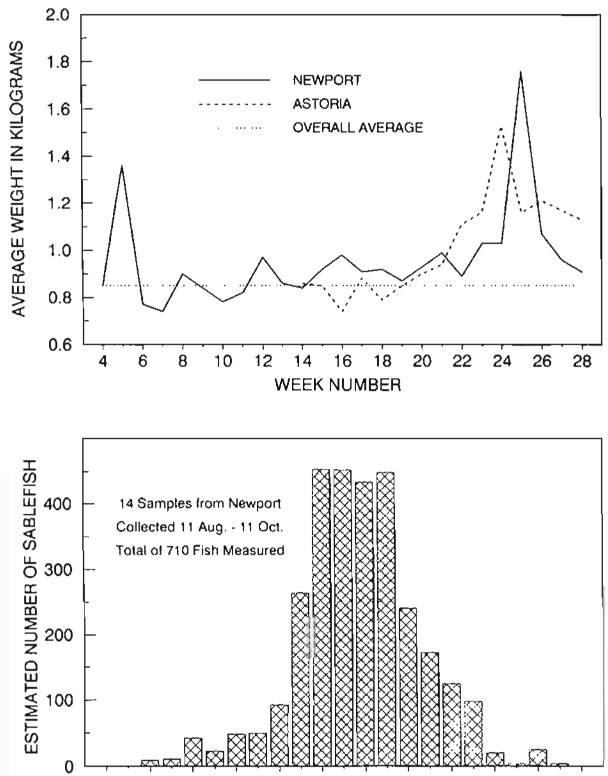

Figure 3

Average fish weight (upper panel) and length composition (lower panel) of sablefish bycatch in shoreside deliveries of whiting. The observations of length-frequency from each subsample were expanded to the estimated total number of sablefish in the delivery by multiplying by the total weight of sablefish over the average weight of the fish in the subsample.

During the latter half of the season the observers collected a limited number of sablefish length-frequency samples from trips landing in Newport. The sablefish in these samples ranged from 33 to 54 cm (Fig. 3, lower panel) and had an average weight of 0.93 kg, which was slightly greater than the season average. Based on the length-at-age information reported in Methot,[2] these sablefish probably ranged from 1.5 to 2.5 years of age.

Analysis of Sablefish Discarded at Sea

Sablefish were discarded at sea during 49 of the trips from Newport that were observed at sea; on 45 of these trips only a portion of the sablefish bycatch was discarded. No discard of sablefish was observed during trips from Astoria. To determine whether the fishermen were discarding mostly small sablefish, for each trip we analyzed the difference in average weight be-

Table 3

Analysis of deviance for average fish weight in the landed sablefish bycatch. The analysis used the identity link with normal errors. Sablefish landed on observed trips had an average weight of 0.863 kg (SE = 0.095). ** = significant at P< 0.01; n.s. = not significant.

			Change in		
Source	Dev[1]	df	Dev	df	F
μ	1,867.8	308			
Port	1,831.5	305	36.3	3	2.02$^{\text{n.s.}}$
Week	998.7	283	869.2	25	9.85**
Boat	1,535.8	290	332.0	18	3.48**
At-sea	1,856.8	307	11.0	1	1.83$^{\text{n.s.}}$
Whiting[2]	1,840.8	307	27.0	1	4.50$^{\text{n.s.}}$
Sablefish[3]	1,850.8	307	17.0	1	2.83$^{\text{n.s.}}$
Boat/Week[4]	760.0	266	238.6	17	4.91**

[1] To account for sample size differences between observations, we used a weighted analysis with weights proportional to sample sizes.

[2] Weight of whiting landed.

[3] Number of sablefish caught.

[4] Boat/Week denotes the model Boat given Week. There were insufficient observations to measure the significance of the Boat·Week interaction.

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[2] Methot, R. 1992. Assessment of the west coast sablefish stock in 1992. *In* Status of the Pacific Coast groundfish fishery through 1992 and recommended biological catches for 1993: stock assessment and fishery evaluation. Appendix D, 96 p. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland, OR 97201.

tween the sablefish that were discarded and those retained. The retained sablefish were marginally heavier than those discarded (Fig. 4) and the average difference in weight between retained and discarded fish (0.063 kg) was statistically different from zero ($P<5\%$, $t=2.49$, 44 df). There were no apparent temporal patterns in the size discrepancy between retained and discarded fish, but there were indications that certain vessels may have selectively retained larger sablefish (Fig. 4, Table 4).

There were 88 trips from Newport that were observed at sea and that caught at least one sablefish, and on 49 of these trips (56%) some sablefish were discarded at sea (Fig. 5, upper panel). Because the number of observations was so limited, we analyzed these data on a biweekly rather than weekly basis. Between time periods and between vessels, there were significant differences ($P<5\%$) in the proportion of trips that discarded sablefish (Table 5). Although one might expect that a crew would be more likely to sort through a catch and discard bycatch when the whiting catches were small, the amount of whiting caught on a trip did not appear to influence whether sablefish were discarded. On the 49 trips that caught and discarded sablefish, a total of 5,639 sablefish were caught; 1,413 (25%) were discarded at sea (Fig. 5, lower panel). This proportion seemed stable through time and between vessels, and seemed independent of the size of both whiting and sablefish catches (Table 6).

Analysis of Trips Observed at Sea That Caught Sablefish

Sablefish were caught and either landed or discarded on 82 of the 146 trips (56%) that were observed at sea and that had well-defined characteristics (as described in "Materials and Methods"; Fig. 6, upper panel). The proportion of trips that caught sablefish was apparently stable with regard to all factors examined: port, week, boat, hours of towing, whiting landed, time of day, latitude, bottom depth, net depth, and net depth off bottom (Table 7). However, when sablefish were taken, the size of the catch (fish per trip) was highly overdispersed (range 1–660; $\bar{x}=49.1$, SD=108.6; Fig. 6, lower panel).

For those trips in the previous analysis that caught at least one sablefish, we examined the number of sablefish caught to determine influential variables. We treated the sablefish bycatch as a Poisson-distributed random variable for which variance was proportional to the expected value (McCullagh and Nelder, 1983). Of the factors examined, the only significant determinant of the sablefish bycatch ($P<1\%$) was the week of the trip, which accounted for about 53% of the total variability

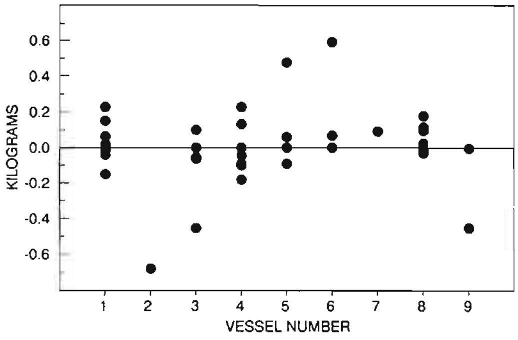

Figure 4
Differences between mean weights of retained and discarded sablefish bycatch (retained – discarded). The data are grouped by vessel, and each point represents one fishing trip.

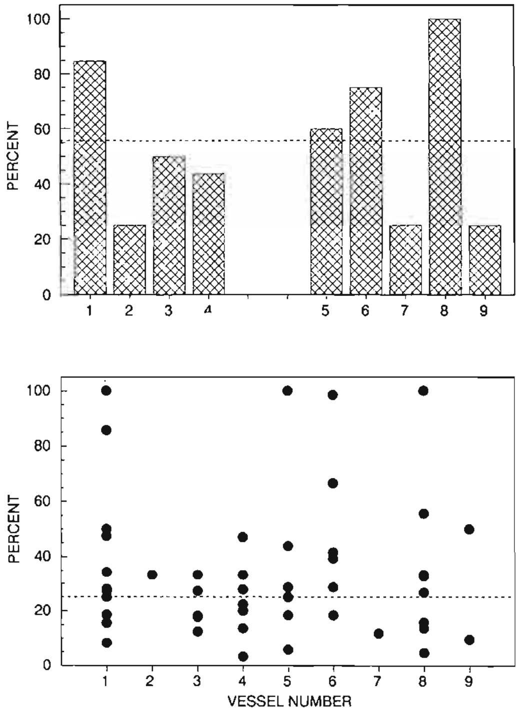

Figure 5
Percentage of whiting trips that discarded sablefish (upper panel), and percentage of the sablefish bycatch that was discarded (lower panel). The data, for observed trips from Newport, are grouped by vessel; each point in the lower panel represents one fishing trip. Sablefish were discarded on 49 of 88 trips (56%, dashed line in upper panel). When sablefish were discarded, on average 25% of the catch was discarded (dashed line in lower panel).

(Table 8). The number of sablefish caught apparently was independent of port, boat, hours of towing, the size of the whiting catch, time of day, latitude, bottom depth, net depth, and net depth off the bottom.

Analysis of All Observed Trips That Landed Sablefish

Sablefish were landed on 310 of the 648 deliveries (56%) observed during the 1992 whiting fishery. The number of sablefish landed ranged from 0 to 1,569 fish per delivery (mean=24.6, SE=106.9). To determine the influential variables we analyzed the number of sablefish landed (as opposed to the number caught), including trips that landed zero sablefish. We treated the number of sablefish landed as a Poisson-distributed random variable. The single most significant factor was week, accounting for about one-third of the total variation in the number of sablefish landed per delivery (Table 9). The factors port, boat, and size of whiting catch landed (pounds) were also highly significant ($P<1\%$). The number of sablefish landed apparently was unaffected by whether or not the trip was observed at sea, however. Port, boat, and size of whiting catch remained significant factors even when given the variation by week. The observations were too sparse to measure the boat·week or port·week interactions. The whiting catch·week interaction was not significant.

Table 4

Analysis of deviance for average fish weight of discarded versus retained sablefish for Newport trips observed at sea. The analysis used the identity link with normal errors. The mean difference between the average weights of retained and discarded fish was 0.0625 kg (SE = 0.0251). ** = significant at $P < 0.01$; n.s. = not significant.

			Change in		
Source	Dev[1]	df	Dev	df	F
µ	109.4	44			
Week	64.5	30	44.9	14	1.49$^{\text{n.s.}}$
Boat	47.8	36	61.6	8	5.80**

[1] To account for sample size differences between observations, we used weighted sums of squares with weights inversely proportional to the variance of the difference between average retained and the average discarded fish:

$$\text{weight} = 1/(1/n_r + 1/n_d),$$

where n_r and n_d are the sample numbers of retained and discarded fish. This is analogous to the standard procedure for comparing two groups with unequal sample sizes (Snedecor and Cochran, 1967).

Table 5

Analysis of deviance for the proportion of Newport trips observed at sea that discarded sablefish. The analysis used the logit link with binomial errors. * = significant at $P < 0.05$; n.s. = not significant.

			Change in		
Source	Dev	df	Dev	df	F
µ	120.9	87			
Biweek	91.5	76	29.4	11	2.22*
Boat	90.2	77	30.7	10	2.62*
Whiting[1]	118.3	86	2.5	1	1.84$^{\text{n.s.}}$
Biweek/Boat[2]	64.2	66	25.9	11	2.42*

[1] Whiting landed weight.

[2] There were insufficient observations to measure the significance of the Boat·Biweek interaction.

Estimates of the Total Bycatch of Sablefish

To estimate the total bycatch of sablefish we calculated the average number of sablefish landed per delivery by port and week, and multiplied these averages by the total number of deliveries (Table 10). We estimate that 27,497 sablefish (SE=2,686.7) were landed at Astoria from July 12 through October 30 and at Newport from May 1 through October 30. Using the overall season average of 24.64 sablefish per delivery (SE=4.20) (Table 9), we estimate that an additional 1,158 sablefish (SE=197.4) were landed by the 47 whiting deliveries made in Astoria and Newport before the start of the observer program. During the whiting season six addi-

Table 6

Analysis of deviance for the proportion of the sablefish bycatch discarded on Newport trips. The analysis used the logit link with binomial errors. n.s. = not significant. The fraction of the sablefish bycatch that was discarded appeared to be independent of all factors examined.

			Change in		
Source	Dev	df	Dev	df	F
µ	1,131.6	48			
Week	715.9	33	415.7	15	1.28 n.s.
Boat	989.0	40	142.6	8	0.72 n.s.
Whiting[1]	1,077.9	47	53.7	1	2.34 n.s.
Sablefish[2]	1,016.8	47	114.8	1	5.31 n.s.

[1] Weight of whiting landed.

[2] Number of sablefish caught.

tional deliveries of whiting were made to two Oregon ports other than Astoria and Newport, which we estimate landed 148 sablefish (SE=25.2). For the entire Oregon shoreside whiting fishery we estimate that 28,803 sablefish were landed (SE=2,659.9).

The estimated number of sablefish landed does not include sablefish that were caught and then discarded. From our analysis of the observed sablefish discards (Table 5), we estimate that sablefish were discarded on 270 whiting trips (56% of the trips from Newport). From the overall season average for Newport of 28.85 sablefish per delivery, and from our finding that on average 25% of the sablefish catch was discarded (Table 6), we estimate that 2,597 sablefish were discarded at sea:

$$2{,}597 = \frac{25\% \text{ discarded}}{75\% \text{ retained}} \cdot (270 \text{ trips}) \cdot (28.85/\text{trip}).$$

We are uncertain whether any of these fish survived being caught and discarded.

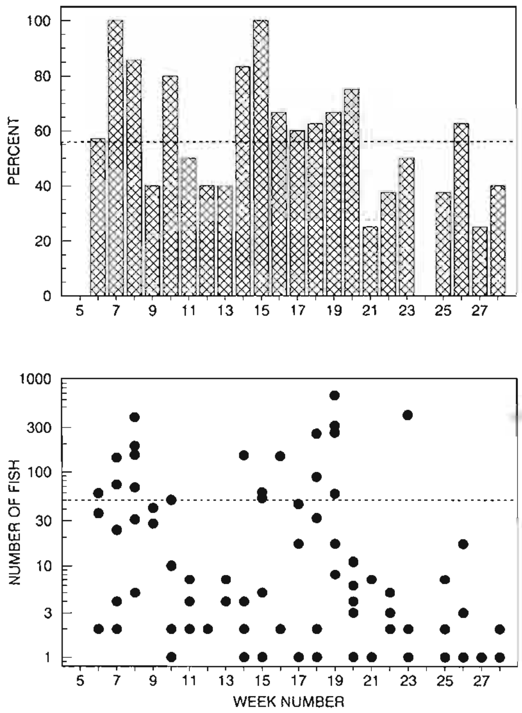

Figure 6

Percentage of whiting trips that caught sablefish (upper panel), and number of sablefish caught (lower panel). The data, for all observed trips with well-defined characteristics (see text), are grouped by vessel; each point in the lower panel represents one fishing trip. Sablefish were caught on 82 of 146 trips (56%, dashed line in upper panel). When sablefish were caught, the average catch was 49 fish per trip (dashed line in lower panel).

Table 7

Analysis of deviance for the proportion of trips observed at sea that caught sablefish. The analysis used the logit link with binomial errors. n.s. = not significant. The fraction of trips catching sablefish appeared to be independent of all factors examined.

			Change in		
Source	Dev	df	Dev	df	*F*
μ	200.2	145			
Port	196.1	144	4.1	1	3.01 n.s.
Week	162.8	122	37.3	23	1.22 n.s.
Boat	178.7	129	21.5	16	0.97 n.s.
Hours towed	198.2	144	2.0	1	1.43 n.s.
Whiting	195.0	144	5.2	1	3.82 n.s.
Time of day	198.4	143	1.8	2	0.64 n.s.
Latitude	179.0	134[1]	12.7	5	1.90 n.s.
Bottom depth	191.1	139	9.1	6	1.10 n.s.
Net depth	148.5	105[2]	1.5	3	0.35 n.s.
Off bottom	141.6	103[2]	8.4	5	1.23 n.s.

[1] There were 6 missing values.
[2] There were 37 missing values.

Table 8

Analysis of deviance for the number of sablefish taken on trips observed at sea that caught sablefish. The analysis used the logarithm link with Poisson errors. When sablefish were caught, the number of sablefish caught per trip ranged from 1 to 660, and varied significantly by week. ** = significant at $P < 0.01$; n.s. = not significant.

			Change in		
Source	Dev	df	Dev	df	*F*
μ	10,667.1	81			
Port	10,657.0	80	10.1	1	0.08 n.s.
Week	5,043.8	60	5,623.3	21	3.19 **
Boat	7,480.6	65	3,186.5	16	1.73 n.s.
Hours towed	10,659.2	80	8.0	1	0.06 n.s.
Whiting	10,201.3	80	465.8	1	3.65 n.s.
Time of day	10,555.4	79	111.7	2	0.42 n.s.
Latitude	9,712.4	73[1]	814.9	5	1.23 n.s.
Bottom depth	10,452.5	78	214.6	3	0.53 n.s.
Net depth	7,058.5	56[2]	357.7	3	0.95 n.s.
Off bottom	7,189.8	57[2]	226.4	2	0.90 n.s.

[1] There were 3 missing values.
[2] There were 22 missing values.

Discussion

The results from the sampling program for the 1992 shoreside whiting fishery in Oregon indicate that this fishery removed a relatively modest number of sablefish and that these were mostly small. Also, despite high variability in the data, we were able to estimate the overall landed sablefish bycatch with reasonable precision, attaining a coefficient of variation of <10%. We were less successful, however, at determining what factors influence the amount of sablefish bycatch, although many different factors were considered.

In our analyses of average sablefish weight (Table 3) and numbers of sablefish landed (Table 9) we found no significant differences between trips observed at sea and those observed only on shore. This confirms our belief that fishermen did not significantly modify their behavior when an observer was on board during a trip.

Because we were puzzled by the apparent lack of sablefish discard on trips from Astoria, we reexamined the data on discards for trips from Astoria to determine whether the observers on these trips may have inadvertently failed to record discards. We found that on the trips from Astoria there were observations of discards of yellowtail rockfish; other rockfish, *Sebastes* spp.; Pacific mackerel, *Scomber japonicus*; jack mackerel, *Trachurus symmetricus*; shad, *Alosa sapidissima*; and sharks. In general there were fewer discards on trips from Astoria than on trips from Newport. We do not know the cause for this.

Table 9

Analysis of deviance for the number of sablefish landed on observed trips. The analysis used the logarithm link with Poisson errors. The number of sablefish landed varied significantly by week, by port, by boat, and with the whiting landings, but did not depend on whether a trip was observed at sea. * = significant at $P < 0.05$; ** = significant at $P < 0.01$; n.s. = not significant.

			Change in		
Source	Dev	df	Dev	df	*F*
μ	75,261.3	647			
Port	73,647.4	644	1,613.9	3	4.70 **
Week	49,668.5	621	25,572.8	26	12.30 **
Boat	64,581.1	628	10,680.2	19	5.47 **
At sea	75,259.3	646	2.0	1	0.02 n.s.
Whiting	73,999.8	646	1,261.5	1	11.01 **
Boat/Week[1]	39,983.0	602	9,685.5	19	7.68 **
Port/Week[2]	47,229.5	618	2,439.0	3	10.64 **
Whiting/Week	48,016.7	620	1,671.8	1	21.59 **
Whiting·Week/ Whiting + Week	45,795.4	594	2,221.3	26	1.11 n.s.
Port/Boat + Week	39,906.6	599	76.4	3	0.38 n.s.
Whiting/Boat + Week	39,523.6	601	459.4	1	6.99 *

[1] Boat/Week denotes the model Boat given Week. There were insufficient observations to measure the significance of the Boat·Week interaction.

[2] There were insufficient observations to measure the significance of the Port·Week interaction.

In our analysis of the trips observed at sea that caught sablefish, our results are consistent with the notions that whiting trips randomly encountered sablefish schools and that the number of sablefish per school varied randomly. This type of compound stochastic process can produce highly overdispersed catches (Sampson, 1988). It is somewhat puzzling that in our analyses of the proportion of trips that caught sablefish (Table 7) and of the numbers of sablefish caught on those trips (Table 8) we found that the size of the whiting landings had no significant effect on sablefish bycatch. Although these results may be artifacts of the relatively small sample sizes, another plausible explanation is that sablefish schools were randomly distributed with respect to whiting schools and that different stimuli prompted school formation in the two species.

Although it is common to report bycatch as a rate per landing of the target species, we did not feel this was appropriate for the sablefish bycatch in the Oregon shoreside whiting fishery because our observations of bycatch were on a trip-by-trip basis, rather than from random samplings of whiting landings. Also, in our analysis of the number of sablefish landed (Table 9), we found a significant intercept in the regression with whiting landings, which is inconsistent with the idea that sablefish bycatch is strictly proportional to whiting landings.

Although the shore-based whiting fishery in Oregon produced a small bycatch of sablefish, the impact of the entire U.S. Pacific whiting fishery was much greater. We have no information about the bycatch of sablefish in shoreside deliveries of whiting to ports in Washington and California. But during the 1992 season the factory trawlers operating at sea reportedly caught a total of 70.3 metric tons of sablefish (King[3]). If these sablefish were similar in size to the fish observed in the shore-based fishery, then the offshore fishery caught about 81,470 sablefish, and more than 110,000 sablefish were removed by the offshore and Oregon shoreside components of the 1992 whiting fishery. This represents 0.9%–

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[3] King, K. 1992. Progress report—1992 whiting fishery. *In* Briefing book for the November 1992 council meeting, supplemental attachment G.2.B. Pac. Fish. Manage. Council, Metro Center, Ste. 420, 2000 S.W. First Ave., Portland, OR 97201.

Table 10

Observed average and estimated total sablefish bycatch by week and port.

	Astoria						Newport					
Week no.	No. trips		Fish/trip		Tot. no. fish		No. trips		Fish/trip		Tot. no. fish	
	Tot.	Samp.	Mean	SE	Est.	SE	Tot.	Samp.	Mean	SE	Est.	SE
1	0	0					10	0				
2	0	0					15	0				
3	3	0					23	2	0.0	0.0	0.0	0.0
4	5	0					25	7	12.1	9.9	303.6	247.1
5	3	0					18	7	0.1	0.1	2.6	2.0
6	4	0					26	18	5.6	1.5	145.9	39.6
7	1	0					29	22	190.8	40.0	5,533.7	1,160.9
8	1	0					39	24	43.1	10.1	1,680.2	395.3
9	1	0					45	32	10.2	1.7	457.0	75.8
10	1	0					44	29	8.2	1.7	361.1	75.0
11	2	0					29	21	1.7	0.3	49.7	7.9
12	1	0					33	15	9.9	5.0	327.8	165.3
13	3	2	0.0	0.0	0.0	0.0	37	22	9.3	4.8	344.8	178.8
14	15	9	51.7	30.4	775.0	455.4	40	16	28.6	10.5	1,145.0	419.2
15	18	15	2.0	0.7	36.0	12.1	39	24	52.9	16.0	2,063.8	622.2
16	27	13	0.6	0.3	16.6	9.2	38	18	78.6	28.8	2,987.2	1,095.6
17	20	14	44.4	18.4	888.6	368.0	23	9	59.2	34.6	1,362.1	795.4
18	27	14	0.7	0.3	19.3	6.9	24	16	149.0	36.0	3,576.0	863.9
19	29	12	59.1	41.8	1,713.4	1,213.5	38	15	47.9	16.0	1,821.5	606.6
20	29	16	2.4	1.2	68.9	35.1	40	16	9.9	4.6	397.5	184.5
21	28	8	2.5	2.0	70.0	55.9	34	19	3.1	1.2	103.8	40.3
22	23	9	1.8	0.6	40.9	14.9	41	20	0.9	0.3	36.9	10.8
23	27	9	1.0	0.5	27.0	12.2	47	24	14.0	9.7	656.0	456.1
24	20	7	0.9	0.3	17.1	5.5	42	25	1.6	0.4	67.2	17.5
25	31	11	0.5	0.2	14.1	7.0	35	17	1.7	0.5	59.7	16.2
26	30	13	0.2	0.1	6.9	2.7	41	27	4.7	1.5	191.3	60.0
27	18	1	0.0	0.0	0.0	0.0	27	17	4.1	1.9	111.2	50.5
28	19	7	0.4	0.2	8.1	4.5	25	21	0.4	0.1	9.5	1.3
29	4	1	0.0	0.0	0.0	0.0	9	2	0.0	0.0	0.0	0.0
Total	390	161			3,702.0	1,349.3	916	485			23,795.1	2,323.3

1.8% of the estimated 6–12 million two-year-old sablefish that have recruited annually to the sablefish fishery in recent years (Methot[2]). In terms of sablefish biomass these removals represent 95.2 t or 1% of the 8,900 t coastwide allowable catch for 1992 (Pacific Fishery Management Council[4]). This is a small source of mortality compared to the assumed 1,220 t of sablefish discarded coastwide by the groundfish trawl fishery in 1992 (Methot[2]).

Acknowledgments

Many people contributed to the success of the whiting observation program, which provided the basic data used in this research project. However, we owe special thanks to Steve Kupillas, our whiting sampling crew chief, and to Diane Rolph and Kathy Murphy, our data entry staff. We are also grateful to Oregon's whiting fishermen for cooperating with this program.

Literature Cited

Baker, R. J. and J. A. Nelder.
1985. The GLIM System Release 3.77. Numerical Algorithms Group Ltd., Oxford, 305 p.

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[4] Pacific Fishery Management Council. 1992. Status of the Pacific Coast groundfish fishery through 1992 and recommended acceptable biological catches for 1993, 80 p. Pac. Fish. Manage. Council, Metro Center, Ste. 201, 2000 S.W. First Ave., Portland, OR 97201.

Draper, N. R., and H. Smith.
1966. Applied regression analysis. John Wiley, New York, 407 p.

Jessen, R. J.
1978. Statistical survey techniques. John Wiley, New York, 520 p.

McCullagh, P., and J. A. Nelder.
1983. Generalized linear models. Chapman and Hall, London, 261 p.

Sampson, D. B.
1988. Fish capture as a stochastic process. J. Cons. Int. Explor. Mer 45:39–60.

Snedecor, G. W., and W. G. Cochran.
1967. Statistical Methods, sixth ed. Iowa State Univ. Press, Ames, 593 p.

Sablefish, *Anoplopoma fimbria*, Stock Assessment in the Inside Waters of Southeast Alaska

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ABSTRACT

The Alaska Department of Fish and Game has conducted annual sablefish stock assessment surveys using longline gear in Chatham and Clarence Straits of southeast Alaska from 1988 through 1992. A total of 74 stations (36 in Clarence Strait and 38 in Chatham Strait) have been repeatedly sampled from 1989 to 1992. The primary objectives were to collect biological data and develop a relative abundance indexing program. A general linear multivariate model (GLMM) was used to estimate the power of the survey to detect linear trends over a 4-year period and between-year changes in CPUE. The current survey would detect a linear change of 20% in Clarence Strait and 22% in Chatham Strait over a 4-year period (power=0.80, α=0.10). For between-year changes in CPUE, the GLMM could detect a 22% change in CPUE for Clarence Strait and a 28% change for Chatham Strait (power=0.80, α=0.10). No significant linear trend was detected in either area. Significant differences in CPUE between years were detected in both areas; however, these differences were followed by significant but opposite differences in CPUE the following year. Biological sampling shows substantial differences in size and age composition of sablefish between the two areas. Sampling in Chatham Strait indicates an adult resident population of sablefish, whereas sampling in Clarence Strait indicates a high proportion of juvenile fish which leave the area as they mature.

Introduction

Sablefish, *Anoplopoma fimbria*, has been harvested in the internal waters of southeast Alaska since the early 1900's, and records indicate that the fishery was well established by 1907. Most of the effort has occurred in the Northern Southeast Inside (NSEI) Subdistrict, where harvests peaked in the mid-1940's (Bracken, 1983a). Regulations in various forms covering seasons, gear, and quotas were in effect in the NSEI and the Southern Southeast Inside (SSEI) Subdistricts[2] from 1945 through 1984. The regulations are summarized in Bracken (1983a). The average landed weight (headed and gutted) of sablefish from the internal waters of southeast

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[1] Now retired. Present address: Box 1201, Petersburg, AK 99833.

[2] The NSEI and SSEI are subdistricts of the Southeast District. Districts and subdistricts are defined in the Alaska Administrative Code, Chapter 5AAC 28.105.

Alaska during the period 1987–92 was 3.1 million pounds, with an exvessel value of $5.2 million.

In 1985 the state of Alaska adopted a license-limitation program for both the SSEI and NSEI Subdistricts. This program was implemented in addition to the season, gear, and quota regulations in place at the time. Although the intent of the program was to provide for a more orderly fishery, it resulted in an increased number of vessels and a dramatic increase in the efficiency of the fleet in both areas (Bracken, 1997). Because of those changes, fishery CPUE data were no longer considered a valid indicator of stock condition.

In 1988 the Alaska Department of Fish and Game (ADFG) began annual stock assessment surveys in the SSEI and NSEI Subdistricts in order to develop a source—independent of the commercial fishery—of reliable information on the status of sablefish stocks. Survey results from 1988 through 1992 are described in this report.

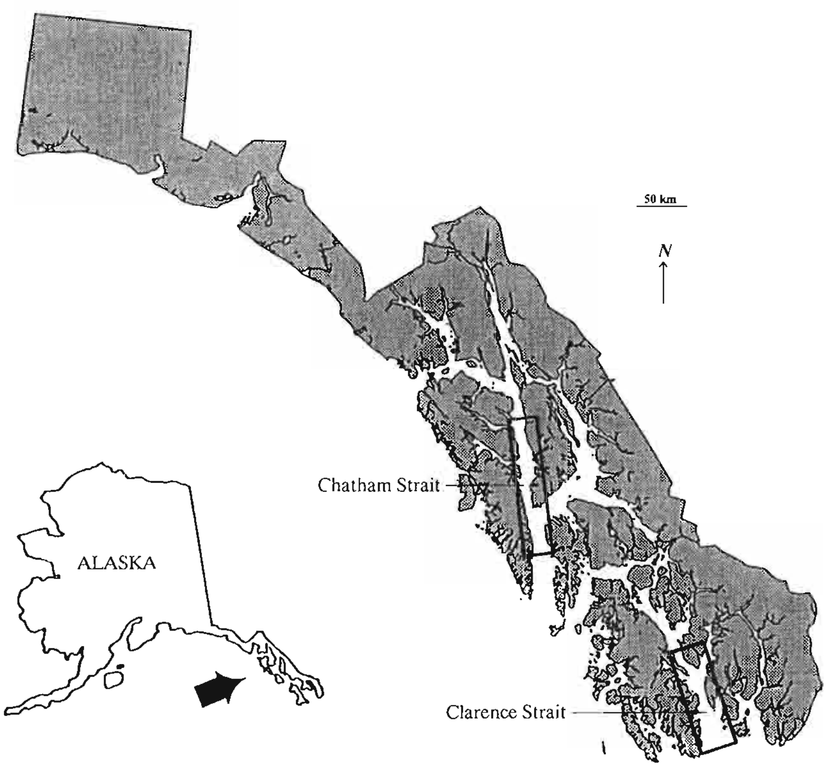

Figure 1
Southeast Alaska, showing the Chatham Strait and Clarence Strait survey areas.

Methods

Survey Activities

The research was conducted in the Clarence Strait portion of the SSEI Subdistrict and the Chatham Strait portion of the NSEI Subdistrict (Fig. 1). The SSEI Subdistrict fishery has usually begun in mid-June, and the survey in that area was conducted during the last two weeks of May. The NSEI Subdistrict fishery has usually begun in the third week of September, and the survey there was conducted from mid-August to as late as September 10. Previous research indicated substantial movement of sablefish into and out of both inside subdistricts (Bracken, 1982, 1983b; Bracken and Richardson[3]), but neither the extent of movement nor how that movement affects the abundance of sablefish there was known. Therefore, conducting the surveys immediately before the fishery was believed to provide the best indicator of stock condition at the time of the fishery.

Survey stations were randomly selected within the three subareas of each subdistrict where most of the harvest had occurred in previous years. Each subarea was overlaid with a grid to facilitate the random selection of stations. To ensure that the survey concentrated on productive sablefish habitat, only points that corresponded to chart depths greater than 200 fathoms (366 m) were selected as sample stations. Once established, the same stations were fished each year, since this is the best method for estimating change in abundance over time (Cochran, 1977).

Longline gear is the only legal gear for the commercial sablefish fishery in the NSEI Subdistrict and is the predominant gear in the SSEI Subdistrict. Longline gear was used for the survey so that the survey results could be compared directly to fisheries data. The number of stations, the number of hooks per station, and the soak time of each set were constrained to a large extent by the time available for the survey. The surveys were conducted from a chartered commercial fishing vessel. State contract regulations limit short-term charters to no more than 14 days, so the surveys were designed to be completed within a 14-day period.

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[3] Bracken, B. E., and B. J. Richardson. 1993. Movement of sablefish tagged in the internal waters of southeast Alaska. Presented at the Intl. Symp. on the Biology and Management of Sablefish, *Anoplopoma fimbria*, Seattle, WA. Box 667, Petersburg, AK 99833.

Snap-on longline gear was used for the survey. Snaps were 13 cm long with 25 cm of gangion line between the snap and the hook. Circle hooks with 1.2 cm between the hook point and the shank were used. Hooks were baited with chopped herring and spaced at approximately 3-meter intervals along the groundline. Groundline diameter was 8 mm (5/16"), and the total length of groundline deployed for each set was approximately 1,600 m. Hooks were counted as they were deployed, and a marker was attached after every 100 hooks. Halibut anchors weighing 20.5 kg were used at each end of the set. Sets were made in the same direction as the tidal current and allowed to soak one hour from the time the last anchor went overboard to the time the first buoy was retrieved and hauling began. The survey gear was modified for the surveys conducted in Chatham Strait in 1991 and 1992: 2.26-kg lead weights were attached to the groundline after every 100 hooks to increase the likelihood that all portions of the groundline reached the bottom in areas of rough topography.

During retrieval of each longline set, the species of each fish brought to the surface and the condition of empty hooks (i.e., baited, unbaited, or broken) was recorded. The 100-hook subsections within a set were tallied separately to obtain estimates of variance among the subsections of each set as well as between sets. This also allowed us to include valid subsections in the analysis of catch per of unit effort (CPUE) rather than excluding the data for an entire station if major gear snarls occurred. CPUE was calculated as the mean number of sablefish per 100 hooks (sablefish/hook).

In 1988, the first year of the survey, we ran three 1,000-hook stations per day. We conducted a variance component analysis (Snedecor and Cochran, 1989) on the 1988 data to determine a combination of number of stations and numbers of hooks per station that would minimize the variance of relative abundance measures. This analysis indicated greater variance among stations than among 100-hook subsections within a station. We therefore increased the number of stations sampled in both areas and accepted the possible consequence of fishing fewer hooks per station due to time constraints. Specifically, in 1989 we increased the number of stations fished per day to four and decreased the number of hooks per station to 500. In all other aspects of the survey, the methods remained the same. In Chatham Strait 38 stations and in Clarence Strait 36 stations were sampled annually from 1989 to 1992 .

Every tenth sablefish caught was sampled for length, weight, sex, and maturity, and its otoliths were extracted for later age determination. Age was read with the break-and-burn method according to guidelines set by the Committee of Age Reading Experts. Otoliths sampled during the 1988–91 sablefish surveys were studied at the ADFG age reading lab in Kodiak; otoliths collected during the 1992 survey were read by a different reader at the ADFG age reading lab in Juneau. Between-reader precision estimates have not yet been made.

The survey design for the 1988 and 1989 surveys included tagging studies. Fish caught at every third station were tagged with Floy[4] anchor tags and released. A total of 2,889 sablefish from both areas were tagged and released. Tagging was discontinued after 1989 because all fish caught were sold to recover charter expenses.

Analysis of Relative Abundance

The principal objective of the survey was to estimate, from repeated longline surveys of the same sampling stations in Chatham and Clarence Straits, the statistical power (1–β) of a general linear multivariate model (GLMM) to detect future changes in sablefish CPUE. Power refers to the probability of statistically detecting a difference of a given magnitude when such a difference actually exists. Generally, the power of a test is influenced by the alpha level; the variance (and, in the case of tests involving multivariate or repeated-measures data, the covariance); and the size of the difference or change in mean levels of various treatments of interest. All else remaining the same, the power of the test generally increases with an increased alpha level or size of the difference to be detected, and decreases with increased variance in the parameter of interest. We used the GLMM because it is a general model that permits testing for trend in repeated measurements, such as an annual fishery survey. The GLMM may be expressed as

$$\mathbf{Y} = \mathbf{XB} + \mathbf{e}$$

where $\mathbf{Y}$ is an $N \times p$ matrix of responses (i.e., CPUE; here, N refers to the total number of fishing stations, and p refers to the number of repeated, annual measures of CPUE at each station [$p = 4$, corresponding to the four years 1989–92]); $\mathbf{X}$ is an $N \times 1$ design matrix; $\mathbf{B}$ is a $1 \times p$ matrix of hypothesized parameters; and $\mathbf{e}$ is an $N \times p$ matrix of errors.

For these analyses, we estimated the power of tests to detect a linear trend in sablefish CPUE over 4 consecutive years and to detect differences between 2 years. In addition to estimating the power of the GLMM to detect future trends in abundance, we also tested for significant linear trends in CPUE and for differences in CPUE between successive years. The power estimates addressed future survey design, whereas the tests for

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[4] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

linear trend and differences between successive years were specific to the data from 1989 through 1992.

