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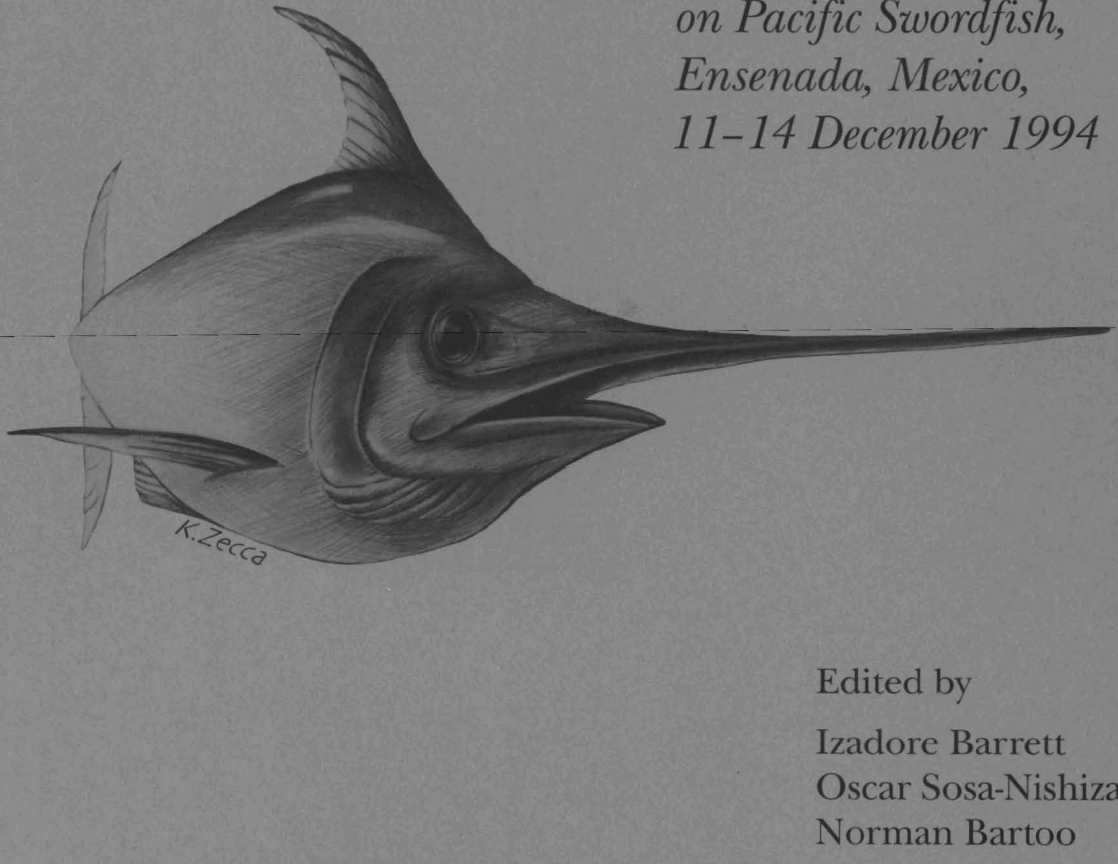
December 1998

Biology and Fisheries of Swordfish, *Xiphias gladius*

Papers from the
International Symposium
on Pacific Swordfish,
Ensenada, Mexico,
11–14 December 1994



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NOAA Technical Report NMFS 142
A Technical Report of the *Fishery Bulletin*

Biology and Fisheries of Swordfish, *Xiphias gladius*

Papers from the International Symposium on Pacific Swordfish, Ensenada, Mexico, 11–14 December 1994

Izadore Barrett
Oscar Sosa-Nishizaki
Norman Bartoo (editors)

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INTRODUCTION

The swordfish, *Xiphias gladius*, is a large migratory oceanic species. It is widely distributed in tropical, temperate, and sometimes cold waters of all oceans, and is usually found in areas with sea-surface temperatures above 13°C. It can reach a maximum size of 540 kg, and is a favorite food fish in many countries. It is excellent for steaks, canning, or teriyaki, the Japanese dish of meat grilled with sugar, soy sauce, and rice wine. Swordfish is harvested commercially throughout its distribution, in both coastal and high-seas fisheries. Sport fisheries for swordfish are very small compared to those for other billfishes, accounting for no more than a few hundred fish per year.

In the Pacific, swordfish has been caught since one can remember. The California harpoon fishery for swordfish started in the early 1900's. Longline vessels of Japan, Taiwan, and Korea have fished in the North Pacific since the early 1950's. A substantial increase in fishing operations targeting swordfish has been observed since the 1980's. Today no less than ten nations, including Chile, Japan, Korea, the Philippines, Taiwan, United States, and Mexico, are fishing across the ocean. The Pacific-wide catch has reached an average of 30,000 metric tons per year in the last 5 years.

The objective of the symposium was to address recent developments in swordfish fisheries, markets, and biological research in the Pacific Ocean. It provided a forum for the interchange of information and ideas. Twenty-five oral papers were presented, of which 22 were accepted as final manuscripts. Each manuscript was sent to two anonymous reviewers, edited, revised, edited again, and doublechecked by each author.

Because of the success of the first symposium, a second symposium was proposed to continue the communication among the group formed in Ensenada; it was held in Hawaii in March 1997, before the publication of this document. We hope to see a third symposium in the future.

We would like to thank Martha Jackson for her work on the final drafts of all the papers; Martin Gutierrez, Bob Skillman, Ricardo Suarez, and Yuji Uozumi for all their ideas as steering committee of the symposium; Gary Sakagawa and the personnel of the Southwest Fisheries Science Center (La Jolla and Honolulu Laboratories) for their useful suggestions; Lupita Martínes, Ulisis Cruz, Nury López, Margarita Margolles, Rogelio González, Cesar Almeida, Leonardo Lizarraga, and Silvia Ibarra from CICESE for their help in the organization of the meeting; and the Third World Academy of Sciences, Northwest Marine Technology, Inc., and the Swordfish Fishery Section of the National Fishing Industry Chamber (CANAINPES) of Mexico for their financial support of the symposium. And we especially thank all the authors for their patience during the long trip to publish this document.

Oscar Sosa-Nishizaki and Norman Bartoo, Ensenada, September 1998.

Development and Present State of the Swordfish, *Xiphias gladius*, Fishery in Chile[1]

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ABSTRACT

The swordfish, *Xiphias gladius*, fishery in Chile was artisanal, for subsistence only, for several decades. From 1938 through 1951, yearly landings ranged between 600 and 2,200 metric tons (t). During 1952–85, landings diminished, fluctuating between 13 and 570 t. After this period, there were important changes in the fishery and landings increased from 764 t in 1986 to 5,959 t in 1991.

continued

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After 1985, a high demand for swordfish products and good prices, probably due to the opening of the international market, made this fishery highly profitable. This led to the replacement of harpoons by gillnets, considerably increasing yield; an increase in the number, quality, and equipment of fishing boats, and the introduction of sea-surface temperature satellite images for obtaining information on potential fishing grounds. Fishing by the industrial sector began in 1986 and contributed 39% of landings in 1991–94.

Recently yields have decreased noticeably, associated with the offshore displacement of fishing grounds and reduction of mean fish size in the catch. These changes have produced some management measures such as the prohibition on new fishing boats entering the fishery.

Introduction

The swordfish, *Xiphias gladius*, fishery in Chile began at least as early as 1938. Catches peaked at around 2,200 metric tons (t) in 1946, then decreased and stayed at low levels for over 35 years (Fig. 1). The recovery in the fishery after 1985 can be explained by the opening of the international market, which generated great demand for this species and good prices for the artisanal fishing sector.

Growth in the artisanal fleet, both in number and capacity of the boats, was also encouraged by a new loan policy. Drift gillnets were introduced and almost totally replaced traditional harpoon fishing. The introduction of sea-surface temperature satellite images to localize potential fishing zones improved the surveying ability first of the artisanal fleet, and later of the industrial fleet.

This paper analyzes the development of the Chilean swordfish fishery between 1985 and 1994, including fishing practices, technology, effort and catch; swordfishing marketing; and relevant legislation.

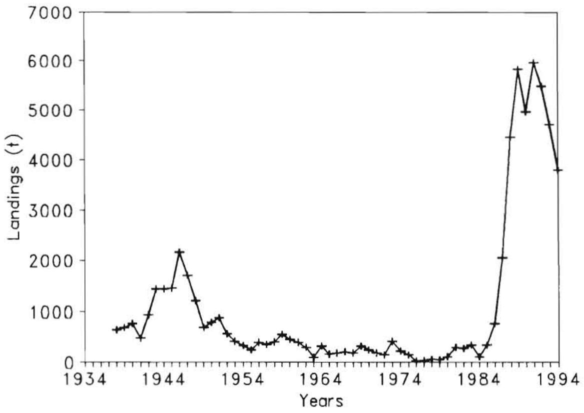

Figure 1
Total annual landings of swordfish in Chile, 1938–94. (Sources: SAG, 1967–77; SERNAP, 1978–94; A. Palma, Yungay 1731, Valparaíso, Chile, personal commun.)

Landings

The pattern of annual swordfish landings (Fig. 1) suggests the fishery might be divided into four stages:

1. Early exploitation: from 1938 until 1951, landings were normally over 600 t (2,146 t in 1946). Almost 100% of the catch was landed in the northern part of the country, in the ports of Arica (18°20'S) and Iquique (20°10'S).
2. Low exploitation: from 1952 to 1985, catches were very low (between 13 and 570 t); in the north, they were almost non-existent. The fishery moved to the central coast, landing in the ports of Valparaíso (33°S) and San Antonio (33°30'S). The manual harpoon was still being used.
3. Expansion: from 1986 until 1991, there was a sustained increase in landings, mainly at the ports on the central coast. Landings reached a peak of 5,959 t in 1991. During this stage the fishing effort obviously increased and there were significant technological developments associated with the introduction of gillnets and the use of satellite images. During this period the fishery developed between 27° and 40°S; the opening of export markets is believed to be the main factor driving this development.
4. Decrease: after the record landings in 1991, landings diminished steadily. Fishing effort still showed an increasing trend, while artisanal yields continued to go down.

Traditionally, the swordfish fishery was conducted by the artisanal sector, mainly within the 200-nautical-mile (n. mi.) exclusive economic zone (EEZ). However, since 1986 industrial sector landings have gradually increased (Fig. 2), both within and beyond this zone. Artisanal landings clearly diminished after 1989; figures for industrial landings, particularly after 1991, included artisanal landings as well in a proportion that remains

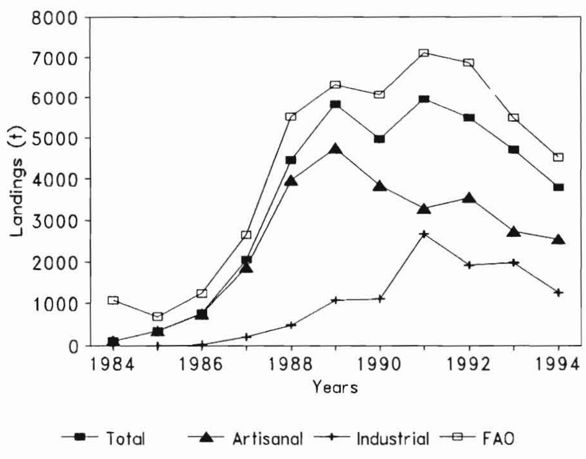

Figure 2
Total artisanal and industrial landings of swordfish in Chile between 1984 and 1994 (SAG, 1967–77; SERNAP, 1978–94; A. Palma, Yungay 1731, Valparaíso, Chile, personal commun.).

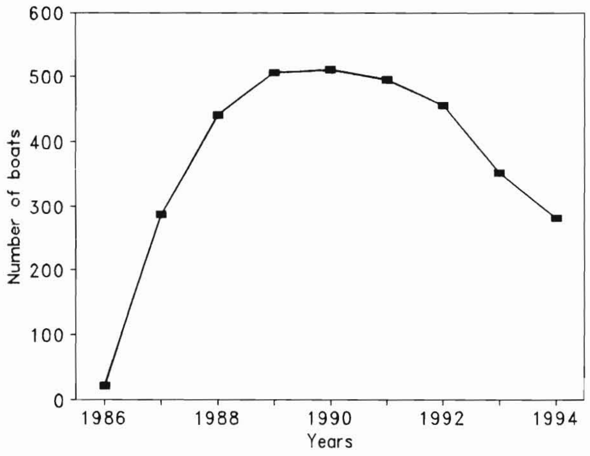

Figure 3
Number of artisanal boats participating in the Chilean swordfish fishery between 1986 and 1994.

Table 1
Distribution by length range of artisanal boats participating in the Chilean swordfish fishery in 1993.

Length (m)	Quantity	Percentage
8–9.9	8	2.1
10–11.9	9	2.4
12–13.9	34	9.0
14–15.9	193	51.4
16–17.9	11	30.6
18–19.9	17	4.5
Total	376	100.0

to be determined. The swordfish is exploited by foreign longliners in international waters off the Chilean coast.

Total national swordfish landings clearly showed a seasonal component, with a peak between March and August during 1985–94 (SERNAP, 1985–94). Between 1985 and 1989 catches were made from January through September; in the 1990–94 period, both the artisanal and industrial sectors registered catches in every month of the year. Until 1984 fishing for swordfish was restricted to the months of March through May, and was conducted exclusively with harpoons.

The Fleet

Artisanal boats

The evolution in size of the artisanal fleet participating in the swordfish fishery shows three stages between 1986 and 1994 (Fig. 3):

1. Until 1989, the number of boats increased, encouraged by loan accessibility and the opening of the international market for Chilean swordfish.
2. From 1989 to 1991, the number of vessels remained at around 500. Boats were equipped with improved technology, and longliners began to operate in international waters.
3. After 1991 the number of boats decreased. The granting of new fishing permits was suspended, and the resource was declared to be fully exploited. An offshore expansion of the fishing zones which were far from the coast limited the operation of small boats, which have less autonomy (González, 1993).

Between 1989 and 1994, artisanal boats increased their length, power, and gross register tonnage (GRT; Fig. 4). In 1993, boats ranged from 8 to 20 m (Table 1). The boats are built of wood (77%), steel (20%), fiberglass (2%), or ferrocement (1%). Wooden boats are represented in all length strata, while steel boats are normally larger.

Industrial Boats

Since 1991 approximately 20 large boats have fished swordfish in Chile, thus modifying the exclusive artisanal character of this activity. These boats vary between 21 and 62 m long; some of them use drifting gillnets

(27%) and others pelagic longline (72%), and some use both fishing methods (1%).

Fishing Methods and Gear

The artisanal fleet normally begins fishing during January in the area off Talcahuano–Valdivia (37°–40°S), moving toward the north and generally ending in September–October off Caldera–Coquimbo (27°–30°S). Drifting gillnets work without major problems in rough weather conditions, while harpoon fishing requires good weather and visibility.

At the beginning of each season (January–May), the small boats usually use both fishing methods in the same trip, the harpoon in daytime and the nets at night. During the rest of the season (June–October), only the net continues to be effective. Although the yield is less at the beginning and end of the fishing season, the high price fetched by swordfish at these times of year compensates for lesser yields.

The industrial fleet uses both gillnets and pelagic drift longline; the latter is used more often because it is more effective.

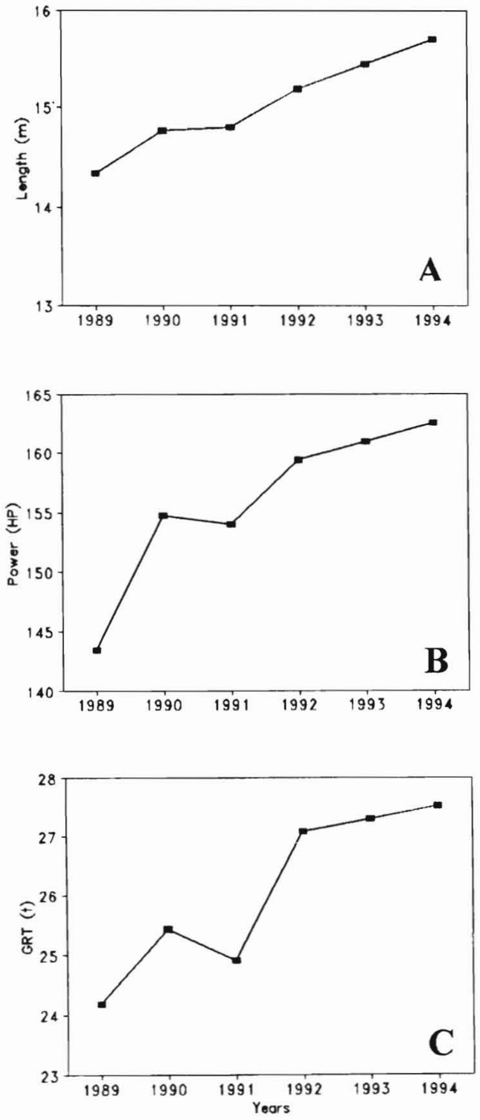

Figure 4

Mean values of (A) length, (B) horsepower (HP), and (C) gross register tonnage (GRT) of artisanal swordfishing boats in Chile between 1989 and 1994.