We used the methods and software of Muller et al. (1992) to estimate the power of the GLMM to detect differences in sablefish CPUE. The software consists of a series of SAS PROC IML modules (SAS, 1988). Required input for the power analysis includes 1) estimates of mean CPUE; 2) the null hypothesis (e.g., H_0: no linear trend in sablefish CPUE) in the form of a hypothesis matrix; and 3) estimates of the variance-covariance structure of the populations of interest, or the variance when testing for differences between years. Estimates of the variance-covariance structure were obtained from the 1989–92 data in the course of testing for differences in CPUE among the four specific years. The null hypothesis may be expressed as

$$\mathrm{H}_0\textbf{: } \mathbf{CBU} = \Xi_0$$

where **C** is a matrix specifying a contrast among predictors (in this case the matrix is [1], since there are no predictors. If, for example, it were desirable to test for differences in 4-year CPUE trends between Chatham and Clarence Straits, then the predictor would be areas, and **C** could be specified as [1–1]); and **U** is a matrix specifying a contrast among repeated measures (this is the contrast of interest in testing for a significant linear trend in CPUE and therefore for estimating the power of that test). An example of a **U** matrix appropriate for testing for a 4-year linear trend in CPUE would be

$$[-0.67082 \quad -0.223607 \quad 0.223607 \quad 0.67082]'.$$

This is very similar to a set of orthogonal contrasts, [–3 –1 1 3], which might be used to test for linearity in curvilinear regression with four levels of the independent variable (e.g., p. 678 in Sokal and Rohlf, 1981):

$$\Xi_0 = 0, \text{ for the case of testing for linear trend.}$$

An example of a representative **B** matrix is

$$[0.093 \quad 0.086 \quad 0.079 \quad 0.073].$$

The elements of this particular **B** matrix represent a sequence of CPUE's (sablefish/hook) that correspond to a hypothesized approximate 21% decline in CPUE over 4 years.

The methods outlined here are generically similar to those used to conduct linear comparisons for analysis of variance (ANOVA; e.g., p. 530 in Sokal and Rohlf, 1981, or p. 226 in Snedecor and Cochran, 1989), or to test for linearity in curvilinear regression using orthogonal polynomials (e.g., p. 678 in Sokal and Rohlf, 1981, or p. 409 in Snedecor and Cochran, 1989).

Although it may be intuitively appealing to use ANOVA to test for interannual trends in CPUE, with years as treatments, a simple ANOVA model is not appropriate because the repeated annual measurement of CPUE at the same stations probably results in nonindependence of CPUE measurements between years, a violation of the independence assumption necessary for valid application of ANOVA. Therefore a repeated-measures or multivariate approach, which accounts for the covariance in CPUE among years, is appropriate for testing for linear trend and for estimating the power of such a test. We used the SAS GLM procedure (SAS, 1987) to test for differences between the 4 specific years.

We estimated the power associated with linear changes of 10%, 15%, 20%, 25%, and 30% in CPUE over a future 4-year period. The beginning reference CPUE for the changes was the mean CPUE from the 4 years 1989–92. For tests of differences between 2 years, we estimated the power to detect changes of 10%, 15%, 20%, 25%, 30%, 35%, and 40% over a 2-year period using the same 1989–92 means. For all actual tests of hypothesis and power estimates we used an alpha level of 0.10. Increasing or decreasing the alpha level would serve to increase or decrease power.

Tests for linear trends in CPUE for each area for the 4 specific years, 1989–92, were conducted with a GLMM. We used the PROFILE transformation in the SAS GLM procedure (SAS, 1987) to test for differences in consecutive years 1989–90, 1990–91, and 1991–92. These tests were conducted with CPUE expressed both as sablefish/hook and kilograms/hook. We computed measures of kilograms/hook as the product of the mean weight of sablefish from our biological samples and the number of sablefish/hook for each station, by year and area.

We examined plots of survey CPUE versus the subsequent commercial fishery mean CPUE to explore the relation between the two measures. The commercial fishery CPUE was estimated from data obtained in interviews with skippers.

Results

CPUE for Longline Subsections

Histograms of CPUE for longline subsections at each station did not indicate any consistent trends in CPUE within each set. However, sets made in shallower water generally had higher catch rates for all subsections than sets made in deeper water. It is presumed that this was primarily because the deeper sets were on the bottom for less time before being retrieved.

Tests for Linear Trend and Between-Year Differences, 1988–92

In Chatham Strait, mean CPUE expressed as sablefish/hook ranged from a high of 0.156 sablefish/hook in 1991 to a low of 0.118 sablefish/hook in 1992 (Table 1). There was no statistically significant trend in CPUE across the 4 years (*P*=0.88); however, there was a significant increase (*P*=0.049) in CPUE between 1990 and 1991, followed by a significant decrease (*P*=0.011) between 1991 and 1992. The relative pattern of CPUE plotted by year was similar when expressed as kilograms/hook, but there were no significant linear trends or differences between consecutive years (Table 2).

In Clarence Strait, mean CPUE varied from a low of 0.082 sablefish/hook in 1990 to a high of 0.10 in 1991 (Table 1). Again, there was no significant linear trend (*P*=0.211) in CPUE across the 4 years. There was a significant decline (*P*=0.081) from 1989 to 1990, followed by a significant increase (*P*=0.026) from 1990 to 1991. As in Chatham Strait, patterns similar to CPUE (sablefish/hook) were evident for CPUE (kilograms/hook), but again there were no significant linear trends or differences between consecutive years (Table 2).

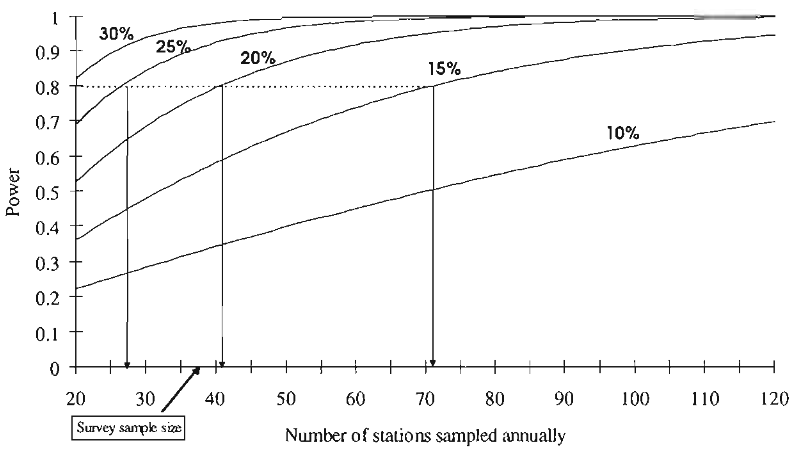

Figure 2

Power of the GLMM to detect a linear trend (percentage increase or decrease) in Chatham Strait survey sablefish CPUE over four consecutive years. Vertical arrows indicate the approximate sample sizes needed to detect changes of 15%, 20%, and 25% in CPUE with a power of 0.8 (α=0.10).

Power Estimates

Assuming an annual sample size of 40 stations and using an alpha level of 0.10 and a power of 0.8, the survey should be able to detect a linear trend that results in approximately a 20% change in sablefish CPUE over 4 years for both areas. A sample size of 41 stations is needed in Chatham Strait (Fig. 2) to achieve the same power as 38 stations in Clarence Strait (Fig. 3). This slightly greater power for the Clarence Strait survey is due primarily to its slightly lower variance in CPUE, as well as to differences in covariance of CPUE among years for the two areas. Our focus on a power of 0.8, α = 0.1, and the hypothetical percentage changes in CPUE do not imply that these are the best criteria to use. These are primarily examples, although we feel the use of α = 0.1 and a power of 0.8 are reasonable objectives to strive for.

Table 1

Sablefish survey CPUE, expressed as sablefish/hook, from stations used in the power analysis, 1989–92. CL = confidence limit; SD = standard deviation.

Area	Year	No. of stations	Upper 90% CL	Mean CPUE	Lower 90% CL	SD
Chatham	1989	38	0.149	0.130	0.112	0.069
	1990	38	0.150	0.123	0.097	0.099
	1991	38	0.181	0.156	0.130	0.096
	1992	38	0.135	0.118	0.100	0.065
Clarence	1989	36	0.103	0.092	0.082	0.038
	1990	36	0.092	0.082	0.071	0.039
	1991	36	0.116	0.100	0.085	0.055
	1992	36	0.110	0.097	0.084	0.047

Table 2

Sablefish survey CPUE, expressed as kilograms/hook, from stations used in power analysis, 1989–92. CL = confidence limit; SD = standard deviation.

Area	Year	No. of stations	Upper 90% CL	Mean CPUE	Lower 90% CL	SD
Chatham	1989	38	0.503	0.440	0.376	0.231
	1990	38	0.546	0.443	0.340	0.376
	1991	38	0.662	0.559	0.456	0.376
	1992	38	0.518	0.444	0.370	0.270
Clarence	1989	36	0.272	0.240	0.209	0.118
	1990	36	0.233	0.198	0.164	0.129
	1991	36	0.262	0.227	0.192	0.131
	1992	36	0.247	0.206	0.166	0.150

For tests between 2 years, the power of the test was markedly higher for Clarence Strait than for Chatham Strait (Fig. 4, 5). This is shown by the estimated sample size of 43 stations needed to detect a change of 20% from the mean CPUE of 0.092 sablefish/hook in Clarence with a power of 0.80, compared to an estimated sample size of 80 stations to detect a 20% change from a mean CPUE of 0.132 sablefish/hook in Chatham Strait. Again, this difference in power can be attributed primarily to the higher variance for Chatham Strait (coefficient of variation [CV] =72%) compared to Clarence Strait (CV = 52%). Also, the power curves for tests between 2 years are flatter than those associated with tests for linear trend. Consequently, changes in sample size for testing between 2 years result in smaller changes in power than equivalent changes in sample size when testing for linear trend.

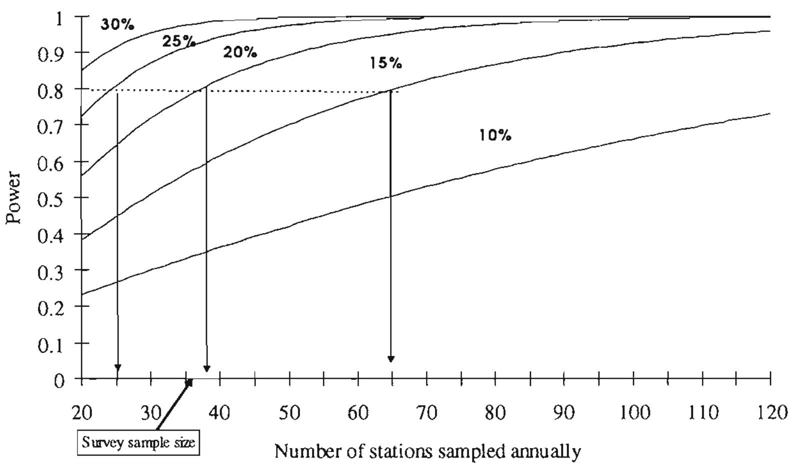

Figure 3
Power of the GLMM to detect a linear trend (percentage increase or decrease) in Clarence Strait survey sablefish CPUE over four consecutive years. Arrows indicate the approximate sample sizes needed to detect changes of 15%, 20%, and 25% in CPUE with a power of 0.8 (α=0.10).

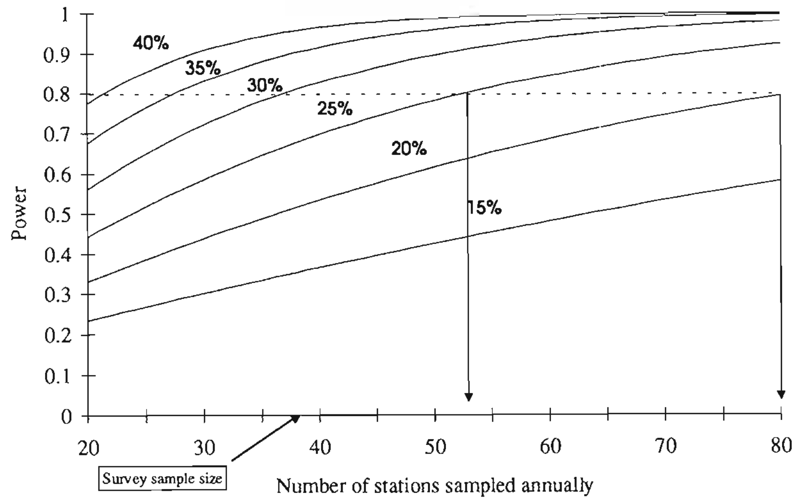

Figure 4
Power of the GLMM to detect change (percentage increase or decrease) in Chatham Strait survey sablefish CPUE between two years. Arrows indicate estimated sample sizes needed to detect changes of 20% and 25% in CPUE with a power of 0.8 (α=0.10).

Comparison of Survey versus Commercial Fishery CPUE

Plots of commercial fishery and survey mean CPUE did not show consistent trends in CPUE (Fig. 6). However, because only a few data points were available for exploring this relationship, the results are inconclusive.

Size, Age, and Sex Composition

From 1988 to 1992, substantial differences existed in the sizes of sablefish sampled in Clarence Strait and in Chatham Strait. In Chatham Strait mean length ranged from 68 to 70 cm, whereas in Clarence Strait mean length ranged from 58 to 62 cm. In addition, in Clarence Strait 43% of the sablefish sampled from 1988 to 1992 were juveniles, whereas in Chatham Strait 9% of the sablefish sampled were juveniles.

Chatham Strait—In Chatham Strait there were no substantial changes in relative frequency distributions for length between years, except for an increase in larger fish in 1992 (Fig. 7). A size mode appeared at 63 cm in 1988. In 1989, 1990, and 1991 the mode was 65 cm, with a second mode of 71 cm in 1991. In 1992 three size modes appeared: 61, 67, and 73 cm. Sex ratios were 52% male in 1988, 50% in 1989, 58% in 1990, 54% in 1991, and 44% in 1992.

Age data indicate that the year classes from 1977 to 1981 were major contributors to the Chatham Strait stock (Fig. 8). Frequency modes are indicated from the 1985 year class in 1991 and the 1983 year class in 1992. Year-class frequency modes vary from year to year in this data and may be attributed to error in age estimates. Stronger than normal recruitment of sablefish from the 1977, 1980, and 1984 year classes has been reported (Sigler, 1989; Fujioka[5]).

Clarence Strait—Length data from sablefish sampled in Clarence Strait (Fig. 9) show a size mode of 53 cm in 1988, 63 cm in 1989, 57 cm in 1990, 61 cm in 1991, and 59 cm in 1992. In 1992 there was a substantial increase in sablefish smaller than 48 cm. Sex ratios were 52% male in 1988, 53% in 1989, 58% in 1990, 61% in 1991, and 54% in 1992.

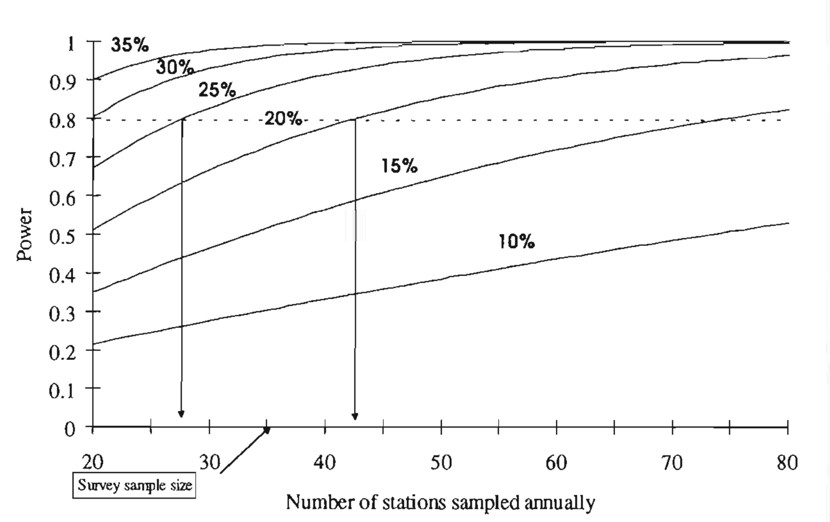

Figure 5
Power of the GLMM to detect change (percentage increase or decrease) in Clarence Strait survey sablefish CPUE between two years. Arrows indicate estimated sample sizes needed to detect changes of 20% and 25% in CPUE with a power of 0.8 (α=0.10).

Age data indicate the presence of sablefish from the late 1970's, but this component was less important in this area than in Chatham Strait (Fig. 10). The 1984 year class was predominant during 1988–90, further supporting the stronger than normal recruitment from the 1984 year class reported by Sigler (1989). In 1991, 4- and 5-year-old sablefish were most abundant, and in 1992, 2- and 3-year-old fish were the predominant age groups.

Discussion

Chatham Strait displayed greater variability in catch rate between stations than did Clarence Strait. There are several possible explanations for this. Chatham Strait is a much larger sampling area, so the sampling intensity per unit of habitat was less. Bottom type and depth, which influence sablefish density, vary much more in Chatham Strait than in Clarence Strait. Changes in gear used to conduct the survey, specifically the addition of weights to the groundline after every 100-hook subsection in 1991 and 1992, may have influenced catch rate. The Chatham Strait survey was conducted by a different vessel and skipper each year, whereas the Clarence Strait survey used the same vessel and skipper all 5 years. Vessel and skipper changes may cause greater year-to-year variation in the actual location that a particular station was fished, and crews may also differ in

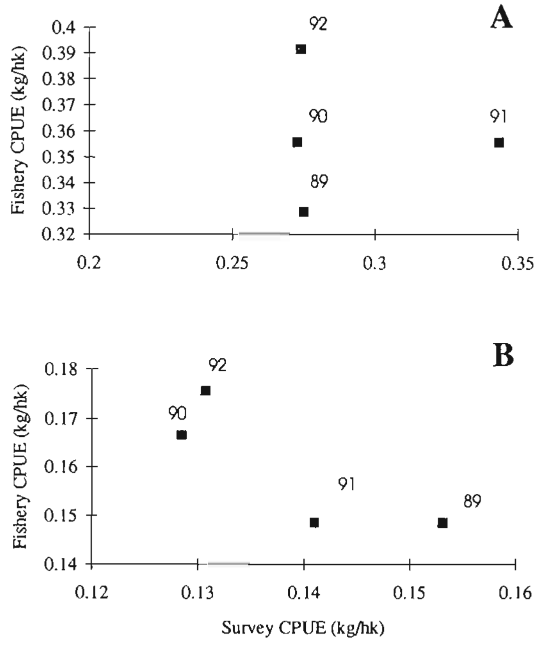

Figure 6
Commercial fishery CPUE versus longline survey CPUE for (A) Chatham Strait and (B) Clarence Strait, 1989–92. Note different *x* and *y* axis scales.

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[5] Fujioka, J. T. 1992. Sablefish. *In* Gulf of Alaska Groundfish Plan Team (ed.), Stock assessment and fishery evaluation report for the 1993 Gulf of Alaska fishery. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510.

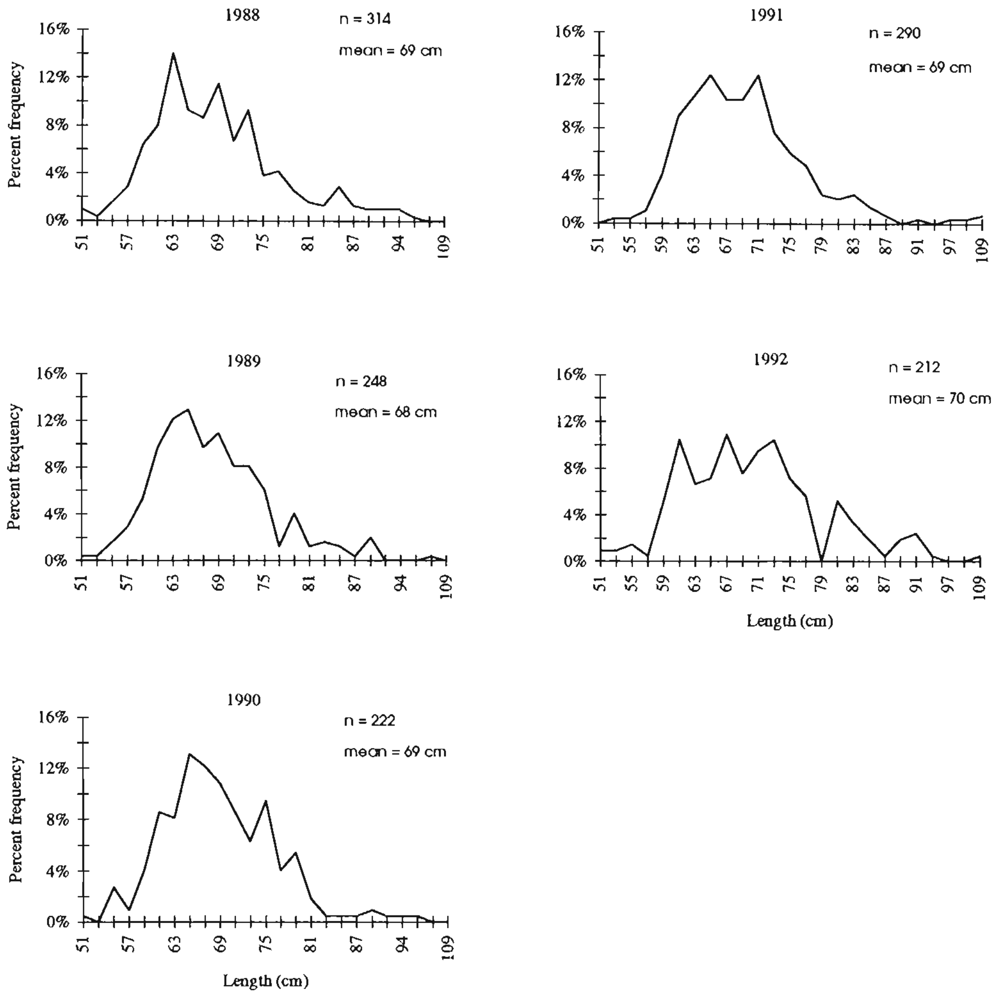

Figure 7

Relative length-frequency distributions of sablefish sampled in Chatham Strait, southeast Alaska, 1988–92. Length data are combined into 2-cm increments.

proficiency of deploying and retrieving the snap-on gear. Finally, depth of gear also influences retrieval rate: the deeper stations in Chatham Strait required nearly twice the buoyline than did the shallower stations. The relatively short soak times (1 hour) mean that any change in the speed of deployment or retrieval of the gear may cause noticeable change in catch rate. In Clarence Strait, the time between retrieving the first buoy and the last hook was relatively consistent; it ranged from 40 to 50 minutes and averaged 43 minutes. In Chatham Strait, retrieval time varied more; it ranged from 45 to 90 minutes and averaged about 70 minutes.

Significant between-year differences in sablefish/hook averages were detected in both areas. But in both areas, significant changes in such averages were followed by significant changes in the opposite direction for the subsequent survey. When measured by kilograms/hook, no significant changes occurred in either area over the 4 years. Because the fisheries are managed with an annual poundage quota, a significant interannual change in kilograms/hook may be of greater concern than a change in number of fish/hook. In either case, basing management decisions on changes in either measure of CPUE between two successive years may be inappropriate unless the changes are substantial. The lack of a significant linear trend in survey CPUE suggests that the current harvest level has not caused a substantial change in sablefish biomass in either area over the past 4 years. The magnitude of change in CPUE that we should strive to detect should be further investigated; this magnitude should ultimately be tied to the relation between CPUE and absolute abundance of sablefish. This will probably be difficult to accomplish, at least within the scope of current survey methods.

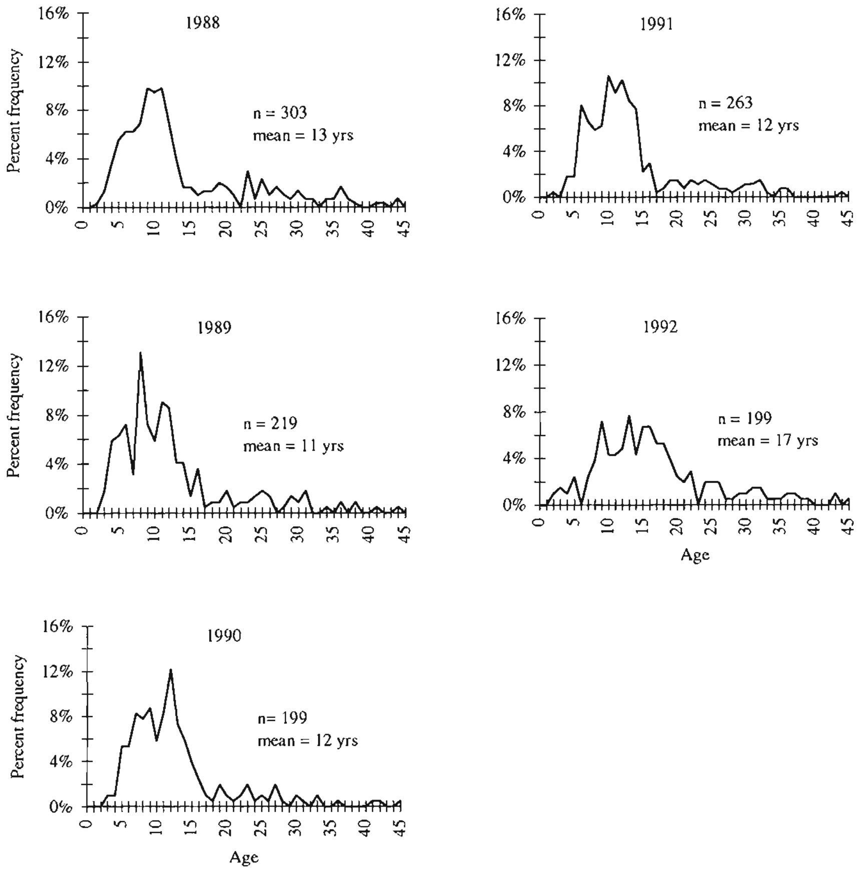

Figure 8

Relative age-frequency distributions of sablefish sampled in Chatham Strait, southeast Alaska, 1988–92.

Some attributes of our survey design tend to increase the likelihood that relative abundance, as measured in the survey, may be approximately proportional to absolute abundance. The survey was conducted with hook-and-line gear; sampling stations were randomly selected; and the short soak time (1 hour) minimized the potential for gear saturation. Also, sablefish do not tend to form discrete schools. Hilborn and Walters (1992) suggest that these characteristics increase the likelihood of a measure of relative abundance being proportional to actual abundance. However, standardized longline experiments conducted in Chatham Strait in 1989 and 1991 as part of a NMFS/ADFG cooperative research project resulted in CPUE's that conflicted with the results of the ADFG survey reported in this paper. Clausen et al. (1997) reported a CPUE of 0.58 sablefish/hook in 1989 and 0.40 sablefish/hook in 1991 from statistical area 345731. The ADFG survey CPUE's from statistical area 345731 were 0.12 sablefish/hook in 1989 and 0.16 sablefish/hook in 1991.

The difference in magnitude of CPUE between the two experiments can be explained by different survey methods; however, since both surveys used standardized methods, the 1989–91 decrease in CPUE indicated by the NMFS/ADFG cooperative survey, and the increase indicated by the ADFG survey are perplexing. Fishery CPUE's from statistical area 345731 showed 0.32 kg/hook in 1989 (15 vessels sampled) and 0.23 kg/hook in 1991 (5 vessels sampled), which shows the same trend as the NMFS/ADFG cooperative survey. A major difference in methods between the two surveys was soak time. The NMFS/ADFG cooperative survey used 4-h soak times, in contrast to 1-h soak times in the ADFG survey. Sigler (1993) conducted experiments using hook timers to quantify time between arrivals of sablefish to longline gear. He reported that initial capture rates vary without trend, then later decrease exponentially. He suggests that visual and auditory stimuli such as the settling of the longline and fish struggling on the gear could maintain initial capture rates of

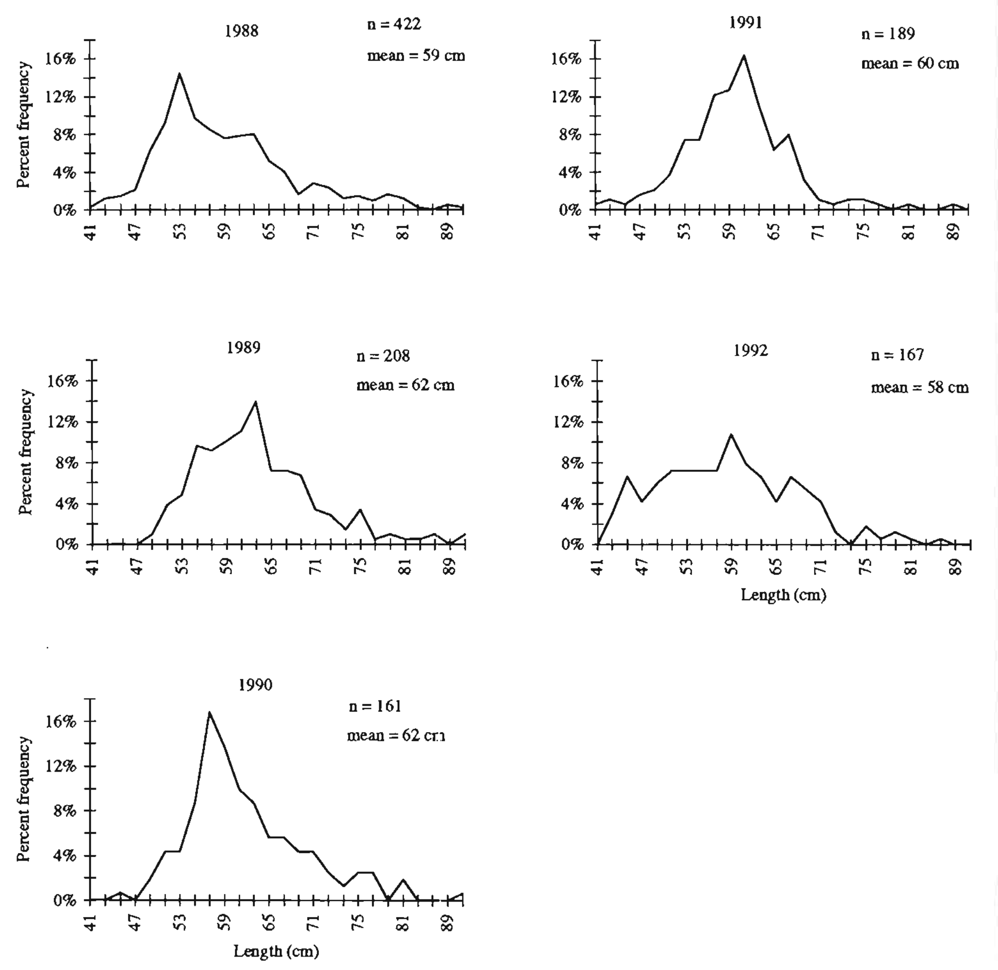

Figure 9
Relative length-frequency distributions of sablefish sampled in Clarence Strait, southeast Alaska, 1988–92. Length data are combined into 2-cm increments.

sablefish. This suggests that initial capture rates vary independently of density of sablefish. The short soak time used in the ADFG survey may have meant that CPUE is not be proportional to sablefish density. Experiments comparing catch rates at different soak times are needed to further investigate whether short soak times may be biasing the survey results.

The apparent lack of a well-defined relation between the survey and commercial fishery CPUE's is probably due to several factors. 1) Rapid changes in the fishing fleet from smaller, less efficient vessels to larger, more efficient vessels substantially increased the overall fishing power of the fleet. 2) Increasing use of squid rather than herring as bait in the commercial fishery may have increased the commercial fishery CPUE. 3) Changes in fleet distribution may have altered fishery performance. Specifically, a substantial portion of the Clarence Strait fishery effort has moved from the survey area to the Dixon Entrance portion of the SSEI Subdistrict over the past several years. The survey boundaries may need to be adjusted to compensate for this change.

Year-to-year variation in the age structure of the population in Clarence Strait is probably a direct result of recruitment from year classes of varying strengths. If this assumption is correct, the Clarence Strait survey may be a good indicator of relative recruitment strengths to the future adult population in other areas, including Chatham Strait. The relatively low occurrence of older fish in Clarence Strait indicates that a large portion of the population leaves the area as it matures. Conversely, the high proportion of mature fish observed in the samples from Chatham Strait suggests a resident adult population. These findings are consistent with the results of ADFG tagging studies, which indicate that tagged sablefish released in Clarence Strait are being recaptured over a large geographic area (Bracken and Richardson[3]). In contrast, the sablefish in Chatham Strait are older, predominantly mature fish, and over

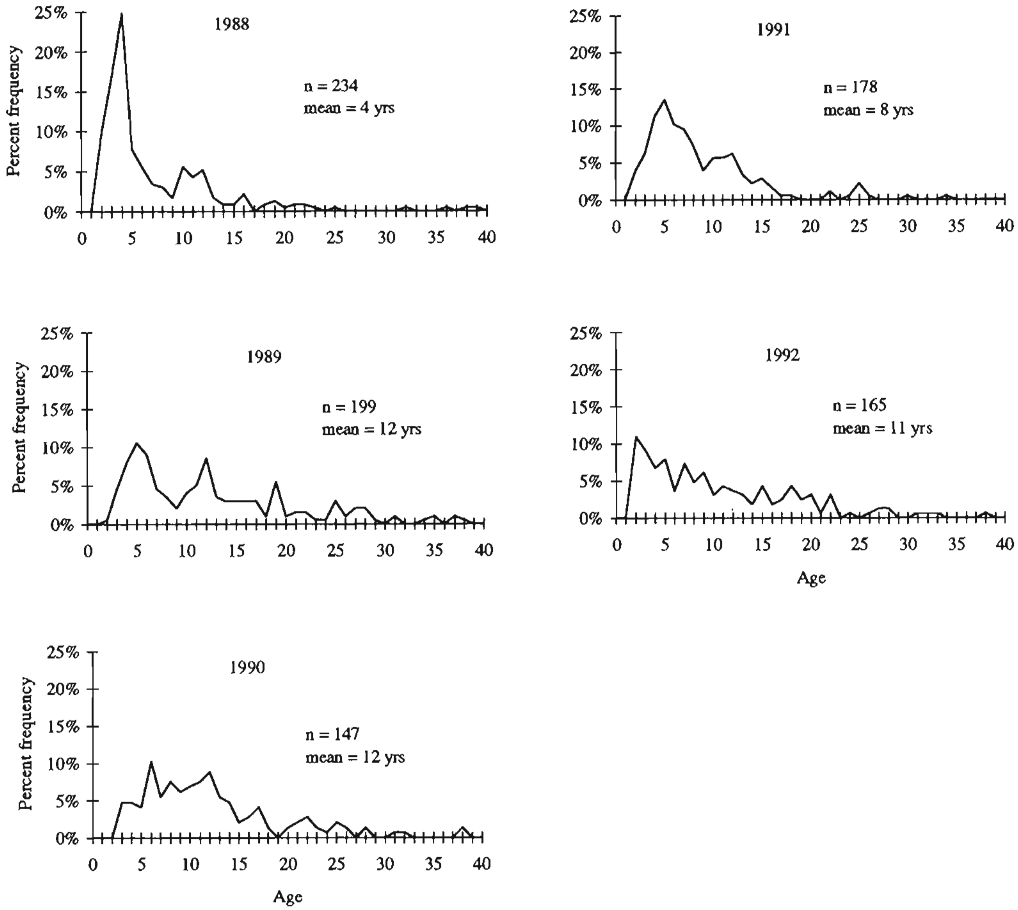

Figure 10

Relative age-frequency distributions of sablefish sampled in Clarence Strait, southeast Alaska, 1988–92.

90% of the juvenile and adult sablefish tagged and released in Chatham Strait were recovered either within the area of tagging or within a few miles of it. Only one sablefish tagged and released in Chatham Strait has been recovered in the SSEI Subdistrict, but 2.7% of the juveniles and 2.7% of the adults tagged in Clarence Strait have been recovered in Chatham Strait.

The survey provides valuable information on population characteristics. Interpreting changes in relative CPUE between any two successive years may not be useful for setting preseason harvest goals. Certainly the number of stations needed to detect reasonable interyear differences in Chatham Strait (n>80) is prohibitive. However, monitoring multiyear trends in survey CPUE will help determine how current harvest strategies affect the sablefish populations in Chatham Strait. The utility of the relative abundance survey in Clarence Strait is less clear. If the population is truly nonresident and part of a larger stock, then this type of relative abundance index or even estimates of absolute abundance may be more difficult to interpret or to use for management within that area.

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Literature Cited

Bracken, B.E.

1982. Sablefish (*Anoplopoma fimbria*) migration in the gulf of Alaska based on Gulf-wide tag recoveries, 1973–1981. Alaska Dep. of Fish and Game Inf. Leafl. 199.

1983a. The history of the U.S. sablefish fishery in the Gulf of Alaska, 1906–1982. *In* B. R. Melteff (coordinator), Proceedings of the International Sablefish Symposium, p. 41–47. Univ. of Alaska Fairbanks, Alaska Sea Grant Rep. 83-8.

1983b. Sablefish migration in the Gulf of Alaska based on tag recoveries. *In* B. R. Melteff (coordinator), Proceedings of the International Sablefish Symposium, p. 185–190. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

1997. License limitation in an Alaska sablefish, *Anoplopoma fimbria,* fishery. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 253–259. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Clausen, D. M., J. T. Fujioka, and J. Heifetz.

1997. Estimates of sablefish, *Anoplopoma fimbria,* abundance in the Gulf of Alaska based on depletion experiments using longlines. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 171–182. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Cochran, W. G.

1977. Sampling techniques. John Wiley and Sons, New York, 345 p.

Hilborn, R., and C. J. Walters.

1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, London.

Muller, K. E., L. M. LaVange, S. L. Ramey, and C. T. Ramey.

1992. Power calculations for general linear multivariate models including repeated measures applications. J. of Am. Statistician Assoc. 87:1209–1226.

SAS Institute Inc.

1987. SAS/STAT guide for personal computers, Version 6 edition. Cary, North Carolina.

1988. SAS/IML user's guide, Release 6.03 edition. Cary, North Carolina.

Sigler, M. F.

1989. Assessment of the Gulf of Alaska sablefish population based on the Japan–U.S. Cooperative Longline Survey, 1987. *In* T. K. Wilderbuer, Condition of groundfish resources of the Gulf of Alaska in 1988. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-165.

1993. Stock assessment and management of sablefish *Anoplopoma fimbria* in the Gulf of Alaska. Ph.D. thesis, Univ. Washington, Seattle, 188 p.

Snedecor, G. W. and W. G. Cochran.

1989. Statistical methods, 8th ed. Iowa State Univ. Press, Ames.

Sokal, R. R., and F. J. Rohlf.

1981. Biometry. 2nd ed. W. H. Freeman, New York.

Utility of an Age- and Sex-structured Model for Sablefish, *Anoplopoma fimbria*, Stock Assessment off the West Coast of Canada

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ABSTRACT

Sablefish, *Anoplopoma fimbria*, is a widely distributed and highly valued groundfish species in the North Pacific. Sablefish has been exploited off the coast of British Columbia since 1888. In this paper we examine the utility of an age- and sex-structured model for sablefish stock assessment off the west coast of Canada. The model computes Bayesian posterior probability distributions for the unfished equilibrium biomass, current stock size, and fishery parameters of interest. In the Bayesian approach, stock size is viewed as a random variable rather than a fixed constant. The dynamics of the sablefish population are described by a standard discrete age–time structured model. The model assumes a Beverton-Holt stock–recruit relationship, and uses catch, effort, survey, and biological sampling data from commercial fisheries and research surveys. Given a known catch history, some indices of abundance (i.e., CPUE, biomass from surveys), and life-history parameters of the sablefish stock, a deterministic trajectory of stock biomass can be estimated. The objective is to search over biological parameters that not only give the best fit between the model trajectory and the multiple observed indices of abundance, but also give a posterior distribution of alternative hypotheses about the unfished equilibrium biomass and current stock size. We also investigated the effects of uncertainties in growth, mortality, recruitment parameters, survey estimates, and CPUE series on the posterior probability distributions.

Introduction

Sablefish, *Anoplopoma fimbria*, is a widely distributed and highly valued groundfish species in the North Pacific. The adults of the species inhabit waters deeper than 200 m and are most abundant between 600 and 800 m (McFarlane and Beamish, 1983). Sablefish are long-lived fish with very rapid initial growth followed by slow growth upon reaching maturity (Beamish and Chilton, 1982). Sablefish spawn from January to March along the Pacific coast at depths greater than 300 m (McFarlane and Beamish, 1983).

The sablefish fishery to 1982 has been described in detail by McFarlane and Beamish (1983). Sablefish has been exploited off the coast of British Columbia since 1888. The early commercial fishery was carried out by specially equipped longline vessels (Ketchen and Forrester, 1954). During the first half of this century the domestic longline fishery fluctuated in response to market demands for food fish and fish liver products. From 1951 to 1971 a low-key domestic fishery operated with trawls and longlines. An international longline fishery operated in the Canadian zone from 1964 to 1980. Heavy exploitation, mainly by the Japanese distant-water longline fleet, occurred from 1969 to 1978. The importance of the domestic sablefish fishery has increased steadily since Canada extended its fishery jurisdiction zone in 1977 (McFarlane et al., 1985). Traps were introduced in 1973, and a major switch from an international longline fishery to a domestic trap fishery took place in 1979–80. Since 1981, the trap fishery has been the dominant fishery in the Canadian zone.

Since Canada extended its fishery jurisdiction in 1977, sablefish have been under quota management. In 1981 license limitation was implemented in an attempt to control effort directed toward sablefish (McFarlane et al., 1985). Individual vessel quotas (IQ's) were introduced for longline and trap vessels in 1990. Vessels were allocated quotas on the basis of historic catch and overall vessel length (Saunders and McFarlane, 1993).

The earliest sablefish stock assessments used two methods based on catch and catch-per-unit-effort (CPUE) data (Ketchen, 1980; Westrheim, 1980; Stocker, 1981). The first involved a regression of CPUE on the average fishing effort over a number of preceding years (Gulland, 1961). The second method employed a dynamic, stochastic version of the Schaefer model (Schnute, 1977). Beginning in 1985 an age-structured method using catch-at-age data was employed (e.g., McFarlane et al., 1985; Saunders et al., 1989).

In this paper we derive Bayesian estimates of the posterior probability of unfished equilibrium, current stock size, and fishery parameters of interest for sablefish off the west coast of Canada. Recent applications of Bayesian methods to fisheries problems are found in Ludwig and Walters (1982), Clark et al. (1985), Walters and Ludwig (1987, 1994), Holbert and Johnson (1989), Parma and Deriso (1990), Thompson (1992), and Hilborn et al. (1994).

Canadian and U.S. management agencies require the presentation of yield options with some degree of risk assessment. Choosing an appropriate yield option for sablefish is a decision-analysis problem. Bayesian statistical procedures provide information to fisheries managers about uncertainty in stock assessments. The Bayesian approach differs from the classical statistical approach in that information is presented as probability distributions for uncertain parameters such as current stock size and maximum sustainable yield (MSY), rather than as ranges or confidence limits on point estimates. The probability distributions obtained with Bayesian procedures form the first step in the decision analysis. The second step, to examine the consequences of yield options under the uncertainty, is just as important, but is not addressed in this paper.

Materials and Methods

Data Sources

Basic commercial catch data (Fig. 1a) used for our analysis are described through 1991 by Saunders and McFarlane (1993). We use two CPUE measures (Fig. 1b) as indices of relative abundance of sablefish biomass: 1) t/10 hachi from the Japanese longline fishery, 1968–79 (hachi is a unit of length and ranges from 58 to 100 m), and 2) kg/trap from the domestic trap fishery, 1979–91. We also used the 1989 and 1991 trap survey biomass estimates in the analysis.

Biomass was estimated on the basis of catch rates from the 1989 and 1991 trap surveys (Saunders and McFarlane, 1993) as the product of the mean catch rates (in number per trap) by depth range, the area of the depth range, and the mean weight of fish in the survey, divided by the area fished by an individual trap. Exploitable biomass was estimated by multiplying biomass estimates by the average proportion of fish greater than 55 cm in each area and depth stratum. The area of sablefish habitat covered in the survey was between 150 and 700 fm. A geographic information system (COMPUGRID) was used to determine the areas of the respective depth strata. The depth strata were defined by 100-fm intervals starting at 150 fm, with the deepest stratum from 550 to 700 fm.

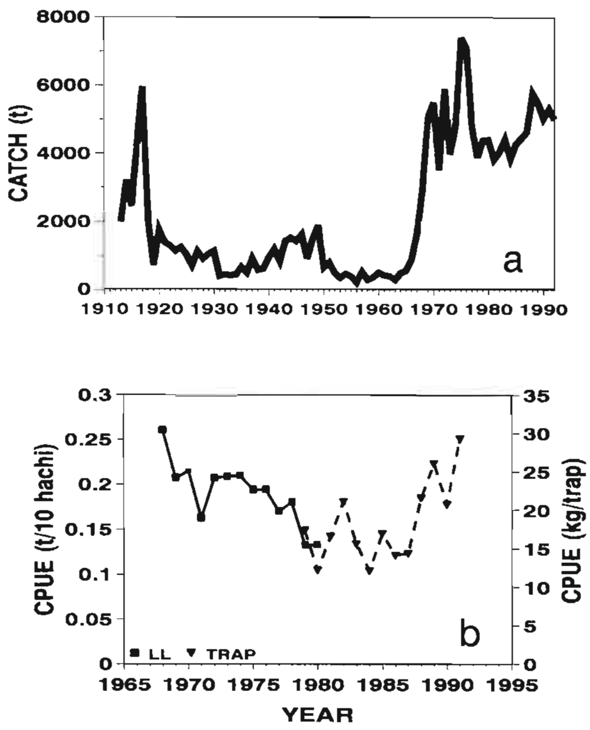

Figure 1

Commercial fishery data for sablefish in the Canadian zone: (a) all-nation catch (t), 1913–91; (b) Japanese longline fishery CPUE (expressed as t/10 hachi), 1968–79, and the domestic trap fishery CPUE (expressed as kg/trap), 1979–91.

Mean weights of sablefish were estimated by dividing the weight of fish caught by the number caught in each area and depth stratum. The area fished by each trap assumed a fishing radius of 50 m, which corresponds to half the distance of the trap spacing used in the commercial fishery. Presumably the spacing of traps is such that overlap effects are minimized. The fishing radius is considerably more conservative than the Eggers et al. (1982) estimate of 4.9 m for longline-caught sablefish.

Table 1

Sablefish life-history parameters used in age- and sex-structured stock reduction analysis. L_∞, k, and t_0 are parameters of the von Bertalanffy growth equation; a and b are parameters of the length–weight relationship, $W = aL^b$ (W in grams and L in cm).

Parameters	Females	Males
Estimate of natural mortality (M)	0.08	0.08
Age of maturity (A_m)[1] (yr)	5.1	4.8
L_∞ (cm)	81.4	66.7
k (yr^{-1})	0.249	0.290
t_0 (yr)	-0.77	-1.07
a	0.0029	0.0029
b	3.2973	3.2973
Recruitment "steepness" = 0.95		

[1] Age at maturity is the 50% point on a logistic model of % maturity as a function of age.

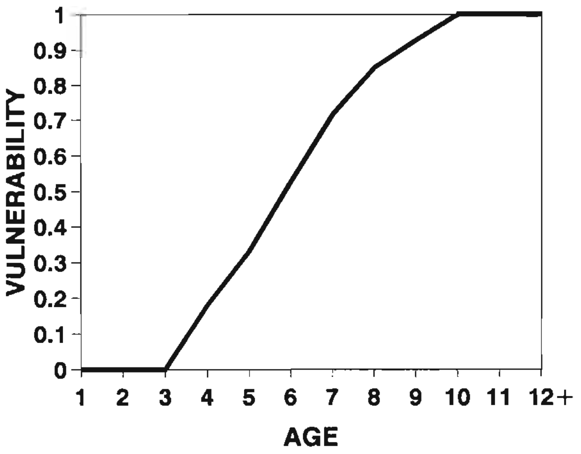

Figure 2
Vulnerability at age for sablefish.

The exploitable biomass was estimated to be 50,800 t in 1989, and 54,800 t in 1991 (Saunders and McFarlane, 1993).

Sablefish life-history parameters were summarized from various sources. Sablefish are long-lived fish with very rapid initial growth followed by slow growth upon reaching maturity. From these parameters (Table 1) the weight, vulnerability, and fecundity schedules (by sex) were constructed. The proportion vulnerable (McFarlane et al., 1985) increases from 10% at age 4 to 100% at age 10 and older (Fig. 2).

Age- and Sex-Structured Model

An age- and sex-structured model (Hilborn et al., 1994) was used to estimate the virgin biomass (B_0) and current biomass (B_{1992}) of the sablefish stock in the Canadian zone. The modeling procedure is very similar to the stock reduction method described by Francis (1992).

The dynamics of the population are described by a standard discrete age–time-structured model (Walters, 1969). The number (N) of age a+1 at the beginning of year t+1 are those alive at the end of the fishery (N'), times the survival from natural mortality (Hilborn et al., 1994):

$$N_{s,a+1,t+1} = N'_{s,a,t}\, s_{s,a} \qquad (1)$$

The biomass of each age and sex ($B_{s,a}$) is the number at age, times the weight at age ($w_{s,a}$), times the vulnerability at age ($v_{s,a}$):

$$B_{s,a} = N_{s,a}\, w_{s,a}\, v_{s,a}\,. \qquad (2)$$

The total vulnerable biomass in year t (B_t) is the sum of biomass at age and sex:

$$B_t = \sum_s \sum_a B_{s,a} \qquad (3)$$

The harvest rate is the observed catch in year t (C_t) divided by the total vulnerable biomass:

$$u_t = C_t / B_t \qquad (4)$$

The number alive after the fishery is the preharvest number, times the harvest rate on fully recruited ages, times the vulnerability at age:

$$N'_{s,a} = N_{s,a}\,(1 - u_t\, v_{s,a}) \qquad (5)$$

Recruitment was deterministic and follows a Beverton-Holt stock–recruitment curve. We explore various forms of the stock–recruitment curve by choosing various levels of "steepness." Steepness (z) is the expected fraction of equilibrium virgin recruitment (R_0) produced when spawning biomass (B_t) is 20% of the virgin spawning biomass (B_0).

The three abundance indices I_{it} (i=1, LL CPUE; i=2, trap CPUE; and i=3, surveys) are treated as normally distributed about their expected values with a constant and known coefficient of variation (CV). The CV for the longline CPUE is assumed to be 0.30 for each year t (t=1968,...,1979), and the CV for the trap CPUE is assumed to be 0.25 for each year t. The 1989 and 1991 trap survey biomass estimates are normal with an assumed CV of 0.3. The relationship between observed indices of abundance and the vulnerable biomass B_t was modeled as

$$I_{it} = q_i B_{it} + x_{it} \tag{6}$$

where $x_{it} \sim N(0;\ c_{it} q_i B_{it})$; q_i is the constant of proportionality of the ith series (i=1,2,3); and c_{it} is the CV for year t of series i.

Likelihood and Posteriors

Estimating the Bayesian posterior distributions for unfished equilibrium (and current) stock sizes involved three steps: 1) formulating a prior probability distribution for B_0 and q; 2) formulating a likelihood function for the multiple abundance indices; and 3) calculating the likelihood over possible values of B_0 and rescaling by their sum to provide the posterior probability for B_0.

Informative prior distributions are assumed for B_0 and for the constant of proportionality that relates the abundance index to biomass. The prior distribution for B_0 is assumed to be uniformly distributed over the interval 80,000–300,000 t. We assume a diffuse prior distribution for q, and that log(q) is uniformly distributed. We eliminate q from the likelihood function by integrating it with respect to q. This analytical integration substantially reduces the number of computations required (Walters and Ludwig, 1994).

Given the model equations, assumed known parameters (M, steepness), schedules (weight, vulnerability, fecundity), abundance indices (LL CPUE, trap CPUE, surveys) and CV's, observed catch history, and discrete values of B_0, a deterministic trajectory of stock biomass is generated. The likelihood is calculated for the three abundance indices based on the deviations between observed and predicted indices of abundance:

$$d_{it} = q_i B_{it} - I_{it}. \tag{7}$$

The likelihood of the individual index I_{it} is given by

$$L(I_{it} | B_0, q_i, c_{it}) = \frac{1}{c_{it} q_i B_{it} \sqrt{2\Pi}} \exp\left(\frac{-d_t^2}{2(c_{it} q_i B_{it})^2} \right). \tag{8}$$

Since c_{it} is assumed known, we will express L ($I_{it}|B_0, q_i, c_{it}$) as L ($I_{it}|B_0, q_i$). The likelihood of B_0 and q_i for series i is given by

$$L(I_i | B_0, q_i) = \prod_t L(I_{it} | B_0, q_i). \tag{9}$$

The likelihood of B_0 for series i is obtained by

$$L(I_i | B_0) = \int \frac{1}{q} L(I_t | B_0, q_i) dq. \tag{10}$$

This is equivalent to integrating the likelihood function with respect to log q or assuming a diffuse prior over log q (Box and Tiao, 1973).

The likelihood of B_0 over all indices is obtained by

$$L(I|B_0) = \prod_i (I_i|B_0). \tag{11}$$

How are the data combined with the prior distribution to generate the posterior distribution for B_0? The tool that allows for this union is Bayes's theorem:

$$P(B_0|data) = \frac{P(data|B_0)P(B_0)}{\sum P(data|B_0)P(B_0)}. \tag{12}$$

$P(B_0 | \text{data})$ is the posterior probability distribution of B_0 given the multiple index data. $P(\text{data} | B_0)$ is the likelihood of the multiple index data if B_0 is true. $P(B_0)$ is the prior probability of B_0 before the data are considered. The denominator, $\Sigma\, P(\text{data} | B_0)\, P(B_0)$, sums the products of the likelihood times the prior distribution over all possible values of B_0.

Sensitivity Analysis

The effects of uncertainty in growth, natural mortality, recruitment parameters, survey biomass estimates, and presence or absence of trap CPUE data were investigated with a sensitivity analysis. We created new weight, vulnerability, and fecundity schedules by increasing and decreasing L_∞ and k of the growth function. For the model run examining the effects of increased growth, L_∞ was increased by 5% and k was reduced by 10%, whereas for the case of reduced growth, L_∞ was reduced by 5% and k was increased by 10%. The estimates of biomass and yield were repeated twelve times. The results were compared with the baseline model run.

Results

Figure 3a shows the posterior distribution for B_0 for the case where survey data were not included in the analysis. The estimate of B_0 is very poorly determined. Including additional data in the form of survey biomass estimates made the posterior distribution sharper (i.e., less diffuse; Fig. 3b). When we included the biomass survey data, the best estimate of B_0 was 120,000 t (Table 2). We consider this the baseline result.

Concomitant to the posterior distribution of B_0 are posterior distributions of current biomass, B_{1992}, and the B_{1992}/B_0 ratio (Fig. 4). The best estimate of MSY was 5,420 t or 4.5% of B_0 (Table 2).

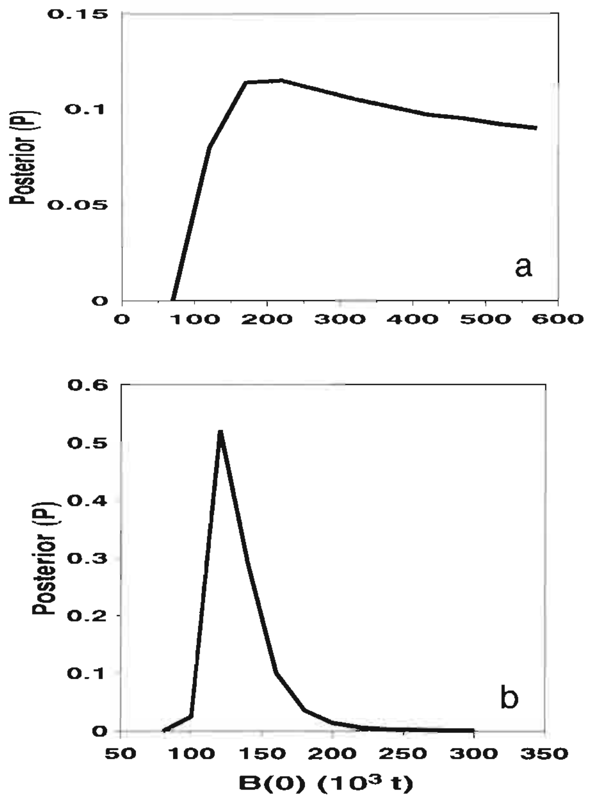

Figure 3

Posterior distribution of virgin biomass (B_0): (a) without abundance estimate from trap survey; (b) with abundance estimate from trap survey. Note different *y* scales.

A virgin stock size of 120,000 t generates a time trajectory of midseason biomass that fits the data reasonably well (Fig. 5). The midseason biomass trend indicates that the stock has been in continual decline since the early 1970's. This decline is inconsistent with the observed trend in trap CPUE.

Results of the sensitivity analysis are presented in Tables 2 and 3. Over all runs carried out in the analysis, B_0 varied between 100,000 and 160,000 t, and B_{1992} varied between 38,000 and 65,600 t. The ratio B_{92}/B_0 is relatively stable (Table 2). Biomass and yield estimates are not very sensitive to changes in the growth parameters. Decreasing steepness from 0.95 to 0.65 produced a drop in MSY of 28.2% (Table 3). The greatest uncertainties about stock size estimates are associated with survey data. Doubling the survey biomass estimate increases the estimate of B_0 by 33%.

Figure 6a shows the posterior distribution for B_0 for the case where trap CPUE data were not included in the analysis. The estimates of B_0 and B_{1992} are very poorly determined (Fig. 6).

Table 2

Estimates for given changes in growth, mortality, steepness, survey biomass estimates, and CPUE series. MSY is maximum sustainable yield.

Run	B_0 (t)	B_{92} (t)	B_{92}/B_0	MSY (t)
Baseline	120,000	58,800	0.49	5,420
Growth (+)	120,000	56,900	0.47	5,110
Growth (–)	120,000	60,300	0.50	5,690
$M = 0.10$	110,000	60,400	0.55	6,550
$M = 0.06$	130,000	59,400	0.46	4,770
Steepness = 0.85	120,000	57,200	0.48	4,750
Steepness = 0.75	130,000	65,600	0.50	4,510
Steepness = 0.65	130,000	62,900	0.48	3,890
Survey × 2	160,000	99,600	0.62	7,220
Survey × 0.5	100,000	38,000	0.38	4,510
Without trap CPUE	125,000	63,900	0.51	5,640

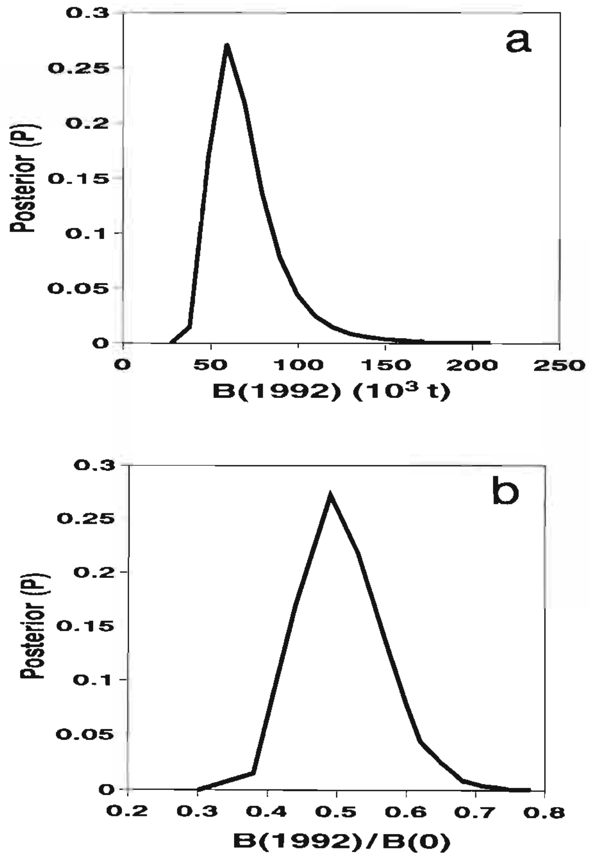

Figure 4

Posterior distributions of (a) the biomass in 1992 and (b) the ratio of biomass in 1992 to virgin biomass (B_0).

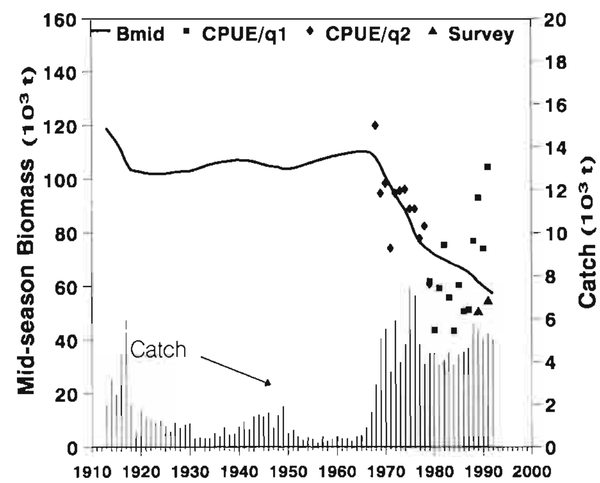

Figure 5

Time series of sablefish catch, CPUE/catchability (q_1=longline and q_2=trap), survey biomass, and estimated midseason biomass (B_{mid}).

Table 3

Percentage changes in estimated biomass and yields for given changes in growth, mortality, steepness, estimated survey biomass, and CPUE series.

Changes in parameters	B_0	B_{92}	MSY
Growth (+)	0	–3.2	–5.5
Growth (–)	0	+2.6	+5.1
M = 0.10	–8.3	+2.7	+21.0
M = 0.06	+8.3	+1.0	–12.0
Steepness = 0.85	0	–2.7	–12.2
Steepness = 0.75	+8.3	+11.6	–16.7
Steepness = 0.65	+8.3	+7.0	–28.2
Survey × 2	+33.3	+69.4	+33.3
Survey × 0.5	–16.7	–35.4	–16.7
Without trap CPUE	+4.2	+8.7	+4.2

Discussion

The age- and sex-structured model presented provides a useful approach to obtaining posterior probability distributions of B_0, current stock size, and fishery parameters of interest. The greater the amount of information about B_0 that is contained in the data, the sharper (i.e., less diffuse) is the posterior distribution. While the Bayesian approach provides an appropriate framework, the model and results presented here must be considered preliminary. The sensitivity of the model to the biomass estimates and the stock–recruitment steepness parameter is of particular concern.

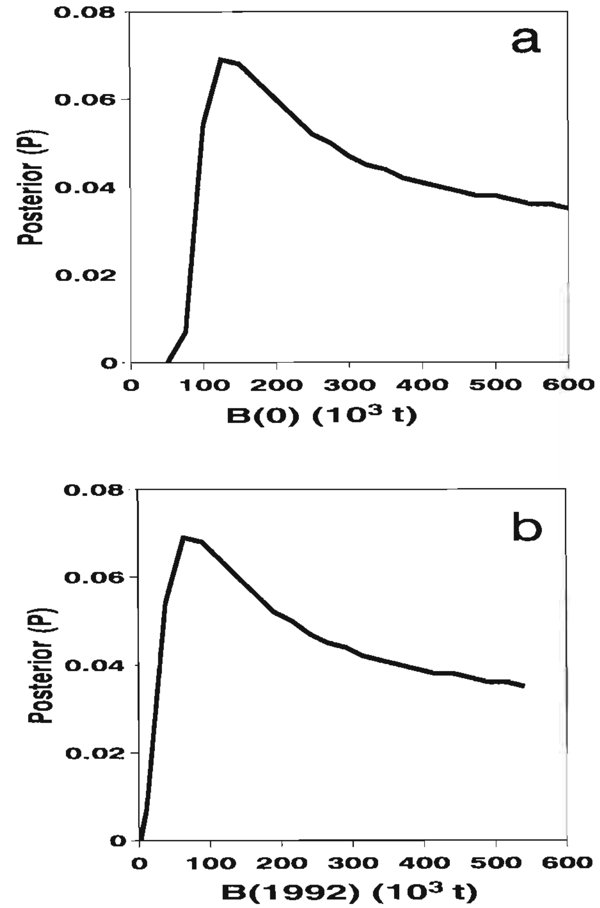

Figure 6

Posterior distributions of (a) the virgin biomass (B_0) and (b) the biomass in 1992 (B_{1992}) for the case where trap CPUE data were not included in the analysis.

Since the model is very sensitive to the biomass estimates, confidence in the results is dependent on a high level of confidence in the surveys, which is lacking because the surveys were not designed to produce absolute biomass estimates, and because assumptions about area fished by the trap require testing. Also the model is sensitive to the stock–recruitment steepness parameter. If there is a weak relation between stock and recruitment (steepness=0.95), MSY is estimated at 5,420 t. On the other hand, if the S–R relation has a steepness of 0.65, MSY is estimated at only 3,890 t. Unfortunately the true value of steepness is unknown. This uncertainty underscores the need for better information about the relation between stock and recruitment.

The biomass information that we have presented indicates that the sablefish stock in British Columbia has been in continual decline since the early 1970's. The estimated abundance trend deviates considerably from the trap CPUE index. The trap CPUE series indicates an increase in the early 1980's which may reflect the recruitment of the strong 1977 year class. We believe that recent increases in trap CPUE are related in some part to changes in place/time/type of fishing. The increase is too rapid to reflect only changes in stock abundance, considering the species' life-history parameters.

The shift in effort occurred in 1990 with the implementation of individual vessel quotas. With the fishery open year-round, fishers immediately began targeting on the west coast of the Queen Charlotte Islands, where catch rates (by weight) were higher and the fish larger. In addition there is anecdotal evidence that the quantity of bait increased during the 1988 and 1989 period when fishers were trying to maximize landings during time-restricted openings, recognizing that their recorded landings would form the basis for vessel quota allocation.

The stock-assessment model as presented must be considered preliminary. A more appropriate model should be developed which takes into account the shift in effort to the north coast of British Columbia. In other words, an effort-standardization analysis must be conducted to account for area differences if a coastwide model is to be used.

The Bayes posterior distributions presented can be used in decision analysis. The distributions are only the first step in the decision-making process. The second step—examining the consequences of harvesting strategies under the uncertainty—is just as important. And this second step will quantify the risk of harvesting sablefish populations.

Literature Cited

Beamish, R. J., and D. E. Chilton.
1982. Preliminary evaluation of a method to determine the age of sablefish (*Anoplopoma fimbria*). Can. J. Fish. Aquat. Sci. 39:277–287.

Box, G. E. P., and G. C. Tiao.
1973. Bayesian inference in statistical analysis. Addison-Wesley, Reading, MA, 588 p .

Clark, C. W., A. T. Charles, J. R. Beddington, and M. Mangel.
1985. Optimal capacity decisions in a developing fishery. Mar. Resour. Econ. 2:25–53.

Eggers, D. M., N. A. Richard, D. G. Chapman, and R. R. Whitney.
1982. A methodology for estimating area fished for baited hooks and traps along a ground line. Can. J. Fish. Aquat. Sci. 39:448–453.

Francis, R. I. C. C.
1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. Can. J. Fish. Aquat. Sci. 49:922–930.

Gulland, J. A.
1961. Fishing and the stocks of fish at Iceland. U.K. Min. Agric. Fish. Food, Fish. Invest. (Ser. 2) 23, 52 p.

Hilborn, R., M. McAllister, and E. Pikitch.
1994. A Bayesian estimation and decision analysis for an age-structured model using biomass survey data. Fish. Res. 19:17–30.

Holbert, D., and J. C. Johnson.
1989. Using prior information in fisheries management: a comparison of classical and Bayesian methods for estimating population parameters. Coastal Manage. 17:333–347.

Ketchen, K. S. (ed.).
1980. Assessment of groundfish stocks off the west coast of Canada (1979). Can. Data Rep. Fish. Aquat. Sci. 185, 213 p.

Ketchen, K. S., and C. R. Forrester.
1954. The sablefish fishery of British Columbia. Bull. Pac. Mar. Fish. Comm. 3:58–72.

Ludwig, D., and C. J. Walters.
1982. Optimal harvesting with imprecise parameter estimates. Ecol. Model. 14:273–292.

McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters of western Canada. *In* Proceedings of the International Sablefish Symposium, Anchorage, Alaska, p. 59–80. Alaska Sea Grant Rep. 83-8.

McFarlane, G. A., W. Shaw, and A. V. Tyler.
1985. Sablefish. *In* A. V. Tyler and G. A. McFarlane (eds.), Groundfish stock assessments for the west coast of Canada in 1984 and recommended yield options for 1985, p. 163–186. Can. Manuscr. Rep. Fish. Aquat. Sci. 1813, 353 p.

Parma, A. M., and R. B. Deriso.
1990. Experimental harvesting of cyclic stocks in the face of alternative recruitment hypotheses. Can. J. Fish. Aquat. Sci. 47:595–610.

Saunders, M. W., and G. A. McFarlane.
1993. Sablefish. *In* B. M. Leaman and M. Stocker (eds.), Groundfish stock assessments for the west coast of Canada in 1992 and recommended yield options for 1993, p. 132–162. Can. Tech. Rep. Fish. Aquat. Sci. 1919, 407 p.

Saunders, M. W., W. Shaw, and G. A. McFarlane.
1989. Sablefish. *In* J. Fargo, M. W. Saunders, and A.V. Tyler (eds.), Groundfish stock assessments for the west coast of Canada in 1987 and recommended yield options for 1988, p. 107–126. Can. Tech. Rep. Fish. Aquat. Sci. 1617, 304 p.

Schnute, J.
1977. Improved estimates for the Schaefer production model: theoretical considerations. J. Fish. Res. Board Can. 34:583–603.

Stocker, M. (ed).
1981. Groundfish stock assessments off the west coast of Canada in 1981 and recommended total allowable catches for 1982. Can. Manuscr. Rep. Fish. Aquat. Sci. 1624, 282 p.

Thompson, G. G.
1992. A Bayesian approach to management advice when stock–recruitment parameters are uncertain. Fish. Bull. 90:561–573.

Walters, C. J.
1969. A generalized computer simulation model for fish population studies. Trans. Am. Fish. Soc. 98:505–512.

Walters, C. J., and D. Ludwig.
1987. Adaptive management of harvest rates in the presence of a risk averse utility function. Nat. Resour. Modeling 1:321–337.
1994. Calculation of Bayes posterior probability distributions for key population parameters. Can. J. Fish. Aquat. Sci. 51:713–722.

Westrheim, S. J. (ed.).
1980. Assessment of groundfish stocks off the west coast of Canada in 1979 and recommended total allowable catches for 1980. Can. Data Rep. Fish. Aquat. Sci. 208, 265 p.

Comparisons of Sablefish, *Anoplopoma fimbria*, Abundance Indices Estimated from Two Longline Surveys

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ABSTRACT

Since 1988 the Japan–U.S. cooperative and the Alaska Fisheries Science Center (AFSC) longline surveys have sampled annually in the Gulf of Alaska. The longlines differ primarily in weighting, hook type, and gangion length and strength. Annual survey and gear-comparison catch rates are computed by station and depth interval, and compared in order to study their functional relationships. Differences between the functional regressions that describe the 1988 and 1989 catch-rate relationships and the 1990–92 surveys are notable. These differences are probably due to the fact that the AFSC gear was not fully standardized until 1990. Changes in survey scheduling and the relocation of sampling effort to nonstandard locations and depths do not appear to be significant sources of variation that might complicate the identification of a common conversion factor between the annual survey catch rates. A gear-comparison study was conducted in 1992 which involved fishing both longlines from the cooperative survey vessel. Efficiency of the AFSC gear decreased relative to the cooperative gear. Differences in gear handling, bait type, and possibly gear weighting may have been contributing factors. A log-linear model is being developed at AFSC to predict abundance indices based on the 1979–89 cooperative survey indices.

Introduction

In 1979 the United States and Japan, through the Alaska Fisheries Science Center (AFSC) and the National Research Institute of Far Seas Fisheries (NRI), initiated a cooperative longline survey of groundfish along the upper continental slope of the Gulf of Alaska. The survey was expanded to the Aleutian Islands in 1980 and to the Bering Sea in 1982. At that time, Japanese longline vessels dominated the fishery for sablefish in Alaskan waters, and the Japanese government supported joint research programs to monitor resource abundance through bilateral agreements. Between 1987 and 1989, the Japanese government withdrew its participation in joint sablefish research as foreign longline fishing was phased out of Alaskan waters. In 1989 the North Pacific Cooperative Fisheries Company (NPCF), a private Japanese company, agreed to conduct the entire survey in return for permission to retain most of the catch.

During its 15-year history, the Japan–U.S. cooperative longline survey has been conducted aboard chartered Japanese longline vessels by scientists from the NRI; the Japan Fisheries Agency (JFA) of Tokyo, Japan; the NPCF; and the AFSC. This survey is the only annual source of industry-independent resource assessment information for sablefish stocks in the Aleutian Islands and Bering Sea regions.

Anticipating termination of the cooperative survey, the AFSC mounted a second longline survey in the Gulf of Alaska in 1988. Presently both longline surveys sample 47 standard stations in the Gulf of Alaska (Fig. 1) with similar longline gear. Since most of the catch is retained by the charter vessels to defray operating costs, there is an incentive for them to maximize catches. Thus it falls on the lead U.S. scientists to monitor and enforce adherence to the scientific operation plans.

These research programs monitor the distribution and abundance of groundfish primarily along the upper continental slope, where sablefish dominate the catches. Survey-generated abundance indices or relative population numbers (RPN) are used to estimate relative sablefish abundance within commercial regula-

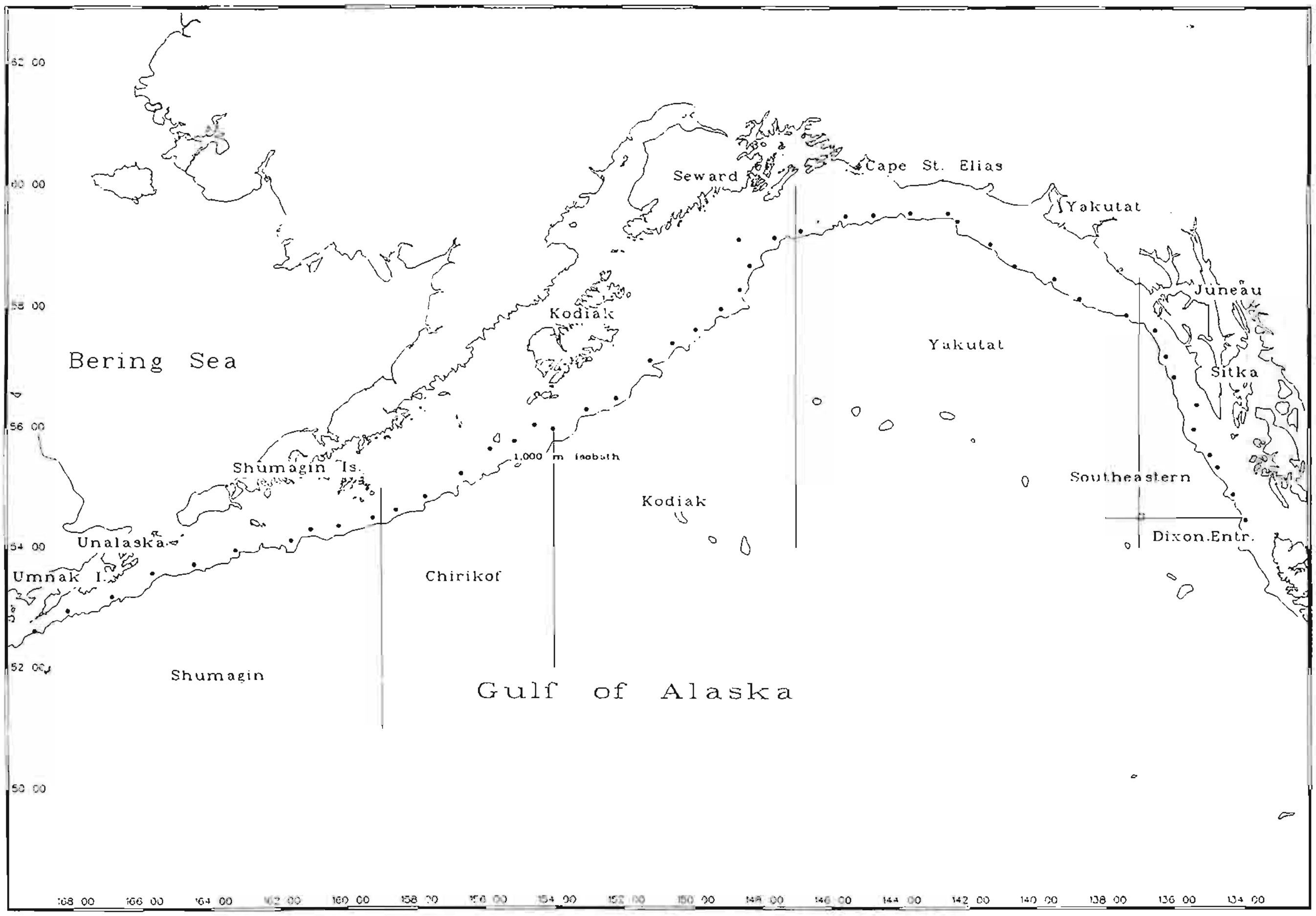

Figure 1

Station locations (dots) for the Alaska Fisheries Science Center and Japan–U.S. cooperative longline surveys of the Gulf of Alaska, and boundaries of International North Pacific Fisheries Commission statistical areas.

tory areas. Both the cooperative survey and the AFSC survey have produced independent annual estimates of sablefish abundance for the upper continental slope of the Gulf of Alaska since 1988. This information strongly influences management decisions on acceptable biological catch and its geographic allocation.