Manual Harpoon

The harpoon is the most antique fishing gear of this fishery; it used only by small artisanal boats. It is composed of a wooden or steel pole with a bronze point. The point carries a segment of steel cable joined to a line of approximately 20 m, to which a rope more than 500 m long is attached. Harpoon fishing is restricted to the months of good ocean and weather conditions, normally between January and May, when the fish dwell at the surface. Boats fishing with harpoons are readily identified by a steel structure at the bow.

Drift Gillnets

The drift gillnet is the gear most used by the artisanal fleet. It consists of a long wall of several mesh panels, about 2,470 m long by 55 m high, made of polypropylene. Floats and buoys are attached approximately every 46 m. The mesh size is 22 inches.

The net is set at dusk and hauled at dawn of the following day. While setting the net, disposable chemical lights are tied every 37 m to attract swordfish prey. Setting depth is between 9 and 55 m, depending on the amount of brightness at night.

Pelagic Drift Longline

The pelagic drift longline is composed of a twined polyethylene or monofilament nylon main line; hook branch lines are part polyethylene or monofilament and part galvanized wire. Approximately 2,000 hooks are set per haul. Horse mackerel, *Scomber* spp., and squid, *Illex* spp., are commonly used for bait.

Longliners fish practically all day long. They mainly use the ports of Coquimbo (30°S) and Valparaíso (33°S) year round. By law, these boats must operate farther than 120 n. mi. offshore. Thus, activity extends from the limit of the EEZ up to 800 n. mi. offshore, between Valparaíso and the northern limit of Chile.

The duration of trips depends mainly on a boat's autonomy and on its catch maintenance system. The industrial boats that use drift gillnets work no more than 15 days, refrigerating the catch with ice in isolated holds. Longliners can work for 2 months, since they have freezing systems in their hold to preserve the catch.

Use of Satellite Images

Since 1986, sea-surface temperature (SST) satellite images have been used in the Chilean pelagic fisheries for finding probable fishing grounds.

Images are prepared with information gathered by AVHRR sensors on NOAA satellites. These images were first introduced in the albacore, *Thunnus alalunga*, and swordfish artisanal fisheries (Barbieri et al., 1989, 1991). The industrial sector exploiting swordfish and small pelagic fish such as the anchovy, *Engraulis ringens*, and sardine, *Sardinops sagax*, also acquires this information, which is then distributed to their fishermen (Yáñez et al., 1994).

An SST image gives information in real time on SST over a wide area. The course of a boat is determined on the basis of the image, the distance, and the time needed to travel to the fishing grounds. Satellite information may be of great help, particularly after a period of bad weather during which the boats stay in port, losing the location of fishing zones. Nevertheless, satellite information has certain technical limitations. The most critical one is cloud cover, which prevents the satellite sensor from detecting SST. Fog also affects temperature readings. Another aspect to be considered is the correct calibration of the sensor with in situ information, which is not always available. A practical limitation is information distribution, presently achieved by using a modem and fax machine.

Although satellite information is available almost daily, two images per week seems to be enough, depending on meteorological conditions, since wind has an important effect on the distribution of SST.

CPUE and Fishing Effort

Artisanal Fleet CPUE

Data on total landings of the artisanal fishing fleet was taken from the logbooks of boats operating from the ports of Valparaíso and San Antonio between 1987 and 1994, representing 68% of total landings of the fleet in this period (Donoso and Montenegro, 1992; Correa, 1993; SERNAP, 1987–94). Fishing logbooks report on each boat's activity: the departure and arrival dates, base port, fishing area, and catch. Similar information is not available for the industrial fleet.

Table 2

Nonparametric statistical test (Kruskal-Wallis) for differences in CPUE between boat length classes.

Years	Boat length range (m)	(K-W)[1]	(χ^2)[2]	n[3]	Conclusion[4]
1987	11–17	11	15	7	accept H_0
1988	11–16	8	13	6	accept H_0
1989	11–16	17	13	6	reject H_0
1990	11–16	5	13	6	accept H_0
1991	12–17	10	13	6	accept H_0
1992	10–18	8	16	8	accept H_0
1993	12–18	9	15	7	accept H_0
1994	10–18	7	16	8	accept H_0

[1] Kruskal-Wallis test statistic.

[2] Chi-square statistic (0,975, n–1).

[3] Number of boat length strata.

[4] H_0: no differences between boat categories.
H_1: boat categories are different.
H_0 is accepted if K-W < χ^2.

Catch per unit effort (CPUE) was used in our analysis of the fishery. Mean monthly $CPUE_m$ was estimated by dividing monthly landings (kg) by monthly effort (days at sea) of the artisanal fleet. Similarly, mean annual $CPUE_i$ was calculated as the average of all $CPUE_m$ in a year. For each year, fishing effort was estimated by assuming that the boats in the artisanal fleet were homogeneous relative to their fishing power. Comparison of annual mean CPUE's for boats of different length classes using the Kruskal-Wallis statistical test showed no significant differences between them, with the exception of 1989 (Table 2).

Estimated $CPUE_i$ shows a remarkable decreasing trend between 1987 and 1994 (Fig. 5a), likewise the biomass estimated by the virtual population analysis (VPA; Fig. 5b) of MacCall (1986), applied to the artisanal and industrial landings of 1987–94 (Table 3). VPA was structured by number at age considering the sampling for lengths and von Bertalanffy growth parameters, since we lacked relevant length–age keys. Weight was estimated as the weighted mean between the weights estimated from the length–weight relation and from age composition in the catch. These weights were later used to estimate annual biomass. Natural mortality, following the Pauly (1980) model, was estimated as 0.123 at a mean temperature of 16°C. Fishing effort for 1987–94 (Table 3) was used to calibrate the VPA.

Table 3
Total landings (artisanal and industrial), CPUE (artisanal), and total effort of the swordfish fishery in Chile, 1987–94.

Year	Landings (t)	Fishing effort (artisanal days at sea)	CPUE (kg/artisanal day at sea)
1987	2,059	5,265	391
1988	4,455	17,200	259
1989	5,824	20,152	289
1990	4,955	19,057	260
1991	5,959	37,715	158
1992	5,481	34,043	161
1993	4,712	38,942	121
1994	3,801	41,315	92

It should be noted that Chilean catches represented on average 80% of annual total landings in the southeastern Pacific (FAO Area 87) for 1987–94 (FAO, 1987–94); and that the southeastern Pacific stock may be a unique unit of self-sustained stock.

The decrease in CPUE reflects the remarkable increase in total fishing effort, which was not followed by the expected increase in landings (Table 3), probably due to a significant decrease in resource abundance and/or to changes in availability produced by interannual variation in environmental conditions. The increased distance of the fishing zones from the coast has required the artisanal fleet to invest a greater number of days at sea, mainly to reach those areas. In 1987 the fishing zone of Valparaíso was located within 40 n. mi. of the coast, while in 1990 it was >160 n. mi., and in 1993–95, 200 n. mi. offshore (Barbieri et al., 1995). This change in fishing areas is likely due to decrease in abundance of the resource, probably caused by the recent development of the Chilean fishing industry and the international longline fishing industry. However, it is also likely that environmental changes have affected the resource distribution, and therefore its availability (González, 1993).

Total Effort

Annual total effort (f_i) by the artisanal and industrial fleets was estimated using the annual total landings of both fleets (C_i) and the artisanal fleet's $CPUE_i$, as $f_i = C_i/CPUE_i$.

Total fishing effort shows a clear increasing trend during 1987–94 (Table 3). The 8-fold increase during this period was associated with the increased number of boats entering the fishery, the technological development of the fleet, knowledge of the fishing zones, and an important decrease in abundance and/or availability of the resource (Barbieri et al., 1990; Ponce and Bustos, 1991; González, 1993).

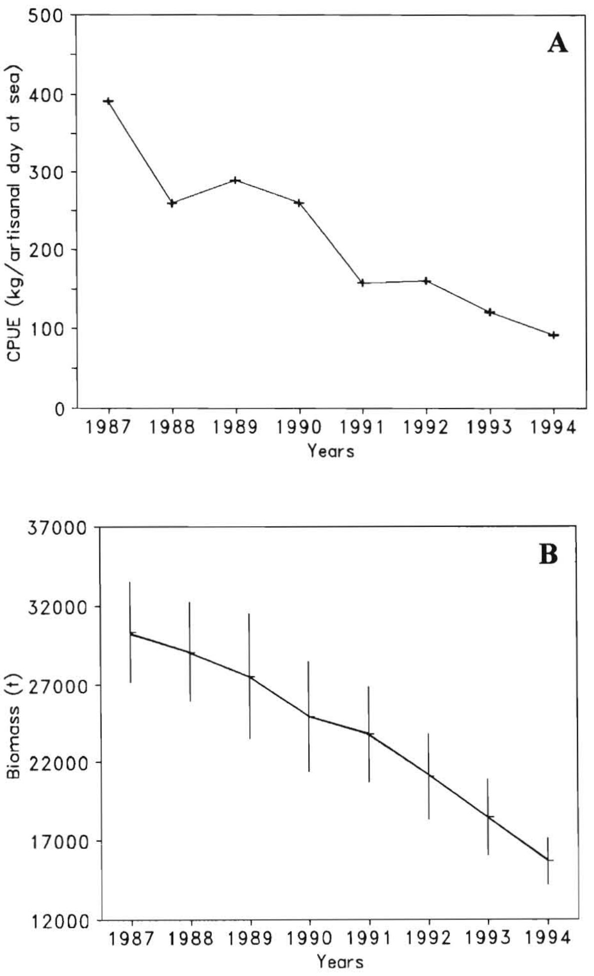

Figure 5
Swordfish abundance in Chilean waters, according to (A) CPUE, 1987–94 and (B) biomass calculated by VPA, 1987–94. Bars indicate standard deviation.

Surplus Production Model

Based on the exponential relation between the landings (artisanal and industrial), the CPUE (artisanal) and the total effort (artisanal and industrial) (Fig. 6), the swordfish fishery in Chile would have reached adequate levels of exploitation between 1988 and 1990. Hereafter, increase in effort is related to diminishing abundance and/or availability. There is no information about the catches of the international longline fleet operating off Chile. In any case, the swordfish fishery in Chile reflects a delicate situation in the present status of the resource.

The Catch

Trunk Weight

The annual frequency distribution of trunk weights (without the head, caudal fin, and guts) of swordfish caught by the artisanal sector (Donoso and Montenegro, 1992; González, 1993) showed a remarkable progressive displacement of the histogram peak toward lower weights (Fig. 7). Since 1989 the mean trunk weight of swordfish caught by this sector has been diminishing (Fig. 8).

The distribution of trunk weights indicates that over 50% of the industrial catch was fish of <40 kg, while the artisanal sector catch was almost entirely fish >40 kg (Fig. 9).

Growth

The relation between length (measured from the tip of the snout to the lower jaw, LJFL) and the trunk weight of swordfish caught by the artisanal fleet in 1994 is shown in Figure 10.

Leiva (1993), by means of a statistical analysis of concordance and variability, established that the second spine of the anal fin is more suitable for the identification of growth rings than spines of the dorsal fin. He calculated the linear relation between the radius of the second spine of the anal fin and LJFL, which showed significant differences between sexes.

On the basis of anal spines of a wide distribution of lengths, Montiel (1996) estimates the following growth functions:

$$\text{females: } \mathrm{LJFL}_t = 282\left[1-\exp\left(-0.2925\times(t-0.1085)\right)\right]$$

$$\text{males: } \mathrm{LJFL}_t = 250\left[1-\exp\left(-0.3216\times(t+0.7545)\right)\right].$$

Stomach Contents

Stomach contents from specimens caught in the central zone of the country during 1989 were analyzed. Five prey fish were found, the most important being the longtailed hake, *Macruronus magellanicus*, and jack mackerel, *Trachurus murphyi* (Fig. 11).

Proportions of the Sexes

Leiva (1993) estimated the proportions of males and females in artisanal catches of swordfish obtained with harpoon and gillnet during the fishing season of 1989 in the central zone (Table 4). During the first 4 months of the fishing season (January–April), females predominate the catch with both gears; during May–July, the proportions of the sexes were even, although the sample contained only specimens caught with nets.

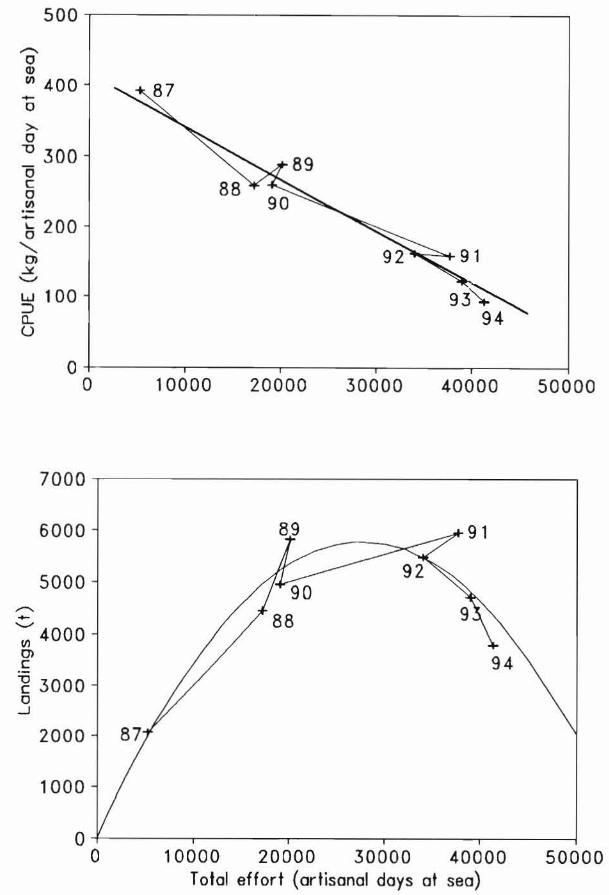

Figure 6

Relation between total landings (artisanal and industrial), CPUE (artisanal) and total effort of the swordfish fishery in Chile (r^2=0.96).

Table 4

Proportions (%) of male and female swordfish in artisanal catches in the central zone of Chile, 1989 (n = 300).

	Harpoon		Gillnet		Total	
Month	Female	Male	Female	Male	Female	Male
Jan–Apr	85	15	100	0	92.5	7.5
May–Jul			51	49	51	49

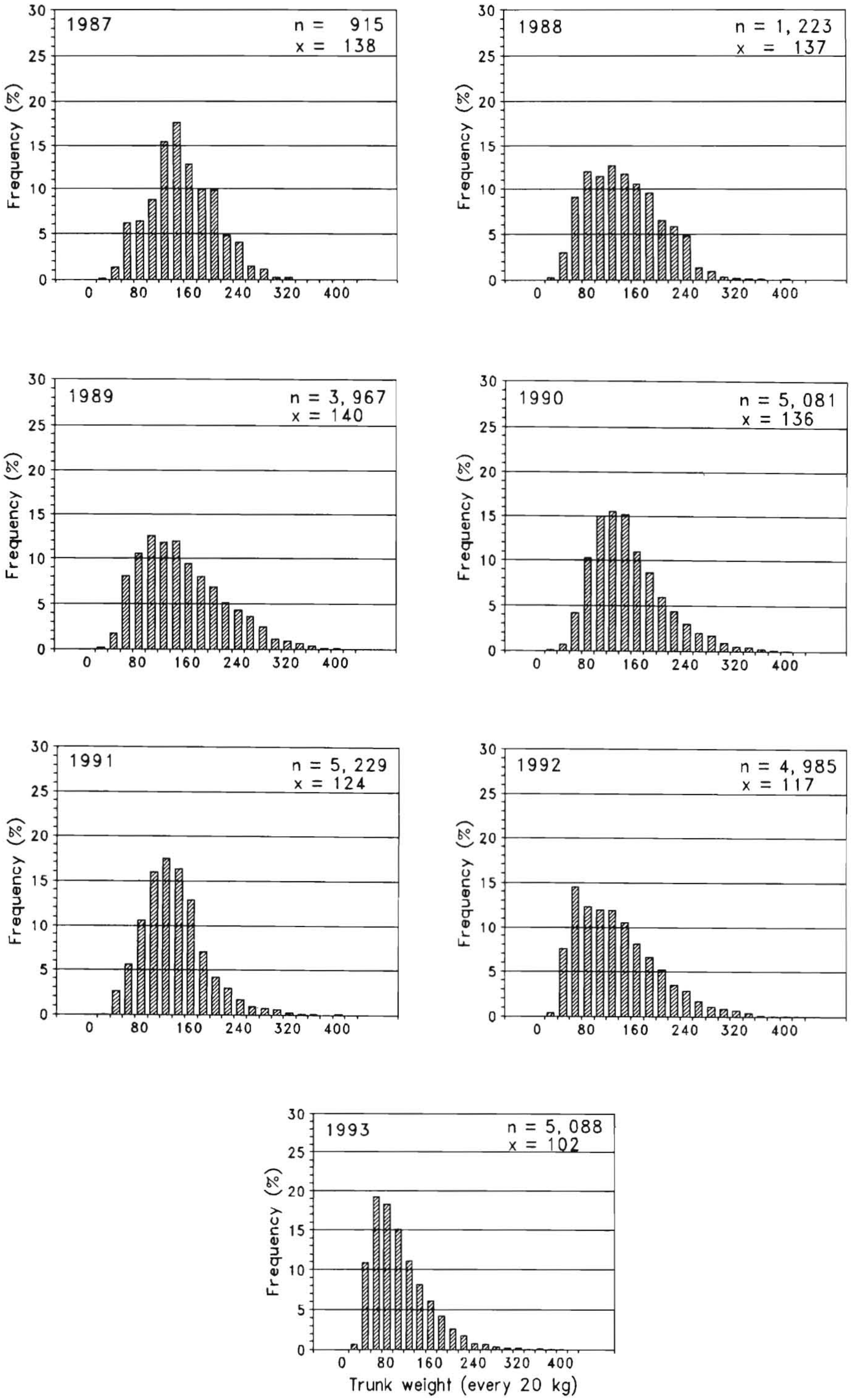

Figure 7

Annual frequency distributions of trunk weight (kg) of swordfish caught by the artisanal sector in Chile, 1987–93 (*n* = number of fish; *x* = mean weight in kg).