An unexpected result has been the frequent disagreement in abundance trends found by the two programs. Generally, the cooperative survey has found a 34% decrease in RPN between 1988 and 1992, while the NMFS survey RPN decreased a more modest 11%. In 1988 and 1989, these independent estimates of RPN were different in magnitude, but similar in trend (Table 1), both indicating decreases of 18%. Since then the two surveys have yielded not only different values of RPN, but often large differences in abundance trends. The cooperative survey showed a decline in RPN of 39% between 1988 and 1991 and a 9% increase between 1991 and 1992. After the initial decline of 18% in the AFSC survey RPN between 1988 and 1989, population estimates recovered to 1988 levels and remained steady in 1990 and 1991, dropping 10% between 1991 and 1992. Although there was a relatively large difference between the 1991 survey RPN estimates, both surveys showed little change in sablefish abundance between 1990 and 1991.

Because indefinite continuation of the cooperative survey is unlikely, it was considered advantageous to establish a basis for comparison of the two surveys, to allow expression of the 1979–87 results of the cooperative survey in terms of the AFSC longline survey. In effect, this would extend the AFSC survey database back to 1979. This paper reports on an investigation into the comparison of the two sets of annual longline survey data based on a measure of relative fishing power. It also investigates probable sources of nonagreement in abundance trends between the two surveys, and reports the results of a study to more directly identify the relative fishing power of the two sampling gears. A predictive model to relate catch rates of the two surveys is being developed at AFSC (Kimura and Zenger, 1997).

Table 1

Sablefish abundance indices (relative population numbers, RPN, in 1,000's) and annual changes in those indices for the upper continental slope (201–1,000 m) of the Gulf of Alaska from the Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative (COOP) longline surveys, 1988–92. Data summarized from Fujioka,[1] page 4.14.

	AFSC survey			COOP survey		
Year	RPN	Annual change	Net change	RPN	Annual change	Net change
1988	422			483		
		−18%			−18%	
1989	345			398		
		+20%			−24%	
1990	416			302		
		0%			− 2%	
1991	418			295		
		−10%			+ 9%	
1992	375		−11%	321		−34%

[1] Fujioka, J. T. 1992. Sablefish. *In* Gulf of Alaska Groundfish Plan Team (eds.), Stock assessment and fishery evaluation report for the 1993 Gulf of Alaska groundfish fishery. North Pacific Fishery Management Council, P.O. Box 103136, Anchorage, AK 99510.

Results of this investigation should be most useful as a study of data quality and to lay the groundwork for future efforts to standardize AFSC and cooperative longline survey results.

Methods and Materials

Vessels and Gear

A number of Japanese commercial longline vessels have been chartered for the cooperative survey. Generally they have been similar in size, about 50–55 m long, and carrying crews of about 23–25 Japanese nationals, two Japanese scientists, and an American scientist. There has been little continuity with respect to vessel, fishing master, and crew, but the Japanese chief scientist was often the same during the 1979–86 surveys.

Two domestic fishing vessels have participated in the AFSC longline survey. In 1988 the survey was conducted aboard the 35-m FV *Prowler*. In the four subsequent years, the 47-m FV *Ocean Prowler* was chartered. The same captain participated in all AFSC longline surveys.

The Japanese longline gear and the AFSC longline gear are similar in many respects (Fig. 2). At each station, both surveys deploy 9.5-mm diameter groundlines composed of 160 skates of longline gear tied together. Each skate is 100 m long and contains 45 hooks. Hooks are spaced 2 m apart. A 3-kg weight is attached where skates are joined. Sixteen kilometers of groundline and 7,200 hooks are fished at each station. One station is fished each sampling day. Both surveys use squid as bait. Although the AFSC survey exclusively uses North Atlantic squid, *Illex illecebrosus*, the cooperative survey sometimes uses squid from the South Atlantic Ocean.

The AFSC gear underwent a period of development in 1988 and 1989 to determine an adequate and efficient weighting arrangement and the best length, thickness, and attachment method for the beckets that secure the gangions to the groundline.

Differences between the two longlines pertain mostly to hook type and gangion construction. Generally the AFSC hooks and gangions are more heavily constructed than those of the cooperative survey longline. The AFSC survey uses size 13/0 (2.75-mm diameter wire) Mustad[1] circle hooks. Hooks are attached to 38-cm gangions that are secured to beckets tied into the groundline (Fig. 2). Gangions are constructed of medium-lay no.-60-thread braided nylon. During the 1988 survey and for part of the 1989 survey, becket material was no.-60-thread braided nylon, but during the 1989 survey all beckets were changed to medium-lay no.-72-thread braided nylon, which has been the standard since then. The cooperative survey uses thinner J-shaped (*tara*) hooks (2.20-mm diameter wire), and 120-cm gangions of no.-48-thread soft-lay twist nylon. Those gangions are tied directly to the groundline.

Although both longline types are held on bottom with 3-kg weights placed between each skate of gear, the AFSC weights are made of lead, and the cooperative weights are rope-bound stones. Because of the density difference between lead and stone, water displacement effectively lightens the stone weighting arrangement more than the lead ball arrangement; thus bottom-tending characteristics of the cooperative survey gear may be different from those of the AFSC longline when set in areas with strong currents.

The gear is extensively maintained each day to ensure that sampling effort remains as standardized as possible. Missing or damaged hooks and gangions are repaired or replaced every day, and excessively damaged skates are replaced.

Survey Area and Operations

Annual Longline Surveys—The survey area is the upper continental slope between the Islands of Four Moun-

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[1] Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

tains (52°50'N 170°W) eastward to Dixon Entrance (Fig. 1). Sampling depths range from about 200 to 1,000 m. Sampling gear is usually set from shallow to deep and retrieved in the same order. Soak times range from 3 to about 11 h for the AFSC survey and 3 to 9–10 h for the cooperative survey.

Survey scheduling has changed somewhat during the study period, from 1988 to 1992. Table 2 lists starting and ending dates for each of the annual surveys. In 1988, the surveys were separated by about 3 weeks (wk) in the western Gulf of Alaska. Because the AFSC survey always samples supplementary stations in deep gullies, the cooperative survey overtakes the AFSC survey, and the time difference is usually reduced to only a few days off southeast Alaska (Table 3). The 1989 surveys were separated by 3 1/2 wk in the western gulf and about 1 1/2 wk in the eastern gulf. The 1990 surveys were separated by about 1/2 wk less than the 1989 surveys. In 1991 and 1992 the AFSC longline survey began later than in previous years to avoid the commercial fishing season in the western gulf, therefore the two surveys overlapped in the western gulf and became farther apart in time as they progressed eastward (Table 3). Occasional, scattered commercial fishing effort occurred during some survey periods, but only in the western Gulf of Alaska. Its effect on survey results is unknown.

The starting and ending positions and depths of station locations are designated in a scientific operations plan. To the greatest extent possible, tracklines registered on plotter paper during earlier surveys are used to standardize the distribution of sampling effort by depth. Use of the Global Positioning System (GPS) during the past two survey years has greatly increased the accuracy of station positioning. Ideally these exact locations are adhered to, although on rare occasions commercial fishing activity by trawlers or longliners at or near a standard station location necessitates moving away from the standard location to avoid gear conflict.

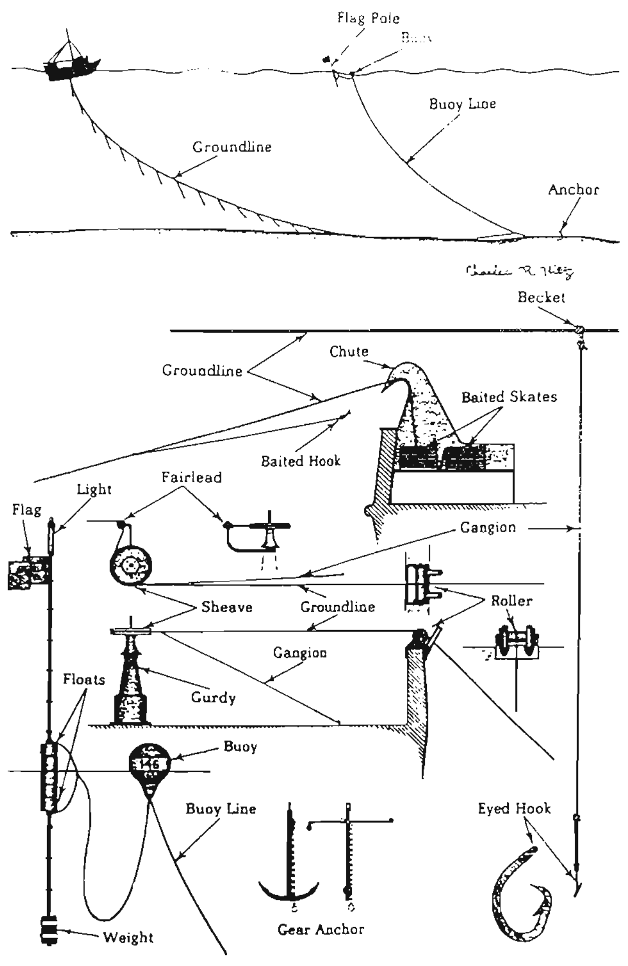

Figure 2
Generalized depiction of longline fishing gear and hauling equipment. Adapted from drawings by Charles R. Hitz of the Resource Assessment and Conservation Engineering Division, AFSC/NMFS, Seattle, Washington.

Gear-Comparison Study—A gear-comparison study was conducted at the end of the 1992 cooperative longline survey, during the first half of September. The chartered Japanese longliner *Anyo Maru No. 22* was used for this work. Twelve sets were made at ten standard longline survey stations between Cape St. Elias and Cape Ommaney in southeast Alaska at 56°00'N latitude (Fig. 1). Each site was sampled with 80 skates of each gear type, fished with alternating pairs of each tied together, for a total of 160 skates per comparison station. Gear was maintained to strict standards on a daily basis as in the annual surveys. This study employed the same bait type (South Atlantic squid) used on the 1992 cooperative survey and the Japanese longline weighting method cited above. Japanese gear was set from *hachi* (flat trays), and AFSC gear was set from shallow tubs.

Table 2
Dates of annual Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative (COOP) longline surveys of the Gulf of Alaska, 1988–92.

Year	AFSC survey	COOP survey
1988	7/7–9/15	7/29–9/17
1989	6/29–9/7	7/28–9/12
1990	6/29–9/5	7/19–9/6
1991	7/15–9/23	7/18–9/4
1992	7/16–9/20	7/18–9/5

Data Collection

Annual Longline Surveys—Both surveys record incidence of species caught, and returned baited hooks for each skate of longline gear; depth of every fifth skate and of skates where depth stratum[2] (hereafter, stratum or strata) changed; and extensive size-composition data. In addition, ineffective hooks are tallied by skate for the AFSC survey only. Ineffective hooks include those that are broken, bent, tangled, or missing. Detailed descriptions of data collection are found in Sigler and Zenger (1989).

Gear Comparison Study—During the gear-comparison study, catch and related data were recorded by skate of gear (as during the annual AFSC surveys), and sablefish length frequencies were recorded by depth stratum. Japanese measuring boards were used to measure all fish. Relative to the AFSC length-frequency boards, the Japanese boards bias lengths by +1/2 cm due to a different length-interval starting point. Unlike the annual surveys, this study did not determine sex for sablefish length frequencies. Ineffective hooks were tallied for both gear types.

Analytical Methods

The average number of sablefish caught per skate, or catch per unit of effort (CPUE), by station/stratum is calculated for each of the two surveys for the years 1988 to 1992. The AFSC survey CPUE is adjusted for ineffective hooks up to a maximum of 5 ineffective hooks. Skates of AFSC survey gear with 6 or more ineffective hooks are not used to compute CPUE. Ineffective hooks are not recorded for the cooperative survey, thus the cooperative survey CPUE is not adjusted.

Another index of abundance, relative population number (RPN), is computed as area-weighted average CPUE's for each stratum, which are then summed across the entire sample region to arrive at an estimate of gulfwide relative sablefish abundance. A detailed treatment of RPN estimation can be found in Sigler and Zenger (1989).

Relationships between annual AFSC survey CPUE and cooperative survey CPUE for matching station/strata are displayed in scattergrams, and the correlation coefficients calculated. Ideally, we would like to predict values for AFSC survey CPUE from the values of cooperative survey CPUE, but these data do not fit the requirements for a Model I or predictive regression (Ricker, 1973; Sokal and Rohlf, 1981; Isobe et al., 1990).

Table 3

Difference in day of the year when each station was sampled by the Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative longline surveys, 1988–92. Negative numbers indicate that the AFSC survey sampled before the cooperative survey.

	Year				
Sta. no.	1988	1989	1990	1991	1992
1	–24	24	–20	–3	–2
2	–22	25	–21	0	0
3	–22	–26	–21	–2	–5
4	–18	–26	–21	–1	–1
5	–21	–26	–21	–1	–1
6	–18	–26	–21	–1	–1
7	–18	–26	–21	–1	–1
8	–18	–26	–21	–1	–1
9	–18	–26	–21	–1	–1
10	–18	–26	–20	–1	–1
11	–18	–26	–19	–1	–1
12	–16	–25	–19	–1	–1
13	–16	–25	–18	4	2
14	–7	–25	–18	4	2
15	–6	–25	–10	9	2
16	–11	–17	–10	3	7
17	–7	–17	–10	8	7
18	–7	–17	–10	8	7
19	–7	–17	–10	8	7
20	–6	–17	–10	8	7
21	–14	–17	–10	8	7
22	–5	–17	–10	8	7
23	–13	–17	–10	8	7
24	–4	–20	–10	8	7
25	–5	–20	–12	8	7
26	–10	–16	–11	7	8
27	–9	–18	–11	7	5
28	1	–18	–11	7	5
29	–3	–18	–11	7	5
30	–9	–18	–11	8	6
31	–4	–18	–11	8	6
32	–4	–16	–10	9	7
33	–4	–16	–10	9	7
34	–4	–16	–10	9	7
35	–4	–11	–6	12	10
36	–4	–10	–6	13	11
37	–4	–10	–5	13	11
38	–3	–10	–5	13	12
39	–2	–9	–4	15	12
40	–2	–9	–4	15	12
41	–2	–9	–3	15	12
42	–2	–9	–3	16	13
43	–2	–9	–2	16	13
44	–2	–6	–2	19	15
45	–2	–6	–1	19	15
46	–2	–6	–1	19	15
47	–2	–5	–1	19	15
Mean absolute difference	9	17	11	8	7

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[2] Stratum definitions: 2 = 101–200 m; 3 = 201–300 m; 4 = 301–400 m; 5 = 401–600 m; 6 = 601–800 m; and 7 = 801–1,000 m.

In this case both variables are subject to unknown measurement error due to intrinsic factors such as fish distribution within a typical station/stratum relative to the positioning of each sampling gear, unmatched or inadequate amounts of sampling effort between surveys within a station/stratum, hook saturation, loss, or preemption by other species. A small amount of error is attributable to measurement (hooking effectiveness) and counting error.

In short, neither survey CPUE can be established as the independent or control variable, in which case a Model I or least-squares regression of the supposed dependent variable on the supposed independent variable is usually biased (Sokal and Rohlf, 1981). Thus for purposes of this report, we can only attempt to establish the functional relationship of the annual bivariate distributions and to study whether that relationship changes over the 5-year survey period.

A Model II (functional) regression can be used to describe the relationship between the sets of station/stratum-matched CPUE where both variables are measured with error. Several relatively simple functional regression models exist, each with its own assumptions, strengths, and weaknesses. There is considerable disagreement among members of the scientific community about the correct functional regression model to employ for given data sets. Most of the discussions with biological applications pertain to biometrics comparisons (Kermack and Haldane, 1950; Ricker, 1973; Jolicoeur, 1975; Kuhry and Marcus, 1977). In particular, discussions deal with comparisons of data sets that fall into different scales (e.g., length–weight relationships, measurements of metabolism versus size, and meristic comparisons), and with the underlying error assumptions of each of the models.

The two models most often cited are the reduced major axis, or geometric mean regression (GMR), and the ordinary major axis, or principal axis regression (PAR). More recently Isobe et al. (1990) proposed another alternative, the bisector of the angle (BAR) between the ordinary least squares (OLS) Y|X and X|Y slopes, which performed better than the GMR and PAR models during simulation tests. Isobe et al. found that PAR was less reliable than GMR or the OLS bisector for astronomical data. Because time constraints did not allow us to test the BAR model with our CPUE data, we do not consider it at this time.

For our CPUE data, the GMR and PAR regression lines were generally quite similar. Because of the possibility that the confidence interval around the GMR slope might be unduly conservative given relatively large sample sizes, and because the data are compared on identical scales, we chose the PAR regression to describe the functional relationship between the CPUE data sets (Jolicoeur, 1975). Additionally, the GMR and PAR models have different error variance assumptions: the ratio of the error variances for PAR is 1, whereas the error variances for GMR are assumed to be proportional (McArdle, 1988). Unfortunately, the error variances are unknown, and their relationship can only be surmised. For the purpose of this paper, we assumed that the data sets possessed similar error variances, and we therefore used the PAR model. Sokal and Rohlf (1981) give computation formulae for the PAR slope confidence limits.

Table 4a

Slope of the principal axis ($\mathrm{BETA}_{\mathrm{par}}$), 95% confidence limits (CL) of the slope, Pearson correlation coefficient (r), and number of data pairs (n) for relationships between station/stratum-matched annual CPUE's of the Alaska Fisheries Science Center longline and Japan–U.S. cooperative longline surveys, 1988–92. All correlations are significant ($P<0.050$).

Year	$\mathrm{BETA}_{\mathrm{par}}$	Lower CL	Upper CL	r	n
1988	0.8498	0.7408	0.9719	0.7101	212
1989	1.1810	0.9571	1.4684	0.5433	211
1990	1.4570	1.2231	1.7563	0.6118	205
1991	1.3979	1.2117	1.6239	0.6843	211
1992	1.3844	1.2238	1.5740	0.7459	200

Comparisons of Sablefish CPUE

Annual Longline Surveys, 1988–92

Scattergrams, Correlations, and Regressions—Station/stratum-matched CPUE's, sample sizes, correlation coefficients, and principal axis regressions for each of the annual surveys are shown in Figure 3. Notable differences in the functional regressions are apparent. The 1988 CPUE relationship showed that the cooperative survey would be expected to produce higher estimates of relative abundance than the AFSC survey; the y intercept was very near zero, and the correlation coefficient was significant (r=0.71, $P<0.001$; Table 4a). In 1989 the relationship changed; at lower levels of CPUE (and supposedly lower sablefish abundance if we assume that CPUE is an indicator of abundance), the cooperative survey catch rates were higher than the AFSC catch rates. The correlation coefficient for 1989 was significant, but was much lower (r=0.54) than any of the other years. The apparent bias at the lower end of the 1989 CPUE range was also much larger than that of any other year.

Functional relationships between the CPUE's were very similar in 1990 and 1991 (Fig. 3). Catch rates for the AFSC survey were generally higher than those of

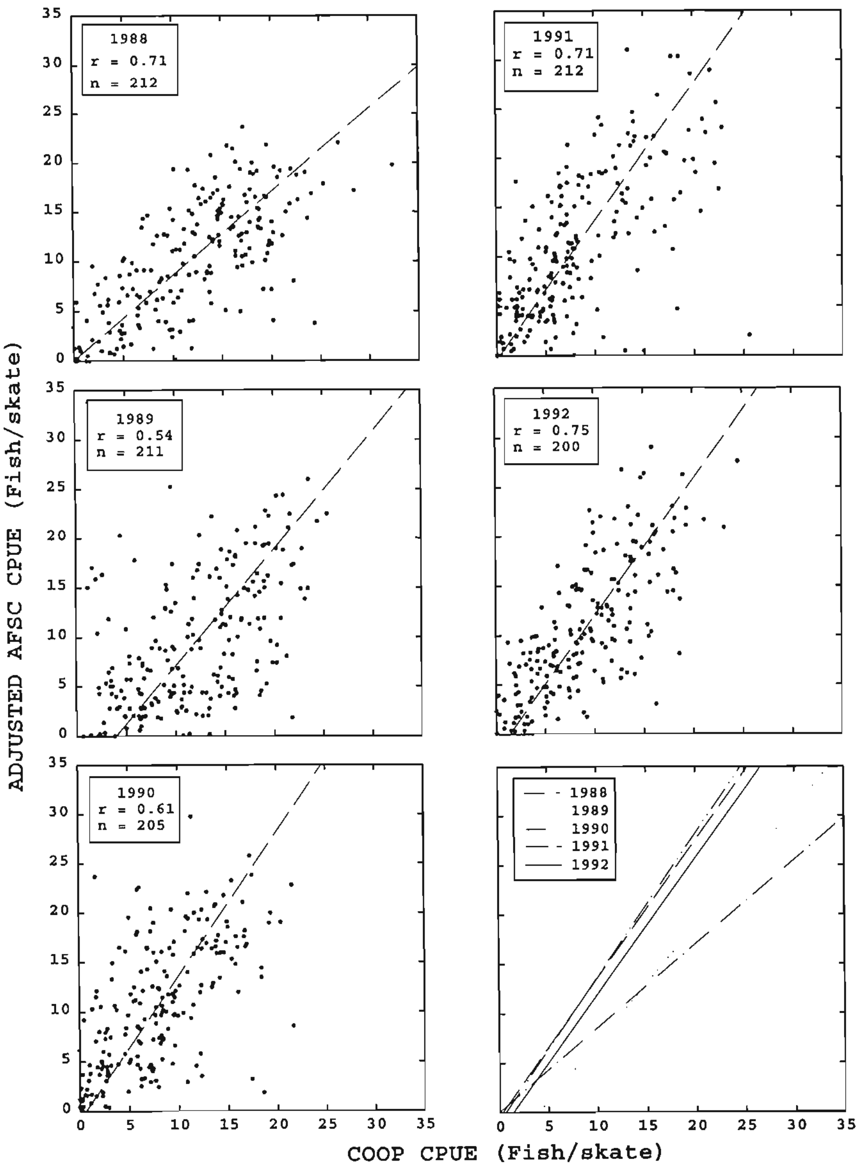

Figure 3

Relationship between sablefish catch rates (CPUE), by matched stations and depth strata, for the Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative (COOP) longline surveys of the Gulf of Alaska, 1988–92. Principal axes of functional regressions, correlation coefficients (*r*), and sample sizes (*n*) are shown.

the cooperative survey across the entire range of CPUE. In 1992 the PAR slope was similar to those of the previous 2 years but was shifted slightly to the right. All three correlation coefficients for 1990 to 1992 were significant ($P<0.001$), and the slopes and 95% confidence limits of the principal axis trend lines were very similar (Table 4a). Although the confidence interval for the 1989 slope overlaps those for 1990 to 1992, the relatively large amount of variability accounts for the overlaps. Regardless, we cannot say that the slope of the 1989 principal axis is significantly different from the slopes for 1990–92.

Gear-Comparison Study—The gear-comparison study conducted at the end of the 1992 cooperative survey verified the linear nature of the relationship between the two longline survey data sets. The adjusted catch rate for the AFSC sampling gear was slightly higher than that for the cooperative survey, with a mean of 18.5 sablefish/skate versus 17.3 sablefish/skate. However, it should be noted that most of the difference was caused by adjustments to the AFSC catch data for ineffective hooks.

Most striking was the change in relative efficiencies of the two gear types. The AFSC gear was less efficient relative to the cooperative gear than when it was fished from the AFSC charter vessel at the same stations about a week to 10 days earlier (Fig. 4). Correlation between gear-specific catch rates was stronger during the gear-comparison experiment (r=0.84) than for corresponding stations sampled during the immediately preceding 1992 longline surveys (r=0.55, Table 4b). The relatively large amount of variation in the survey CPUE data caused considerable spread in the confidence limits for the principal axis slope. It is unlikely that the slopes of either principal axis shown in Figure 4 could be shown to be significantly different. Small sample size may be a main weakness of these data comparisons. Thus a resampling scheme to estimate confidence limits of the y intercepts could show no difference between them.

The change in efficiency mentioned above could have been due to differences in bait (North Atlantic *Illex illecebrosus* vs. South Atlantic squid); the Japanese crew's inexperience with the AFSC gear, particularly related to the proper baiting of circle hooks; or perhaps differences in groundline weighting. These factors were not tested. Given the relatively short time between the surveys and the gear-comparison study, it is unlikely that seasonality changes were a factor. It is assumed—since the cooperative gear was fished in its normal mode, and the AFSC gear was not—that the relative increase in cooperative CPUE was due to something other than seasonal changes or random error.

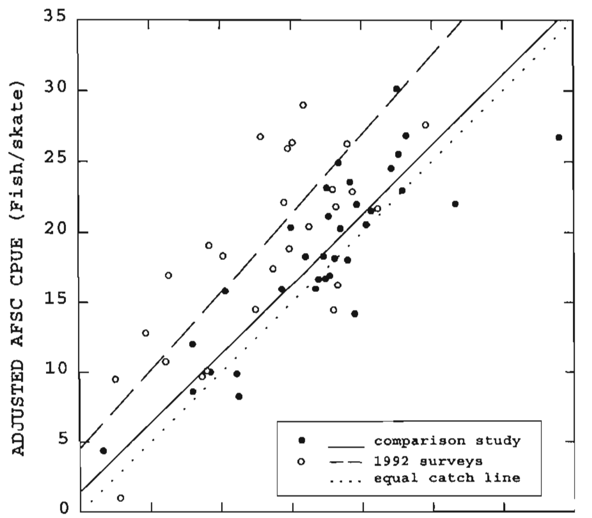

Figure 4

Sablefish catch rates (CPUE), by matched stations and depth strata, and principal axes of functional regressions for the 1992 longline gear-comparison study and the 1992 Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative (COOP) longline surveys of the Gulf of Alaska. Comparison-study stations had been sampled previously during the 1992 AFSC and COOP longline surveys.

It should be noted that the gear comparison was conducted on very productive sablefish grounds, targeting depths known to produce high catch rates. Had the AFSC charter vessel jointly fished the same areas, or had the gear-comparison study included less productive grounds, the resultant AFSC-specific mean catch rate might have been higher than that of the AFSC gear fished from the cooperative vessel. Thus it appears that the gear-comparison study furnished more new questions than answers.

Size compositions of sablefish captured by each gear type during the gear tests and the 1992 longline surveys were very similar (Fig. 5), but the AFSC gear tended to retain slightly more sablefish smaller than 55 cm. Small rightward dislocations in the length-frequency distributions of fish caught in the 1992 cooperative longline survey and of fish caught on the AFSC gear during the gear-comparison study were probably caused by a +1/2-cm bias built into the Japanese measuring boards (Fig. 5). That bias reflects a difference in zero-point interpretation and has been constant throughout the history of the cooperative longline survey.

Gear Standardization—Inconsistencies between survey-specific catch rates that lead to differences in relative abundance estimates (RPN) are not surprising when one considers the differences in sampling gears and the changes in the AFSC survey sampling gear in 1988 and 1989. The two survey sampling gears differ primarily in hook type, gangion length and strength, and

Table 4b

Slope of the principal axis ($BETA_{par}$), 95% confidence limits (CL) of the slope, Pearson correlation coefficient (r), and number of data pairs (n) for relationships between station/stratum-matched annual CPUE's from the longline survey and gear-comparison study.

Source	$BETA_{par}$	Lower CL	Upper CL	r	n
Surveys	0.7155	0.3611	1.2487	0.5525	33
Comparison	1.0080	0.8011	1.2689	0.8424	35

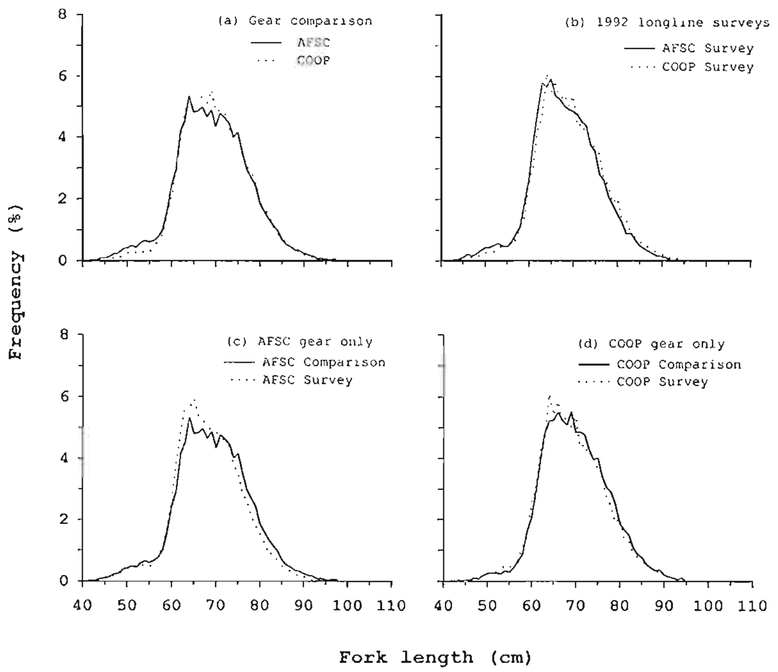

Figure 5

Length frequencies of sablefish sampled at comparison stations during the 1992 longline gear-comparison study and the 1992 Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative (COOP) longline surveys of the Gulf of Alaska.

weighting. Total numbers of hooks and total effective groundline lengths are the same. As mentioned above, the AFSC survey gear underwent a period of development in 1988 and 1989 to establish a standard groundline weighting technique and the best length, thickness, and attachment method for the beckets that secure hooked gangions to the groundline. The influence of these changes on CPUE and the AFSC survey estimates of sablefish abundance for 1988 and 1989 is unknown, but it is likely that inadequate groundline weighting could have significantly affected catch rates in areas with high current or tidal flow. During recovery of sampling gear, we commonly observed incidences of missing beckets, and thus missing hooks, in 1988 and less frequently in 1989. During 1989, when stronger beckets were introduced, and in subsequent years, the proportion of skates rejected because of too many ineffective hooks decreased from 7% in 1988, to 3% in 1989–92.

There appear to be plausible explanations for the differences between the 1988 and 1989 CPUE relationships and those from the 1990–92 surveys. The trend of the AFSC gear increasing in efficiency relative to the cooperative gear probably reflects known changes in AFSC survey gear in 1988 and 1989, and possibly deviations from standard cooperative survey procedures that occurred in 1989 and 1992 (discussed below).

Deviations from Survey Design—One of our basic assumptions is that the station locations are consistent with those presented in the scientific operations plan or that, if the station is moved, sampling effort is distributed over depth intervals in a manner similar to that at the original site. We also assume that the time periods between the surveys are short enough to be unimportant and that catches of one survey do not affect catches of the other. Survey sampling periods have not always been well-matched (Table 2, 3) and—especially in the cooperative survey—the standard stations have not always been sampled at the location called for in the scientific operations plan (Table 5).

Usually the only acceptable reason to move to an alternate location is that another vessel is occupying the standard site. Almost always the AFSC has adhered to planned station locations. However, fishing masters in charge of the cooperative survey charter vessels have sometimes refused to fish a station if, for instance, a vessel was known to have fished there the previous day. Generally the fishing master has moved to another location (usually nearby). To move the set to an alternative location does not guarantee higher catch rates, but given the monetary incentive, it does permit skill and experience on the fishing grounds to influence gear placement.

Figure 6 summarizes functional regressions for AFSC and cooperative survey stations separated by 2 n.mi. or less, and those separated by more than 2 n.mi. Only 1991 and 1992 show detectable differences. Judging by the *y* intercept, it appears that if any CPUE increase was realized by moving the cooperative stations, it was where CPUE was relatively small, and thus the motivation to move the station may have been higher.

To test the influence of the location and date effects shown in Tables 3 and 5, multiple regression analyses were performed for each year. In all cases except one, neither the location effect, the date effect, nor their interaction term strengthened the predictive ability of the regression. The 1992 date effect was significant (P=0.001), but in view of its singular occurrence and the problem with errors in variables mentioned above, that result should be viewed with skepticism.

In some cases, sampling effort appears to have been distributed so that a greater proportion fell into depth intervals where sablefish catch rates were highest. This led to lower sampling rates in the other, less productive depth intervals. The effect of this is not clear.

Coefficients of variation of the annual proportional distributions of effort were computed to show the relative amount of variability of sampling density by depth interval involved in the two sampling programs over the 5-year study period. A lower value of the coefficient of variability reflects higher interannual consistency in gear distribution by depth, and indicates a higher degree of sampling standardization. Comparisons of the AFSC effort distribution by depth (Table 6) to that of the cooperative survey (Table 7) show that, on the average, the AFSC program placed sample gear more consistently among depth intervals than the cooperative program. Some of the cooperative program's variability in gear placement seems due to targeting of productive depth zones with proportionally more sampling effort. Comparison of effort distribution by stratum (Table 7) with CPUE by stratum (Table 8) shows this to be particularly common in 1989: Shumagin and Chirikof International North Pacific Fisheries Commission (INPFC) statistical areas, stratum 5; Kodiak INPFC area, stratum 6; Yakutat INPFC area, strata 5 and 6; and Southeastern INPFC area, stratum 6.

Summary and Recommendations

Sampling errors in both CPUE variables render least squares regression an inadequate tool to predict one

Table 5

Distance in nautical miles between Alaska Fisheries Science Center longline survey stations and matching Japan–U.S. cooperative longline survey stations, Gulf of Alaska, 1988–92.

	Year				
Sta. no.	1988	1989	1990	1991	1992
1	0.6	0.5	1.3	0.5	19.2
2	0.4	13.8	0.7	3.3	6.9
3	2.7	1.6	0.4	7.5	6.2
4	0.9	1.5	0.8	4.1	3.4
5	0.9	1.7	2.0	7.1	3.8
6	1.2	1.1	0.9	3.7	4.9
7	0.3	14.9	14.7	11.6	5.8
8	0.3	0.4	7.1	1.3	1.4
9	0.8	1.2	0.9	4.1	4.3
10	0.3	1.1	0.8	0.6	6.1
11	1.0	1.7	1.7	5.7	5.8
12	0.7	1.0	0.4	4.6	5.7
13	1.0	1.8	9.3	3.6	4.6
14	0.8	0.5	8.2	8.0	0.7
15	1.0	1.9	0.7	0.9	0.9
16	8.3	4.0	3.1	3.2	2.4
17	0.5	0.9	0.9	0.9	1.4
18	1.5	1.5	2.8	1.8	2.3
19	4.9	4.4	5.0	4.3	6.9
20	1.0	0.7	1.2	0.8	1.3
21	1.1	0.5	1.0	1.1	1.1
22	0.6	1.3	7.3	1.9	2.0
23	0.5	0.7	0.8	1.0	1.1
24	0.9	0.6	20.1	0.7	0.5
25	1.7	1.8	1.8	1.4	1.8
26	0.8	0.5	0.8	0.9	7.2
27	11.9	11.3	11.2	10.9	11.1
28	0.6	1.2	1.4	1.5	1.6
29	2.4	3.1	3.5	2.7	3.1
30	0.6	0.6	0.6	1.2	0.7
31	0.7	2.0	1.5	2.3	1.5
32	2.8	3.3	2.9	3.2	3.4
33	0.7	0.6	0.4	0.6	0.5
34	0.3	0.4	0.7	0.5	0.7
35	0.4	0.3	0.1	8.0	0.3
36	0.4	0.7	0.5	0.7	0.5
37	0.2	0.5	0.3	0.8	0.7
38	0.3	0.7	0.5	1.0	1.2
39	5.0	6.2	6.2	4.6	3.5
40	0.5	0.6	0.5	0.6	0.4
41	0.7	1.3	1.2	0.8	0.8
42	1.8	9.7	1.8	1.9	2.5
43	1.8	1.3	1.3	1.7	2.3
44	1.0	1.5	1.3	0.9	1.0
45	0.5	0.4	0.2	1.0	1.0
46	1.0	1.2	1.5	1.4	1.0
47	1.3	0.5	0.5	0.3	0.1
Mean distance	1.5	2.3	2.8	2.8	3.1

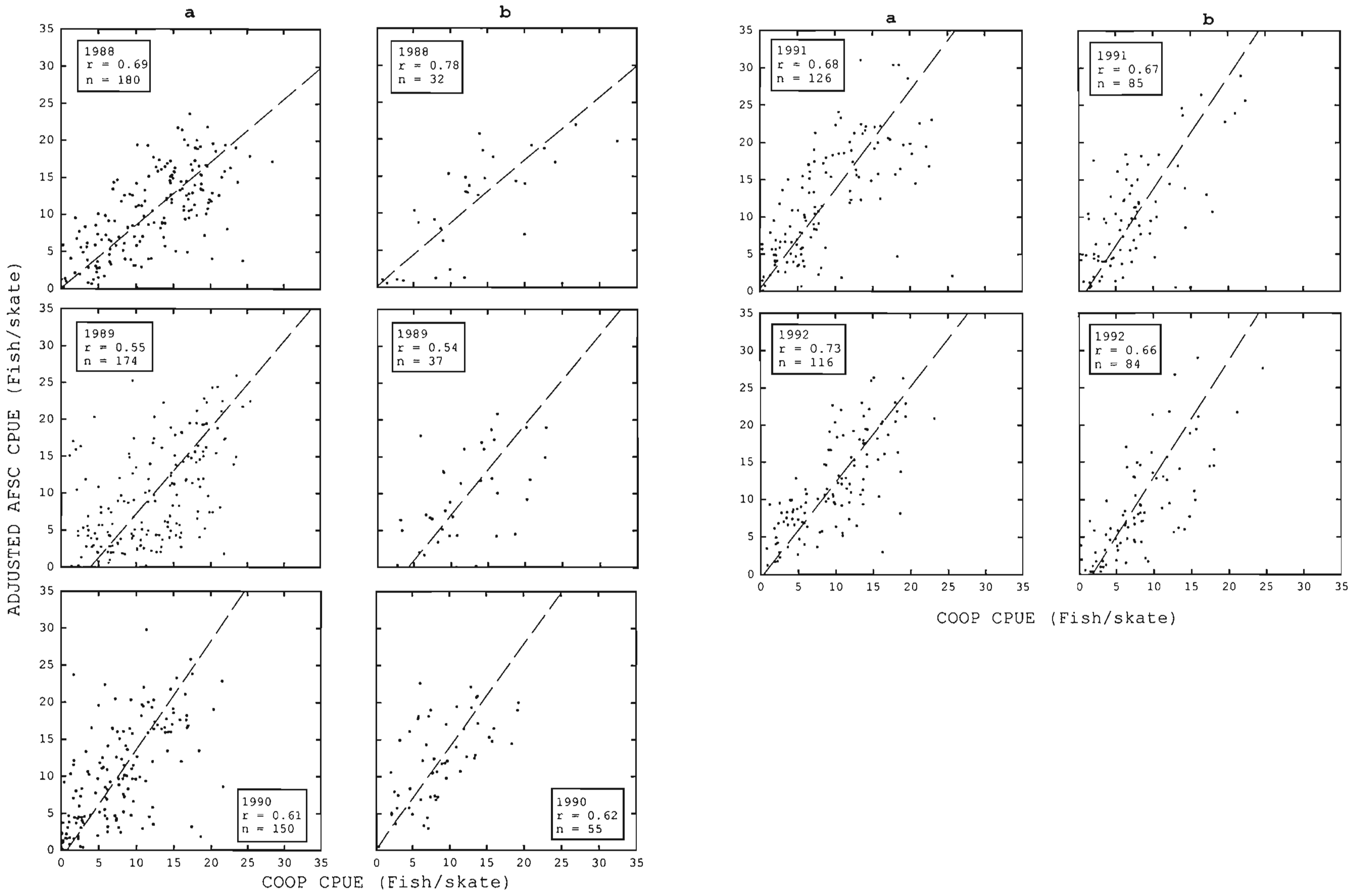

Figure 6

Sablefish catch rates (CPUE) from the 1988–92 Alaska Fisheries Science Center (AFSC) and Japan–U.S. cooperative (COOP) longline surveys of the Gulf of Alaska, compared by station and depth stratum, for (a) COOP station separated from AFSC station by two miles or less; and (b) COOP station separated from AFSC station by more than two miles. Dashed lines show principal axes of functional regressions.

Table 6

Distribution of sample effort by depth stratum (strata 3–7) and International North Pacific Fisheries Commission (INPFC) statistical area during Alaska Fisheries Science Center longline surveys of the Gulf of Alaska, 1988–92. Stratum definitions: 3 = 201–300 m; 4 = 301–400 m; 5 = 401–600 m; 6 = 601–800 m; and 7 = 801–1,000 m.

INPFC area	Depth stratum	1988 (%)	1989 (%)	1990 (%)	1991 (%)	1992 (%)	5-y average	C.V.[1]
Shumagin	3	28.3	28.1	30.7	27.7	35.0	30.0	0.09
	4	24.4	23.0	24.2	22.3	23.5	23.5	0.03
	5	31.9	30.5	27.2	34.9	31.7	31.2	0.08
	6	13.0	14.7	12.3	11.1	9.8	12.2	0.14
	7	2.4	3.6	5.6	4.0	0.0	3.1	0.60
Chirikof	3	30.3	31.4	31.1	28.3	26.4	29.5	0.06
	4	23.9	25.3	21.1	22.8	21.3	22.9	0.07
	5	28.3	23.0	24.6	28.6	25.9	26.1	0.08
	6	16.5	14.2	13.6	14.9	16.8	15.2	0.08
	7	1.0	6.1	9.5	5.4	9.6	6.3	0.50
Kodiak	3	22.5	20.7	21.6	21.6	15.8	20.4	0.12
	4	13.8	12.8	12.4	12.9	10.5	12.5	0.09
	5	35.4	30.0	33.9	32.8	28.8	32.2	0.08
	6	27.2	28.0	23.1	25.0	28.5	26.4	0.08
	7	1.1	8.4	9.1	7.8	16.5	8.6	0.57
Yakutat	3	12.5	11.0	8.5	11.0	8.6	10.3	0.15
	4	9.5	8.8	11.1	10.8	10.9	10.2	0.09
	5	34.0	31.7	35.8	36.2	33.3	34.2	0.05
	6	34.8	35.6	30.1	32.0	37.5	34.0	0.08
	7	9.2	12.8	14.5	10.0	9.7	11.2	0.18
Southeastern	3	6.8	8.3	6.2	8.9	7.4	7.5	0.13
	4	10.4	5.7	6.6	8.6	8.2	7.9	0.21
	5	31.1	21.1	26.0	21.6	24.7	24.9	0.14
	6	32.9	44.4	43.1	33.1	34.6	37.6	0.13
	7	18.7	20.5	18.2	27.7	25.0	22.0	0.17

[1] C.V. = coefficient of variation.

Table 7

Distribution of sample effort by depth stratum (strata 3–7) and International North Pacific Fisheries Commission (INPFC) statistical area during Japan–U.S. cooperative longline surveys of the Gulf of Alaska, 1988–92. Stratum definitions: 3 = 201–300 m; 4 = 301–400 m; 5 = 401–600 m; 6 = 601–800 m; and 7 = 801–1,000 m.

INPFC area	Depth stratum	1988 (%)	1989 (%)	1990 (%)	1991 (%)	1992 (%)	5-y average	C.V.[1]
Shumagin	3	20.9	11.8	20.1	18.0	29.0	20.0	0.28
	4	23.1	13.1	20.1	25.2	19.6	20.2	0.20
	5	39.5	52.2	45.8	41.7	36.5	43.1	0.13
	6	14.9	21.3	12.4	13.8	10.4	14.6	0.25
	7	1.7	1.5	1.7	1.3	4.5	2.1	0.56
Chirikof	3	22.4	21.5	23.0	30.4	31.9	25.8	0.17
	4	17.5	12.9	14.2	16.6	18.3	15.9	0.13
	5	36.2	45.7	38.6	29.2	29.0	35.7	0.18
	6	17.6	17.9	19.1	20.2	16.3	18.2	0.07
	7	6.3	2.0	5.1	3.6	4.5	4.3	0.34
Kodiak	3	16.7	13.7	13.5	15.8	12.3	14.4	0.11
	4	13.8	9.3	11.5	16.2	10.7	12.3	0.20

continued

Table 7 (continued)

INPFC area	Depth stratum	1988 (%)	1989 (%)	1990 (%)	1991 (%)	1992 (%)	5-y Average	C.V.[1]
Kodiak	5	36.1	32.9	33.8	35.2	36.9	35.0	0.04
	6	28.5	42.0	34.5	27.2	35.1	33.5	0.16
	7	4.9	2.0	6.7	5.3	5.0	4.8	0.32
Yakutat	3	8.8	12.9	10.4	10.5	8.8	10.3	0.15
	4	6.0	5.9	9.0	10.8	5.7	7.5	0.28
	5	28.2	36.7	27.4	30.9	25.9	29.8	0.13
	6	48.6	42.5	41.4	37.2	48.7	43.7	0.10
	7	8.4	2.0	11.8	10.6	11.0	8.8	0.41
Southeastern	3	10.4	5.4	7.0	10.1	7.5	8.1	0.24
	4	5.8	3.6	6.7	11.6	5.5	6.6	0.40
	5	21.9	19.6	18.4	29.2	25.7	23.0	0.17
	6	45.2	62.4	58.6	40.1	52.7	51.8	0.16
	7	16.6	9.1	9.3	9.0	8.7	10.5	0.29

[1] C.V. = coefficient of variation.

Table 8

Catch per unit of effort (sablefish per skate) by depth stratum (strata 3–7) and International North Pacific Fisheries Commission (INPFC) statistical area during Japan–U.S. cooperative longline surveys of the Gulf of Alaska, 1988–92. Stratum definitions: 3 = 201–300 m; 4 = 301–400 m; 5 = 401–600 m; 6 = 601–800 m; and 7 = 801–1,000 m.

INPFC area	Depth stratum	Year				
		1988	1989	1990	1991	1992
Shumagin	3	12.3	6.5	5.4	6.2	6.7
	4	10.7	4.5	4.0	5.3	5.4
	5	12.1	11.6	7.7	5.6	4.8
	6	9.8	8.2	6.9	3.3	2.2
	7	5.1	5.1	3.9	0.9	0.9
Chirikof	3	14.0	7.8	9.4	6.1	12.1
	4	14.4	6.2	5.9	7.4	8.5
	5	15.1	11.1	9.4	7.3	10.8
	6	15.9	12.4	12.0	6.7	9.3
	7	11.7	2.1	3.8	8.1	6.8
Kodiak	3	10.1	12.2	11.5	9.4	7.0
	4	8.7	5.4	4.0	6.6	4.4
	5	13.9	13.1	12.0	9.1	8.2
	6	17.4	19.0	13.2	12.6	12.1
	7	11.4	12.2	6.6	6.7	12.7
Yakutat	3	4.7	5.6	5.0	5.5	6.1
	4	7.2	7.7	4.7	6.8	6.8
	5	17.5	13.0	8.2	11.0	11.5
	6	18.5	16.0	12.3	13.4	14.1
	7	12.1	14.9	9.1	8.8	11.7
Southeastern	3	9.9	6.4	3.2	4.1	4.5
	4	11.5	6.7	6.5	9.5	9.0
	5	18.3	16.2	8.5	13.5	14.2
	6	20.8	17.3	13.0	19.3	15.8
	7	16.7	14.9	14.1	15.7	12.1

CPUE from the other. Principal axes simply demonstrate the general relationship between the two variables. However, as an exploratory exercise, the influence of differences in sample date, and distance from the standard sample site were tested by multiple regression analysis. Neither test helped to explain variability in the relationship between the two survey CPUE's.

The AFSC gear was fully standardized only after 1989, and apparent deviations from standard station locations were particularly pronounced during the 1989 cooperative survey. Thus future comparisons of catch rates from the two longline surveys should concentrate on the data from 1990, 1991, and 1992. Similar analyses should be performed on future data sets to monitor comparability of the AFSC and cooperative longline surveys. At AFSC, work is being completed to identify that relationship using a log-linear model (Kimura, 1988), thus allowing relative population indices (RPN) to be estimated for the years 1979–89.

Regarding the gear-comparison experiment conducted at the end of the 1992 cooperative survey, the most striking result was the relative change in efficiency of the AFSC gear when it was fished from the cooperative survey vessel. Most of the difference between the two gear-specific CPUE's was caused by adjustments for ineffective AFSC hooks. In terms of uncorrected CPUE, the two gear types performed virtually the same. Thus it appears that there are survey-specific factors at work that did not allow the AFSC gear to fish at its usual efficiency. Bait type, crew experience with a specific gear, or gear rigging probably all combined to influence CPUE. It appears that a more meaningful gear-comparison experiment might have featured proximal parallel sets by both charter vessels, each using its customary gear. Future surveys should maintain strict gear standardization and matched sampling locations between the two surveys.

Literature Cited

Isobe, T., E. D. Feigelson, M. G. Akritas, and G. J. Babu.
1990. Linear regression in astronomy. I. Astrophysical J. 364:104–113.

Jolicoeur, P.
1975. Linear regression in fisheries research: some comments. J. Fish. Res. Board Can. 32:1491–1494.

Kermack, K. A., and J. B. S. Haldane.
1950. Organic correlation and allometry. Biometrika 37:30–41.

Kimura, D. K.
1988. Analysing relative abundance indices with log-linear models. N. Am. J. Fish. Manage. 8:175–180.

Kimura, D. K. and H. H. Zenger Jr.
1997. Standardizing sablefish (*Anoplopoma fimbria*) long-line survey abundance indices by modeling the log-ratio of paired comparative fishing CPUEs. ICES J. Mar. Sci. 54:48–59.

Kuhry, B., and L. F. Marcus.
1977. Bivariate linear models in biometry. Syst. Zool. 26:201–209.

McArdle, B. H.
1988. The structural relationship: regression in biology. Can. J. Zool. 66:2329–2339.

Ricker, W. E.
1973. Linear regression in fishery research. J. Fish Res. Board Can. 30:409–434.

Sigler, M. F., and H. H. Zenger Jr.
1989. Assessment of Gulf of Alaska sablefish and other groundfish based on the domestic longline survey, 1987. U.S. Dep. Commer., NOAA Tech Memo. NMFS F/NWC-169, 54 p.

Sokal, R. R., and F. J. Rohlf.
1981. Biometry. 2nd ed. W. H. Freeman, London.

Geographic Apportionment of Sablefish, *Anoplopoma fimbria*, Harvest in the Northeastern Pacific Ocean

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ABSTRACT

An age-structured model of the sablefish population in the northeastern Pacific Ocean that includes movement, survival, and recruitment was constructed to examine yield per recruit and harvest policies. The model includes a Markov transition matrix that specifies the probability that a fish of a given age will move from one fishery regulatory area to another in one year. Estimates of yield per recruit are sensitive to assumptions about the geographic distribution of recruitment. If most recruitment occurs in the eastern areas of the Gulf of Alaska, then fisheries in the western regions will benefit from low exploitation rates. Conversely, if recruitment occurs in all geographic areas, then fisheries in the eastern area will benefit from low exploitation rates. In general, when evaluated under the current annual exploitation rate of about 10% over a 100-year period, policies that apportion harvest among regulatory areas based on areal estimates of available biomass or on the steady-state distribution of biomass computed from the transition matrices gave similar results. The current policy of apportionment is based on a weighted moving average of areal estimates of available biomass. This policy adapts to current information about geographic distribution of biomass, reduces the effects of annual fluctuations in biomass estimates due to measurement error, and does not require estimates of movement probabilities for implementation.

Introduction

The apportionment of catch limits among geographic areas for many groundfish fisheries is based on the geographic distribution of estimated abundance. Surprisingly, few studies have compared alternative methods of apportioning catch limits, partly because of sparse information on the spatial aspects of many fish populations. The purpose of this paper is to explore alternative methods of apportioning the annual catch limits for a highly migratory species: sablefish, *Anoplopoma fimbria*, in the northeastern Pacific Ocean.

Plans are under way to manage the United States fishery for sablefish in the northeastern Pacific Ocean by individual transferable fishing quotas (IFQ's) on an areal basis. Under this management system, an individual will own the right to a certain portion of the catch limit within an area. Thus, apportioning the catch limit among areas can have important social and economic effects.

Annual catch limits for sablefish in waters managed by the North Pacific Fishery Management Council (NPFMC) are typically apportioned among fishery regulatory areas in direct proportion to geographic distribution of estimated biomass (Gulf of Alaska Groundfish Plan Team[1]). Tagging experiments indicate rapid mixing of sablefish among regulatory areas; the pattern of movement is related to fish size and age (Heifetz and Fujioka, 1991). Movement is primarily westward for small, mostly immature sablefish, and eastward for large, mature sablefish. Large sablefish in the Eastern Gulf of Alaska regulatory area (EGOA) tend to remain there. This pattern of movement has not been directly considered in the development of harvest strategies in the past.

In this paper, we use movement rates estimated from tagging data reported by Heifetz and Fujioka (1991) together with other sablefish population parameters to model the movement, survival, growth, and recruitment of an age-structured population. Including movement rates in a population model is an important step towards understanding the spatial dynamics of an exploited population.

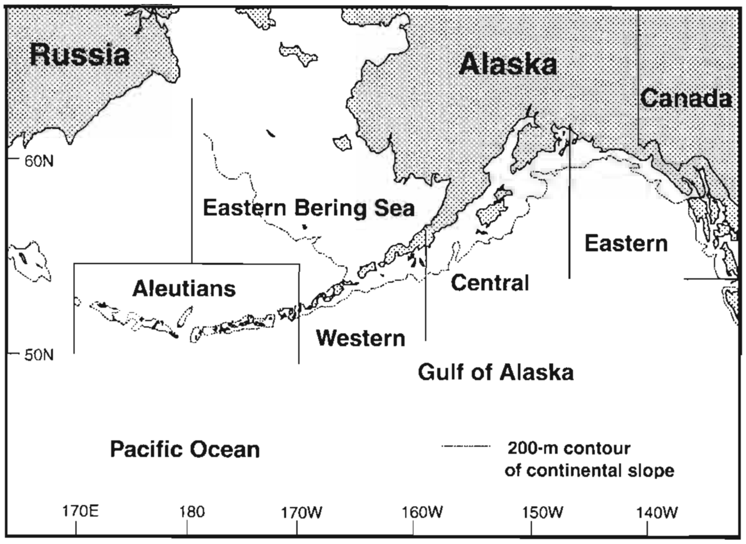

Figure 1
Northeastern Pacific Ocean, showing North Pacific Fishery Management Council regulatory areas.

Our study is divided into two parts, each with different objectives. First, yield per recruit by area is analyzed to explore the implications of movement and assumptions about the geographic distribution of recruitment with regard to sablefish population dynamics. Second, alternative strategies for geographic distribution of harvest are evaluated. Trends in yield, yield variability, reproductive potential, and catch per unit of effort are examined.

Methods

Model Description

In our population dynamics model, we attempt to accommodate the dynamics of the survival, movement, and recruitment process and the methods used by the NPFMC for setting sablefish catch limits in the northeastern Pacific Ocean (Fig. 1). Typically, a biomass-based acceptable biological catch (ABC) for all regulatory areas combined is computed by multiplying available biomass B for all areas combined by an exploitation rate μ. This ABC is then apportioned to the five regulatory areas based on some policy. We equate ABC with a catch limit and assume that the entire limit is taken each year. Because sablefish in the northeastern Pacific Ocean are a fully utilized species and managed on a quota system, this assumption is approximately correct.

Given numbers at age a in area r at the beginning of year t, $N(t,a,r)$, weight at age, $w(a)$, availability at age, $s(a)$, and apportionment (proportion of catch limit allotted to area r in year t), $P(t,r)$, available biomass is

$$B(t,a,r) = N(t,a,r)w(a)s(a).$$

The total catch limit among areas is

$$Q(t) = \mu B(t),$$

which is apportioned to areas as

$$Q(t,r) = P(t,r)Q(t).$$

Exploitation rate by area is

$$\mu(t,f) = \frac{Q(t,r)}{\sum_a B(t,a,r)}.$$

Catch in numbers at age is then obtained as

$$C(t,a,r) = \mu(t,r)N(t,a,r)s(a).$$

For convenience, natural mortality M is assumed to occur continuously throughout the year, and fishing is assumed to occur instantaneously at the beginning of a year. Abundance in each area after fishing and natural mortality is

$$N^*(t,a,r) = \big(N(t,a,r) - C(t,a,r)\big)\big(\exp(-M)\big).$$

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[1] Gulf of Alaska Groundfish Plan Team. 1992. Current status of stocks and acceptable biological catches. *In* Stock assessment and fishery evaluation report for the 1993 Gulf of Alaska groundfish fishery, p. 13–33. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510-2252.

Table 1

Estimates of population parameters for sablefish in the northeastern Pacific Ocean. Fraction mature and availability at age are from Sigler and Fujioka (1993). Growth parameters for length (L; cm) and weight (w; kg) are adapted from Lowe et al. (1991).

	Age, a										
	3	4	5	6	7	8	9	10	11	12	13–75
Natural mortality, M	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Maturity, $m(a)$	0.002	0.032	0.232	0.629	0.868	0.949	0.977	0.988	0.993	0.998	1.00
Availability, $s(a)$	0.15	0.32	0.48	0.63	0.73	0.82	0.88	0.93	0.97	1.00	1.00

von Bertalanffy length–age model

$L_a = L_\infty\,[1 - \exp(-k(a - t_0))]$

$L_\infty = 80.550$

$k = 0.171$

$t_0 = -3.220$

Allometric weight–length model

$w(a) = cL_a^{\,b}$

$c = 2.72 \times 10^{-6}$

$b = 3.325$

Movement is assumed to occur instantaneously at the end of a year. Given the Markov matrix of annual movement rates $\boldsymbol{\Theta}(a)$ where the (i,j)th element of $\boldsymbol{\Theta}(a)$ is the proportion of age-a fish that move from area i to area j in a year, the row vector of numbers at age a+1 at the beginning of year t+1 after movement is

$$\mathbf{N}(t+1,a+1) = \mathbf{N}^{*}(t,a)\boldsymbol{\Theta}(a). \qquad (1)$$

Quinn et al. (1990a) describe a similar population dynamics model with movement. The order of events in our formulation is different from theirs. We have movement occur at the end of a year, whereas they have movement occur at the beginning of a year. The order of events is somewhat arbitrary, and alternative orders should not produce substantially different results (Getz and Haight, 1989).

Table 1 summarizes population parameters for natural mortality, weight, availability, maturity, and growth for sablefish in the northeastern Pacific Ocean. Although male and female sablefish have different growth patterns, we use growth parameters for both sexes combined because movement rates are estimated for both sexes combined. Movement rates given in Heifetz and Fujioka (1991) are based on fish length. We convert these length-specific movement rates to age-specific movement rates by using von Bertalanffy growth parameters (Table 2).

Table 2

Annual movement rates from one area to another for different age groups of sablefish; adapted from Heifetz and Fujioka (1991).

From area i	To area j EGOA	CGOA	WGOA	EBS	AL
Age 3–4					
EGOA	0.489	0.378	0.109	0.012	0.012
CGOA	0.194	0.484	0.229	0.047	0.046
WGOA	0.078	0.322	0.308	0.145	0.147
EBS	0.010	0.073	0.160	0.710	0.047
AL	0.005	0.040	0.093	0.049	0.813
Age 5–8					
EGOA	0.712	0.227	0.054	0.003	0.004
CGOA	0.273	0.476	0.199	0.023	0.029
WGOA	0.134	0.409	0.285	0.072	0.100
EBS	0.029	0.165	0.246	0.494	0.066
AL	0.013	0.077	0.128	0.034	0.748
Age ≥9					
EGOA	0.751	0.200	0.044	0.002	0.003
CGOA	0.472	0.426	0.074	0.011	0.017
WGOA	0.262	0.116	0.517	0.046	0.059
EBS	0.095	0.181	0.259	0.287	0.178
AL	0.047	0.103	0.155	0.018	0.677

EGOA, Eastern Gulf of Alaska; CGOA, Central Gulf of Alaska; WGOA, Western Gulf of Alaska; EBS, Eastern Bering Sea; AL, Aleutians.

Geographical Yield per Recruit

First, we investigate the effects on yield of different geographic distributions of recruitment. Assuming that recruitment is independent of spawning biomass allows use of the basic-yield-per-recruit model of Beverton and Holt (1957) to compute expected yield. In our analysis, we assume that recruitment, which begins at age 3, is independent of spawning biomass but dependent on area. That is, recruitment for all areas combined is held constant, but recruitment may differ among areas. Given that recruitment starts at age 3, the abundance of a cohort at age 3 is

$$N(t,3,r)=R(r).$$

The population dynamics model simulates a 75-year period with $\mu=0$ to initialize the population; then yield per recruit $Y(r)/R$ is calculated for each area separately over a range of $0.0 \le \mu \le 0.7$ as

$$\frac{Y(r)}{R}=\frac{\mu\sum_{a} s(a)N(a,r)w(a)}{R},$$

where R is recruitment for all areas combined. Because R is a constant on both sides of the above equation, it can be eliminated to compute $Y(r)$. Apportionment among areas is set in proportion to available biomass in each area. Thus the exploitation rate among areas was constant, i.e., $\mu=\mu(r,t)$.

We construct three alternative hypotheses concerning the geographic distribution of annual recruitment to examine effects on areal yields (Table 3). Hypothesis A: recruitment occurs equally in all areas. Hypothesis B: most recruitment occurs in the EGOA, with a progressively lower proportion in the more westward areas. Hypothesis C: all recruitment occurs in the EGOA.

These hypotheses represent a range that we believe reasonably approximates the uncertainties about geographic distribution of recruitment. Considered in development of these hypotheses is the pattern of sablefish movement (Heifetz and Fujioka, 1991). The westward movement of immature sablefish may compensate for the centering of recruitment in the eastern areas. Thus two of the three hypotheses have the highest proportion of recruitment in the EGOA. Estimation of the geographical distribution of recruitment and assignment of probabilities to alternative hypotheses may be possible from survey data. This is not within the scope of our study.

Table 3

Three hypotheses for the geographic distribution of annual recruitment of sablefish.

	Area[1]				
Hypothesis	EGOA	CGOA	WGOA	EBS	AL
A	0.20	0.20	0.20	0.20	0.20
B	0.40	0.30	0.20	0.05	0.05
C	1.00	0.00	0.00	0.00	0.00

[1] EGOA, Eastern Gulf of Alaska; CGOA, Central Gulf of Alaska; WGOA, Western Gulf of Alaska; EBS, Eastern Bering Sea; AL, Aleutians.

Alternative Apportionment Policies

In this part of the study, we modify the simulation model of the yield-per-recruit analysis to add biological realism and measurement error. Stochasticity is incorporated by basing recruitment on past observations (Sigler and Fujioka, 1993). Each year a recruitment level is randomly chosen from the 12 past observations (Fig. 2). This method does not assume any functional form to the stock–recruitment relationship, but instead assumes there is no relationship between stock size and resulting recruitment and that recruitment levels observed in the past are equally likely to occur in the future. Recruitment is distributed among the areas according to the three hypotheses of the yield-per-recruit analysis.

Four alternative policies of apportionment of sablefish catch quotas among areas are evaluated.

Policy 1—Constant apportionment among areas. Because there are five areas, all $P(t,r)=0.20$.

Policy 2—Set the areal catch limits proportional to estimated available biomass in each area. Given estimated available biomass $\hat{B}(t,r)$ summed over all ages in an area, apportionment is

$$P(t,r)=\frac{\hat{B}(t,r)}{\sum_{r}\hat{B}(t,r)},$$

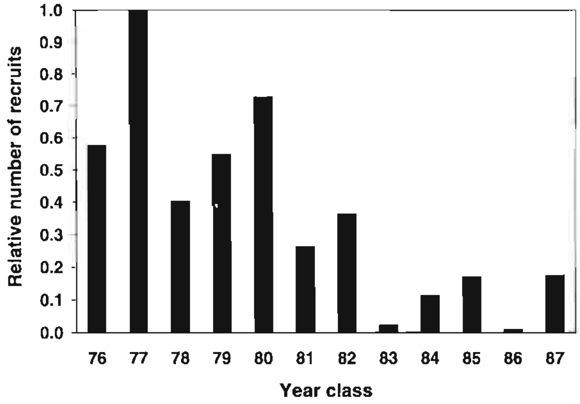

Figure 2

Estimated relative number of sablefish recruits, 1976–87 (Sigler and Fujioka, 1993).

where

$$\hat{B}(t,r) = B(t,r) + \varepsilon(t).$$

Variable $\varepsilon(t)$ is a normally distributed random error term with mean 0 and constant coefficient of variation (CV) (i.e., variance = $B^2(t,r)\mathrm{CV}^2$). This error term represents measurement error associated with the estimation of available biomass. The CV is estimated to be 0.10 based on analysis of areal variability observed in the annual longline survey of sablefish in the Gulf of Alaska (Sigler[2]).

Policy 3—Set the catch limits proportional to a weighted moving average of apportionment given in policy 2. The most recent year is given a weight of two, and the prior four years are given a weight of one. This is the present method of apportionment (Gulf of Alaska Groundfish Plan Team[1]).

Policy 4—Apportion areal catch limits on the basis of the estimated steady-state distribution of available biomass. Given Equation 1, a steady-state distribution of available biomass exists for each level of exploitation and recruitment hypothesis. As long as the $\Theta(a)$'s do not change, the distribution of available biomass will approach a limit. The expected value of the steady-state distribution is determined by simulation. The population dynamics model is simulated for 200 years with stochastic recruitment. This simulation is replicated 200 times, each with a different random sequence of recruitment. The apportionments for this policy are based on the mean of the 200 replications of the geographic distribution of available biomass at the end of the 200-year period. Exploitation rate among areas is constant, i.e., $\mu = \mu(r,t)$. Table 4 shows the apportionments based on this policy. Stochastic recruitment causes variability in the estimates of the steady-state distribution of available biomass.

Table 4

Apportionment of sablefish harvest among areas for three hypotheses of the geographic distribution of annual recruitment based on the mean steady-state distribution of available biomass for 200 replicates. Exploitation rate equals 0.10. The coefficient of variation is shown in parentheses.

	Area[1]				
Hypothesis	EGOA	CGOA	WGOA	EBS	AL
A	0.41 (0.07)	0.26 (0.02)	0.15 (0.03)	0.05 (0.19)	0.13 (0.08)
B	0.45 (0.05)	0.28 (0.04)	0.15 (0.03)	0.04 (0.13)	0.09 (0.04)
C	0.52 (0.03)	0.27 (0.04)	0.13 (0.02)	0.02 (0.07)	0.06 (0.07)

[1] EGOA, Eastern Gulf of Alaska; CGOA, Central Gulf of Alaska; WGOA, Western Gulf of Alaska; EBS, Eastern Bering Sea; AL, Aleutians.

Performance Criteria—Two hundred replications over 100 years are performed for each combination of the four apportionment policies and three recruitment hypotheses, giving 12 scenarios. A common random-number sequence is used for each scenario. Exploitation rate μ is set at 0.10, which approximates the current level of exploitation (Fujioka[3]; Lowe[4]). An example of the apportionments resulting from a typical replication for recruitment hypothesis B is shown in Figure 3.

To evaluate the effects of different apportionment policies, we compare attributes among policies. These attributes include average annual yield, yield variability, risk, and catch per unit of effort (CPUE). Average annual yield is the mean of the 200 replications. Yield variability is the mean of the 200 replications for the coefficient of variation (CV) of the annual yield. Risk is arbitrarily defined as the proportion of the time that spawning biomass in an area was less than 30% of the unfished level. Spawning biomass in an area is

$$SB(t,r) = \sum_a N(t,a,r)m(a)w(a).$$

The unfished level of spawning biomass is found by letting $\mu = 0$.

It may be contended that the definition of risk chosen is unfounded because we have assumed that recruitment is independent of spawning biomass. We believe this risk is still a useful attribute for policy comparisons, because there is considerable uncertainty about the relationship between stock and recruitment for sablefish. We assume that CPUE is proportional to the density of fish in an area, where density is defined as an

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[2] Sigler, M. Auke Bay Lab., NMFS, NOAA, 11305 Glacier Hwy., Juneau, AK 99801-8626. Personal commun., March 1993.

[3] Fujioka, J.T. 1992. Sablefish. *In* Gulf of Alaska Groundfish Plan Team (eds.), Stock assessment and fishery evaluation report for the 1993 Gulf of Alaska groundfish fishery, section 4. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510-2252.

[4] Lowe, S. A. 1992. Sablefish. *In* Bering Sea and Aleutian Islands Plan Team, (eds.), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions as projected for 1993, section 8. N. Pac. Fish. Manage. Council, P.O. Box 103136, Anchorage, AK 99510-2252.

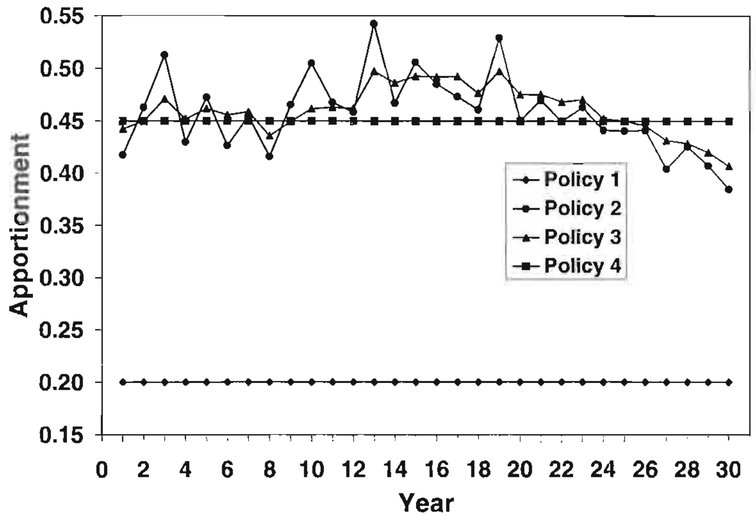

Figure 3
Time series of catch-limit apportionments for the Eastern Gulf of Alaska that would result from the four policy options, under hypothesis B.

area's available biomass divided by its available habitat for sablefish. Available habitat is defined as the combined area of gullies deeper than 400 m and continental shelf deeper than 200 m (Fujioka[3]). Attributes are presented for each regulatory area and for all regulatory areas combined.

Results

Geographic Yield per Recruit

Results of the geographic yield-per-recruit analysis are sensitive to assumptions about the geographic distribution of recruitment (Fig. 4). For hypothesis A (all areas have equal recruitment), the exploitation rate that results in maximum yield per recruit ($\mu_{\max}$) is much lower for the Eastern Gulf of Alaska regulatory area (EGOA) than for the other areas. As exploitation rate increases, a higher proportion of sablefish are caught in the more westward areas before they can return to the EGOA. Thus the highest yield for the EGOA is obtained under low fishing rates where fish are allowed to grow, mature, and move to the EGOA. For hypothesis B–most recruitment originates in the Western Gulf of Alaska (WGOA), Central Gulf of Alaska (CGOA), and EGOA–the same trend is evident. For hypothesis C (all recruitment originates in the EGOA), $\mu_{\max}$ is much lower for the Aleutians (AL) and to some extent the Eastern Bering Sea (EBS) and WGOA than for the more eastward areas. Under this hypothesis, the westward areas depend on migrants from the EGOA because no recruitment occurs in the westward areas. With a low μ, fish that recruit to the eastward areas can move westward before they are caught.

Alternative Apportionment Policies

Results differ among the regulatory areas, but the three recruitment hypotheses provide similar results for most attributes (Table 5). Thus, results apply to the average of the three recruitment hypotheses.

For the easternmost regulatory areas (EGOA and CGOA), average annual yields are lowest for policy 1 (equal apportionment) and similar for the other three policies. Yields for policy 1 are only 43% of the yields for the other policies in EGOA and about 74% in CGOA. The pattern is reversed in the more westward areas (WGOA, EBS, AL), where policy 1 has the greatest yield. For these westward areas, yields for policies 2–4 were only about 20%–70% of the yield obtained for policy 1. For all areas combined, yields are lowest for policy 1 and similar among the other policies.

Regardless of area, yield varies most for policy 2. For the EGOA yield varies least for policy 3, whereas for the CGOA and the more westward areas, yield varies least for policy 4. For all areas combined, yield varies least for policy 1 and most for policy 2.

In the EGOA and (marginally) the CGOA, CPUE is greatest for policy 1 and similar for the other policies. In the more westward areas, CPUE for policies 2–4 is similar, but is lower for policy 1. For these westward areas, CPUE for policy 1 is 65%–80% of the maximum CPUE within an area. For all areas combined, CPUE is similar for policies 2–4 and substantially lower for policy 1.

In the EGOA, the risk of overfishing (the proportion of the time spawning biomass is below 30% of the unexploited level) is lowest for policy 1 and similar among the other policies. In the CGOA, all policies had the same level of risk. In the WGOA, BS, and AL, risk is greatest for policy 1. For policy 1 in these westward areas, spawning biomass is below 30% of the unexploited level 13%–48% of the time compared to only 3%–6% of the time for the other policies. For all areas combined, risk is slightly greater for policy 1 and identical among the other policies.

Discussion

Our goal was to incorporate movement patterns of sablefish into a yield-per-recruit analysis, evaluate alternative apportionment policies, and examine the sensitivity of results to different hypotheses about geographic distribution of recruitment. Including movement rates in an age-structured model of sablefish has increased our understanding of how the fisheries for sablefish in different areas may interact with each other.

The yield per recruit in an area is a function of exploitation rate, movement rate, and the distribution of recruitment. If the populations in the westward areas are mostly maintained by migrants from other areas and not by recruitment, as hypothesized by Sasaki (1985) and Beamish and McFarlane (1988), then fisheries in the westward areas may benefit from low overall exploitation rates. Conversely, if recruitment occurs throughout the northeastern Pacific Ocean, then fisheries in the eastern areas will benefit from low overall fishing rates. Future analyses should focus on estimating the geographical distribution of recruitment from age-composition data collected during surveys.