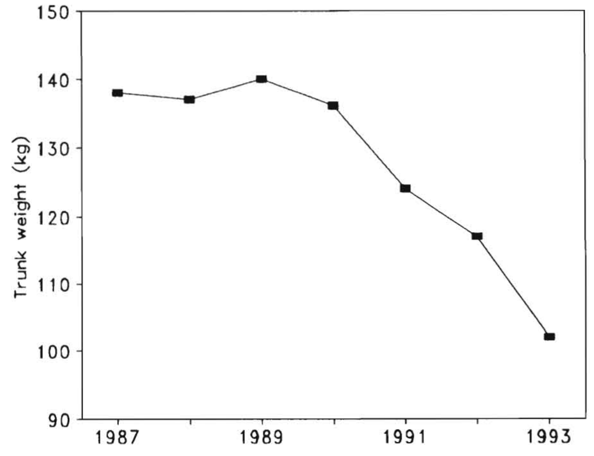

Figure 8
Annual mean weight of swordfish trunks caught by the artisanal sector in Chile, 1987–93.

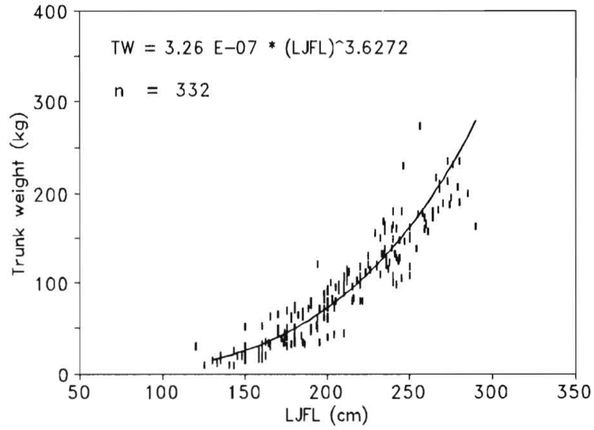

Figure 10
Relation between length (lower jaw–fork length, LJFL) and trunk weight (TW) of swordfish caught by the artisanal fleet in 1994.

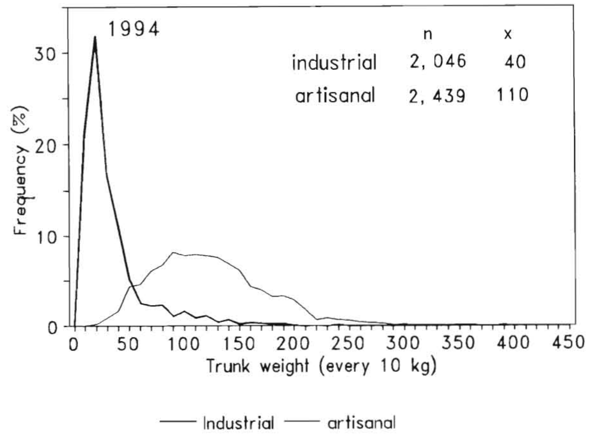

Figure 9
Frequency distributions of trunk weights (kg) of swordfish caught by the artisanal and industrial fleets in 1994 (n = number of fishes; x = mean weight).

The Market

During the 1993 season, swordfish transactions totaled US $25 million. In 1992, transactions were 12.7% less, but prices were 4.9% higher. During recent years the orientation is toward the North American market, where the catch is destined for luxury restaurants and some supermarket chains. In the U.S.A. the Chilean product competes mainly with exports from Caribbean countries, and to a certain point with local catches.

The freight on board price (FOB) for fresh-frozen Chilean swordfish has a clear seasonal behavior; best prices are during the first quarter, then they decline until June and thereafter recover until February.

Legislation

The State of Chile regulates the fishing methods and areas for swordfish and associated fauna in waters of national jurisdiction. Since January 1991, Decree 293 has been implemented to control this fishery.

Decree 293

Article 1—Subjects all boats participating in the swordfish fishery within the Territorial Sea (12 n. mi. off the coast) and in the Exclusive Economic Zone (EEZ) (200 n. mi. off the coast) to this regulation.

Article 2—Establishes that the fishery is composed by the target species *Xiphias gladius* and its associated fauna, mainly tunas belonging to the genera *Thunnus* and *Gasterochisma*, marlins of the genus *Tetrapturus*, and billfishes of the genera *Istiophorus* and *Makaira*.

Article 3—Bans landing in Chilean ports of swordfish caught by boats that have broken these rules.

Article 4—Establishes that a) boats of total length of less than 28 m with current authorization may conduct-extractive fishing activities on the swordfish resource

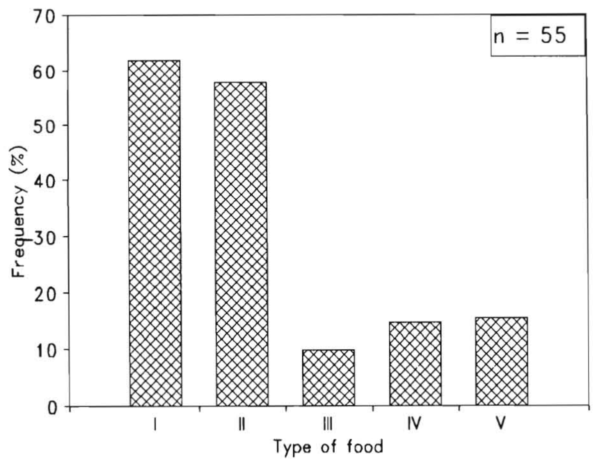

Figure 11
Stomach contents of swordfish captured in Chile during 1989. I = longtailed hake, *Macruronus magellanicus*; II = jack mackerel, *Trachurus murphyi*; III = shrimp, *Heterocarpus reedi*; IV = other fish remains; V = squids, *Loligo gahi* and *Dosidicus tunicata*.

and its associated fauna in the Territorial Sea and EEZ, and b) boats with current authorization, of total length equal to or over 28 m, may only operate in this fishery within the EEZ west of 120 n. mi. off the coast.

Article 5—Establishes that the gillnets used in this fishery may not exceed a total length of 1,350 fathoms (fm), measured on the floatline.

Article 6—Fixes the maximum surface of nets, for boats with total length less than 28 m, at 25,000 fm^2.

Article 7—Boats of total length of at least 28 m may use gillnets with a maximum surface of 37,500 fm^2.

Article 8—Fixes at 1,200 the maximum number of hooks to be set on each haul for boats fishing with longline. For boats with a total length of at least 28 m, a maximum of 2,000 hooks is allowed on each fishing haul.

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Swordfish, *Xiphias gladius*, and the Fisheries for Tunas and Billfishes in the Australian Fishing Zone

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ABSTRACT

Fishing operations that take swordfish, *Xiphias gladius*, in the 200-nautical-mile Australian fishing zone (AFZ) are summarised and data collections are reviewed. Swordfish are incidental in commercial tuna longline catches in the AFZ; most are taken by licensed Japanese longliners, but some come from a domestic longline fishery which includes a rapidly-growing section targeted on swordfish. Although swordfish are taken in most of the eastern, southern, and western AFZ, swordfish catches and catch rates are highest in the central eastern area of the AFZ. Average annual logbook-reported catch for the last 5 yr was

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about 750 tons. Neither harpooning nor tangle netting for swordfish occurs in the AFZ. Rare incidental catches of swordfish are taken in the troll/handline tuna fishery, but they have not been reported from the bait-boat or purse-seine tuna fisheries. The number of swordfish caught by recreational anglers is quite small.

Japanese logbook data have been collected and stored in the Australian Fishing Zone Information System since 1979. Domestic longline logbooks have been collected since 1985, but comprehensive coverage was not achieved until 1989. No catch data are routinely collected from recreational anglers. Virtually no biological research has been undertaken on swordfish in Australia, but a program of observer cruises aboard Japanese longliners has operated since 1979, providing catch size composition data and limited biological observations.

Introduction

Swordfish, *Xiphias gladius*, has been prized in the Mediterranean and United States as prime table fish because of its moist, rich, light-colored flesh, but it has never been an important commercial species in Australia. This reflects the absence of regular landings until the establishment of a domestic longline fishery in the late 1980's. Even then, levels of mercury present in the flesh of larger fish were higher than the Australian Food Standard acceptable limit at the time (National Food Authority, 1992 and updates), which restricted the extent to which the catch could be marketed. The permissible mean content was 0.5 ppm, with a 1.5 ppm maximum for an individual fish. Recent adjustment of the Standard, whereby the mean has been increased to 1.0 ppm, has increased the marketable component of the catch.

To facilitate consideration of the swordfish resources in waters adjacent to Australia, the present paper provides a summary of past and current fishing activities that catch swordfish in the Australian 200-nautical-mile fishing zone (AFZ) (Fig. 1). A review of the nature and extent of Australian fisheries data on swordfish is also presented. A summary review of distribution, life history, stock structure, the commercial and recreational fisheries, and resource status of swordfish in the AFZ, concentrating on the Australian situation but including broader comment where relevant, is provided in Kailola et al. (1993).

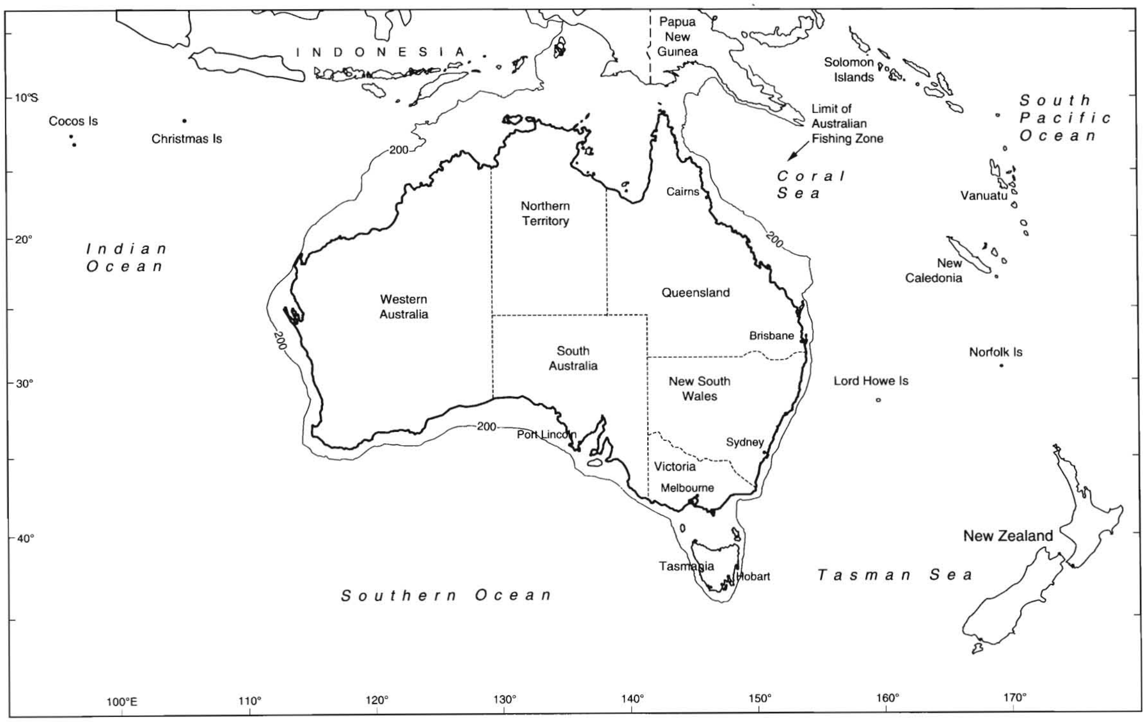

Figure 1

The Australian 200-nautical-mile fishing zone (AFZ; dotted line) and localities mentioned in the text.

Distribution of Swordfish

Swordfish occur predominantly in oceanic waters of the AFZ; they are distributed beyond the edge of the continental shelf from the far northeast of the zone, around the south edge of the continent, to the far northwest (Kailola et al., 1993). Concentrations are found in the central eastern and the southwestern regions of the zone. These aggregations are in areas influenced by the East Australian Current (off the Pacific coast) and the Leeuwin Current (off the Indian Ocean coast), warm currents which move southwards through the eastern and western sectors of the zone (Fig. 2, taken from Cresswell, 1987). The eastern concentrations are also located in the vicinity of several seamounts (Fig. 3). Larvae have been found in the oceanic regions of the northeast and northwest of the zone (Fig. 4, taken from Nishikawa et al., 1985). In some years (perhaps three times in the last 20 years, including 1985 and 1994), small juveniles (1–15 kg) have been reported from continental shelf waters at around 60 fathoms (fm) off the New South Wales central and southern coast such that there have been occasional incidental recreational catches (Goadby[1] and Pepperell[2]). Because these occurrences have been rare, they have generated considerable interest in the popular angling media. The distribution reported in 1985 was from Sydney to Narooma (350 km south of Sydney) on the New South Wales south coast, with fish in the 1–2 kg range. The distribution was farther north in 1994, from South West Rocks (400 km north of Sydney) to Ulladulla (200 km south of Sydney), and fish were initially around 4 kg.

In the Northern Hemisphere, the northern extension of the land masses and associated temperature regimes presumably prevent interchange of North Pacific and North Atlantic swordfish. In the Southern Hemisphere, interchange between the South Atlantic and South Pacific seems unlikely because of the southward extension of South America. On the other hand, interchange between the South Atlantic and Indian Oceans, and between the South Pacific and Indian Oceans, would appear feasible given the sea-surface temperatures at the southern boundaries of the intervening land masses. Regarding interchange between the Indian and Pacific Oceans, it is not clear whether swordfish represent a single stock in the AFZ or whether sub-structuring occurs. Swordfish are reported to be rare in waters shallower than 200 m (Williams et al., 1994). The shallow waters across northern Australia probably inhibit substantial east–west interchange in the tropical region. Distribution is more or less continuous around the remainder of the AFZ, but catches south of the Australian mainland and around southern and western Tasmania (Fig. 5) are relatively low despite substantial longlining effort in the latter region in austral summer. Swordfish are usually found in waters with surface temperatures greater than 13°C (Williams et al., 1994). The southern range of swordfish catches is reasonably consistent with the August (austral winter) 13°C mean sea-surface isotherm for eastern Australia (Fig. 6), although in February (austral summer) the 13°C isotherm is well south of Tasmania. Even so, swordfish are rare in the summer catches of longliners southwest of Tasmania; there may not be much interchange in the cool temperate region between the eastern and southwestern AFZ. Reported preferred sea-surface

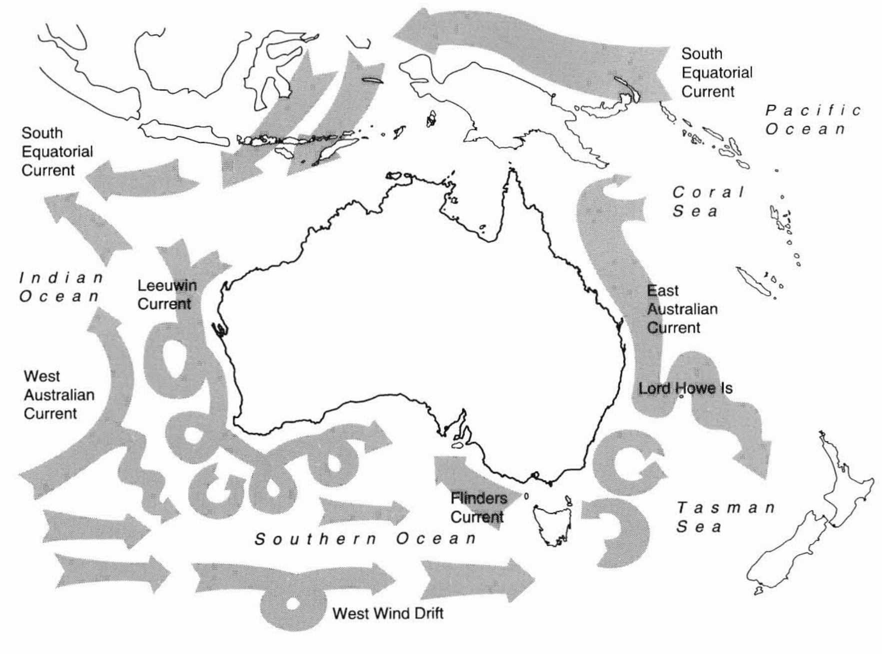

Figure 2
Ocean currents in the vicinity of Australia (after Cresswell, 1987).