In our study, yield per recruit was evaluated under one apportionment strategy and with constant overall recruitment. A more comprehensive analysis of yield per recruit should include analysis of alternative policies and alternative stock–recruitment relationships.

In our results, we presented an evaluation of apportionment policies on the basis of the current estimated exploitation rate of 10%. We have also evaluated these policies with considerably higher exploitation rates (i.e., 20% and 30%), and the results were qualitatively similar.

Which is the most appropriate apportionment policy is unclear, because a particular policy did not dominate across all hypotheses and attributes. Policies 2–4 performed similarly across all attributes because, on average, the apportionments for these three policies are similar. Policy 1 had the lowest overall variability in yield but substantially higher risk in the westward areas, and the lowest overall CPUE. If an objective is to optimize CPUE and maintain spawning biomass on an areal basis, then policy 1 is not appropriate. Given the uncertainty about the location of sablefish spawning areas, a policy that maintains spawning biomass in each area is desirable.

Policies 2 and 3 have some appealing attributes. They adapt to current information about geographical distribution of available biomass and do not require estimates of movement rates for implementation. Policy 3 tends to produce less variable yields than policy 2 because policy 3 is less sensitive than policy 2 to annual fluctuations in biomass estimates due to measurement error. For policy 3, the most recent year is given a weight of two and the prior four years are each given a weight of one. This weighting scheme has been chosen somewhat arbitrarily, and alternative weighting schemes may be more appropriate. If the method of weighting is based on the ratio of survey measurement error to total variability (i.e., measurement error plus variability in natural mortality, recruitment, and movement rates), then an exponential weighting scheme is appropriate (Meinhold and Singpurwalla, 1983).

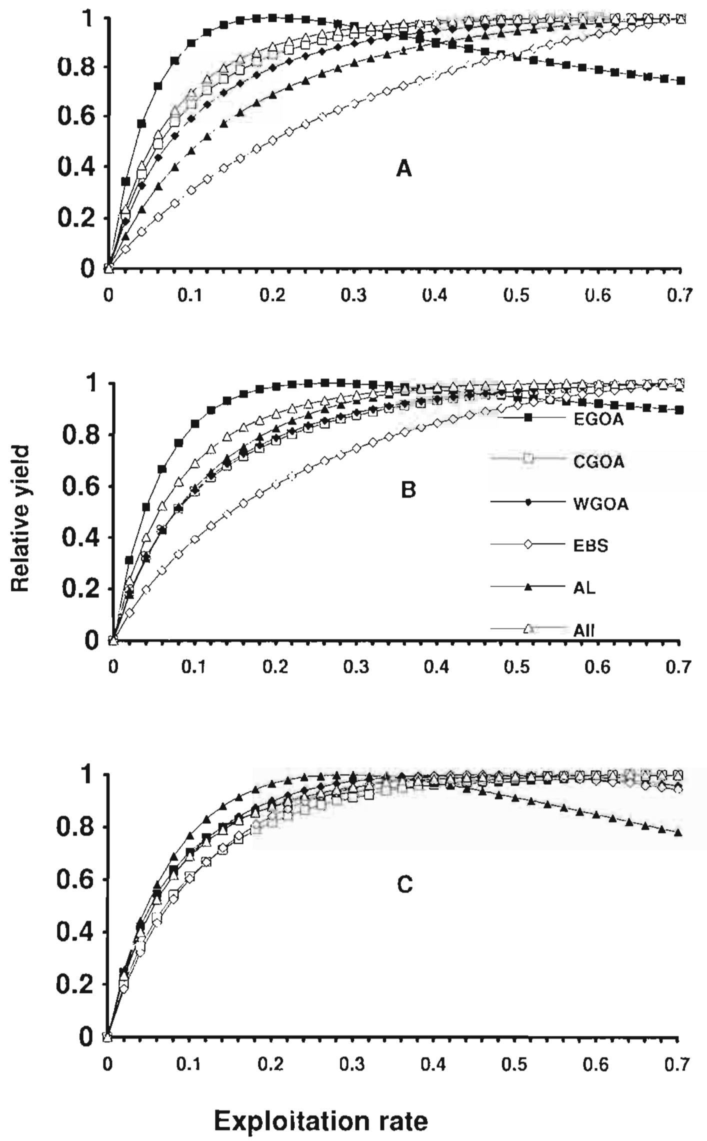

Figure 4
Yield by regulatory area for three hypotheses (A–C) about the geographic distribution of sablefish recruitment.

Table 5

Average yield, coefficient of variation (CV) of yield, CPUE, and risk for four policies of apportionment of sablefish catch limits. Yield and CPUE are expressed relative to the maximum for a particular hypothesis.

		Hypothesis															
		A				B				C				Average			
Area[1]	Policy	Yield	CV	CPUE	Risk	Yield	CV	CPUE	Risk	Yield	CV	CPUE	Risk	Yield	CV	CPUE	Risk
EGOA	1	0.19	0.20	1.00	0.07	0.19	0.20	1.00	0.05	0.20	0.20	1.00	0.04	0.20	0.20	1.00	0.06
	2	0.42	0.21	0.94	0.10	0.46	0.21	0.93	0.09	0.52	0.21	0.90	0.08	0.46	0.21	0.92	0.09
	3	0.41	0.18	0.94	0.10	0.46	0.18	0.93	0.09	0.52	0.18	0.90	0,08	0.46	0.18	0.92	0.09
	4	0.41	0.19	0.94	0.10	0.45	0.19	0.93	0.08	0.51	0.19	0.90	0.08	0.46	0.19	0.92	0.09
CGOA	1	0.19	0.20	0.59	0.05	0.19	0.20	0.57	0.05	0.20	0.20	0.51	0.05	0.20	0.20	0.56	0.05
	2	0.25	0.22	0.60	0.05	0.27	0.22	0.57	0.05	0.27	0.22	0.49	0.06	0.27	0.22	0.55	0.05
	3	0.25	0.20	0.60	0.05	0.27	0.20	0.57	0.05	0.27	0.20	0.49	0.06	0.27	0.20	0.55	0.05
	4	0.26	0.19	0.60	0.05	0.27	0.19	0.57	0.05	0.27	0.19	0.49	0.06	0.27	0.19	0.55	0.05
WGOA	1	0.19	0.20	0.60	0.11	0.19	0.20	0.50	0.13	0.20	0.20	0.38	0.15	0.20	0.20	0.49	0.13
	2	0.15	0.22	0.69	0.04	0.15	0.22	0.59	0.04	0.13	0.22	0.45	0.06	0.14	0.22	0.56	0.05
	3	0.15	0.21	0.68	0.04	0.15	0.21	0.59	0.04	0.13	0.21	0.45	0.06	0.14	0.21	0.56	0.05
	4	0.15	0.19	0.68	0.04	0.15	0.19	0.59	0.05	0.13	0.19	0.45	0.06	0.14	0.19	0.56	0.05
EBS	1	0.19	0.20	0.07	0.14	0.19	0.20	0.03	0.29	0.20	0.20	0.02	0.46	0.20	0.20	0.04	0.30
	2	0.05	0.28	0.08	0.02	0.04	0.28	0.05	0.03	0.02	0.28	0.03	0.05	0.04	0.28	0.05	0.03
	3	0.05	0.27	0.08	0.02	0.04	0.27	0.05	0.03	0.02	0.27	0.03	0.06	0.04	0.27	0.05	0.04
	4	0.05	0.19	0.08	0.03	0.04	0.19	0.05	0.03	0.02	0.19	0.03	0.06	0.04	0.19	0.05	0.04
AL	1	0.19	0.20	0.09	0.14	0.19	0.20	0.04	0.41	0.20	0.20	0.02	0.89	0.20	0.20	0.05	0.48
	2	0.13	0.25	0.11	0.02	0.09	0.25	0.07	0.03	0.06	0.25	0.04	0.06	0.09	0.25	0.07	0.04
	3	0.13	0.24	0.11	0.02	0.09	0.24	0.07	0.03	0.06	0.24	0.04	0.06	0.09	0.24	0.07	0.04
	4	0.13	0.19	0.11	0.03	0.09	0.19	0.07	0.04	0.06	0.19	0.04	0.06	0.09	0.19	0.07	0.04
All areas combined	1	0.97	0.09	0.47	0.07	0.97	0.09	0.43	0.07	1.00	0.09	0.38	0.07	0.98	0.09	0.43	0.07
	2	1.00	0.11	0.67	0.05	1.00	0.12	0.67	0.06	1.00	0.13	0.66	0.07	1.00	0.12	0.66	0.06
	3	1.00	0.10	0.67	0.05	1.00	0.11	0.67	0.06	1.00	0.12	0.66	0.07	1.00	0.11	0.66	0.06
	4	1.00	0.10	0.66	0.06	1.00	0.11	0.67	0.06	1.00	0.12	0.66	0.07	1.00	0.11	0.66	0.06

[1] EGOA, Eastern Gulf of Alaska; CGOA, Central Gulf of Alaska; WGOA, Western Gulf of Alaska; EBS, Eastern Bering Sea; AL, Aleutians.

Policy 4 does not depend on biomass estimation on an areal basis for implementation, but does require knowledge of movement patterns. In our analysis, we assumed there was no error in information about movement patterns and that movement patterns change with age but not over time. There is considerable uncertainty about the estimates of movement rates used in this study (Heifetz and Fujioka, 1991). In addition, movement rates may exhibit some temporal variability. Temporal shifts in movement rates may be related to population abundance, environmental factors, or food abundance (Beverton and Holt, 1957; MacCall, 1990; Polacheck, 1990).

We do not examine the determination of an optimal policy of apportionment of catch limit among regulatory areas, which requires the definition of a function that incorporates the objectives of fishery management such as maximizing yield and minimizing yield variability and risk (e.g., Quinn et al., 1990b). Geographic optimization of harvest can produce higher sustained yields than harvests without geographic restrictions (MacCall, 1990).

In conclusion, for populations that have high mixing rates among geographic areas, such as sablefish in the northeastern Pacific Ocean, an apportionment policy based on the geographic distribution of estimated biomass, such as policies 2 and 3, is reasonable. In general, such policies are robust to alternative recruitment hypotheses. For implementation, such policies require estimates of biomass but do not require estimates of movement rates. The current apportionment policy for sablefish (policy 3) also reduces the effects of annual fluctuations in biomass estimates due to measurement error.

Applying our techniques to other migratory populations may prove worthwhile. Modifications such as the inclusion of a functional stock–recruitment relationship or variability in movement rates should be examined.

Acknowledgments

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Literature Cited

Beamish, R. J., and G. A. McFarlane.
1988. Resident and dispersal behavior of adult sablefish (*Anaplopoma* [sic] *fimbria*) in the slope waters off Canada's west coast. Can. J. Fish. Aquat. Sci. 45:152–164.
Beverton, R. J. H., and S. J. Holt.
1957. On the dynamics of exploited fish populations. Fishery investigations series II, vol. 19. Marine fisheries. Great Britain Ministry of Agriculture, Fisheries and Food. HMSO, London, 533 p.
Getz, W. M., and R. G. Haight.
1989. Population harvesting: demographic models of fish, forest, and animal resources. Princeton Univ. Press, Princeton, NJ, 391 p.
Heifetz, J., and J. T. Fujioka.
1991. Movement dynamics of tagged sablefish in the northeastern Pacific. Fish. Res. 11:355–374.
Lowe, S. A., J. T. Fujioka, and J. M. Terry.
1991. Bioeconomic analysis of a minimum size limit for Gulf of Alaska sablefish using a yield per recruit model. Fish. Res. 11:307–320.
MacCall, A. D.
1990. Dynamic geography of marine fish populations. Univ. Washington Press, Seattle, 153 p.
Meingold, R. J., and N. D. Singpurwalla.
1983. Understanding the Kalman filter. Am. Statistician 37:123–127.
Polacheck, T.
1990. Year around closed areas as a management tool. Nat. Resour. Modeling 4(3):327–354.
Quinn, T. J., II, R. B. Deriso, and P. R. Neal.
1990a. Migratory catch-age analysis. Can. J. Fish. Aquat. Sci. 47:2,315–2,327.
Quinn, T. J., II, R. Fagen, and J. Zheng.
1990b. Threshold management policies for exploited populations. Can. J. Fish. Aquat. Sci. 47:2,016–2,029.
Sasaki, T.
1985. Studies on the sablefish resources in the North Pacific Ocean. Bull. Far. Seas Fish. Res. Lab. (Shimizu) 22, 108 p.
Sigler, M. F., and J. T. Fujioka.
1993. A comparison of policies for harvesting sablefish (*Anoplopoma fimbria*) in the Gulf of Alaska. *In* G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II (eds.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 93-02.

The Evolution of Sablefish, *Anoplopoma fimbria*, Fisheries Management off Alaska: From Open Access To IFQ's[1]

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ABSTRACT

The sablefish fishery off Alaska has been characterized by a rapid Americanization over the past 10 years in both the Gulf of Alaska and the Bering Sea/Aleutian Islands. Predominately foreign until the passage of the Magnuson Act in 1976, the fishery has evolved rapidly since then, becoming totally domesticated by the mid-1980's. Landings of sablefish off Alaska averaged around 36,000 metric tons (t) annually from 1968 through 1977, almost all by foreign fisheries. From 1977 to the mid-1980's, annual landings decreased to around 13,000 t as foreign fisheries were phased out. Since 1985, annual landings have climbed back to around 30,000 t in a wholly domestic fishery.

Beginning in the early 1980's, the rapid domestication of this increasingly valuable fishery created a number of challenges for managers. Gear conflicts, allocation competition between gear types, rapid expansion of effort in the longline fishery, and ever-shortening fishing seasons have been at the forefront of issues addressed by federal managers over the past 10 years. By 1987, it was apparent that this fishery, in particular the longline fishery in the Gulf of Alaska, was quickly becoming similar to the halibut 'derby' fishery, which had one or two 24-h openings each year, with thousands of boats converging on limited fishing grounds. For example, the number of vessels fishing for sablefish in the Gulf of Alaska increased from 200 in 1984 to nearly 800 in 1994, while season lengths decreased from nearly year-round to only a few weeks in some areas.

In an effort to head off serious problems in the sablefish fishery, the North Pacific Fishery Management Council began considering limited-entry management alternatives. After several years of analyses, public hearings, and often bitter debate, the Council adopted an individual fishing quota (IFQ) management program on December 8, 1991. That program has since been approved by the U.S. Secretary of Commerce, and implementation is scheduled for 1995. Throughout consideration of this management option, the Council grappled with issues of initial allocation of fishing rights, transferability of those rights, potential monopolies of power, and the possible social and economic effects of an IFQ program. In this paper, I examine the overall development of the program as well as how the Council decided some of its specific elements. I also look at some of the pitfalls encountered and lessons learned in development of a large-scale limited-entry program.

Management Background

Americanization of the Fishery

Two of the most important objectives of the Magnuson Fishery Conservation and Management Act of 1976 (Magnuson Act) were to allow depressed fish stocks to rebuild and to provide an opportunity for U.S. domestic fisheries to expand and replace foreign and joint-venture fisheries. Both objectives have been met in the Alaskan sablefish fishery, which became one of the first to be fully utilized by domestic harvesters and processors, both in the Gulf of Alaska and the Bering Sea/Aleutian Islands. The transition from a foreign to a domestic fishery was completed by 1995.

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[1] This paper borrows heavily from Oliver, C. W., M. Hartley, and J. Terry. 1992. Supplemental environmental impact statement/regulatory impact review/initial regulatory flexibility analysis for the proposed sablefish and halibut IFQ program off Alaska, prepared for the N. Pac. Fish. Manage. Council, 605 W. 4th Ave., Ste. 306, Anchorage, AK 99501-2252.

Since the mid-1980's, the sablefish fishery has been the single most important groundfish fishery in the Gulf of Alaska, both in numbers of participants and value of the catch. Ex-vessel value of sablefish landings in the gulf has increased from about $6.6 million in 1984 to $65.4 million in 1988 (Kinoshita et al., 1993). In recent years values have leveled off somewhat, with annual harvests of 20,000 to 25,000 t, which still exceed $50 million annually. Landings and value of the sablefish resource in the Bering Sea/Aleutian Islands are considerably smaller, in the vicinity of 3,000 to 4,000 t annually.

The Americanization of the fishery has not been without problems for fishermen and fisheries managers, with the domestic capacity exceeding the amount necessary to fully utilize the resource, and continuing to grow. The first serious problems between competing domestic fishermen resulted in Amendment 14 to the Gulf of Alaska Fishery Management Plan (FMP) in 1985. This amendment allocated specific percentages of the sablefish resource among user groups (trawl and longline fishermen) and phased out pot gear in the Gulf of Alaska for harvesting sablefish. In 1989, gear allocations were extended to the Bering Sea/Aleutian Islands management area.

Problems in the Fishery

At about the same time that Amendment 14 was being developed, the North Pacific Fishery Management Council (hereafter, the Council) and the industry began considering solutions to the ever-growing problems in the fixed-gear sablefish fishery. The vast majority of the overall sablefish quotas at this point are allocated to fixed gear, primarily in the Gulf of Alaska. Although a higher percentage of the quotas in the Bering Sea and Aleutian Islands are allocated to trawl gear, the relatively low quotas in these areas do not allow for a substantial trawl fishery. Thus the IFQ program was developed specifically for the fixed-gear fishery, and the remainder of this discussion applies only to that fishery. The IFQ program involves only those portions of the total quotas that are allocated to fixed gear.

As early as 1983, some industry participants asked the Council to ensure that the sablefish fishery did not turn into the kind of derby exhibited in the halibut fishery. The sablefish fishery was already beginning to show some signs of such an evolution, with seasons becoming shorter and the number of participants growing rapidly. The Council identified ten specific problems in the sablefish fishery as a result of this growing effort: allocation conflicts, gear conflict, deadloss, bycatch loss, discard mortality, excess harvesting capacity, product quality, safety, decreased economic stability in fisheries and communities, and inhibited rural community development. In 1985 discussion of a moratorium on further entry into the fishery began.

Proposed Solutions

In 1985, pursuant to Amendment 14, the regional director of the National Marine Fisheries Service (NMFS), at the request of the Council, implemented a September 26, 1985, cutoff date for the sablefish fishery, stating that there was sufficient harvesting capacity to catch all of the optimum yield (OY) for sablefish in the waters off Alaska. The purpose of this cutoff date was to notify industry that participation in the fishery after that date might not count toward credit in future limited-entry programs that might be implemented. After establishing this cutoff date, the Council appointed a Sablefish Management Committee (later renamed the Fishery Planning Committee and given a broader mandate which included all groundfish species for future management planning) to examine alternative management methods for the sablefish fishery.

The Council served notice at this time that the industry would be expected to play a leading role in developing a management alternative that was supported and accepted by the industry. In 1986 and 1987, industry surveys were conducted by the Council and by independent industry groups to ascertain a preferred approach for managing this fishery. The responses to these surveys covered a wide range of sentiment, but a common thread among the majority of those surveyed was that some type of limited-access program should at least be considered.

In 1987, the Council also solicited proposals for management recommendations specific to the sablefish fishery. The Council's solicitation generated 59 proposals from industry, with recommendations ranging from continuing the status quo to the use of traditional management tools to some type of limited-entry program. Based on the responses to this solicitation, as well as the results of the surveys mentioned above, the Council, in September 1987, adopted a Statement of Commitment which read, in part:

> Expansion of the domestic fleet harvesting fish within the EEZ off Alaska has made compliance with the Magnuson Act's National Standards and achievement of the Council's comprehensive goals more difficult under current management regimes. The Council therefore is committed to pursue alternative management methods that will support the comprehensive goals adopted by the Council and achieve more productive and rational efforts and harvest levels in the groundfish fisheries.

The statement went on to say that, in order to fulfill this commitment, the Council will

> Develop strategies for license limitation or use of individual fishing quotas (IFQ's) in the sablefish longline fisheries. The process will begin at the September 1987 meeting, and the Council intends to implement the selected management strategy for the 1989 season.

Although the Council's projected date for implementation has proven to be quite ambitious, this action set in motion the development of the IFQ program, which was nearly 10 years in the making and is now scheduled for implementation in March 1995.

Individual Fishing Quota Program Development

Taking the Plunge

Following its 1987 Statement of Commitment, the Council sponsored a series of public workshops to gather further input from the public and industry on limited-entry management alternatives. These workshops were held in the spring of 1988 in Homer, Kodiak, Petersburg, Sitka, and Seattle, the major centers of involvement by the sablefish longline fleet. The aim of these meetings was to define acceptable limited-access programs.

In April of 1988, the Council initiated formal analyses to evaluate a range of management alternatives for the sablefish longline fishery. Staff began developing five major management options for this fishery: 1) status-quo open access, 2) open access, to include sablefish and halibut as bycatch in other longline fisheries, 3) IFQ's, 4) license limitation, and 5) a program combining permits, IFQ's, and open access.

From this initial investigation, the Council determined that continued open access was an unacceptable alternative for managing the sablefish fishery, and that the staff should focus on the license-limitation and IFQ alternatives. A third alternative, annual fishing allotments, was added in 1989; it was a combined system incorporating a partial open-access fishery. In November 1989, these alternatives were made available for public review and became the basis for the Council's next round of decision making.

After consideration of these management alternatives in January 1990, the Council determined that neither annual fishing allotments nor license limitation were appropriate for solving the problems facing the fishery. Annual fishing allotments would combine open access with a form of IFQ's, resulting in a more complicated management program that would not eliminate the problems associated with open-access management and the derby style of fishery. Likewise, it was determined that license limitation in itself would not address the derby nature of the fishery, nor would it address the other problems in the fishery without a great reduction in the current size of the fleet. At this time the Council began to focus its efforts on developing some type of IFQ program as the preferred management alternative for the fishery.

Throughout 1990 and 1991 the Council, its Fishery Planning Committee, its staff, and the fishing industry worked on refining various IFQ programs. In early 1991 the Council also began developing similar IFQ alternatives for the halibut fishery, with the goal of ultimately melding the two programs into a single IFQ program for sablefish and halibut. In December 1991, the Council tentatively approved a preferred IFQ alternative for both fisheries. Approval was contingent upon the completion of a further staff study to examine the interactions of the two fisheries under a single IFQ program, and to provide additional information about the IFQ program's potential socioeconomic effects on coastal communities.

After reviewing this final analysis, the Council gave its final approval to the IFQ program at its April 1992 meeting. In all, this issue had been on the Council's agenda for 27 meetings, including every meeting since 1988. Following the Council's approval, the program was submitted for additional public comment through the National Environmental Protection Act (NEPA) review process, and then for review by the Secretary of Commerce. Final, formal approval by the Secretary came on November 9, 1993, after the proposal had proved to be one of the most complicated and controversial fishery management programs ever enacted in the United States.

In the rest of this discussion, I will look at some of the program's specific provisions and why they had to be included in order to make the program acceptable to a majority of the industry.

Developing the Specific Elements of the Program

Industry Involvement

Critical to the success of the overall program, as well as to the development of its specifics, was participation by the fishing industry in the developmental stages. Certainly, not all sectors of the industry supported this program, though unanimous support was not necessary for the program to succeed. However, it was critical to involve even those who did not support the program, because they would have to live and fish under the program once it was put into place.

The Council process is a very public process with close involvement by members of the fishing industry and their representatives. This is particularly true in the North Pacific, where fishermen exhibit an unusual amount of business and political savvy about fisheries management. A long-term interest in the health of the resource has been the basis for management decisions in the North Pacific, at both the Council and the industry levels. The type of vesting created by an IFQ program goes hand-in-glove with the attitudes exhibited by the fishing industry in the North Pacific.

Throughout the process of IFQ program development, the Council received input from thousands of industry participants in the form of letters, participation in public workshops, and oral testimony at Council meetings. Indeed, the various alternative IFQ programs examined by the Council were a product of the industry itself. Shaping the final preferred alternative required compromise by various segments of the industry until a program emerged that was acceptable to the majority of those directly involved.

A vital aspect of the industry's involvement in the process took the form of an industry panel appointed by the Council to act as a sounding board on specific elements of the program, particularly as they related to its administration, monitoring, and enforcement. The IFQ Industry Implementation Team consisted of various representatives of the fishing industry, and worked closely with agency personnel in developing a system of monitoring and enforcement that would accomplish the goals of the Council and NMFS, while at the same time recognizing the realities of the fisheries. Even after approval of the program, this group continues to meet and advise the Council on various aspects of the program as it evolves into actual implementation. Once up and running, the program will continue to benefit from the guidance of this industry panel as, undoubtedly, numerous bugs are worked out of the system.

Initial Allocation—Who Gets to Fish?

Not surprisingly, one of the most contentious aspects of the IFQ program was determining who would receive the fishing privileges created by the management regime. The Council was very cognizant that windfalls might be created as it privatized the sablefish (and halibut) fisheries and assigned indefinite harvest rights. With nearly 800 vessels and thousands of individual participants involved in the sablefish longline fishery, there was no shortage of persons seeking a claim to the IFQ's to be allocated. Vessel owners, vessel operators, and crew members all made convincing arguments as to their stakes. Ultimately, the Council decided to award the initial allocations of IFQ's to vessel owners or to leaseholders of vessels under bareboat charter agreements. In bareboat charters, a vessel is leased by a fisherman who assumes all responsibilities of operation, including furnishing his own gear and provisions and assuming all other business aspects of the operation such as hiring and paying crew, filing tax or other business forms, and marketing the catch.

Though other fishery participants certainly had a legitimate involvement in and dependence on the fishery, it was the vessel owners who had taken the primary financial risk in Americanizing the fishery. Certainly other problems would have been associated with awarding to IFQ's to crew members, for example, a lack of verifiable records of length and magnitude of involvement in the fishery. The fact that catch records are available for specific vessels convinced the Council that it would be best to award IFQ's to vessel owners.

Having decided to allocate the IFQ's to vessel owners and leaseholders, the Council was still concerned about windfall profits. Although the Magnuson Act does not allow for fees beyond those necessary for licensing vessels, the Council proceeded with the program with the acknowledgement that the Magnuson Act could be amended in the future to allow collection of fees to manage and enforce the program. The Magnuson Act does require that recent participation, as well as past fishing patterns and dependence on the fishery, be taken into account when establishing limited-entry programs. Thus the Council established a recent-participation window as a means to qualify for quota shares (QS) upon which annual IFQ's would be based. Although the program was not finally approved by the Council until 1992, the participation window stipulated that a person must have made legal fixed-gear sablefish landings in any of the three years 1988, 1989, or 1990 in order to qualify for the IFQ program. The cutoff date of 1990 was established early in the development of the program in order to head off further, speculative entry into the fishery. (This date is different from the September 26, 1985, cutoff date referred to earlier. Though established for similar purposes, the 1985 cutoff date was abandoned because of the amount of time elapsed during development of the program.) By stipulating this three-year window, the Council attempted to ensure that only currently active fishermen would qualify for the program.

If a person qualified, however, actual catch histories would be considered. The program stipulates that a person would use his best five of six years' landings from 1985 to 1990 as the basis for QS calculation. One year could be dropped from the calculation for whatever reason. Thus a fisherman would not be penalized for one bad year. In designing the program this way, the Council awarded fishing privileges to active fishermen, but also recognized long-term participation and dependence on the fishery.

It is important to note that the method for QS/IFQ calculation effectively awards a percentage of the available quota of fish in a given management area, as opposed to allocating a fixed poundage. The Council was acutely aware of the experience in the New Zealand IFQ program, where the allocation of fixed amounts of fish resulted in a government buy-back program of over $50 million when the amount of fish allocated greatly exceeded that available. Under the Council's sablefish IFQ program, individual poundages of fish will vary each year with the overall total allowable catch (TAC).

Socioeconomic Safeguards

Among the Council's major concerns when structuring this program were its potential sociocultural effects, particularly on Alaskan coastal communities which rely on this fishery as a large part of their economic base. Many of these communities have fleets comprising predominately smaller vessels which deliver their catch to shoreside plants. A major fear of opponents of the program (as well as supporters) was that the fleets of small boats and the communities in which they are based would suffer as larger vessels with superior bargaining power bought up the QS/IFQ's.

Several safeguards were built into the program to address these concerns. QS/IFQ's would be designated for vessel categories based on vessel size and could not be traded outside these categories. This would ensure that the original amount allocated to each category would remain forever in that category, though fleet consolidation within a particular category could still occur.

The categories were 1) vessels under 60' in length, 2) vessels over 60', and 3) any vessel categorized as a freezer vessel. The categories for the halibut IFQ's are further broken down for socioeconomic reasons particular to that fishery. The basic intent of these vessel categories was to maintain, to some degree, the current fleet structure while still allowing consolidation, and therefore protecting coastal community interests.

Similarly, a "block" plan has recently been adopted to further ensure the continued viability of the small boat fleet in Alaska. This amendment will lock some of the IFQ's issued to individuals into blocks which can only be traded as blocks, with the stipulation that no one can own more than two blocks in a particular management area. Any initial IFQ allocations of less than 20,000 pounds will be deemed a block, and can only be traded as such, within the appropriate vessel category.

In addition to the vessel categories and block provisions, ownership and use caps prevent any one person or entity from acquiring too large a share of the resource. For example, unless it is initially allocated, no one can acquire more than 1% of the total available QS, nor can anyone catch more than 1% of the resource on a single vessel in a given year. These provisions are designed to further ensure against monopolies in the fishery.

Finally, and perhaps most important, specific provisions restrict the sale or transfer of QS/IFQ's to prevent absentee ownership of the resource. In other words, the Council wanted to ensure that the fishing privileges stay in the hands of fishermen, as opposed to speculative investors. The Council accomplished this goal by requiring that anyone purchasing QS/IFQ's after the initial allocation (except for freezer vessel QS/IFQ's) be an individual with experience in the fisheries. This person would then have to be on the vessel fishing the IFQ and must sign the fish ticket upon landing. In this way, the fishing privileges should, for the most part, remain in the hands of people actually on the fishing grounds.

The provisions outlined above seem overly restrictive and unnecessary to some, though they were critical to the overall acceptability of the program, particularly to fishermen residing in Alaska's smaller coastal communities. Political acceptability of this type of program is necessary for its success. Similarly, the Community Development Quotas (CDQ's) created by this program were another key part of its overall acceptability. The CDQ program sets aside percentages of both the sablefish and halibut resources in the Bering Sea for economically disadvantaged coastal communities in western Alaska. Predominately native communities will benefit from a direct allocation of the resource to further their initiatives for developing fisheries.

I have discussed only a few of the many provisions of the program, but they represent some of the major considerations leading to its overall approval. The program could have been developed in a much simpler, more straightforward manner, but doing so would likely have alienated many of those in the industry whose support was necessary to move the program from the drawing board to reality.

Administration and Enforcement

Another major issue in the development of the sablefish IFQ program was monitoring and enforcement. The potential for highgrading, black marketing, and overall quota busting gave rise to very serious concerns over the conservation of the resource. The program would surely fail if an adequate monitoring and enforcement regime were not developed. Though the specifics of the enforcement regime are beyond the scope of this paper, enforcement is a critical and necessary part of the overall program. The NMFS has established a series of requirements for operators and fish processors to report and account for their catches under the program. Industry cooperation and involvement in the development of this monitoring program were critical to its acceptance by industry.

In essence, each operator will be issued a quota card which functions much like a bank card at an automatic teller machine. As with a bank account, a computerized system will track account information for each card holder. When a landing is made, at registered processors only, this system will verify the balance in a card holder's account to ensure that the designated balance is not exceeded. The amount of the landing will be automatically deducted from the existing balance until a person's IFQ for the year is exhausted. Because of the difficulty of matching landings exactly to an IFQ account, there will be a provision for slight overages. With permanent enforcement in the major ports and spot checks in many of the smaller ports, there is general confidence that the program can be implemented without substantial cheating and overharvest. Severe penalties for violation of the program will serve as an added deterrent.

It is estimated that the program will cost about $2.5 million per year to monitor and enforce, beyond the costs of fishery management programs currently in place. As noted earlier, it is possible that the costs of this program may be borne in the future by the fishermen who benefit from the program—the holders of the IFQ fishing privileges.

Some Lessons Learned Along the Way

The development of this program has been a slow, arduous process, partly because of its complicated nature, and party because it is a new and different approach to fishery management, an approach not embraced by all sectors of the industry. One of the lessons from this process is the necessity of bringing all sectors of the public and industry on board in the development of such a program. Without the intimate involvement of the fishermen themselves, this program would never have made it from the drawing board to the fishing grounds. Though intuitively obvious, the necessity of this process of compromise and fine tuning cannot be overemphasized. Many of the other lessons learned in this process are less obvious, but perhaps equally important to fishery managers and fishermen who may be looking at IFQ's as a management alternative for other fisheries.

Timing

When the Council first announced that it was seriously considering limited entry in 1987, it served notice of intent to have a program implemented by 1989, a mere two years in the future. In actuality, the process took closer to nine years, with implementation now scheduled for 1995. The factor of timing in the process needs to be viewed from two perspectives: 1) the amount of time necessary to develop a program that is acceptable to the fishing industry and the agencies responsible for managing the fishery, and 2) the amount of time that may lapse between approval of such a program and its actual implementation.

Enough has probably been said regarding the first aspect of timing: it does take a long time to develop a program acceptable to enough of the participants in a fishery. The second aspect is less obvious, but carries some significant implications. Under the authority of the Magnuson Act and other regulatory jurisdictions in the United States, it may take quite some time for a program to go from Council and industry acceptance to actual implementation. The timing of secretarial review makes up one part of this gap; another is getting the infrastructure in place to administer, monitor, and enforce the program. This can take from several months to several years. In the case of the sablefish program, the Council approved the program in April of 1992, and the Secretary made final approval in November of 1994, a year and a half later.

Actual implementation will occur yet another year and a half later, to allow for the application, appeals, and issuance process for the IFQ program. During this three-year gap between Council and industry approval and actual implementation, many aspects of the fishery may change, potentially affecting the original program's specific provisions. Changing technologies, gear types, ownership structures, and even the biology of the fish themselves may affect the workings of the program. Keeping in mind the time required to get this type of program in place and assessing potential changes in the nature of the fishery can undoubtedly further the development of the program.

Data Considerations

Under current management practices in most of the major U.S. fisheries, the primary objective is to monitor overall catch levels of fish and ensure that they do not exceed levels deemed acceptable by stock-assessment scientists. Thus the management and information gathering relative to these fisheries is not geared to a transition to privatization. This becomes particularly relevant when the program, like that for sablefish, is based on past catch histories of individual operators within a given fishery. The questions of who gets to fish and how much are usually traced back through individual records of participation in the fishery, either by relative landings, time in the fishery, vessel size, or some combination thereof. The difficulties in tracing this type of individual track record may become apparent only when the agency attempts to piece it together.

It is critically important that any fishing industry that may foresee IFQ's in its future determines early in the process what the allocation criteria will be, and then starts collecting and assembling the necessary information. One of the major hurdles in developing this program was simply reconstructing the individual catch data for thousands of participants over a period of several years. Such reconstruction promises to be an even greater challenge as we consider limited-entry programs for all groundfish and crab fisheries in the North Pacific. In many cases, it may be wise to ascertain early on whether the necessary data exist to carry out the specifics of a program, particularly as they relate to the initial allocation of fishing privileges. A central, comprehensive database became a critical component in both the development and implementation phases of the sablefish IFQ program.

Summary

Whether IFQ's prove to be the solution for management of the sablefish fixed-gear fishery remains to be seen. With implementation beginning in 1995, it will probably be a few years before the verdict is in. This type of program seems successful for the Canadian sablefish fishery, though the structure of the Alaskan fishery is very different. With the Council considering IFQ's as a management option for all other groundfish and crab fisheries, all eyes will be focused on this program as a major test case for large U.S. fisheries.

Literature Cited

Kinoshita, R. K., A. Greig, J. D. Hastie, and J. M. Terry.
1993. Economic status of groundfish fisheries off Alaska, 1992. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-25, 102 p.

Choosing a Harvest Strategy for Sablefish, *Anoplopoma fimbria*, Based on Uncertain Life-History Parameters

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ABSTRACT

Harvest rates for sablefish, *Anoplopoma fimbria*, in the Gulf of Alaska, Bering Sea, and Aleutian Islands have been determined in the past by various approaches, including equilibrium yields, subjective risk-averse-population projections, conservative maximum-sustainable-yield (MSY) exploitation rates, and $F = M$ and $F_{0.1}$ exploitation rates. The current method adjusts the fishing rate as spawning biomass deviates from a reference level. The fishing rate at the reference level is that which would reduce the spawning biomass-per-recruit ratio to 35% of its unfished value. Maintaining the population at the biomass reference level, currently assumed to be 35% of the unfished level, is intended to attain a high proportion of MSY. The choices of fishing rate and reference biomass were based on general results that are appropriate for a range of typical groundfish life-history parameters, but have not been computed specifically with sablefish parameters; nor has the strategy of varying the fishing rate been thoroughly examined. This study applied life-history parameters estimated for sablefish and found that the existing fishing rate and biomass guidelines are appropriate, and that the adjustable-rate strategy provides a greater proportion of maximum yield with less risk of overfishing than a constant fishing rate.

Introduction

The quota recommended for the commercial fishery of sablefish, *Anoplopoma fimbria*, in the Gulf of Alaska, Bering Sea, and Aleutian Island regions is obtained by applying an appropriate fishing rate to the projected biomass, as it is for many groundfish species managed by the North Pacific Fishery Management Council (NPFMC). Clausen et al. (1997), Lowe and Fujioka (1997), and Zenger (1997) describe how biomass is estimated and some of the uncertainty in the values. Uncertainty in the appropriate fishing rate is also mentioned. Choices of fishing rate in the past have included 1) the equilibrium-yield fishing rate; 2) $F = M$, the fishing rate equal to natural mortality rate; 3) $F_{0.1}$, the fishing rate where the increase in yield-per-recruit per increase in fishing rate is one-tenth the rate of increase at the origin (Gulland and Boerema, 1973); and 4) catch rates that result in 5-year projections of biomass that remain above the all-time measured low level. Ideally, the fishing rate that produces the maximum sustained yield (MSY) would be used, but this requires knowing the relationship between stock size and recruitment, which is currently unknown.

Sissenwine and Shepherd (1987) and Gabriel et al. (1989) show a rationale for choosing fishing rates based on spawning stock biomass per recruit (SSBR). Fishing rates that result in expected SSBR that is no less than the reciprocal of actual or expected recruits per spawning biomass will allow year classes to replace their parent biomass. Such a replacement fishing rate, F_{rep}, is often estimated by F_{med}, the fishing rate that achieves the median observed recruit-per-spawning-biomass ratio. Providing enough SSBR to allow such replacement has been adopted as an objective for management of fisheries in New England (Sissenwine and Shepherd, 1987). Clark (1991) demonstrated that fishing rates defined by SSBR, relative to SSBR with no fishing, provide a high proportion of maximum yield for a range of stock–recruitment conditions. The NPFMC is currently using such fishing rates to manage various fisheries.

Currently, the fishing rate for sablefish in NPFMC waters is determined as an adjustable fishing rate, varying with biomass. When biomass is at 35% of estimated unfished biomass, the fishing rate would be set at $F_{35\%}$, the rate that decreases SSBR to 35% of its unfished level. As biomass varies from the 35% level, the fishing rate varies proportionately. The choice of fishing rate is based on Clark's (1991) findings that for many life histories typical of groundfish, an $F_{35\%}$ to $F_{39\%}$ constant-fishing-rate strategy will attain, in equilibrium, a high proportion of MSY for a range of stock–recruitment relationships. The choice of the reference biomass level is also based on Clark's (1991) paper, in which he reported that keeping spawning stock biomass (SSB) at 35% of the unfished level is even more robust to differences in biological parameters and stock–recruitment relationships than the constant-fishing-rate strategy, and provides a higher proportion of MSY. Such a biomass-based strategy, similar to an escapement-based strategy for salmon, is applied not by employing a particular fishing rate, but by adjusting catch to maintain SSB at the desired level.

Although Clark's (1991) strategies were robust for a variety of life histories, the parameters specific to sablefish were not employed. Also, Clark indicated disadvantages of both the biomass-based and the constant-fishing-rate strategies. He suggested that a hybrid strategy might combine the advantages of both, but made no specific suggestion for the form of such a strategy. The purpose of this study is to verify Clark's findings for sablefish life-history parameters and to compare the theoretical performance of a hybrid strategy, such as the adjustable-fishing-rate strategy currently used for sablefish, to the constant-fishing-rate and constant-biomass strategies of Clark (1991).

Methods

Sablefish are commonly believed to become available to the fishery at an age of about 5 years. They mature about a year later, and almost all are recruited and mature by age 10. Availability and maturity were computed in the study as logistic functions of length; the parameters defining length (L_{50}) and slope at the inflection point are shown in Table 1. Sablefish continue to gain body weight for more than 30 years, and at a natural mortality rate of 0.10, maximum cohort biomass occurs around age 8 (Fig. 1). In this study, growth in weight is modeled by converting von Bertalanffy growth in length to weight using the parameters in Table 1, whereas Clark (1991) modeled growth in weight with a Brody curve. The Brody growth parameter would be about 0.88 for sablefish.

Relative yield per recruit and biomass per recruit are calculated for a range of fishing rates. As in Clark (1991), these values are then applied to stock–recruitment curves (expressed relative to unfished levels of biomass) to compute the corresponding equilibrium yield and biomass. Fishing strategies are then compared in terms of equilibrium (average) yields and biomass under different scenarios of recruitment and a misestimated parameter. Yields are expressed relative to maximum yield for each recruitment relationship, and SSBR and SSB are expressed as percentages of their respective unfished levels.

Although the age at which 50% of a cohort becomes available to the fishery is currently assumed to be five

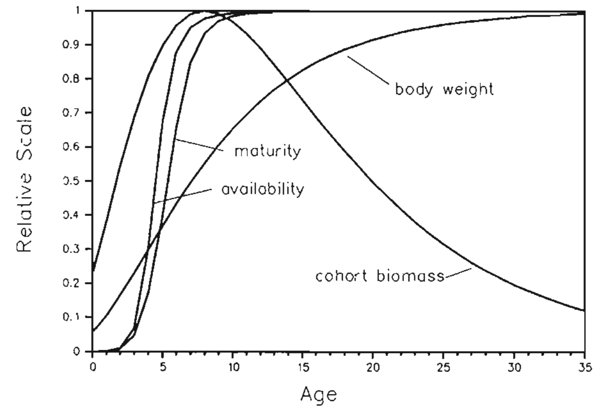

Figure 1
Sablefish body weight, cohort biomass, availability, and maturity by age (sexes combined).

Table 1
Life-history parameters for sablefish in the Gulf of Alaska, Bering Sea, and Aleutian Islands regions.

Parameter			Value	
Natural mortality rate: *M*			0.10	
Length (cm) to				
weight (kg): W = $a\ L^b$		a	0.0000048	
		b	3.22	
	Females			Males
Growth (von Bertalanffy):				
L_∞	89.3 cm			71.8 cm
K	0.142			0.200
t_0	−3.20 y			−3.23 y
Maturity:				
length at 50% (L_{50})	65.0 cm			57.0 cm
logistic slope parameter	0.40			0.40
Availability:				
length at 50% (L_{50})	59.4 cm			56.5 cm
logistic slope parameter	0.424			0.424

years, it may be as young as three years (Varosi et al.[1]). The parameter (L_{50}) defining the inflection is decreased to model 50% availability at 3.5 years, to measure sensitivity to this source of uncertainty. Natural mortality rate, another uncertain parameter, is also altered to test the robustness of the SSB and SSBR guidelines.

The biomass reference point is computed from unfished biomass level, which is estimated in practice by multiplying estimated average recruitment by unfished SSBR. The uncertainty in this parameter, as well the effect of its estimate changing over time in a trending population, are not addressed in this study.

Clark (1991) examined three Beverton and Holt stock–recruitment relationships and three Ricker stock–recruitment relationships. In this study, however, we eliminated the intermediate version in each case, and examined two of each type. For both the Beverton and Holt relationship and the Ricker relationship, the less productive curve had a potential density-dependent response in recruitment success 4 times greater than at unfished spawning stock size, as indicated by the slope of the stock–recruitment curve at the origin. The more productive curve for both relationships had a success factor 16 times greater than at unfished stock levels. These correspond to the Kimura (1988) shape parameter A = 0.750 and 0.938 for the Beverton and Holt curve, and A = 1.386 and 2.772 for the Ricker curve.

Results

Results for both the constant SSBR (fishing rate) strategy and the constant SSB (biomass) strategy indicate that Clark's (1991) guidelines are appropriate for sablefish. The single relative SSBR value where the minimum relative yield of all stock–recruitment relationships is maximized occurs at about 35% of the unfished level (Fig. 2). This value agrees with Clark's results, which ranged from 35% to 39%. He referred to the fishing rates that attained such SSBR's ($F_{35\%}$ or $F_{39\%}$), as the "maximin" fishing rates (F_{mmy}). The single relative SSB that attains the highest relative yield is slightly above 34%, again close to Clark's results (Fig. 3).

Decreasing the age of 50% availability by 1.5 years only slightly changed the relative values of the optimal SSBR (from 35% to 36%) and SSB (from 34% to 35%). The fishing rate that attains the given value of SSBR, however, is more sensitive, resulting in a decrease in $F_{35\%}$ from 0.13 to 0.106. Likewise, increasing natural mortality from 0.10 to 0.20 (well within the plausible range) nearly doubles $F_{35\%}$.

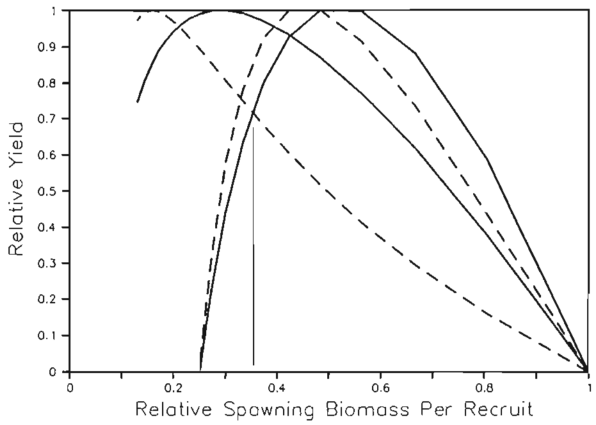

Figure 2
Relative yields of two Beverton and Holt (solid lines) and two Ricker (broken lines) stock–recruitment relationships as a function of spawning stock biomass per recruit (SSBR) relative to unfished SSBR.

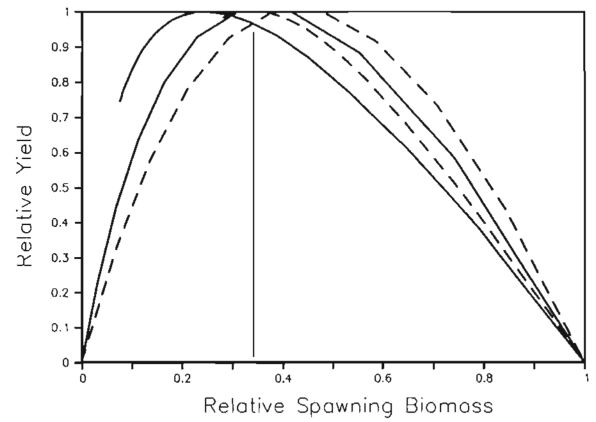

Figure 3
Relative yields of two Beverton and Holt (solid lines) and two Ricker (broken lines) stock–recruitment relationships as a function of spawning stock biomass (SSB) relative to unfished SSB.

The relationship of relative yield, relative SSB, and fishing mortality rate (F) for each stock–recruitment model can be seen in a simple phase diagram (Fig. 4a), where SSB as a function of fishing rate is shown in the right quadrant, and yield as a function of SSB is shown in the left quadrant. Yield as a function of a particular fishing rate, F, can be determined by tracing the SSB(F) through the SSB axis common to both quadrants.

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[1] Varosi, E. R., M. F. Sigler, and T. R. Rutecki. 1993. Recruitment curve for sablefish in Alaska based on fish tagged as juveniles. Paper presented at the International Symposium on the Biology and Management of Sablefish, *Anoplopoma fimbria*, April 13–15, 1993, Seattle, WA.

In Figure 4b, where only the most and least productive scenarios are shown, the constant SSB strategy is represented by the horizontal solid line, and the constant SSBR or constant-fishing-rate strategy (at $F_{mmy} = F_{35\%} = 0.13$) by the vertical solid line. The intersections of the strategy lines with the stock–recruitment-specific SSB curves indicate the equilibrium (average) SSB's, which in turn determine the equilibrium (average) relative yield (dashed arrows). It is clear that the biomass strategy does well, attaining nearly all the maximum yield for either stock–recruitment relationship. The constant-rate fishing strategy, however, although attaining 70% of maximum yield, drives the least productive population to 13% of its unfished level and underexploits the more productive population.

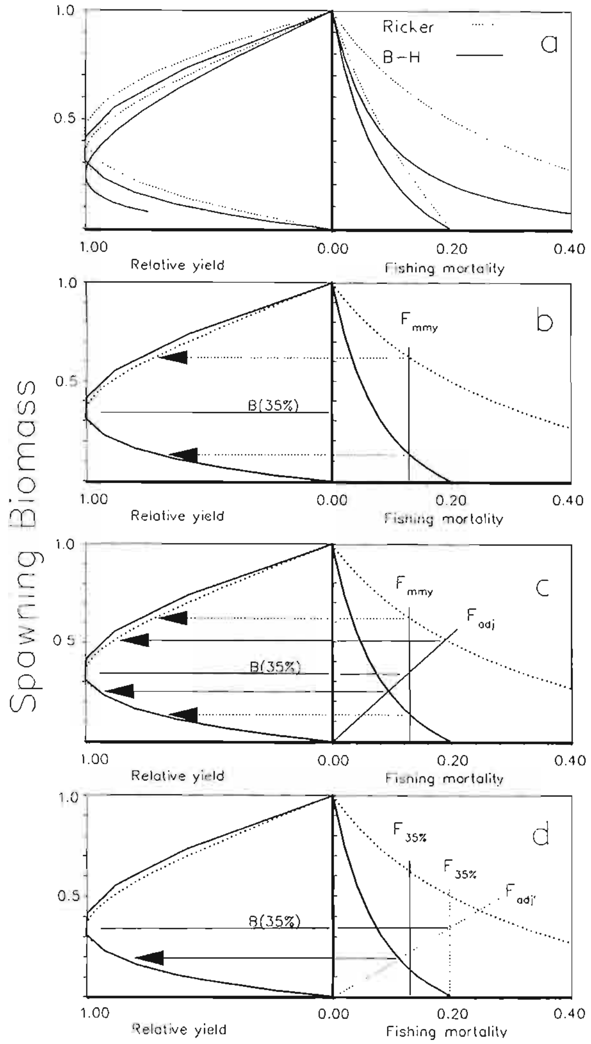

Figure 4

Phase diagram of relative yield as a function of relative spawning stock biomass (SSB) and SSB as a function of fishing mortality (a) for two Beverton and Holt (B-H) and two Ricker stock–recruitment relationships; (b) for constant SSB strategy (horizontal solid line) and constant-rate strategy (vertical solid line), with only most and least productive stock–recruitment curves shown; (c) for adjustable-rate strategy (sloped solid line through the origin and the intersection of the two other strategies); and (d) for constant-fishing-rate strategy (dotted vertical line) and for adjustable-rate strategy (dotted sloped line), with $F_{35\%}$ overestimated by 50% in both cases. Intersections of the strategy lines with the biomass curve determine the corresponding equilibrium biomass points, which in turn determine equilibrium yield. See text for detailed explanation of figure.

The adjustable-rate strategy is represented by a sloping line, $F_{(adj)}$, through the origin and the intersection of the other two strategies in the right quadrant (Fig. 4c), so when biomass is at 35% of unfished level, $F = F_{mmy} = 0.13$, and when biomass varies from $B(35\%)$, F varies proportionately. Average points for each recruitment relationship are shown at the corresponding intersections with the strategy line and the respective F vs. SSB lines.

Average yield under the adjustable-rate strategy is 90% or more of maximum yield (solid arrows), compared to 70% for the constant-fishing-rate strategy (Fig. 4c). Average SSB of the less productive stock–recruitment relation is about 25% of unfished levels under the adjustable-rate strategy, nearly double that resulting from the constant-rate strategy (13%). For the more productive stock, SSB decreased from about 62% to 50%, while yield increased from about 72% to 88% under the adjustable-rate strategy.

Discussion and Conclusions

These results indicate that Clark's (1991) general reference points appear appropriate for sablefish, and that combining the reference points into an adjustable-rate strategy is also appropriate. Although the target-biomass strategy is the most robust and produces the highest percentages of maximum yield, strict application of that strategy to marine groundfish in Alaska is not practical. Populations and population estimates fluctuate considerably. Unnecessarily abrupt closures and openings from year to year—should the biomass estimates range above and below the reference biomass—can be avoided with the adjustable-rate strategy.

The constant-fishing-rate strategy did not perform as well as the adjustable-rate strategy when the correct values of life-history parameters were used. In reality, the values of parameters are not known, and the estimated value for $F_{35\%}$ is sensitive to uncertainty about life-history parameters. Because the natural mortality rate and the age at which sablefish become available to the fishery are uncertain, the estimated value of $F_{35\%}$

could be in error. Figure 4d illustrates an example of overestimating $F_{35\%}$ by 50% under the constant-rate strategy and under the adjustable-rate strategy. The effect of overestimation of $F_{35\%}$ is alleviated somewhat by adjustment to the fishing rate, so that loss of yield and reduction of SSB are not as severe as under the constant-rate strategy.

The adjustable-rate strategy also reduces the risk of overfishing. In a previous simulation study of sablefish, where overfishing was the major concern, adjustable-rate harvest strategies were compared to a constant-rate strategy (Fujioka[2]). The procedure used to determine acceptable biological catch for the Gulf of Alaska, Bering Sea, and Aleutian Islands regions was simulated with 10% uniform random measurement error in the survey abundance index and with a twofold error in the expansion to absolute biomass. The assumed recruitment was stock-independent and was resampled from previous estimates. The risk of overfishing was considered relative to the extent to which the simulated population fell below the all-time measured low point, which occurred in 1980. Compared to a constant-rate strategy, the adjustable-rate strategies significantly reduced the risk of overfishing, and attained nearly the same yield but with lower fishing effort. Harvest strategies compared under additional recruitment scenarios indicated similar results (Sigler and Fujioka, 1993).

Sissenwine and Shepherd (1987) and Gabriel et al. (1989) also point out that the appropriate fishing rate may not necessarily be constant. Temporal trends in environmental and predator–prey conditions, or density-dependent changes in survival and recruitment may require that F_{rep} be adjusted by weighting the most recent observations more heavily in estimating the appropriate current replacement rate. Heavier weighting of most recent sablefish recruitment, which has been low, would result in a downward adjustment of F_{rep} from its long-term average.

This study does not reduce any uncertainty about the biology and productivity of sablefish, but does reconfirm the appropriateness and rationale of the adjustable-rate strategy currently used to determine quotas for sablefish in the Gulf of Alaska, Bering Sea, and Aleutian Islands areas. The adjustable-rate strategy is a practical compromise of the constant-biomass and constant-rate strategies. Compared to the constant-rate strategy, it adapts to errors in biomass and fishing-rate estimation, and attains a higher proportion of maximum yield while reducing the risk of overfishing. Until sablefish recruitment processes are better known, the optimal SSB and SSBR guidelines as determined by Clark (1991) seem the most appropriate.

Acknowledgments

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Literature Cited

Clark, W. G.
1991. Groundfish exploitation rates based on life history parameters. Can. J. Fish. Aquat. Sci. 48:734–750.

Clausen, D. M., J. T. Fujioka, and J. Heifetz.
1997. Estimates of sablefish, *Anoplopoma fimbria*, abundance in the Gulf of Alaska based on depletion experiments using longlines. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 171–182. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Gabriel, W. L., M. P. Sissenwine, and W. J. Overholtz.
1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. N. Am. J. Fish. Manage. 9:383–391.

Gulland, J. A., and L. K. Boerema.
1973. Scientific advice on catch levels. Fish. Bull. 71:325–335.

Kimura, D. K.
1988. Stock-recruitment curves as used in the stock-reduction analysis model. J. Cons. Int. Explor. Mer 44:253–258.

Lowe, S. A., and J. T. Fujioka.
1997. Methods used in the determination of acceptable biological catch for Alaska sablefish, *Anoplopoma fimbria*. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 159–169. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Sigler, M. F., and J. T. Fujioka.
1993. A comparison of policies for harvesting sablefish (*Anoplopoma fimbria*) in the Gulf of Alaska. *In* G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II (eds.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 93-02.

Sissenwine, M. P., and J. G. Shepherd.
1987. An alternative perspective on recruitment overfishing and biological reference points. Can. J. Fish. Aquat. Sci. 44:913–918.

Zenger, H., Jr.
1997. Comparisons of sablefish, *Anoplopoma fimbria*, abundance indices estimated from two longline surveys. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria*, p. 215–228. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

---

[2] Fujioka, J. T. 1990. A comparison of five harvest policies applied to sablefish in Alaskan waters. *In* Environmental assessment/regulatory impact review/initial regulatory flexibility analysis for Amendment 21 to the Fishery Management Plan for Groundfish of the Gulf of Alaska and Amendment 16 to the Fishery Management Plan for Groundfish of the Bering Sea/Aleutian Islands, Appendix III. Document submitted to the N. Pac. Fish. Manage. Council, Anchorage, AK, July 1990. Alaska Fish. Sci. Cent., NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070. Unpubl. manuscr.

License Limitation in an Alaska Sablefish, *Anoplopoma fimbria*, Fishery

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ABSTRACT

The State of Alaska adopted a limited-entry program for the sablefish longline fishery in the Northern Southeast Inside Subdistrict of southeast Alaska beginning with the 1985 season. Under that program, only licensed fishermen who had landed sablefish from within the area during an open fishing season prior to January 1, 1985, were eligible to apply for future participation. The long-term goal is to restrict the total effort to the 1984 level of 73 permit holders by implementing a point system. The annual season was shortened from 5 days in 1984 to 24 hours beginning in 1987. Despite the short seasons, the annual harvest objectives have been consistently exceeded. The average number of hooks set and pounds landed per vessel per day increased significantly. In 1992, the eighth year of the program, the number of participants (120) was still well above the target level (73). Through the 1992 season the program had not met the original goals of restricting the number of participants or promoting a more orderly fishery. New regulations adopted for this fishery in 1994 are described.

Introduction

In the State of Alaska fisheries regulatory system, the Alaska Board of Fisheries (the Board) is responsible for establishing regulations to allocate fisheries resources among users. Such regulations include seasons, guideline harvest ranges (GHR's), closed areas, gear type, vessel size, and gear restrictions. All regulations passed by the Board are subject to review by the state attorney general's office to assure consistency with the statutes. The Alaska Department of Fish and Game (ADFG) is responsible for managing fisheries according to the regulations established by the Board. Responsibilities include setting harvest objectives within the GHR's, setting the length of the fishing period within the season, and closing areas by emergency order to protect a resource from overexploitation. The Commercial Fisheries Entry Commission (CFEC) is responsible for license-limitation programs. The statutes spell out fairly specific conditions that must exist before a fishery can qualify for limited entry. Two such conditions are excess effort that causes economic hardship, and difficulty in conforming to biological yield objectives.

Since 1906, a directed fishery for sablefish, *Anoplopoma fimbria*, has existed in the internal waters of northern southeast Alaska, an area now known as the Northern Southeast Inside Subdistrict (NSEI; Fig. 1). The fishery has been managed with a fishing season since 1945 and with an annual quota since 1972. In 1982 regulations were adopted to restrict the fishery to longline gear.

The number of vessels participating in the NSEI sablefish fishery increased from 50 in 1980 to 73 in 1984, an increase of 46% in 5 years. During that same period, the season was shortened from 76 days to 5 days (Table 1) in an attempt to remain within the preseason harvest objective.

In 1984, the fishing industry petitioned CFEC to include the NSEI sablefish longline fishery in the State of Alaska Limited Entry Program. Both CFEC and ADFG questioned the potential success of a license-limitation program in the absence of additional restrictions such as gear limits or individual harvest (trip) limits. This concern arose because, by statute, the limited-entry program restricts only the number of participants, not the fishing capability of individual vessels in the fleet. License limitation was considered by both agencies primarily as a means of restricting new entrants into the

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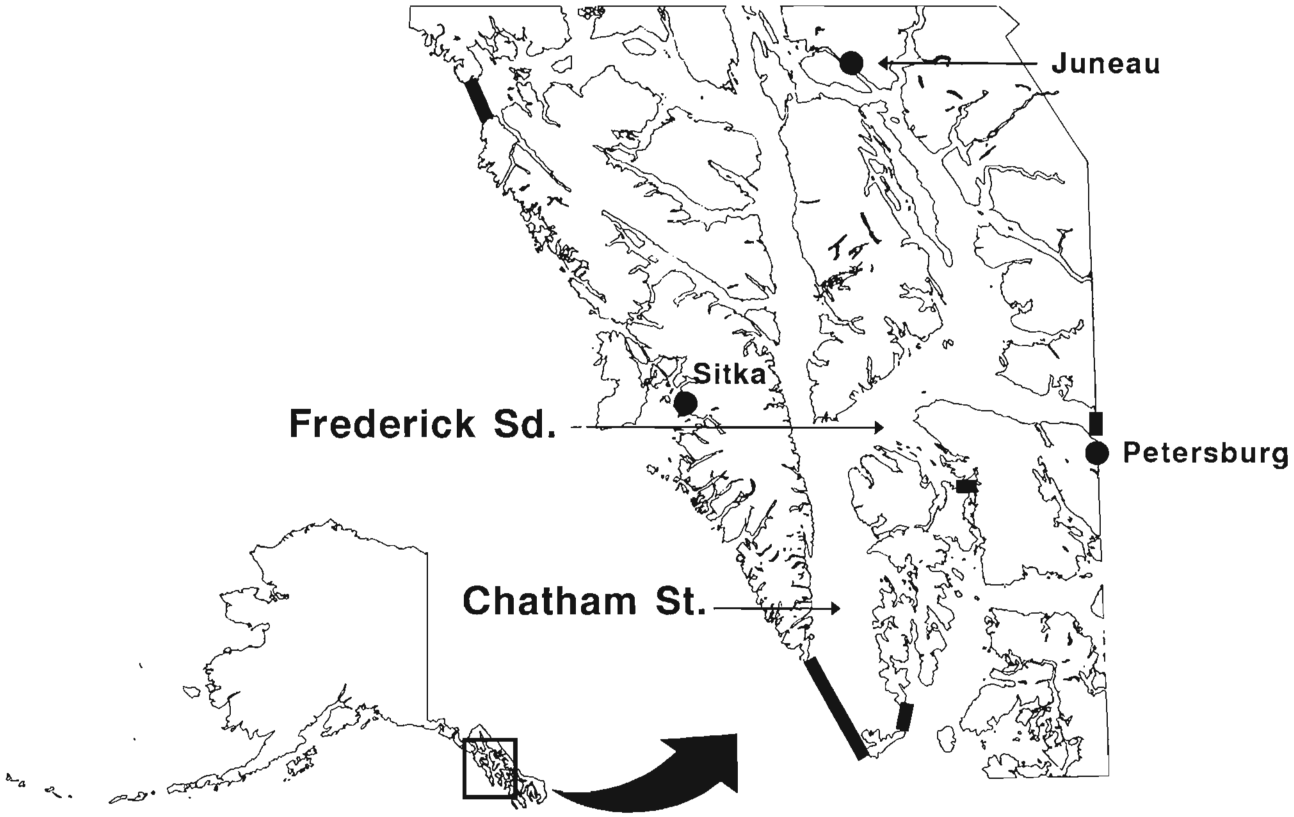

Figure 1
Northern Southeast Inside (NSEI) management area of the Alaska Department of Fish and Game.

Table 1
Catch, effort, and price per pound from the NSEI Subdistrict of southeast Alaska sablefish fishery, 1980–94. A dash indicates no data available.

Year	Vessels	Pounds landed	Harvest objective	Days fished	Hooks/vessel per day	Lbs/vessel per day	Average price per lb	Pounds per hook
1980	50	865,119	1,000,000	76	4,675	228	$0.42	0.28
1981	42	667,888	850,000	40	—	—	$0.51	—
1982	38	781,470	850,000	15	4,195	1,371	$0.71	0.49
1983	61	1,166,470	1,000,000	12	4,568	1,594	$0.56	0.67
1984	67	1,122,843	1,000,000	5	4,791	3,352	$0.64	0.74
1985	112	2,005,394	1,500,000	3	9,796	5,968	$1.00	1.10
1986	146	2,600,000	1,500,000	2	9,919	8,904	$1.04	1.01
1987	162	2,468,829	1,500,000	1	17,239	15,240	$1.35	1.07
1988	158	2,747,724	1,800,000	1	20,822	17,391	$1.63	1.01
1989	151	2,412,089	2,000,000	1	22,318	16,252	$1.19	0.73
1990	121	2,068,588	2,000,000	1	23,118	18,153	$1.71	0.79
1991	127	2,509,263	2,200,000	1	26,611	21,105	$2.75	0.79
1992	120	2,840,722	2,500,000	1	28,514	23,673	$1.84	0.87
Addendum								
1993	122	3,641,897	2,800,000	1	31,194	29,851	$1.54	1.01
1994	121	2,965,954	3,000,000	30	—	—	$2.70	—

fishery while a comprehensive management plan was being developed. Because there were no regulations in place to restrict individual effort, it was felt that even if the number of participants was stabilized or reduced, any reduction in the number of vessels could easily be offset by increases in efficiency.

The Alaska limited-entry program was designed for the salmon fisheries, where vessel size and gear restrictions were already in place. It was recognized that a limited-entry program would not reduce current effort, but only prevent additional vessels from entering the fishery. The industry continued to support limited entry, citing the potential influx of new entrants to the NSEI sablefish fishery as a result of earlier closures of the Gulf of Alaska sablefish fishery. Fishers contended that any influx of new vessels would further stress a fishery which many believed to be already overcapitalized.

It was ultimately decided that the benefits of limiting new entrants outweighed future problems resulting from increases in individual effort. An important factor in this decision was managers' perception that, if necessary, fleet efficiency could be controlled by subsequent regulations. The program was adopted beginning with the 1985 season.

This report provides catch and effort information from 1980, five years before the inception of the NSEI sablefish limited-entry program, and examines the first nine years of the program, through 1992. An additional section describes substantial changes in fisheries management that occurred in 1994 as the result of new regulations adopted by the Board in 1993 and 1994.

Description of the Limited Entry Program

Under the State of Alaska Limited Entry Program, permits are issued to individual fishermen on the basis of past participation. Only fishermen who had participated in the NSEI sablefish fishery during a regular season prior to a cutoff date of January 1, 1985, were eligible to apply for future participation. A court decision (*Johns* v. *State, CFEC,* 758 P.2d 1256, Alaska 1988, as reported in Schelle and Muse[2]) set the maximum number of fishermen eligible to receive permanent permits at no less than the peak number that had participated in any of the four years before the cutoff date for the program. In 1984, a peak number of 73 individual fishermen participated in the NSEI Subdistrict sablefish fishery during two open fishing periods; therefore a target number of 73 permits was adopted for this fishery.

The number of past participants who applied for permits greatly exceeded the target number. In 1987 a more restrictive point system was adopted to limit the number of fishermen who would receive permanent permits. Under the point system any fisherman who was the operator of a vessel that had been used to harvest sablefish from NSEI during an open season at any time from 1975 through 1984 was eligible to apply for a permit.

Points were awarded for each year fished from 1975 to the January 1, 1985, cutoff date, but a greater number of points were awarded to those applicants who landed sablefish during three qualifying years, 1982 through 1984. Unless there were "extraordinary circumstances," an individual must have fished during at least one of the qualifying years to be considered under the point system. Extraordinary circumstances included vessel loss, illness, or other hardships which might have prevented fishing during a qualifying year. The extraordinary-circumstances provision is built into the limited-entry program to assure that persons are not unduly restricted because of legitimate hardship situations beyond their control.

Points awarded for income dependence and extraordinary circumstances are adjudicative, and often take considerable time and effort to resolve. Currently 36 claims are in the hearing process, with no verified points nine years after enactment of the program. Fishers in this category have "claimed points" which may or may not eventually be verified (Schelle[3]). Meanwhile those who filed the claims continue to fish with interim permits.

Data Sources

The data used to monitor the NSEI sablefish fishery come from several sources. By regulation, all landings of fish from the waters of Alaska, including the internal waters of southeast Alaska, are reported on ADFG fish tickets. The information provided by the fish tickets is augmented by supplemental data from monitoring programs that include fishery overflights and interviews with skippers. The adjusted fish-ticket database provides the official ADFG estimate of total harvest from the area.

An intensive skipper interview program conducted by ADFG in the major southeast Alaska ports during the sablefish season provides detailed catch and effort data.

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[2] Schelle, K. O., and B. Muse. 1989. License programs under Alaska's limited entry statutes: policy decisions under statutory constraints. Paper presented at The 119th Annual Meeting of the American Fisheries Society, Anchorage, AK. Alaska Commercial Fisheries Entry Commission, 8800 Glacier Hwy., #109, Juneau, AK 99801.

[3] Schelle, Kurt O. Alaska Commercial Fisheries Entry Commission, 8800 Glacier Hwy., #109, Juneau, AK 99801. Personal commun.

Information from this program includes number of hooks set, number of hooks retrieved, type of hooks used, hook spacing, type of bait, etc. Pounds per hook (CPUE) is calculated by dividing the total number of hooks set by a vessel during the season by the landed weight reported on the fish ticket from that vessel. Since the limited-entry program began, skipper interviews have supplied information from an average of 55% of the participating vessels, which have landed over 60% of the total fish from the area. Results from this program are expanded to estimate total effort and CPUE for the fishery.

Fisheries Statistics Under the Limited-Entry Program

Harvest and Season Length

The sablefish harvest in the NSEI Subdistrict increased from 1,123,000 lb, or 509 metric tons (t) dressed weight in 1984—the year before the limited-entry program began—to over 2,000,000 lb (907 t) dressed weight in 1985 (Table 1). The season was reduced to 48 hours in 1986 and further to 24 hours in 1987 and subsequent years in an attempt to remain within the harvest objectives. Even with the reduced season, the harvest remained well above the objectives (Table 1). The 1992 harvest of over 2,800,000 lb (1,270 t) dressed weight was the highest reported from the NSEI fishery since 1957.

Effort

The number of participating vessels increased from 73 in 1984 to a peak of 162 in 1987. The numbers dropped slightly in 1988 and 1989 as some participants were disqualified from the program after the initial point system was adopted. The number of points required for further participation was raised in 1989, resulting in a further reduction from 151 participants in 1989 to 121 participants in 1990 (Table 1). Recent effort has stabilized at approximately 121 vessels, 66% above the target number of 73 vessels for this fishery.

The fishery is restricted by regulation to hook-and-line gear, but there are no restrictions on the amount of gear that can be operated by each vessel. The average amount of gear operated per vessel has increased steadily since the limited-entry program began. In 1984, the year before the program began, each vessel set an average of 4,791 hooks per day. By 1992 that amount had increased to 28,514 hooks per day, an increase of over 495% (Table 1).

Improvements in electronics and hydraulics, an increase in average vessel size, a change from "J" hooks to "circle" hooks, conversion from dressed to round fish deliveries, and—most recently—a switch from herring to squid as the preferred bait have all improved the fleet's efficiency. The conversion from primarily dressed fish deliveries to primarily round fish deliveries in the late 1980's eliminated the need for on-board processing and greatly increased the number of fish that could be handled aboard a vessel during a short fishing period. The increased vessel efficiency is demonstrated by the harvest records. In 1984 the fleet averaged 3,352 lb (1.5 t) dressed weight per vessel per day; by 1992 the average harvest had increased to 23,673 lb (10.7 t) per vessel per day (Table 1).

Discussion

The NSEI sablefish limited-entry program was requested by the fishing industry as a means to prolong the fishing season, promote a more orderly fishery, and prevent an influx of large vessels from the Gulf of Alaska sablefish fishery from entering the area. It was the intent of CFEC and ADFG that the limited-entry program be adopted as a first step in a comprehensive management program, not as a primary management tool for this fishery. Regulations restricting the fishery to longline only and authorizing ADFG to set the season length were both in place before the limited-entry program was adopted. No additional regulations have been adopted since the program began, and individual effort and efficiency have increased dramatically in the absence of additional restrictions. This increased efficiency was predicted by CFEC (Schelle and Muse[2]) and ADFG.[3]

Since the limited-entry program began, the season was decreased from 72 hours to 24 hours, and yet the annual harvest objectives have consistently been exceeded. Fishers frequently report that the frenzied nature of the fishery causes conflicts between vessels on the fishing grounds. Gear is often cut or broken off and left on the grounds at the end of the fishing period. The derelict gear increases the risk of future entanglement and often causes additional gear loss. The difficulty in accurately determining the additional sablefish mortality resulting from this practice affects the estimates of total fishing mortality. Fishers also complain that they are forced to fish in inclement weather or "lose the season." This poses a serious threat to life and equipment, particularly for the smaller vessels in the fleet. These problems can all be attributed to the very short annual fishing periods which are necessary in order to remain anywhere near the harvest objectives.

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[3] Collinsworth, D. 1985. Memo from Commissioner Collinsworth to the CFEC. Alaska Commercial Fisheries Entry Commission, 8800 Glacier Hwy., #109, Juneau, AK 99801.

In 1989 and again in 1991, ADFG submitted proposals to the Board requesting regulatory changes. Proposals included gear and trip limits to be used in conjunction with the limited-entry program to increase the likelihood of remaining within the annual harvest objectives. Even a pilot individual fishing quota (IFQ) program was discussed. The industry did not support additional regulations and convinced the Board to reject the proposals. Instead, the industry wanted more time for the limited-entry program to reduce the fleet to the target effort level.

The provision that sets the target number of participants at the highest number in the four years preceding the enactment of limited-entry increases the likelihood of excess harvesting. This happens because in order for a fishery to be placed under limited entry, it must be determined that additional participation could result in economic hardship for the existing fleet or threaten the resource. In other words, most fisheries have already reached a problem level of excess effort before they are considered for a limited-entry program.

In a fishery such as the NSEI sablefish fishery, where fleet turnover was high before the cutoff year, enactment of such a program often substantially increases the number of participants in the years immediately following implementation. This occurs because all applicants who satisfy the requirement of past participation are issued interim-use permits. All applicants who have verified or unverified qualifying points are then allowed to continue to participate until the point system is fully implemented, often many years later. Resolving the adjudicative elements of the point system often prolongs the period during which the number of participants remains considerably higher than the target number.

The excess harvesting capability in the NSEI sablefish fishery has been exacerbated by the rapid increase in the efficiency of individual vessels. During the 1992 season, each vessel deployed nearly six times more hooks per day than during the 1984 season. At the 1992 level of 120 vessels, the entire fleet deployed nearly 10 times more hooks than were deployed in 1984. Subtle improvements in fishing technology over the past decade have substantially increased in the fleets' ability to harvest fish. Unless other restrictive measures are adopted, excess harvesting will likely continue even if the number of participants is eventually reduced to the target number of 73 permits.

Notable changes in the NSEI fishery would have occurred over the past decade with or without the limited-entry program. The ex-vessel value of sablefish has nearly doubled during that period (Table 1). The increased value combined with increased sablefish quotas in the Gulf of Alaska have stimulated a dramatic growth in longline activity, accompanied by substantial increases in the number and average size of specialized longline vessels available to participate in West Coast groundfish fisheries.