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[1] Goadby, P. 1994. 38 Stirling Ave., North Rocks, NSW 2151, Australia. Personal commun.

[2] Pepperell, J. 1994. Pepperell Research, P.O. Box 818, Caringbah, NSW 2229, Australia. Personal commun.

temperatures for swordfish in the North Pacific are around 18–22°C (Williams et al., 1994), and this is consistent with the area of peak concentration of swordfish catch off eastern Australia in austral winter (Fig. 5).

Fisheries

The tuna and billfish fisheries[3] of the AFZ consist of

- Japanese and joint-venture Australia–Japan longline fisheries;
- a domestic longline fishery;
- domestic surface fisheries;
- a recreational fishery;
- a Japanese handline (surface) fishery.

Occasional troll catches of tunas had always been taken around the Australian coast, but a significant commercial tuna fishery was not established until the early 1950's, when bait-boat techniques for southern bluefin tuna, *Thunnus maccoyii,* were successfully used off New South Wales and South Australia (Caton, 1991). Japanese longline fishing expansion into the Southern Hemisphere during the 1950's saw the establishment of operations throughout much of the area now encompassed by the AFZ, but it was not until 1985 that a viable domestic longline fishery was established.

Swordfish are regularly taken as incidental catch by the longline tuna fisheries.[4] The average annual (July–June) catch of swordfish reported in logbooks by the Japanese longline fishery during the period 1988–89 to 1992–93 was 742 metric tons (t), with fish of an average processed weight of 47 kg. This compares with about 30 t reported annually in domestic longline fishery logbooks in the last three years (East Coast Tuna and Billfish Assessment Group[5]).

The Australian surface fisheries use bait-boat, purse seine, or trolling gear. Rare incidental catches of swordfish are taken by troll gear, but there are none from the bait-boat and purse-seine fisheries. There are no harpoon fisheries because surface "basking" behavior of swordfish is rarely reported in Australia.

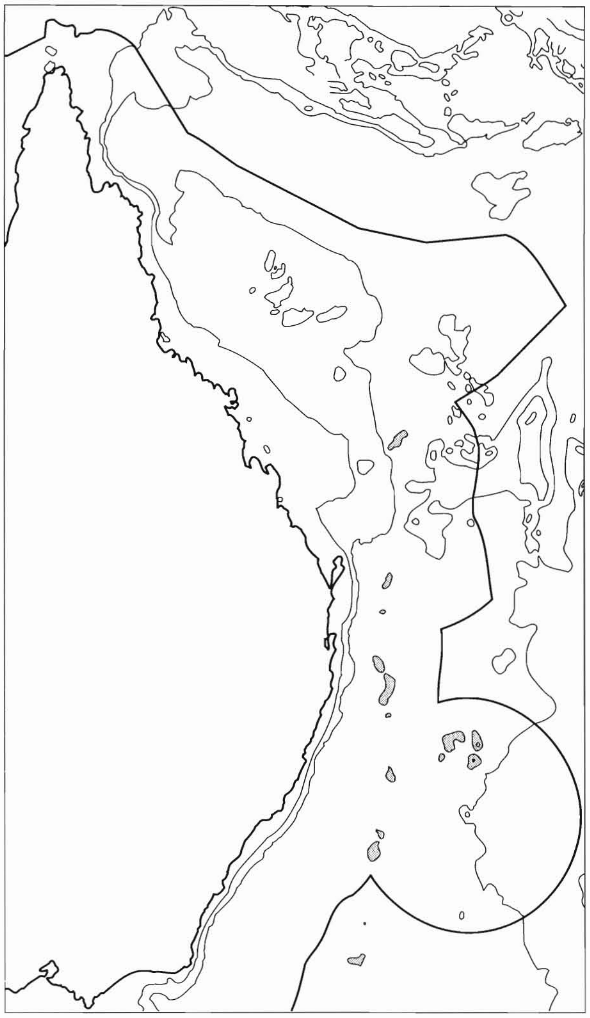

Figure 3
Seabed topography adjacent to eastern Australia; the 200-m and 2,000-m isobaths are shown, and seamounts are shaded. Heavy line indicates the boundary of the Australian Fishing Zone (source: Kailola et al., 1993).

The Japanese handline fishery is a seasonal (October–December) activity in the Coral Sea around 15°–20°S which takes surface aggregations of yellowfin, *Thunnus albacares,* and bigeye, *T. obesus,* tunas. There is no incidental swordfish catch.

A pelagic gillnet fishery involving vessels from Taiwan operated around northern Australia (north of 15°S between 120°E and 140°E) from the mid 1970's until the introduction of gear restrictions in 1986. The restrictions limited the maximum length of net set to 2.5 km and made the fishery uneconomic. Spanish mackerels, *Scomberomorus* spp., and various sharks were the targets of this fishery. Observers reported incidental catches of black marlin, *Makaira indica,* and sailfish,

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[3] The description here of the tuna and billfish fisheries of the AFZ is largely reproduced from Caton and Ward (1991), Albacore tuna and its fisheries in the Australian fishing zone. Bur. of Rural Res. Working Pap. WP/3/91, 43 p. Their report has been updated and modified to emphasize aspects relevant to swordfish.

[4] In addition, since this manuscript was accepted, there has been a major expansion of domestic longlining targeted on swordfish, with a 1997 catch of about 1,500 t.

[5] East Coast Tuna and Billfish Assessment Group. 1994. Fisheries assessment report, east coast tuna and billfish fishery 1994. Aust. Fish. Manage. Auth., Box 7051, Canberra Mail Centre, Canberra, ACT 2610, Australia.

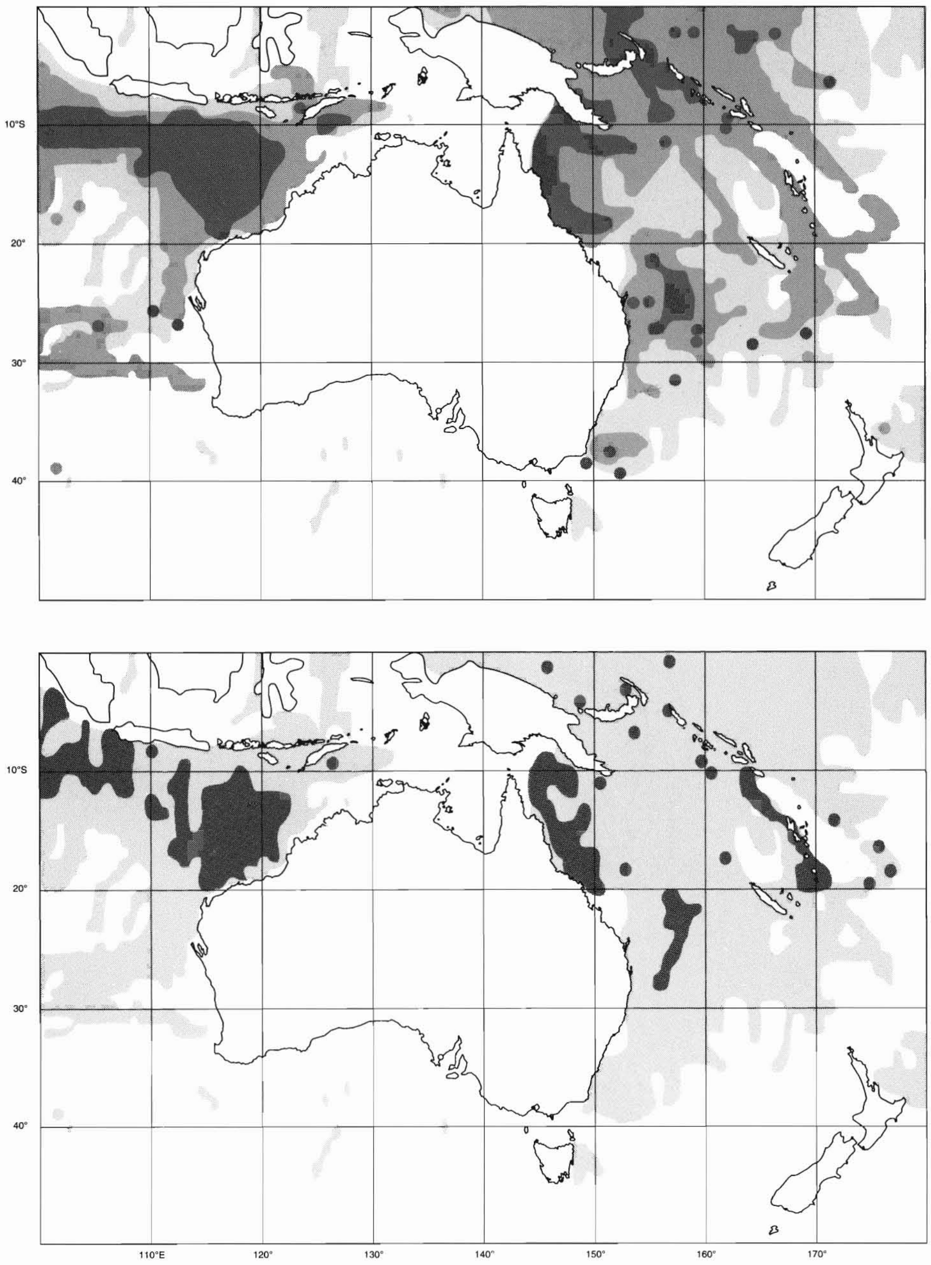

Figure 4

Distribution of sampling effort, and swordfish larvae caught, in waters off Australia (after Nishikawa et al., 1985). Upper: volume of water strained; denser shading indicates greater sampling effort. Lower: presence of larvae; shading indicates area sampled, denser shading indicates presence of larvae.

Istiophorus platypterus, but no swordfish were reported. Across the southern Australian continental shelf there is a large-mesh bottom-set gillnet fishery for small (1–2 m) sharks. No incidental swordfish catches are reported from that fishery. A large-mesh shark netting program protects swimming beaches off New South Wales and Queensland. No incidental swordfish catches are reported there. Apart from the activities summarized above, there are no fishing operations in the AFZ that use gear likely to take swordfish.

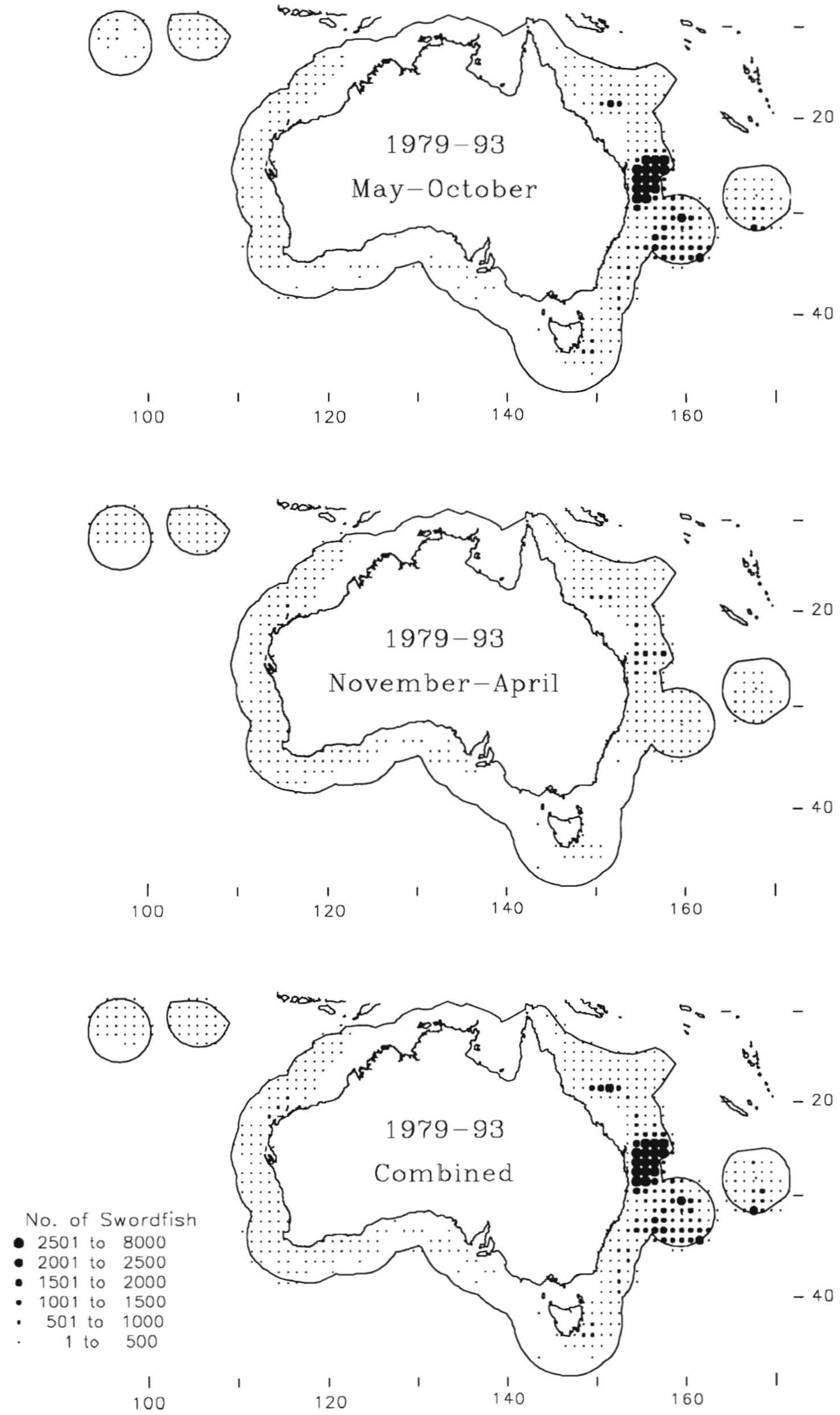

Figure 5

Distribution (by 1-degree square) of swordfish catch (number of fish) by Japanese bilateral-licensed and joint-venture longliners in the Australian Fishing Zone during May–October (top) and November–April (center), and yearly (bottom), 1979–93 combined (from Australian Fishing Zone Information System logbook data).