The fleet in 1992 is very different than it was when the program was first adopted. A provision of the Alaska Limited Entry Program requires that a permit holder must be aboard a vessel during all fishing and transporting activities. Permit holders who own smaller, less efficient vessels are being offered large guaranteed sums to fish aboard larger, more efficient vessels, whether or not they are responsible for the fishing operation. At the same time, many permit holders are actively seeking larger, more competitive vessels to fish aboard in order to remain competitive.

By the 1992 season, transferable NSEI sablefish permits were trading at $150,000 or more, and offering large sums to a permit holder to fish for a season was less expensive than purchasing a permit. Vessels that paid such sums had to fish harder to increase their harvest in order to pay the guaranteed amount to the permit holders and still turn a profit. Those who had purchased permits also felt compelled to fish even harder to make a reasonable return on their investment.

To date, the changes in fleet composition, the increased efficiency of the gear, and the large number of participants have negated any perceived advantages of the limited-entry program. The program has not met its stated goals of restricting the fleet size to the 1984 level or providing for a longer, more orderly fishery. As a result of the high effort levels and increases in fleet efficiency, the harvest objectives are consistently exceeded, increasing the risk of overexploitation.

Before adopting the program, both CFEC and ADFG recognized that additional regulations would be necessary in conjunction with limited entry in order to develop a successful long-term management program for the NSEI sablefish fishery. But additional regulations require the Board's approval, and the Board has not been receptive to staff requests for more restrictive regulations. Proposals to consider additional management options will again be presented to the Board in November 1993. Unless additional management measures are adopted, the present fleet's capability to harvest extraordinary amounts of sablefish in a very short period greatly increases the possibility of overexploitation, potentially diminishes the value of the resource, and increases the safety risks for those participating in this fishery.

Addendum

This report was originally submitted for publication before the 1993 season. Substantial regulatory changes were made during 1993 and 1994, and this report would be incomplete without a summary of the new regulations and how they were developed.

During the 1993 season, effort increased to an average of nearly 31,200 hooks per boat per day (Table 1). The reported 1993 harvest of 3,642,000 lb dressed weight was the highest since 1947. Estimates from interview data indicate an additional unreported mortality of between 100,000 and 200,000 lb due to gear left on the grounds after the fishery closed. These estimates are considered conservative because of many fishers' reluctance to report substantial amounts of lost gear. Including dead loss, the estimated total mortality for the 1993 season approached 4,000,000 lb (1,814 t) dressed weight.

The NSEI sablefish harvest has exceeded 4,000,000 lb only twice in the 87-year history of the fishery in 1942 and again in 1947. During that period of high harvests, the CPUE dropped dramatically from 120 lb per skate to 75 lb per skate (ADFG historic catch records), and the sablefish stocks remained at low levels in the area for over 30 years. These data suggest that harvests near the level taken during the 1993 fishery may not be sustainable.

A review of current stock status (Bracken et al., 1997), recent fisheries performance, and historic fisheries data was presented to the Board during November 1993 meetings in Sitka. On the basis of this information, the Board increased the upper end of the GHR to 3,000,000 lb from the previous level of 1,500,000 lb, but with the stipulation that ADFG must manage the fishery to remain within the 3,000,000-lb limit for the 1994, 1995, and 1996 seasons.

The Alaska Longline Fishermen's Association (ALFA) submitted a proposal to limit the amount of gear each vessel could use. Officers in the Fish and Wildlife Protection (FWP) Division of the Department of Public Safety indicated that they could not support gear limits because of the difficulty in enforcing the large number of hooks involved. Because the 1993 harvest had exceeded 3,600,000 lb and because fleet efficiency was expected to increase, it was obvious that some modifications to the existing regulations would be necessary in order to remain within the newly adopted 3,000,000-lb harvest limit. The Board chairman requested that the executive director of ALFA coordinate a management workshop with staff and industry to explore options for the fishery and to develop management alternatives. The issue was tabled for further consideration at the March 1994 Board meeting in Anchorage.

The management workshop requested by the Board was held on February 3 and 4, 1994, in Sitka. Representatives from three area processors, ADFG, CFEC, and FWP, as well as 28 NSEI Subdistrict sablefish permit holders attended. The ADFG staff explained that, unless new regulations were adopted, the 1994 fishing period would be reduced to less than 24 hours in order to remain within the 3,000,000-lb harvest limit. The CFEC representative stated that reductions in the number of permits should not be expected before 1996. The FWP representative reiterated that his agency could not support ALFA's preference for gear limits as a management alternative because of enforcement problems.

Processors were concerned with declining product quality and value as a result of poor handling and because fish were being held too long before processing. These problems were attributed to the short season and the large number of fish being landed in such a short time. Concerns were expressed that this trend compromised earlier efforts to have fish from this fishery recognized by the market for their top quality.

Fishers complained of crowding on the grounds, particularly because of the increasingly larger amounts of gear being set. Gear is frequently set on top of earlier sets, making retrieval difficult and often resulting in lost gear. Concerns for vessel and crew safety during the short openings were also addressed. Many considered safety to be a paramount factor in any management decision.

Once industry representatives realized that no action would mean reduced fishing time, a constructive discussion ensued. The group compiled an impressive list of possible management alternatives, which were placed on a survey which was subsequently mailed to all NSEI sablefish permit holders. The survey was to be completed and returned no later than March 1.

Of the 121 eligible NSEI sablefish permit holders, 68—56 percent—responded to the survey. Of the respondents, 75 percent favored preseason registration; 63 percent favored a vessel size limit; 85 percent favored trip or fishing period limits; 62 percent preferred a 30-day open fishing period over several other options ranging from 24 hours to 2.5 months; and 88 percent favored a sunset clause to terminate the trip-limit regulation at the end of the 1996 season. Slightly over 79 percent of the respondents favored holding annual or biennial staff/industry meetings to continue discussions of management options. Further reductions in season length and gear limits received relatively little support.

A summary of the industry workshop and the results of the survey were presented to the Board at the March meeting as requested. After considerable deliberation, all of the regulations that received majority support on the industry survey, except the vessel size limit, were adopted by unanimous vote of the Board. The Board also reaffirmed its regulatory mandate to manage the fishery within a 3,000,000-lb dressed-weight limit for the next three seasons.

New regulations include:

1. Each eligible permit holder is allowed to harvest an equal share of the annual harvest objective. That

share is determined by dividing the annual NSEI sablefish harvest objective by the number of eligible permits at the beginning of each season. The annual harvest objective is to be based on the results of the ADFG preseason abundance-indexing survey. This regulation will be repealed immediately after the 1996 season unless extended or modified at the 1996 Board meetings.

2. The annual permit limit may be taken by an individual permit holder at any time during a 30-day fishing season, which is to be set by ADFG between September 1 and November 15. Existing regulations will be used to establish the opening date of the 30-day season.
3. All permit holders must register in writing at least seven days before the opening date of the season. The registration form must be signed by the vessel owner and must list all permit holders who will be aboard the vessel during the fishery. Permit holders are not allowed to transfer between vessels once the season starts.
4. There is no restriction on the number of permit holders who can register to fish aboard a single vessel, and no limit to the size of a landing if it does not exceed the cumulative limits of all permit holders aboard the vessel. Conversely, a small-vessel operator may make multiple landings if the cumulative landings do not exceed the annual harvest limit.

The Board justified the 30-day season because they felt that the longer season will reduce gear loss, decrease risks to life and safety, and improve product quality. Allowing more than one permit holder per vessel is intended to minimize the economic hardships that might occur if operators of larger vessels were restricted to a single harvest limit. Registration was requested by ADFG as a way to track landings. This is particularly important where more than one permit is fished on a single vessel or when a vessel operator makes more than one delivery to reach the harvest limit.

During the 1994 season each eligible permit holder was allowed to harvest up to 24,500 lb dressed weight. The opening date was delayed until September 22 to avoid conflicting with a halibut opening. The first season under the new regulations is still being evaluated. Early reports, however, indicate that the fishery progressed smoothly and that product quality improved. Registration forms indicate that a higher percentage of permit holders fished their own vessels than in recent years, and no complaints were received about vessel crowding or weather-related problems.

At the average 1992 ex-vessel value of $2.70 per pound dressed weight, each individual limit was worth approximately $66,150, and some fishers received over $75,000 for their limits. The industry apparently recognized the value of a guaranteed annual limit and the marketing flexibility of a longer season. The price of transferable permits increased from approximately $150,000 before the new regulations to offers of more than $230,000 by the end of the 1994 season.

The most notable improvement from a management perspective was that the 1994 harvest of 2,965,000 lb remained within the regulatory cap of 3,000,000 lb, and reported dead loss was minimal. This was the first season during which the total catch remained within the preseason harvest objective since the limited-entry program was adopted in 1985.

It should be noted that the regulations providing for individual annual harvest limits and the 30-day season which were adopted for this fishery in 1994 could not have worked with an open-access fishery. Combining a license-limitation program with other conventional regulations to promote a manageable sablefish fishery, as originally envisioned by ADFG and CFEC staff before the inception of the limited-entry program in 1985, finally became a reality ten years later.

Acknowledgments

Beverly Richardson maintains the sablefish catch and effort databases used for this report. Kurt Schelle of CFEC deserves thanks for his thorough review of the manuscript and the valuable details he provided about the Alaska Limited Entry Program.

Literature Cited

Bracken, B. E., D. A. Gordon, and D. C. Carlile.
1997. Sablefish, *Anoplopoma fimbria,* stock assessment in the inside waters of southeast Alaska. *In* M. Wilkins and M. Saunders (eds.), Biology and management of sablefish, *Anoplopoma fimbria,* p. 195–206. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 130.

Development and Management of the Sablefish, *Anoplopoma fimbria*, Fishery in Prince William Sound, Alaska

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ABSTRACT

The annual harvest of sablefish in Prince William Sound increased from <10 metric tons (t) prior to 1984 to 50 t in 1984 and 175 t in 1985. Because stock assessment data for sablefish in Prince William Sound were lacking, yield per unit area was estimated from the 1985 guideline harvest range for similar habitat in Clarence Strait in southeast Alaska. An estimated yield ranging from 0.06 to 0.25 t per square nautical mile resulted in a guideline harvest of 40–140 t for Prince William Sound since 1986. The approach of using the harvest per unit of habitat for one area to establish harvest guidelines for a second area is unique in sablefish management and has provided sustainable yield in the Prince William Sound fishery. Annual harvest rates have generally increased since the late 1980's. Increasing fishing effort and improved technology have made this open-access fishery more difficult to manage; the record harvest of 196 t in 1992 exceeded the guideline during the shortest season on record. Future management strategies will include weekly fishing periods and increased stock assessment efforts. In addition, improved bathymetric mapping techniques indicated that the area of suitable sablefish habitat was underestimated by 26%. As a result, the guideline harvest will be increased to 44–175 t in 1993.

Introduction

The commercial fishery for sablefish, *Anoplopoma fimbria,* is one of the oldest fisheries off the coast of Alaska. Although landing documents extend back only to 1906, sablefish were probably harvested in the late 1800's (Bracken, 1983a). Full domestic utilization of sablefish resources in the Central Gulf of Alaska Regulatory Area of the Exclusive Economic Zone (EEZ; formerly referred to as the Fishery Conservation Zone, or FCZ) occurred for the first time in 1984, when domestic vessels harvested the entire optimum yield (OY) level set for that area.

Because it was defined as part of the territorial seas, the Prince William Sound area was not closed with the sablefish fishery in the adjacent EEZ. Fishing effort in Prince William Sound increased after closures in the adjacent federal waters. Three factors that increased fishing effort for sablefish in Prince William Sound were 1) biological or economic declines in the more traditional local fisheries, such as shrimp and crab; 2) the protected nature of the area, which makes Prince William Sound more fishable than the adjacent offshore waters during periods of poor weather; and 3) favorable market conditions for sablefish. No abundance, age, or size-composition data were available for this relatively unfished sablefish stock, and commercial harvests were poorly documented before the mid-1980's. In an effort to manage this resource for long-term, sustained yield, it was necessary to develop a guideline harvest range and, subsequently, to adopt management strategies that maintained harvest levels within this range.

The maximum depth in the Prince William Sound management area exceeds 800 m, and the aggregate surface area exceeds 9,500 km^2 (Fig. 1). About 27% of Prince William Sound is deeper than 275 m (150 fathoms; Mortenson[1]) and is considered sablefish habitat.

Harvest data were compiled from commercial fish-ticket landing records. Sablefish from Prince William Sound are delivered primarily to the ports of Seward, Whittier, Valdez, and Cordova. Annual harvest data are reported as metric tons (t), except for landed size-composition data, which are reported as pounds. Before 1984, fewer than 10 t of sablefish were commercially harvested each year from the Prince William Sound area (Fig. 2). However, sablefish harvests increased to 50 t in 1984 and 174 t in 1985 (Morrison[2]). The increase in harvest rates, especially the 250% increase from 1984 to 1985, generated concerns about the sustainable yield, because there were no abundance or fishery performance data from Prince William Sound. Catch-rate data were limited to voluntary logbook reporting, which represented only 11% of the 1984 fishing effort and 6% of the 1985 effort. In addition, no fisheries-independent surveys have been conducted to assess sablefish resources in Prince William Sound (Parks and Zenger[3]; Haynes and Urban[4]).

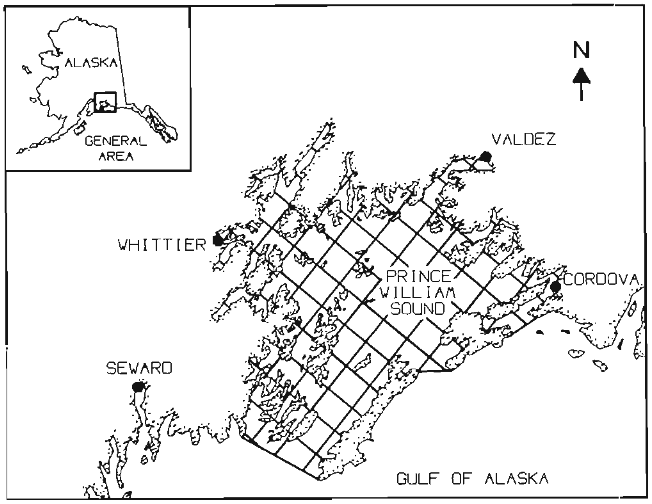

Figure 1
Prince William Sound management area.

Clarence Strait, Alaska, has oceanographic characteristics similar to the Prince William Sound area. Both areas also have considerable shoals and limited deep-water connections to the Gulf of Alaska. Commercial sablefish harvest records for Clarence Strait date to 1969 (Bracken[5]). Because of similar oceanographic conditions and the successful, long-term management of sablefish in the Clarence Strait area, yield data for Clarence Strait were used to establish a preliminary harvest guideline for Prince William Sound (Morrison[2]).

Morrison[2] determined the area of suitable sablefish habitat in both Prince William Sound and Clarence Strait. On the basis of harvest locations reported by fishermen, he assumed all waters deeper than 275 m (150 fathoms) were suitable sablefish habitat. Using a process similar to that described by Lowe,[6] Morrison measured the suitable habitat from standard National Oceanographic and Atmospheric Administration nautical charts by using a grid overlay and a compound planimeter. A guideline harvest range for Clarence Strait had been established in 1980, with its upper and lower

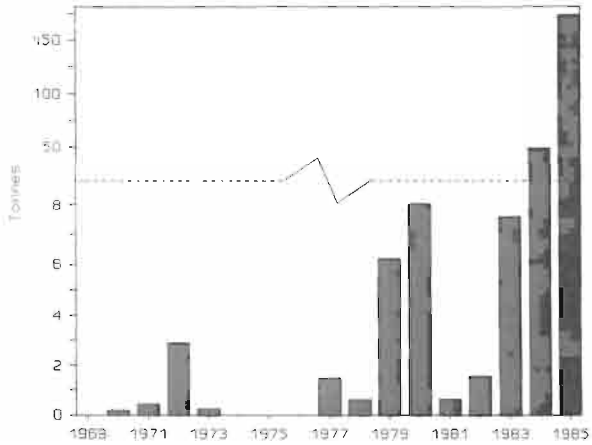

Figure 2
Commercial sablefish landings from Prince William Sound before 1986. Horizontal line at 9 t indicates change of scale on *y* axis.

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[1] Mortenson, D. Alaska Dept. of Natural Resources, 3601 C St., Ste. 1324, Anchorage, AK 99503. Personal commun.

[2] Morrison, R. 1987. Estimating the guideline harvest range for sablefish in inside waters of Prince William Sound. Reg. Inf. Rep. Alaska Dep. Fish Game, Div. Commercial Fisheries, Anchorage, AK.

[3] Parks, N. B., and H. Zenger. 1979. Trawl survey of demersal fish and shellfish resources in Prince William Sound, Alaska: spring 1978. NWAFC Proc. Rep. 79-2. Northwest Fisheries Science Center, NMFS, 2725 Montlake Blvd. E., Seattle, WA 98112.

[4] Haynes, E., and D. Urban. 1993. Prince William Sound trawl assessment. Final report. State/federal natural resource damage assessment. Fish/Shellfish Study no. 18. NMFS, Auke Bay Lab., Alaska.

[5] Bracken, B. E. Box 1201, Petersburg, AK 99833. Personal commun.

[6] Lowe, S. AFSC, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115-0070. Personal commun.

limits calculated as two standard deviations around the average sablefish harvests from 1969 to 1979 (Bracken, 1983a). The specific harvest goal within the guideline range for Clarence Strait was determined by examining the trend in catch per unit of effort (CPUE; obtained from logbooks and skipper interviews) and the size composition of the commercial catch. Morrison converted the guideline harvest range for Clarence Strait to yield per unit of area, and then applied this figure to the estimated area of sablefish habitat in Prince William Sound. In recent years, the midpoint of the guideline range has been used as the annual harvest goal for Prince William Sound sablefish.

Harvested Stock Composition

Although no age data were available from commercial landings, a crude index of sablefish size composition was compiled from landing reports. Most sablefish are delivered to processors as "eastern cut," which involves removal of the viscera and the head to the cleithrum. Because processors generally pay fishermen on a sliding scale based on dressed sablefish size, most processors also report sablefish landings in size categories of dressed weight in pounds (Table 1).

The cumulative deliveries within size categories, where size classes were reported, were used to develop indices of harvest size composition. In essence, the size categories were used to approximate the exploited biomass. Division of the landed biomass within a size category by the size category (i.e., total pounds of a size category divided by the mean size of the category) also provided an index of numerical composition. Composition data were compiled for 1987–92 sablefish harvests from Prince William Sound and for 1989–92 from the adjacent waters of the Gulf of Alaska. The indices of biomass composition and numerical composition allowed a crude comparison within and between fisheries.

Table 1
Size categories generally applied by sablefish processors (Bechtol and Morrison, pers. observation).

	Size Category					
	1	2	3	4	5	7
Minimum size (lb)	0	2	3	4	5	7
Maximum size (lb)	<2	<3	<4	<5	<7	>7

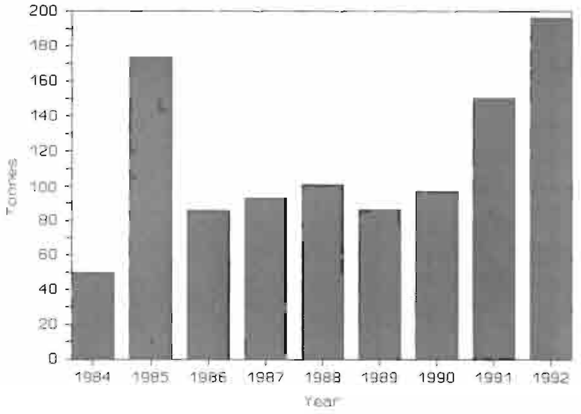

Figure 3
Commercial sablefish landings from Prince William Sound, 1984–92.

Establishing the Guideline Harvest Range

Morrison[2] estimated the areas of potential sablefish habitat as 1,382 square nautical miles (nm^2) for Clarence Strait, and 567 nm^2 for Prince William Sound. The guideline harvest established for Clarence Strait at the time of Morrison's study was 85–340 t, with a midpoint of 213 t. Converting to yield per unit area resulted in a range of 0.06–0.25 t/nm^2. Extrapolation to the 567 nm^2 of suitable habitat estimated for Prince William Sound produced a harvest range of 35–139 t; note that rounding differences resulted in the 34–142 t shown in Morrison.[2] On the basis of the estimate that a harvest of 40–140 t would provide sustainable yield, the sablefish fishery in Prince William Sound has been managed since 1985 for a midpoint harvest goal of approximately 91 t.

Harvests under a Guideline Range

Following the implementation of a harvest guideline of 40–140 t, sablefish harvests from the Prince William Sound area were relatively stable from 1986 to 1990, ranging from 86 to 101 t annually (Table 2; Fig. 3). The sablefish seasons in Prince William Sound have become progressively shorter, and the 1992 season produced a record harvest in 17 days, the shortest season on record. Also in 1992, the Prince William Sound fishery was, for the first time, closed before the adjacent federal waters of the Gulf of Alaska (Bechtol[7]). In addition, the 1991

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[7] Bechtol, W. R. 1992. Review of the Central Region groundfish fisheries: 1992 report to the Alaska Board of Fisheries. Alaska Dep. Fish and Game, Anchorage, Reg. Inf. Rep. 2A92-23.

Table 2
Annual effort, harvest, and ex-vessel value of the commercial sablefish fishery in Prince William Sound, 1984–92.

			Harvest						Fishing season	
Year	Vessels	Landings	Pounds	Tons	Price ($/lb)	Ex-vessel value	Tons/ landing	Tons/ vessel	Opened	Closed
1984	20	37	109,920	50	0.46	$ 50,673	1.35	2.49	1/01	12/31
1985	29	108	383,290	174	0.60	$229,974	1.61	5.99	1/01	11/20
1986	32	36	189,850	86	0.63	$119,606	2.39	2.69	4/01	6/21
1987	71	120	205,350	93	0.64	$131,424	0.78	1.31	4/01	6/25
1988	53	147	222,206	101	0.99	$219,984	0.69	1.90	4/01	7/21
1989	26	98	190,633	86	0.89	$169,663	0.88	3.33	6/12	12/31
1990	70	257	213,974	97	0.69	$147,642	0.38	1.39	4/01	8/07
1991	72	147	331,314	150	0.91	$301,496	1.02	2.09	5/15	6/22
1992	49	112	432,676	196	0.94	$406,715	1.75	4.00	5/15	6/01

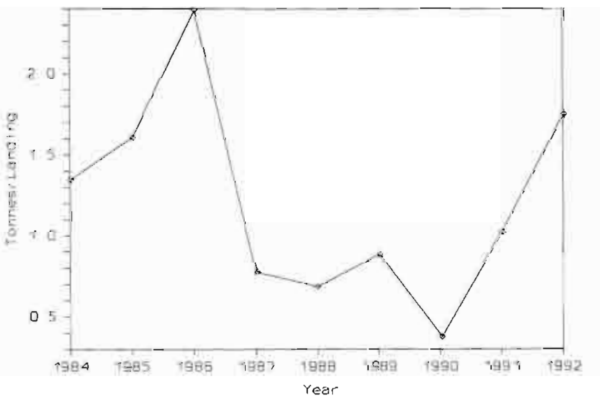

Figure 4
Average landings for commercial sablefish vessels fishing Prince William Sound, 1984–92.

and 1992 sablefish harvests exceeded the upper end of the harvest range by 7% and 40%, respectively. Annual participation in the fishery has ranged from a low of 26 vessels in 1989 to a high of 72 vessels in 1991 (Table 2). The mean quantity of sablefish delivered per landing, while highly variable, has generally increased since the mid-1980's, especially from 1990 to 1992 (Table 2; Fig. 4).

Harvest Composition

The biomass composition of the sablefish harvest changed substantially between years and areas (Fig. 5). A single size category did not dominate the Prince William Sound catch from year to year, but trends in size categories appear over consecutive years. For ex-

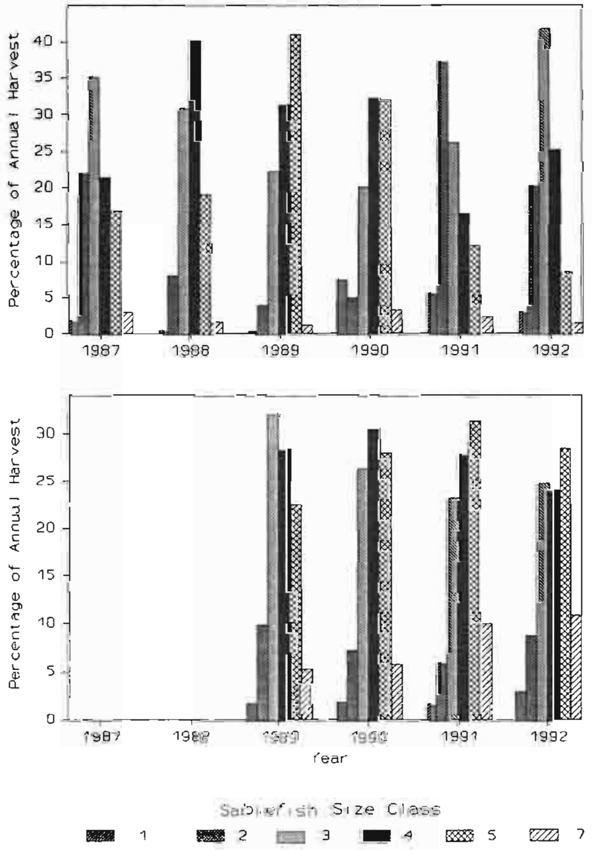

Figure 5
Biomass composition by size class for sablefish harvested from (upper) Prince William Sound and (lower) the adjacent federal waters of the Exclusive Economic Zone in the Gulf of Alaska. Size class definitions from Table 1. Note differing *y* axis scales.

ample, the 3-lb category dominant in 1987 was followed by dominant 4- and 5-lb categories in 1988 and 1989, respectively. Similarly, in the Gulf of Alaska, the 3-lb category dominant in 1989 was followed by dominant 4- and 5-lb categories in 1990 and 1991, respectively. From 1987 to 1992, a single (but annually changing) dominant size category was a greater portion of landings in Prince William Sound (34%–42%) than in the Gulf of Alaska (28%–33%). However, during no year did a single size dominate the harvests in both Prince William Sound and the Gulf of Alaska.

Landings from the Gulf of Alaska appear to have a greater proportion of large fish. Sablefish ≥7 lb constituted from 5% to 11% of the Gulf of Alaska harvests since 1989, whereas they constituted less than 4% of all annual harvests in Prince William Sound.

Although the numerical abundance composition by sablefish size category changed between years and areas, trends were less consistent in Prince William Sound (Fig. 6). The 3-lb size category was numerically dominant in catches from Prince William Sound in 1987, followed by a strong 4-lb category in 1988 and a dominant 5-lb category in 1989. In contrast, 3-lb fish have been the most abundant, and 4-lb the second most abundant, in harvests from the Gulf of Alaska since 1989.

Effectiveness of Harvest Guidelines

Fishermen have reported increased catch rates resulting from improvements in fishing gear technology, particularly the application of circle hooks and better electronics for determining bottom depth and contours. The increased fishing effort in the mid-1980's resulted in greater efforts to manage and monitor the fishery (Fig. 2, 3). Regulations adopted by the Alaska Board of Fisheries in 1986 established that

1) fishermen must obtain a Prince William Sound sablefish fishery permit before commercially fishing for sablefish in Prince William Sound, and
2) the sablefish fishery in Prince William Sound opens by regulation in conjunction with the commercial sablefish fishery in the adjacent EEZ.

The annual harvest guideline of 40–140 t has provided for continued sablefish yield from Prince William Sound since 1986, despite environmental variability and increased fishing pressure. However, there remain many uncertainties about the Prince William Sound sablefish resource. Because the 1985 and 1992 harvests exceeded the upper end of the guideline range by 24% and 40% without any apparent decline in stock production, the guideline range may actually underestimate sustainable yield. Because there are no measurements of stock abundance, it cannot be determined if this range optimized surplus production.

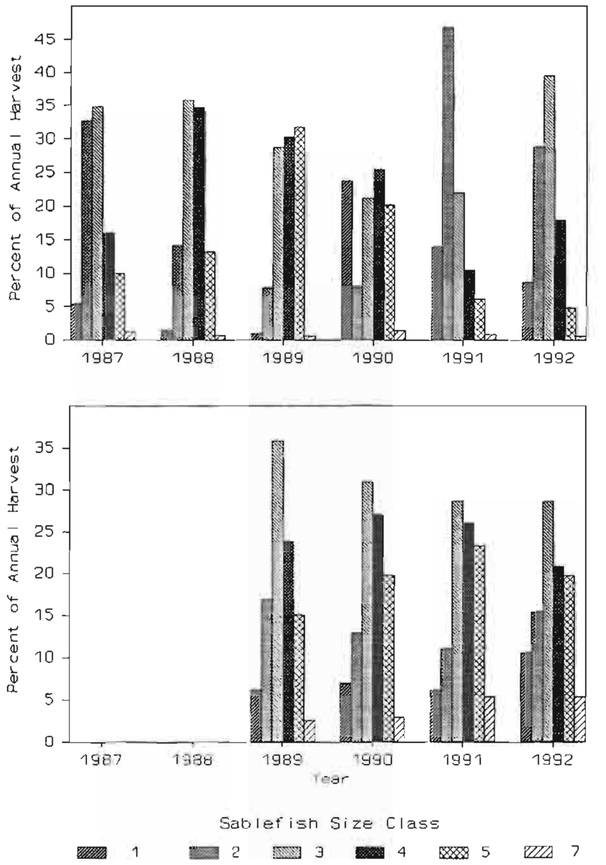

Figure 6
Numerical abundance composition by size class for sablefish harvested from (upper) Prince William Sound and (lower) the adjacent federal waters of the Exclusive Economic Zone in the Gulf of Alaska. Size class definitions from Table 1. Note differing *y* axis scales.

It is not known if Prince William Sound sablefish are a discrete stock. Confirmation that they are would lend support to a yield-per-habitat approach. Extensive sablefish tagging programs in southeast Alaska and the greater Gulf of Alaska have generated numerous tag recoveries in gulf waters adjacent to Prince William Sound. However, few, if any, tagged fish have been recovered inside Prince William Sound (personal observations; Bracken, 1983b). The lack of tag recoveries from Prince William Sound suggests that migration of sablefish into Prince William Sound from the adjacent waters may be limited. The size composition of harvested fish also indicates that these stocks may be independent (Fig. 5, 6). Large sablefish were more common in the Gulf of Alaska catch than in Prince William Sound harvests. However, such differences may reflect age-specific distribution patterns, particularly with regard to where specific fisheries occur. Studies in other areas found different migrations by juvenile and adult sablefish (e.g., Beamish and McFarlane, 1983; Bracken, 1983b). Although size categories are not presumed to correlate directly to annual growth, some trends are suggested. Trends observed from 1987 to 1992 indicate that 4-lb sablefish may dominate the biomass of the 1993 harvest from Prince William Sound (Fig. 5). Assuming that catch sampling will be improved in the future, subsequent yield models may be improved by accommodating age- and size-distribution characteristics.

Although production parameters are unknown, several factors indicate that a larger annual harvest may be sustainable. Computerized bathymetric mapping data (Mortenson[1]) now indicates that the area of Prince William Sound with depths greater than 150 fathoms is 712 nm^2, or 26% larger than that used by Morrison.[2] Extrapolation of Morrison's estimated yield per unit area would effectively result in a harvest guideline of 44–175 t. In addition, the yield model probably underestimated, to some extent, the area of suitable habitat by limiting it to waters deeper than 275 m (150 fathoms). Recent interviews with fishermen indicate that suitable habitat may extend to 100-fm depth. McFarlane and Beamish (1983) also suggested that adult sablefish off British Columbia are typically found at depths exceeding 200 m (110 fm). For the existing yield model, it is recognized that both sablefish production and fishing effort are not likely to be evenly distributed and that the estimated yield per unit of habitat involves averaging potential yield over the area of potential habitat. Future extrapolation of potential yield data between areas may be improved by including consideration of sablefish production with respect to differences in depth composition between the areas. A more comprehensive model might also incorporate qualitative habitat characteristics.

The increase in the quantity of sablefish delivered per landing may reflect greater fishing effort directed specifically at sablefish (Fig. 4). In the 1980's, halibut and sablefish seasons lasted longer and overlapped, and a bycatch of sablefish was allowed during a concurrent halibut fishery. Thus a significant portion of landings reported during the 1980's represented sablefish harvested incidentally during halibut fisheries. An increase in the market value of sablefish also resulted in more intensive fishing effort, especially since declines in more traditional shellfish and salmon fisheries renewed interest in groundfish (Table 2). In addition, the emergence or potential implementation of individual fishing quotas (IFQ's) and other methods designed to reduce or stabilize effort in many of the groundfish fisheries may have indirectly increased participation in the remaining open-access fisheries. For example, new vessels may be used preferentially in Prince William Sound because future access to Gulf of Alaska fisheries is not guaranteed.

The effect of marine animals on sablefish production and the sablefish fishery is also poorly understood. For example, killer whales, *Orcinus orca*, have learned to selectively forage on sablefish being retrieved on longline gear (Dalheim[8]). Whereas killer whales are estimated to have consumed an additional 10% to 25% of the 1987 commercial harvest (Matkin[9]; Schroeder and Morrison[10]), fishermen reported relatively few whale encounters in 1991 and 1992 (Francine[11]). As sablefish seasons have become progressively shorter, whales have fewer opportunities to exploit this food resource. The decreased removal of sablefish from longline gear by whales probably contributed to the larger vessel landings in 1991 and 1992 (Fig. 4).

Future Management Strategies

In recent years, increasing fishing pressure has made the Prince William Sound sablefish fishery more difficult to manage for the established guideline harvest level. In-season management authority of commercial fisheries by the Alaska Department of Fish and Game is limited to time-and-area closures. As a result, management strategies for this fishery during the 1993 season will limit fishing time and allow more effective monitoring of harvests. Beginning in 1993, the sablefish fishery in Prince William Sound will open for weekly fishing periods of 72 hours, from noon on Mondays until noon on Thursdays. A 4-day weekly closure period will allow more accurate weekly updates of harvests. This change is being made to restrict fishing time and allow fishing periods that accommodate the current habits of the fishing fleet and processors; because most vessels are small (≤15 m) and lack refrigeration, processors encourage no more than 3 fishing days between deliveries. Allocative regulations and regulations that extend beyond time-and-area authority are established by the Alaska Board of Fisheries following substantial public input. Several regulations to restrict the current open access to the Prince William Sound groundfish fisheries may be addressed by the Alaska Board of Fisheries in 1993–94.

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[8] Dalheim, M. E. 1988. Killer whale (*Orcinus orca*) depredation on longline catches of sablefish (*Anoplopoma fimbria*) in Alaskan waters. NWAFC Proc. Rep. 88-14. Northwest Fisheries Science Center, NMFS, 2725 Montlake Blvd. E., Seattle, WA 98112.

[9] Matkin, C. O. 1988. Status of Prince William Sound killer whales and the sablefish fishery in late 1987. Report for Alaska Sea Grant Program, Cordova, AK. North Coast Oceanic Soc., P.O. Box 15244, Homer, AK. Unpubl. rep.

[10] Schroeder, T. R., and R. Morrison. 1988. 1987 Lower Cook Inlet area annual finfish management report. Reg. Inf. Rep. Alaska Dep. Fish Game, Anchorage, AK.

[11] Francine, J. Hubbs–Sea World Research Inst., 1700 South Shores Rd., San Diego, CA 92109. Personal commun.

A major limitation to the management of Prince William Sound sablefish stocks continues to be the lack of fishery-independent assessment surveys. Previous surveys have typically been short-term (Parks and Zenger[3]), not designed with population assessment as the primary objective (Haynes and Urban[4]), or primarily directed toward other species (e.g., Trowbridge[12]). However, with minor modifications to ongoing shellfish trawl surveys, the Alaska Department of Fish and Game hopes to expand assessment of groundfish species such as sablefish in future years. It is hoped that such assessments will evaluate and monitor the success of the guideline harvest-range model developed through extrapolation of sablefish yield per area from the long-term fishery in southeast Alaska.

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Barry Bracken provided substantial insight into sablefish biology and the establishment of the guideline harvest range. Critical review by Robert Wilbur and several anonymous reviewers is appreciated. Contribution PP 0081 of the Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau, Alaska.

Literature Cited

Beamish, R. J., and G. A. McFarlane.
1983. Summary of results of the Canadian sablefish tagging program. *In* B. R. Melteff (ed.), Proceedings of the International Sablefish Symposium, p. 147–183. Univ. Alaska, Fairbanks, Alaska Sea Grant Report 83-8.

Bracken, B. E.
1983a. The history of the U.S. sablefish fishery in the Gulf of Alaska, 1906–1982. *In* B. R. Melteff (ed.), Proceedings of the International Sablefish Symposium, p. 41–47. Univ. Alaska, Fairbanks, Alaska Sea Grant Report 83-8.
1983b. Sablefish migration in the Gulf of Alaska based on tag recoveries. *In* B. R. Melteff (ed.), Proceedings of the International Sablefish Symposium, p. 185–190. Univ. Alaska, Fairbanks, Alaska Sea Grant Rep. 83-8.

McFarlane, G. A., and R. J. Beamish.
1983. Biology of adult sablefish (*Anoplopoma fimbria*) in waters off western Canada. *In* B. R. Melteff (ed.), Proceedings of the International Sablefish Symposium, p. 59–80. Univer. Alaska, Fairbanks, Alaska Sea Grant Report 83-8.

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[12] Trowbridge, C. 1992. A bottom trawl survey for crabs in the Prince William Sound Management Area, August 3–18, 1992. Reg. Inf. Rep. 2A92-31. Alaska Dep. Fish Game, Div. Commercial Fisheries, Anchorage, AK.

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