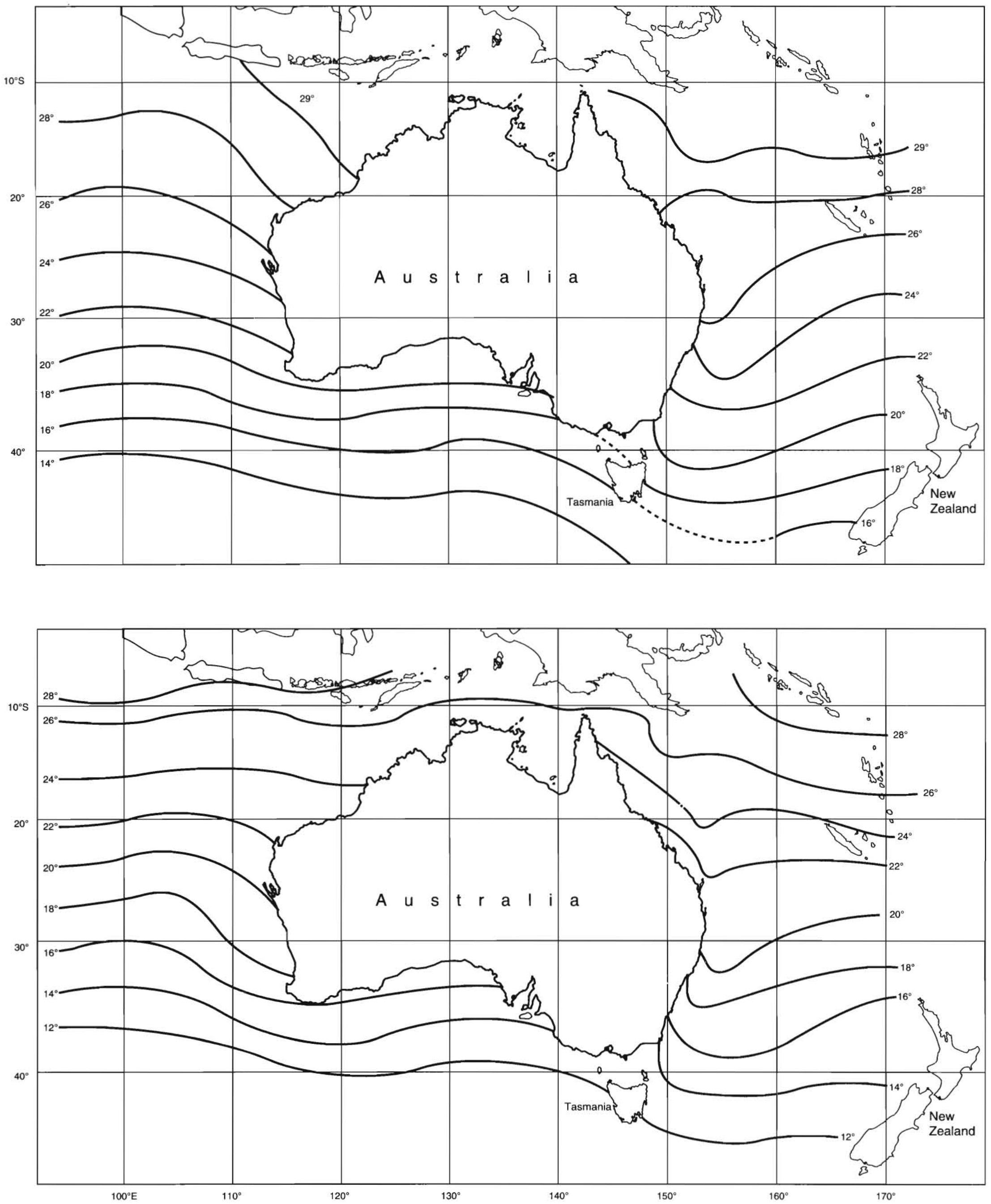

Figure 6

Austral summer (February; top) and winter (August; bottom) mean sea-surface temperature isotherms adjacent to Australia from Edwards (1979) for eastern Australia and Hydrographic Department (1992) for western and southern Australia.

Japanese and Joint Australia–Japan Longline Fisheries

Substantial Japanese longline activity occurs in eastern, southeastern, and western areas of the AFZ,[6] and sword-

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[6] Since the time this manuscript was accepted, Japanese fishing activity in the AFZ, as well as access to Australian ports, has been prohibited, because the bilateral access agreement lapsed on 31 October 1997 and was not renewed, and may not be unless Australia and Japan resolve their differences over management of southern bluefin tuna.

fish are regularly taken as an incidental catch (Fig. 5). Japanese longlining commenced in the region in the 1950's and was well established by 1960 (Ward, 1996). The vessels freeze their catch and land it in Japan for sale at sashimi markets.

The vessels operating in the AFZ may be separated into several loose groups, partly reflecting port of origin, target species, and company links. The fleets tend to adopt different campaign patterns, operating in different seasons and areas of the AFZ, as follows.

Large longliners (350 t or more) operate adjacent to and south of Tasmania during May–August and October–January. Southern bluefin tuna are the target and swordfish are a minor bycatch. At other times these longliners fish for southern bluefin as far westward as the southern Atlantic and, to a lesser extent since the mid-1980's, eastward to the waters around New Zealand. Vessels of this Southern Ocean fleet are generally the largest and most seaworthy of the Japanese distant-water longline fleet, remaining away from Japan for up to 18 mo, though calls at foreign ports are made every 2 or 3 mo.

Large longliners operate in the western AFZ during September to January, some augmenting more southern and more extensive southern bluefin tuna operations. Bigeye tuna and southern bluefin tuna are the main target of operations off the southwestern coast, whereas bigeye tuna; marlins, *Makaira* and *Tetrapturus* spp.; and yellowfin tuna are important in the northwest. Swordfish are an incidental catch in these operations.

Smaller longliners (180–350 t), mostly from the northern islands of Japan, fish a mixture of tunas and billfishes in equatorial and tropical waters. The vessels concentrate on the eastern AFZ, some incorporating activities in New Zealand, Hawaii, or both. They take yellowfin tuna and bigeye tuna in the Coral Sea, and these species plus southern bluefin tuna in the Tasman Sea. Billfishes (particularly swordfish and striped marlin, *Tetrapturus audax*, and albacore tuna, *Thunnus alalunga*, constitute a significant bycatch, but at times (especially in July–September and around periods of full moon) swordfish are the target of operations off southern Queensland and south of Lord Howe Island.

Prior to commencement of operation of the AFZ in 1979, Japanese longline vessels were generally free to operate within the area now encompassed by the zone, apart from waters within 12 nautical miles (n. mi.) of the coast (Caton and Ward, 1996a). With establishment of the AFZ they became subject to progressively more severe access restrictions (Caton and Ward, 1996b). Initially these restrictions closed waters north of 35°S across southern Australia and formalised voluntary seasonal closures off southern Australia which Japanese longliners had adopted in 1971 (Fig. 7). Subsequent restrictions had the most impact off the east coast, and were associated with expansion of Australian commercial and recreational fisheries. In the south they also addressed concern over the biological status of southern bluefin tuna, and off northeastern Australia they reflected a desire by gamefish anglers to protect spawning fish and to maintain good strike rates of large black marlin.

Currently, the far southeast of the zone (around Tasmania) is the only area where a 12-n.-mi. limit still applies. Elsewhere, the zone is either totally closed to access or is closed within 50 n. mi. of the coast (Fig. 8). Displacement of Japanese longliners from areas where southern bluefin tuna was the target species has increased activity levels in areas where yellowfin tuna and bigeye tuna were the targets. As most swordfish are taken in association with the latter species, there have been effects on the distribution and extent of swordfish catches.

Access arrangements permitted the annual licensing of 350 Japanese longliners between 1979 and 1983, 290 longliners between 1984 and 1989, and 250 longliners since then. However, these limits were well above the actual fleet numbers in the AFZ and did not act as a restraint on fishing effort; during the 1980's the number of Japanese longliners actually undertaking licensed fishing operations in the AFZ ranged between 109 and 184. Since late 1990, more restrictive limits on vessel numbers have controlled the distribution of fishing effort within the AFZ. In 1995, for example, 20 longliners could be licensed for the Australian west coast and 55 longliners during each 4-mo period for the east coast north of 34°S. Off Tasmania, a limit on the southern bluefin tuna catch was a substitute for vessel limits.

From 1989 to 1995, up to 50 Japanese longliners operated in the AFZ under joint-venture arrangements with Australian companies, mainly in the fishery for southern bluefin tuna. Their style of operation was essentially identical to that of Japanese longliners licensed under the Australia–Japan bilateral access arrangements. However, they had the advantage of access to the AFZ across southern Australia. The joint-venture arrangement was terminated in late 1995, with no plans at that time for resumption.

Domestic Longline Fishery

Experimental, small-vessel longlining was carried out irregularly off the Australian east coast in the 1950's, 1960's, and 1970's. A viable commercial fishery was not established until the mid-1980's, after fishers operating off the New South Wales central and southern coasts successfully air-freighted high-quality, fresh-chilled yellowfin tuna to the Japanese sashimi market. By the late 1980's, more than 1,000 t of yellowfin were landed

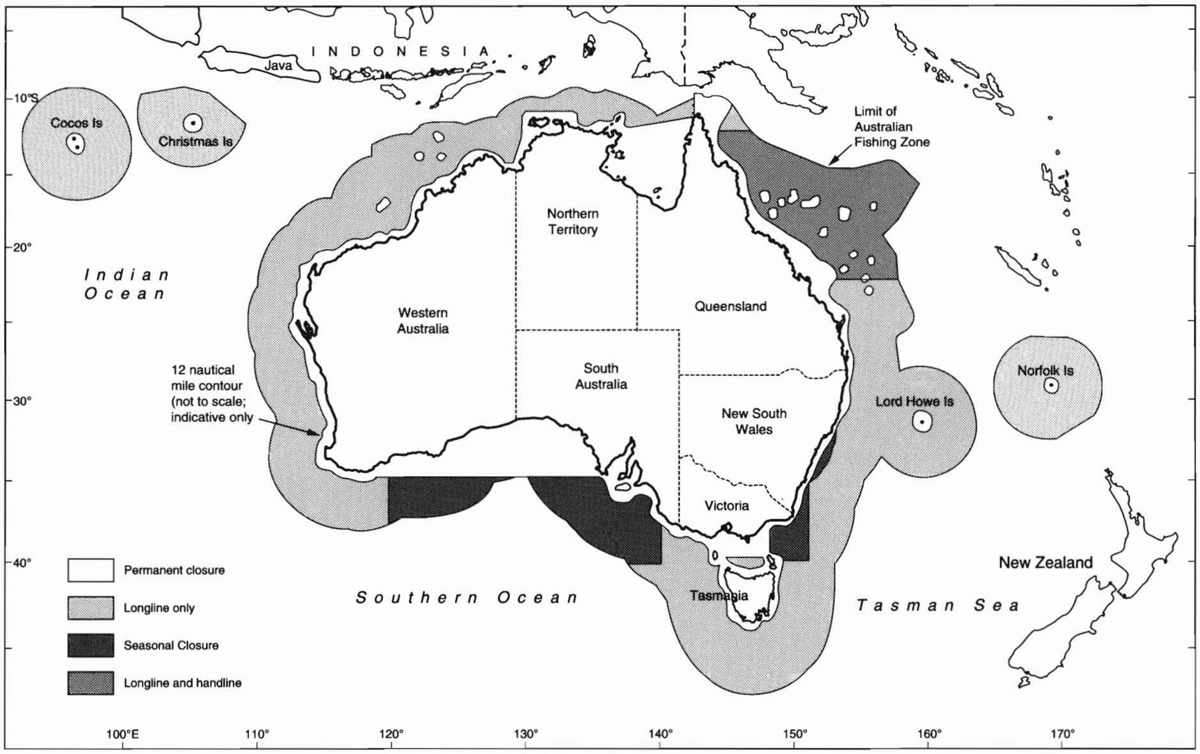

Figure 7

Areal and seasonal access restraints applying to Japanese tuna longline vessels in the Australian Fishing Zone, 1979–80 (from Caton and Ward, 1996b).

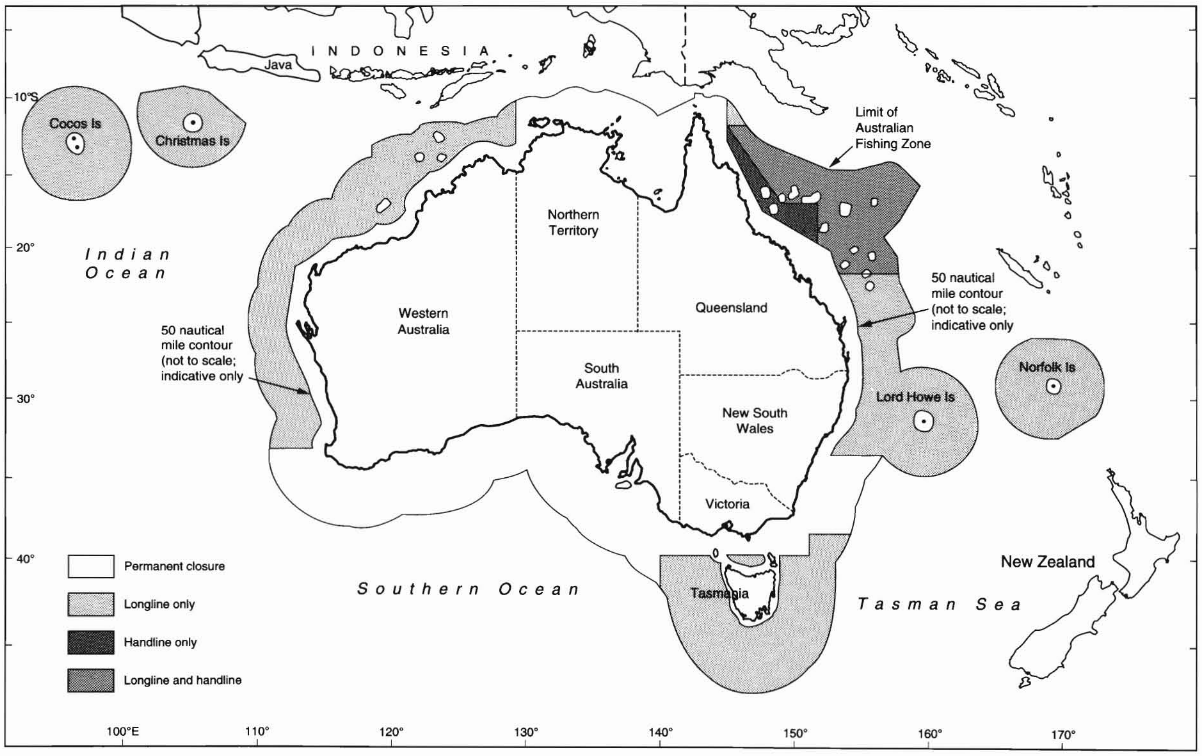

Figure 8

Gear and operational area restraints applying to Japanese tuna longline vessels in the Australian Fishing Zone, 1993–1994 (from Caton and Ward, 1996b).

annually, with over 130 full-time participants endorsed for longlining and a further 120 longlining on a part-time basis. Many vessels have since left the fishery or are not fishing because of variable yellowfin catch rates, high freight charges, and unpredictable prices at sashimi markets for the smaller fish. Catch has decreased to around 550 t.

The domestic east coast longline fishery is managed by zone (Fig. 9), and the number and size of vessels is endorsed for each zone. Specific arrangements are quite complex; essentially, separate zones are established inshore and offshore of 50 n. mi. from the coast. Within 50 n. mi. (12 n. mi. adjacent to eastern Tasmania), vessel size is not to exceed 32.67 m overall length. Off northeastern Australia, the inshore region is encompassed by the Great Barrier Reef Marine Park, and longlining is virtually impractical there. To the north and outside the Park there is an intermediate area where sets are restricted to 500 hooks and all billfish must be returned. Vessels have various rights of access to zones, depending upon their history in the fishery, vessel size, and target species.

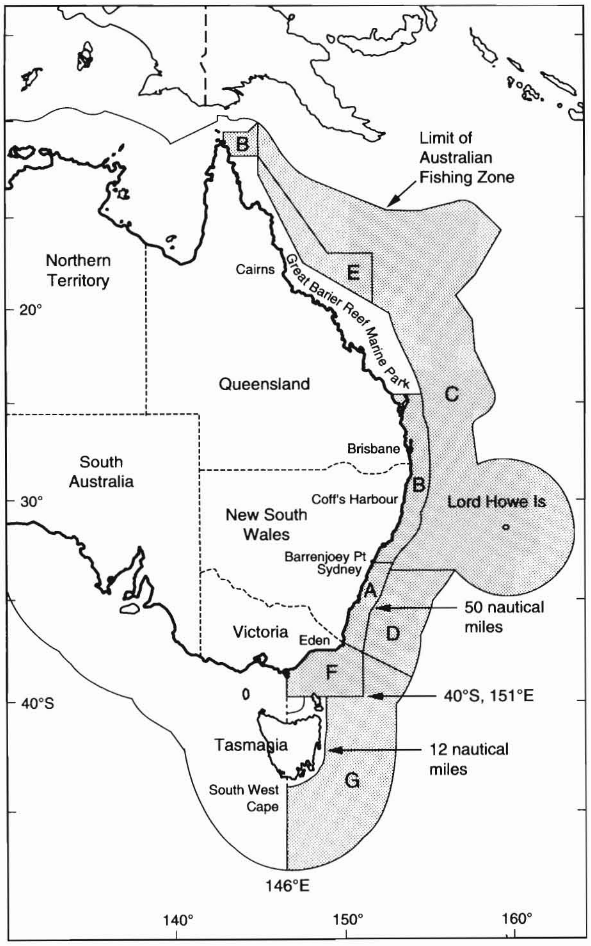

Figure 9

Management zones for domestic east coast tuna longliners (from Australian Fisheries Management Authority).

Many local longliners fish part-time in trawl, trap, and dropline fisheries. While 170 domestic longline endorsements have been issued for the fishery, only 30–40 vessels longline regularly (East Coast Tuna and Billfish Assessment Group[4]). Half of their yellowfin catch now supplies a growing local sashimi trade. A diversification to winter longlining for southern bluefin tuna off southern New South Wales is renewing interest in the fishery. The southern bluefin tuna catch is restrained by a system of individual transferable quotas; operations are subject to the purchase or lease of quota. There is no catch limit for any of the other longline species.

Yellowfin, southern bluefin, and bigeye tunas are the target species for the domestic fishery.[4] Yellowfin comprise about 60% and southern bluefin tuna about 30% of the reported retained catch of Australian longliners, but very high prices for individual large southern bluefin and bigeye tuna influence profitability. Swordfish constitutes a minor component of the catch (Table 1). Its lower value compared with the tunas makes air-freighting to Japan unprofitable at times. Instead, small quantities are sold fresh on the Sydney and Melbourne fish markets.

Despite a change during 1995 in national mercury content standards, swordfish mercury content still imposes a significant obstacle to marketing. The current Australian Food Standards Code Standard A12 (National Food Authority, 1992 and updates) for mercury in fish covers, among other things, swordfish. If the fish can be sampled in groups of five, whether whole fish or fillets, then the mean mercury content for five samples may not exceed 1.0 ppm.[7] Within that group of five, no individual sample may exceed 1.5 ppm. If the fish are unable to be sampled as a group, then the mercury content of an individual fish may not exceed 1.0 ppm. While this is the national recommended standard, its adoption or application by states is variable.

Australian longliners fish mostly outside the 200-m depth contour within 60 n. mi. of the New South Wales coast, but activity has expanded recently off northern Queensland in the vicinity of Cairns. The yellowfin season commences off southern Queensland and northern New South Wales in August and spreads to the south as the East Australian Current pushes warm (18°–22°C) water southward. By April most of the yellowfin catches come from the far south coast of New South Wales. Southern bluefin tuna catches commence in May to the south of New South Wales and continue to September, when operations are centered off Sydney.

Domestic longline vessels are smaller (10–20 m) than those operated by the Japanese in the AFZ. The domes-

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[7] The limit was 0.5 ppm prior to 1995.

Table 1

Annual (July–June) swordfish catch (metric tons) by the Australian domestic longline fishery, 1988–89 to 1992–93 (from Australian Fishing Zone Information System logbook data).

Year	Catch (t)	Year	Catch (t)
1988–89	12.6	1991–92	31.5
1989–90	10.9	1992–93	29.0
1990–91	34.1		

tic vessels usually set between 400 and 800 hooks before sunrise each day, store their catch in ice slurry, and generally return to port after one or two days fishing. Australian tuna catch rates are often higher than Japanese longliners because inshore productivity is higher, fresh bait is used, and the shorter longlines target oceanic frontal regions or topographic features where tuna appear to aggregate. Components of the fleet operate in the region of Lord Howe Island, as far south as southeastern Tasmania, and in the region adjacent to Cairns off northern Australia, but most activity is concentrated between southern Queensland and southern New South Wales.

A logbook program, established in 1985 but not fully supported by field liaison until 1988, now covers most of the longline fleet. In the case of swordfish, logged catches (Table 1) probably under-represent catch because mercury content restrictions prevent marketing of larger fish. In such cases, the fish might not be landed nor recorded in logbooks.

Recreational Fishery

Recreational fishers take a wide range of pelagic species along the east coast at various locations from Cairns (north Queensland) to Eaglehawk Neck (80 km east of Hobart, Tasmania) and near Lord Howe Island. The main concentrations of activity in the east are off central and southern New South Wales, Brisbane (Queensland), and Cairns. Low levels of recreational fishing activity for pelagic fishes are also reported from Western Australia and, to a lesser extent, South Australia and Northern Territory.

Swordfish have provided an intriguing challenge for anglers because, despite enthusiastic efforts, few are caught. In his authoritative overview of Australian fisheries, Theo Roughley, who was Superintendent of New South Wales Fisheries from 1939 to 1952 and President of the Great Barrier Reef Game Fish Angling Club in 1937, stated, "No broadbill swordfish has yet been landed by an angler in Australian waters, and fame awaits the angler who first succeeds in catching this elusive fish. It is known to occur here for it has been washed ashore in several Australian states, including New South Wales, Queensland, South Australia and Western Australia" (Roughley, 1951, p. 265). Apart from years like 1994, when small juveniles penetrate relatively close inshore and are taken occasionally during trolling, it was not until 1989 that a 56-kg swordfish was landed that qualified for record status under international game fishing regulations (Kailola et al., 1993). Since then, others have been taken as a result of targeted fishing with Cyalume "light sticks" at night. The largest taken to date on rod and reel was 98 kg in April 1990 (Pepperell[2]). There is now an annual swordfish tournament run from Merimbula (450 km south of Sydney) in southern New South Wales each Easter. Even so the number taken remains very low, and the size of fish is less than 50 kg (Goadby[1] and Pepperell[2]).

Fishing Statistics in the Japanese Longline Fishery

The following is based on data gathered from Japanese longline vessel logbooks since commencement of operation of the Australian Fishing Zone in 1979. A substantial global time series of data aggregated by 5° × 5° squares by month for the previous twenty years exists in Japanese annual "yellow book" longline records (Fishery Agency of Japan, 1962–1980), but those data are not addressed here.

Effort

Since commencement of operation of the AFZ and maintenance of a national logbook program late in 1979, the annual level of Japanese longline activity in and adjacent to the zone[8] has fluctuated between 16.5 million (1991) and 31.6 million (1989) hooks, with a slight decline overall (Fig. 10). Longlines deploying 2,500–3,500 hooks are set and retrieved in a 24-hr period. Total days fished each year has declined (Fig. 11). To some extent the decline has been counteracted by an increase in the number of hooks set per day per vessel (Table 2; Fig. 11).

Catches

Seasonal distributions of Japanese longline (bilateral and joint-venture) swordfish catches, aggregated for

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[8] The logbooks of Japanese longliners working in the vicinity of the AFZ boundary and moving back and forth into and out of the zone include details of operations both within and outside the AFZ.

Table 2

Annual effort, operational days, and average hooks set per day by Japanese and Australia–Japan joint-venture longliners in and adjacent to the Australian Fishing Zone, 1980–93. (Source: Australian Fishing Zone Information System logbook data; the logbooks of Japanese longliners working in the vicinity of the AFZ boundary and moving back and forth into and out of the zone include details of operations both within and outside the AFZ.)

Year	Effort (10^6 hooks)	Vessel days	Hooks per vessel day	Year	Effort (10^6 hooks)	Vessel days	Hooks per vessel day
1980	18.15	7,262	2,499	1987	23.36	8,245	2,833
1981	31.29	12,714	2,461	1988	25.76	8,982	2,868
1982	23.89	9,357	2,553	1989	31.56	10,822	2,916
1983	24.11	9,107	2,647	1990	27.15	9,399	2,889
1984	21.18	7,966	2,659	1991	16.46	5,616	2,931
1985	20.06	7,232	2,774	1992	20.05	6,679	3,002
1986	19.99	7,155	2,794	1993	23.93	7,901	3,029

1979–1993, are indicated in Figure 5. The central area of the eastern AFZ has consistently been the main area of swordfish catch. Current operations are subject to the permanent closure of the area inshore of 50 n. mi. from the coast. Japanese longliner access to eastern seamounts has not changed, but the productive area close to the east coast around 27°S is no longer accessible. Recent (1990–93) distributions of effort and catch are shown in Figure 12. There is some annual variation in location of activities (compare the 1993 effort distribution pattern with those for 1990–92), probably associated with changes in activity patterns of target species. The lower swordfish catches in 1993 around 25°S coincide with lower effort levels there in that year.

Most changes in operational areas by Japanese longliners in recent years have been associated with operations directed at southern bluefin tuna. The establishment of Australia–Japan joint ventures re-opened access to a wider area south of 34°S (compare 1990–91 with 1992–93), and effort increased off southern and southwestern Australia. There has been a resumption of incidental swordfish catches there, but the central southern region and southwestern Tasmanian regions still show very low catch levels despite substantial effort southwest of Tasmania.

Annual (calendar year) Japanese longline (bilateral and joint-venture) catches by species in and adjacent to the AFZ since 1980 are provided in Table 3 for the main species taken, with breakdowns for the northeastern, southeastern, and western regions. Annual effort level and catch in number of swordfish and yellowfin, southern

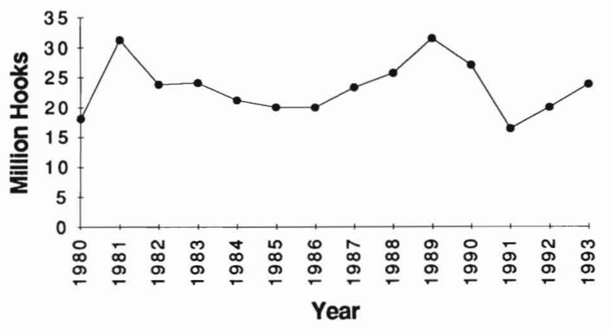

Figure 10

Annual nominal effort (million hooks set) by Japanese tuna longliners in and adjacent to the Australian Fishing Zone, 1980–93.

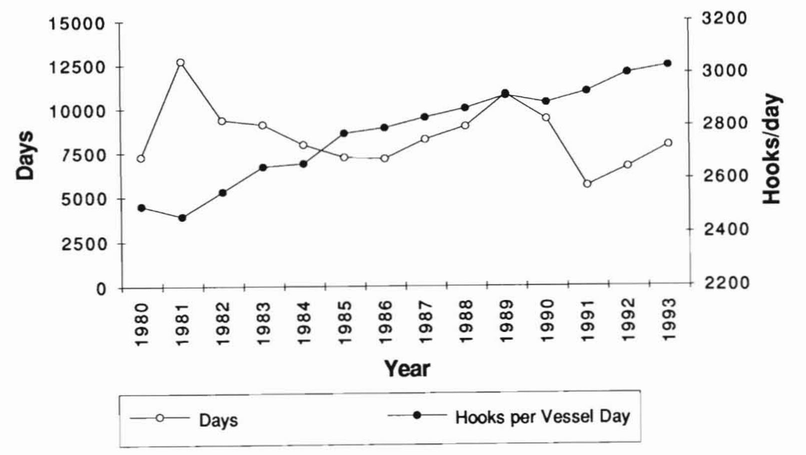

Figure 11

Annual operational days and average hooks per set by Japanese tuna longliners in and adjacent to the Australian Fishing Zone, 1980–93.

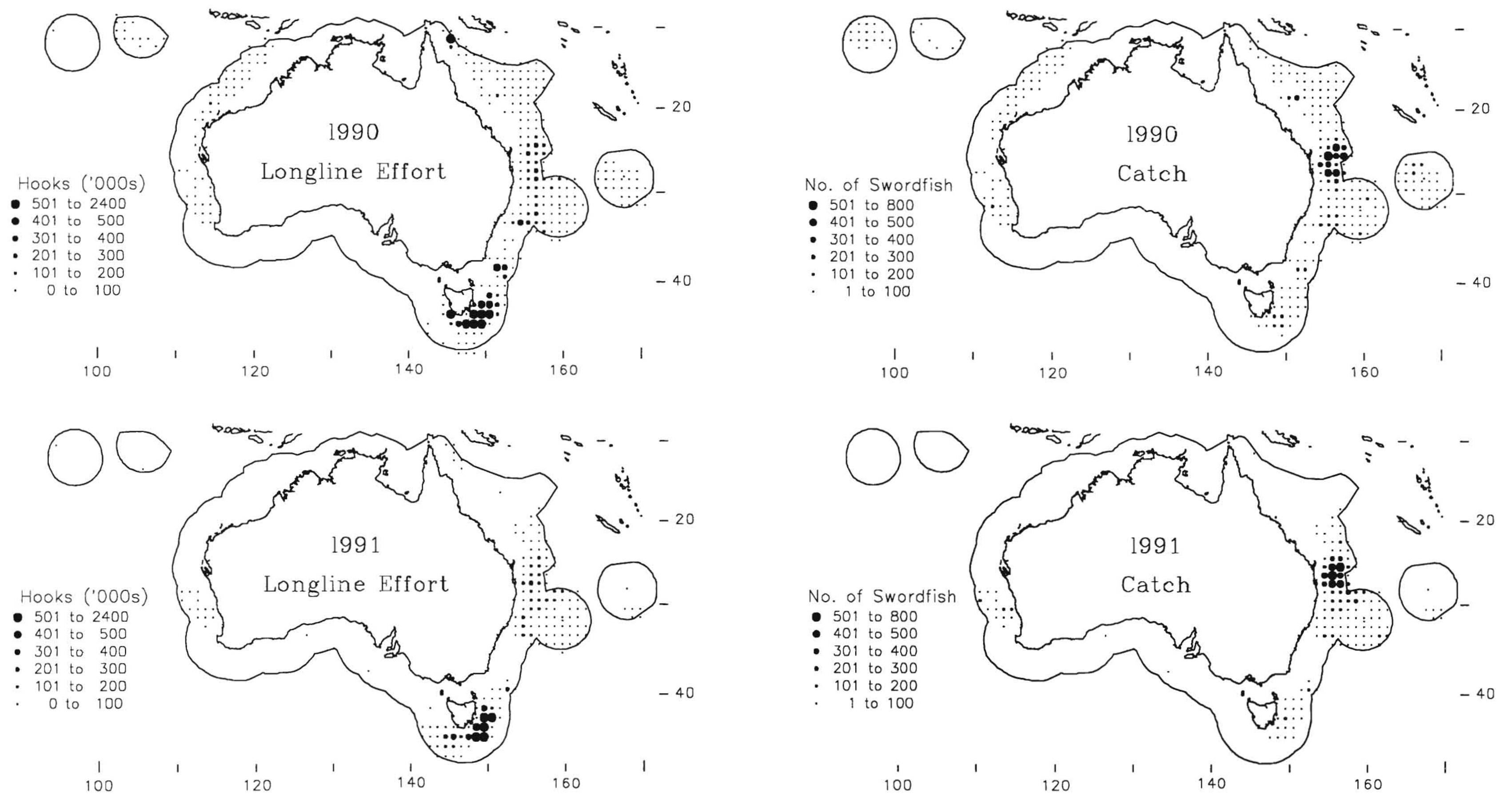

Figure 12

Annual distribution of total fishing effort (hooks set) and swordfish catch (number of fish) by Japanese and Australia–Japan joint-venture tuna longliners in the Australian Fishing Zone, 1990–93 (from Australian Fishing Zone Information System logbook data).

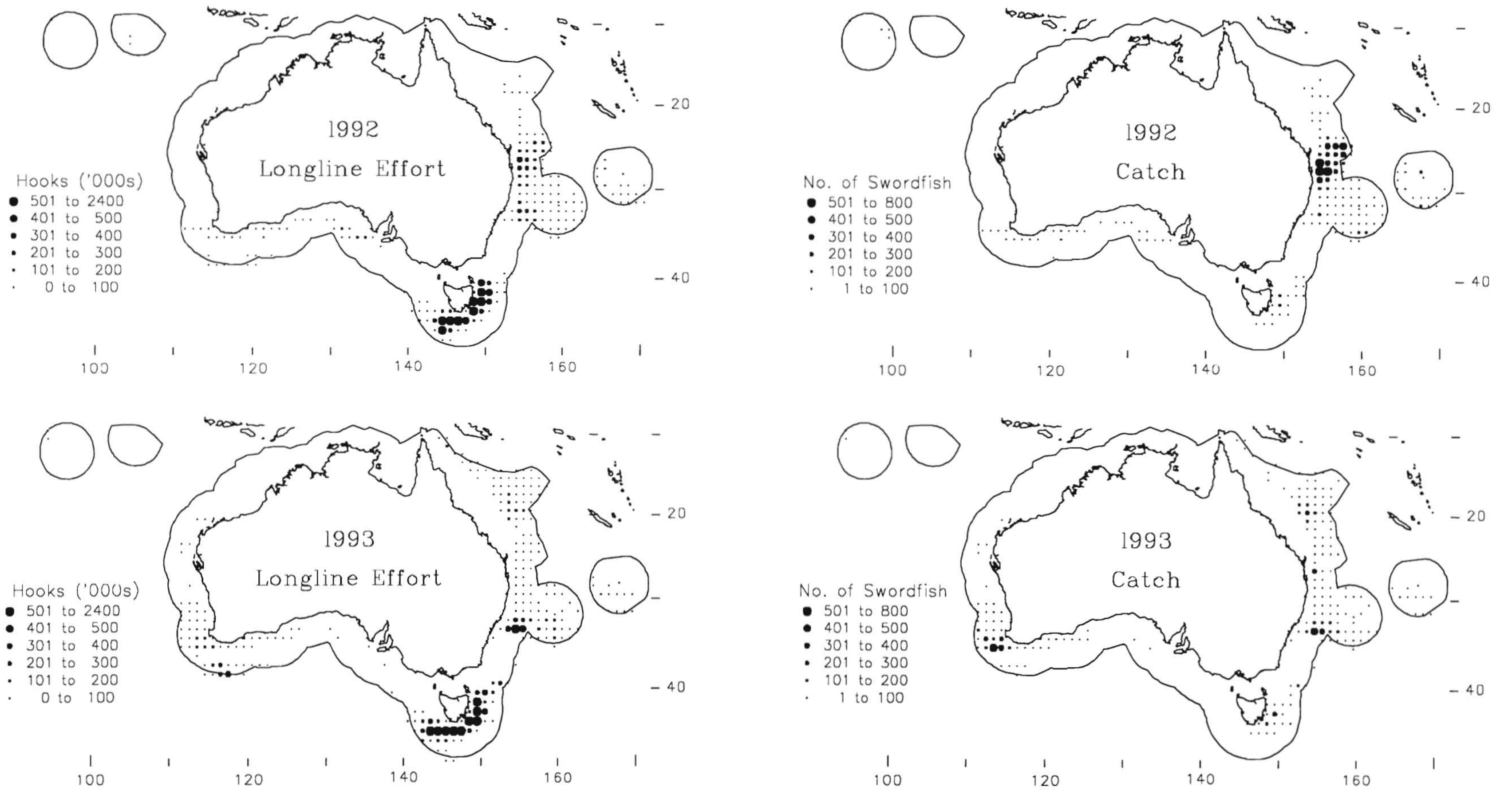

Figure 12 (continued)

bluefin, and bigeye tuna for these areas are shown in Figure 13. It can be seen that the principal tuna species in the northeast is yellowfin (albacore are abundant but are not a primary target) and in the southeast, southern bluefin tuna. In contrast, the western region supports a mixed fishery in which bigeye has been an important component of the catch, with yellowfin and southern bluefin tuna also important at times. Swordfish is reasonably represented in the northeastern and, to a lesser extent, western regions but is insignificant in the southeast.

Changes in the management of southern bluefin tuna in the AFZ and globally caused modification of

Table 3

Annual Japanese and Australia–Japan joint-venture longline effort (million hooks) and catches (number of fish) by species, in and adjacent to the northeastern, southeastern, western, and entire Australian Fishing Zone, 1980–93. (Source: Australian Fishing Zone Information System logbook data; the logbooks of Japanese longliners working in the vicinity of the AFZ boundary and moving back and forth into, and out of, the zone include details of operations both within and outside the AFZ).

Region	Year	Hooks (× 10^6)	Swordfish	Yellowfin	Southern bluefin	Bigeye	Albacore	Striped marlin	Sharks	Blue marlin	Black marlin	Sailfish
Northeast (N of 35°S; E of 140°E)	1980	3.82	6,532	21,706	8,190	7,672	10,744	4,237	2,351	587	1,085	621
	1981	11.19	12,991	78,678	10,221	11,021	60,174	13,201	11,988	2,192	1,811	1,075
	1982	13.12	21,880	64,015	400	14,706	74,999	19,577	12,796	5,243	4,197	1,922
	1983	8.33	10,984	65,807	555	18,869	97,750	5,522	6,939	2,089	2,032	1,279
	1984	8.06	11,803	25,965	937	11,744	74,793	7,017	6,217	1,095	1,879	931
	1985	9.31	15,281	80,712	136	19,038	113,603	6,434	5,652	1,467	1,148	1,047
	1986	7.21	13,428	32,958	172	17,081	101,572	3,640	4,659	741	287	438
	1987	8.83	15,097	73,995	257	15,809	103,891	4,321	6,985	1,630	1,995	2,323
	1988	15.68	24,493	126,061	540	21,915	170,631	7,548	10,277	6,102	2,240	2,378
	1989	15.68	16,556	87,576	1,439	21,330	170,025	12,354	9,150	4,956	1,044	2,403
	1990	12.27	11,932	93,007	1,680	24,196	151,418	5,902	5,777	4,046	519	4,182
	1991	6.24	11,120	32,875	1,088	9,783	86,717	3,202	6,399	344	259	692
	1992	6.69	11,876	36,073	1,435	9,490	100,489	2,646	716	401	182	737
	1993	7.89	6,939	64,776	12,322	7,439	162,178	3,812	774	653	361	2,228
Southeast (S of 35°S; E of 140°E)	1980	10.22	684	93	45,897	307	8,341	75	8,616	2	2	0
	1981	12.31	1,949	733	61,128	663	30,362	567	9,412	8	6	2
	1982	5.54	1,517	416	30,408	1,200	30,293	382	9,668	36	9	3
	1983	9.32	1,261	301	38,157	1,222	42,932	823	7,119	23	24	1
	1984	3.88	1,211	361	17,257	743	16,685	504	2,653	11	4	7
	1985	3.45	1,467	581	6,337	881	13,707	383	1,374	13	20	5
	1986	3.01	694	662	7,958	1,020	15,402	189	5,490	10	4	0
	1987	6.71	975	831	15,651	852	16,430	129	4,952	11	2	9
	1988	8.44	1,222	1,788	19,188	1,262	17,513	380	2,367	32	9	9
	1989	14.2	5,287	5,620	54,615	3,831	134,542	978	8,881	39	16	14
	1990	12.94	2,222	802	51,777	1,087	62,247	138	4,717	0	2	2
	1991	9.47	1,756	2,187	55,575	1,465	33,452	221	38,688	7	1	4
	1992	12.02	2,912	607	67,253	1,167	28,403	155	122	4	3	0
	1993	12.68	2,884	751	83,457	811	32,138	355	576	16	17	1
Western (W of 140°E)	1980	4.1	1,153	3,796	20,575	11,110	5,372	684	430	215	295	7
	1981	7.79	1,834	17,138	38,414	17,849	21,374	1,296	2,823	630	550	115
	1982	5.23	742	10,270	11,203	8,404	3,639	729	692	428	666	43
	1983	6.45	1,179	12,591	11,368	23,460	10,639	1,545	2,628	388	704	92
	1984	9.24	1,922	31,460	18,567	22,488	10,379	6,540	1,648	1,485	2,750	294
	1985	7.31	2,460	23,652	8,028	18,445	13,317	3,672	2,085	1,298	2,515	166
	1986	9.76	1,922	26,818	9,708	26,268	12,055	1,167	559	1,446	1,405	220
	1987	7.82	2,166	16,480	4,884	33,355	11,851	1,108	1,029	458	878	231
	1988	1.64	446	8,626	911	4,129	2,795	266	246	394	634	176
	1989	1.68	433	7,165	1,222	3,109	1,560	118	391	297	441	192
	1990	1.94	901	11,554	514	7,967	3,952	109	2,006	426	320	29
	1991	0.74	731	449	1,305	2,151	255	0	224	3	4	3
	1992	1.34	423	457	25,400	4,869	2,274	3	18	12	7	8
	1993	3.36	2,593	1,738	11,118	12,364	4,275	40	36	11	24	36

continued

Table 3 (continued)

Region	Year	Hooks (× 10^6)	Swordfish	Yellowfin	Southern bluefin	Bigeye	Albacore	Striped marlin	Sharks	Blue marlin	Black marlin	Sailfish
Total AFZ	1980	18.15	8,369	25,595	74,662	19,089	24,457	4,996	11,397	804	1,382	628
	1981	31.29	16,774	96,549	109,763	29,533	111,910	15,064	24,223	2,830	2,367	1,192
	1982	23.89	24,139	74,701	42,011	24,310	108,931	20,688	23,156	5,707	4,872	1,968
	1983	24.11	13,424	78,699	50,080	43,551	151,321	7,890	16,686	2,500	2,760	1,372
	1984	21.18	14,936	57,786	36,761	34,975	101,857	14,061	10,518	2,591	4,633	1,232
	1985	20.06	19,208	104,945	14,501	38,364	140,627	10,489	9,111	2,778	3,683	1,218
	1986	19.99	16,044	60,438	17,838	44,369	129,029	4,996	10,708	2,197	1,696	658
	1987	23.36	18,238	91,306	20,792	50,016	132,172	5,558	12,966	2,099	2,875	2,563
	1988	25.76	26,161	136,475	20,639	27,306	190,939	8,194	12,890	6,528	2,883	2,563
	1989	31.56	22,276	100,361	57,276	28,270	306,127	13,450	18,422	5,292	1,501	2,609
	1990	27.15	15,055	105,363	53,971	33,250	217,617	6,149	12,500	4,472	841	4,213
	1991	16.45	13,607	35,511	57,968	13,399	120,424	3,423	45,311	354	264	699
	1992	20.05	15,211	37,137	94,088	15,526	131,166	2,804	856	417	192	745
	1993	23.93	12,416	67,265	106,897	20,614	198,591	4,207	1,386	680	402	2,265

Japanese longline campaign strategies in the AFZ. Reduced access to southern bluefin tuna areas off New South Wales and South Australia brought about a reduction of effort in the southeast until the mid-1980's. Subsequent relocation of activities to the southeastern Tasmanian area led to increased effort there. Levels of effort off Tasmania remained high through the early 1990's as a result of the establishment of joint-venture activities. The incidental swordfish catch has varied in conjunction with these changes in the distribution and extent of fishing effort directed at southern bluefin tuna.

In the northeastern area, restrictions on marlin fishing and on inshore access forced operations farther offshore. In addition, these offshore areas had to support some of the displaced southern bluefin tuna operations. As a result, effort levels in the region remained moderately steady through the mid-1980's while southeastern effort decreased. After 1989, more restrictive controls on effort in the northeastern area and the improving southern bluefin tuna access resulted in reduced activity in the northeast.

The major drop in effort off western Australia between 1988 and 1992 was in part linked to extension of the permanent closure area to include all waters within 50 n. mi. of the coast. However, it was also associated with declining global catch rates for southern bluefin tuna, effort restraints in the adjacent high seas area resulting from the seasonal closures introduced by Japan to implement its major cut in quota for 1989–90, and a concentration of southern bluefin tuna effort off eastern Tasmania (where viable catch rates persisted). Increased western region effort in 1993 resulted from the less-restrained operational conditions applying to the joint-venture fleet. The incidental swordfish catch changed in conjunction with those changes in distribution and level of fishing effort.

Catch Rates

Annual November–April (austral summer) and May–October (austral winter) nominal fishing effort, swordfish catches in number, and number of swordfish caught per thousand hooks from 1980 to 1993, based on Japanese longline daily logbook data, are provided in Table 4. Plots of summer and winter effort, catches, and catch rate for the northeastern (north of 20°S), central eastern (20°–35°S), and southeastern (south of 35°S) AFZ are shown in Figure 14. In the main swordfish region and season (central eastern AFZ in austral winter), catch rate was reasonably stable from 1980 to 1988, but overall has declined slightly. The low 1993 catch rate emphasizes this trend, but the pattern of effort distribution in that year (Fig. 12) was different from that in 1990–92, as mentioned previously. It is possible that decreased swordfish catch rates reflect the changes in access conditions and resultant patterns of targeting rather than changes in local abundance. Further examination is warranted.

The graphs showing longline effort, catch, and catch rate in the northeastern and southeastern areas and in summer in the central eastern area (Fig. 14) depict activity where swordfish is a relatively minor component of the catch. In the northeast, summer catch rates declined during 1980–93, whereas winter rates were variable. In the southeast, summer catches and catch rates were negligible; winter catch rates are low and have declined since effort increased in the mid-1980's. This probably reflects increased southern bluefin tuna

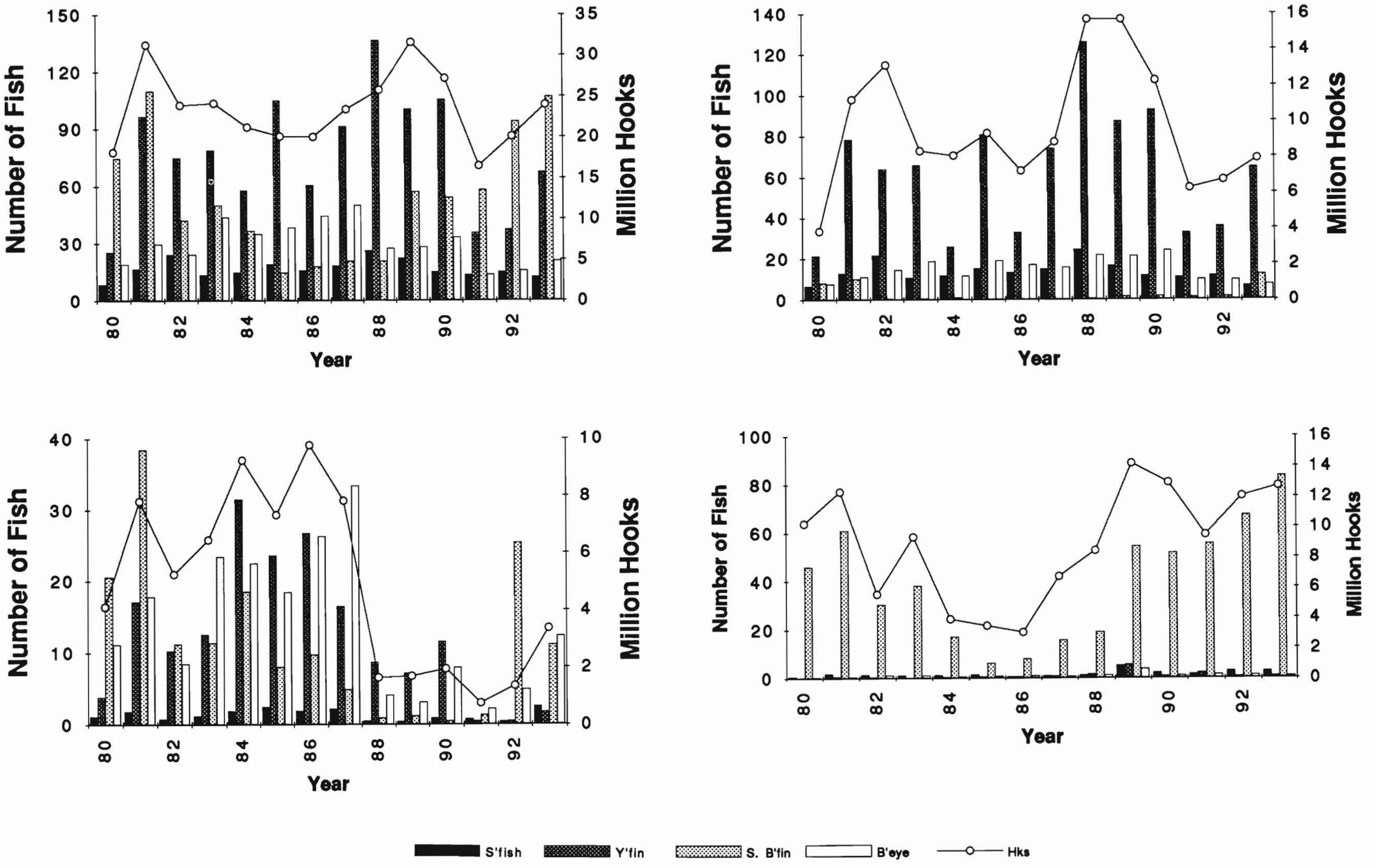

Figure 13

Annual Japanese and Australia–Japan joint-venture longline effort and catches of swordfish and southern bluefin, yellowfin, and bigeye tunas in and adjacent to (clockwise from top right) the northeastern, southeastern, western, and entire Australian Fishing Zone, 1980–93. S'fish = swordfish; Y'fin = yellowfin tuna; S. B'fin = southern bluefin tuna; B'eye = bigeye tuna; Hks = hooks. (Source: Australian Fishing Zone Information System logbook data; the logbooks of Japanese longliners working in the vicinity of the AFZ boundary and moving back and forth into and out of the zone, include details of operations both within and outside the AFZ.)

Table 4

Annual Japanese and joint-venture Australia–Japan longline November–April (summer) and May–October (winter) swordfish catches (number of fish), longline effort (million hooks), and catch rate (number of fish per 1,000 hooks) in and adjacent to the northeastern, central eastern, and southeastern Australian Fishing Zone, 1980–93. Summers are taken as commencing in the prior year, so that, for example, summer 1980 was November 1979–April 1980. Because these data span 12 months from November to October, totals are not equivalent to those in Table 3 which is based on data for calendar years. (Source: Australian Fishing Zone Information System logbook data; the logbooks of Japanese longliners working in the vicinity of the AFZ boundary and moving back and forth into, and out of, the zone include details of operations both within and outside the AFZ.)

		Summer			Winter		
Region	Year	No.	Million hooks	No./1,000 hks	No.	Million hooks	No./1,000 hks
Area A	1980	115	0.437	0.26	73	0.209	0.35
(N of 20°S)	1981	94	0.234	0.40	257	0.297	0.87
	1982	632	1.844	0.34	575	0.763	0.75
	1983	412	1.152	0.36	167	0.521	0.32
	1984	141	0.568	0.25	1,048	0.701	1.49
	1985	523	0.669	0.78	752	0.843	0.89
	1986	100	0.538	0.19	12	0.033	0.37
	1987	57	0.277	0.21	330	0.175	1.89
	1988	678	1.883	0.36	582	0.741	0.79
	1989	728	1.768	0.41	637	1.005	0.63
	1990	287	2.310	0.12	573	0.607	0.94
	1991	1	0.044	0.02	9	0.006	1.48
	1992	10	0.034	0.30	7	0.030	0.23
	1993	58	0.396	0.15	1,041	1.616	0.64
Area B	1980	1,219	1.143	1.07	4,258	2.209	1.93
(20°–35°S)	1981	3,944	2.141	1.84	8,053	7.431	1.08
	1982	3,985	3.724	1.07	14,908	7.414	2.01
	1983	5,313	2.365	2.25	9,189	5.152	1.78
	1984	454	0.787	0.58	9,903	6.261	1.58
	1985	315	0.681	0.46	13,936	7.090	1.97
	1986	492	0.800	0.61	13,045	6.258	2.08
	1987	200	0.345	0.58	13,882	7.380	1.88
	1988	948	1.474	0.64	22,395	11.600	1.94
	1989	1,595	1.577	1.01	14,079	11.800	1.19
	1990	422	0.802	0.53	10,685	8.758	1.22
	1991	254	0.414	0.61	10,866	5.790	1.88
	1992	721	0.554	1.30	11,163	6.124	1.82
	1993	896	1.154	0.78	4,940	4.721	1.05
Area C	1980	12	5.314	0.00	674	1.070	0.63
(S of 35°S)	1981	85	11.500	0.01	1,864	4.357	0.43
	1982	31	5.018	0.01	1,486	3.501	0.42
	1983	172	2.743	0.06	1,089	3.471	0.31
	1984	38	5.602	0.01	1,173	3.227	0.36
	1985	29	0.149	0.20	1,438	0.806	1.78
	1986	7	2.687	0.00	687	2.784	0.25
	1987	3	0.269	0.01	972	5.317	0.18
	1988	35	1.698	0.02	1,187	4.709	0.25
	1989	73	4.268	0.02	5,214	13.200	0.40
	1990	336	3.766	0.09	1,886	9.178	0.21
	1991	10	0.022	0.45	1,746	8.596	0.20
	1992	9	0.932	0.01	2,903	8.271	0.35
	1993	374	4.329	0.09	2,510	8.267	0.30

effort at the extreme of the swordfish range, rather than a trend in swordfish abundance there.

It should be emphasized again that the catch rate data outlined above are derived from nominal effort. Observers aboard foreign longliners point out that various factors can influence swordfish catch rate, in particular moon phase, time of setting and hauling, and bait. Some fishing masters target swordfish off the central east coast at periods of full moon. This will depend on location of operations, anticipated catch rate, current price, and success of other components of the vessel's campaign.

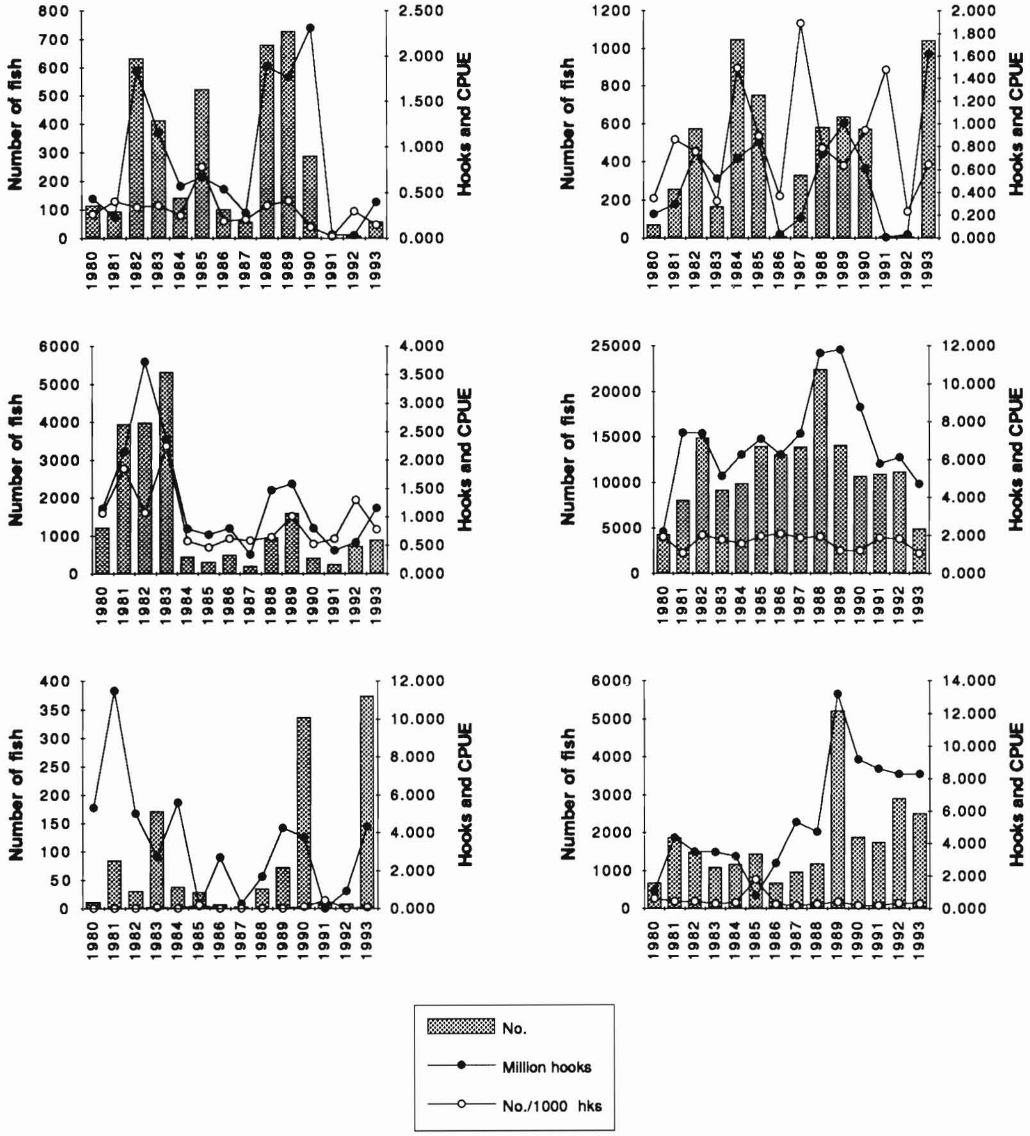

Figure 14

Annual November–April (left) and May–October (right) Japanese and Australia–Japan joint-venture longline effort (million hooks), swordfish catches (number of fish), and catch rate (number of fish per 1,000 hooks) in and adjacent to the northeastern (top), central eastern (middle), and southeastern (bottom) Australian Fishing Zone, 1980–93. (Source: Australian Fishing Zone Information System logbook data; the logbooks of Japanese longliners working in the vicinity of the AFZ boundary and moving back and forth into and out of the zone include details of operations both within and outside the AFZ.)

Size Composition

Average weights of swordfish (processed weight of gross catch/number of fish in gross catch) calculated from Japanese longline logbook data for 1984–90 combined show a trend of increasing size with increasing latitude (Fig. 15). However, length frequency distributions compiled from data gathered by Australian observers on the Japanese vessels (Fig. 16) do not show a clear trend of increase in modal length with latitude. The observed occurrence of swordfish >200 cm orbit-to-fork length[9]

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[9] Length from the eye to the caudal fork, using the posterior of the boney surround of the eye as the forward reference point.

(OFL), i.e. >320 cm bill-to-fork length,[10] is consistent with an increase in average weight with latitude. Fish larger than 250 cm OFL (370 cm bill-to-fork length) only occurred south of latitude 30°S.

The observer data relate to many fewer fish than those represented in logbook data, and they are from a much-reduced time period. For each swordfish observed, observers are requested to measure upper-jaw (bill) -to-fork length, lower-jaw-to-fork length (LJFL), orbit-to-fork length, and, more recently, cleithrum-to-fork length. Not all measurements were available for each fish. One of the authors (M. Scott), who is an observer, suggests that swordfish length measurements may have been less frequently taken in northern waters (north of 20°S) because the larger numbers of tunas and other billfish requiring attention reduced the time available to sample swordfish. This may have biased the data toward larger fish if, as the logbook data suggest, small fish are more abundant in lower latitudes.

The relationship between orbit-to-fork length and lower-jaw-to-fork length, derived from 1,408 pairs of observer measurements of swordfish between 70 cm and 300 cm LJFL, was

$$\mathrm{OFL} = 0.8971 \times \mathrm{LJFL} - 1.5944 \ (r^2 = 0.9383).$$

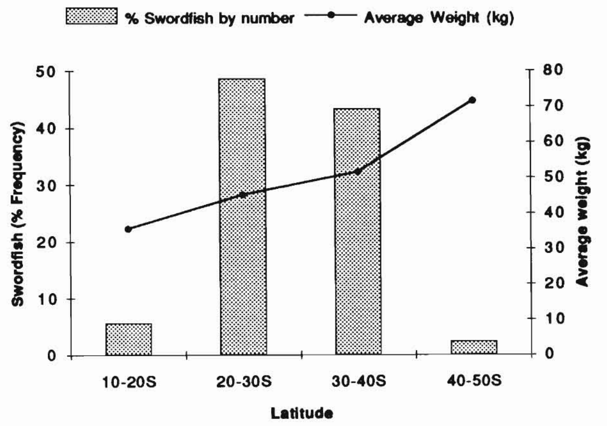

Figure 15

Latitudinal distribution of Japanese and Australia–Japan joint-venture swordfish catches (% frequency by 10-degree band, 1980–90 combined) and of average processed weight of swordfish in the eastern Australian Fishing Zone (from Australian Fishing Zone Information System logbooks).

Fishing Statistics in the Domestic Longline Fishery

Logbook data for the domestic fishery commenced in the mid-1980's and is incomplete for early years. Current coverage is more comprehensive, but swordfish catch is probably under-represented. Distribution of total effort and swordfish catches are shown for 1990–93 in Figure 17. The centers of activity are off southern and central New South Wales, off southern Australia west of Port Lincoln, southeast of Tasmania, and off northeastern Queensland. Reported swordfish catches are very low, mainly coming from the area of highest effort and reflecting the incidental nature of the catch. Comparison with areas of high Japanese catches suggests that expansion of domestic effort northwards off eastern Australia in the region of 27°S could generate improved swordfish catches.

Research

Surveys

For many years the strandings of isolated swordfish around various parts of Australia indicated that the species occurred in the region, but no specific surveys or studies were directed at the species. Early Australian research on tunas and billfishes was primarily concerned with assessing their commercial potential. Most research surveys were centered off the southeastern Australian coast, where the Council for Scientific and Industrial Research (later the Commonwealth Scientific and Industrial Research Organisation, CSIRO) carried out experimental fishing around 1940 (e.g. Serventy, 1947). Small catches of the now commercially exploited tunas were taken with trolling gear. Subsequently, a commercial troll and later a bait-boat fishery for southern bluefin tuna were established, and there were attempts at tuna longlining and purse seining. None of this activity generated indications of potential for commercial swordfish operations.

Experimental Fishing

An experimental fishing project which involved 25 longline sets using chemical light sticks was undertaken off southeastern New South Wales between May 1989 and May 1991 (Williams[11]). Each set consisted of 400 to 550 hooks (450 on average), with 6–10 (predominantly

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[10] The length from the anterior tip of the upper jaw (the "sword") to the caudal fork.

[11] Williams, K. F. 1993. Target longlining for broadbill swordfish using chemical light sticks. Report on FIRDC Project 88/62. WW Fisheries Consultants, 167 Burraneer Bay Rd., Cronulla, NSW 2230, Australia, 13 p.

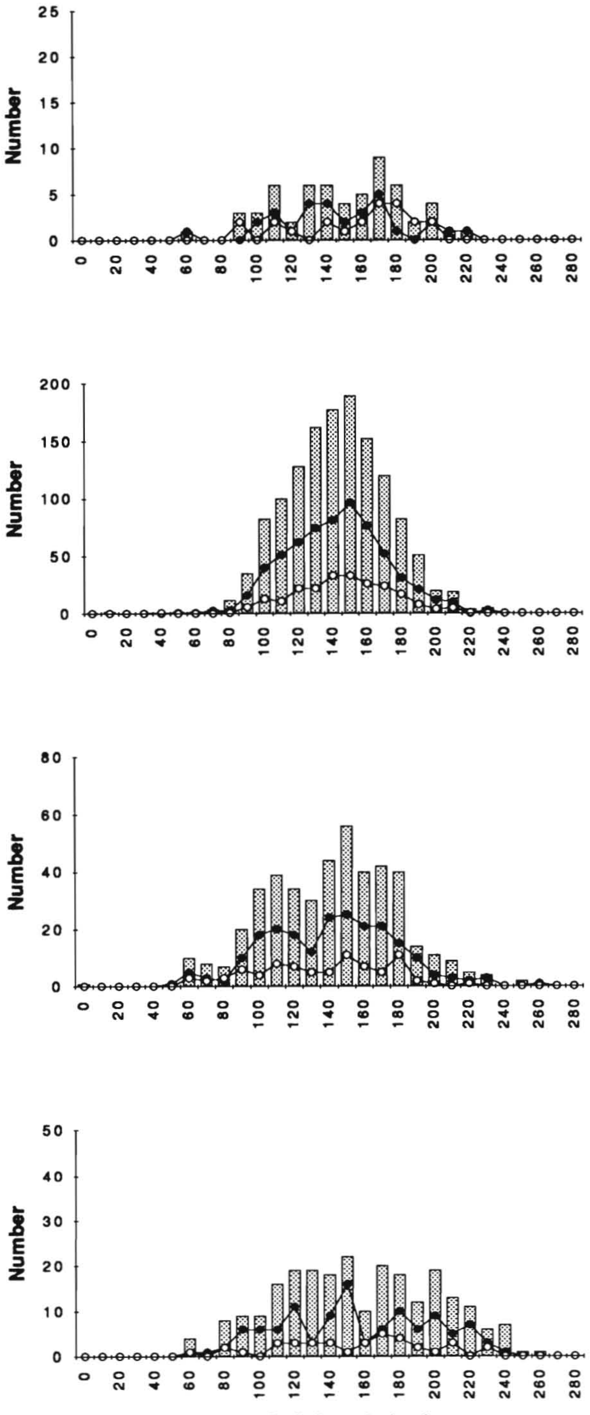

Figure 16
Length frequency distribution of swordfish in 10-degree latitude bands (from top to bottom, 10–20°S, 20–30°S, 30–40°S, and 40–50°S) in catches of Japanese and Australia–Japan joint-venture longliners in the eastern Australian Fishing Zone, 1990–93. Circles indicate males, dots indicate females, and bars indicate totals (including some fish of unspecified sex). (Source: Observer Programme, Australian Fisheries Management Authority.)

6) hooks per basket and 11,110 hooks total in the 25 sets. For all sets, half of the hooks were set with a light stick and the other half were set without, the gear alternating every two baskets, so that the light-stick sectors were separated by about 1 km of "dark" gear. The total swordfish catch was 37 on light-stick hooks and 1 on dark hooks. Over an extended period outside the trials, involving sets totalling 49,620 hooks, the vessel's catch rate was 0.68 swordfish/1,000 hooks, while during the trial period it was 3.42 swordfish/1,000 hooks overall and 6.66 swordfish/1,000 light-stick hooks. Swordfish catch rate off the east coast by Japanese longliners, for sets when at least one swordfish was caught, was 1.68 swordfish/1,000 hooks. For comparison, using that criterion, the project vessel returned catch rates during the trials of 5.29 swordfish/1,000 hooks overall and 10.32 swordfish/1,000 light-stick hooks.

Yellowfin tuna catch rates showed a statistically significant bias of 3:1 in numbers of fish caught on light-stick hooks versus dark hooks, but the overall yellowfin catch rates during the trial sets were generally similar to those during non-trial sets and to yellowfin catch rates of other vessels. Williams[11] suggests that this may perhaps indicate a degree of competition between light-stick and dark hooks.

Catches and catch rates of both species were better during first-quarter, full, and last-quarter moon phases than during the new moon.

Fishery Monitoring and Biological Sampling

From 1986 to 1988 a study of the biology of tuna and billfish resources of the eastern AFZ was carried out to assemble information in support of their management (Bureau of Rural Resources[12]). The study concentrated on yellowfin tuna. The main legacy of the project in relation to swordfish has been the impetus it provided for establishment of a domestic logbook collection.

Since establishment of the AFZ in 1979 there has been a program involving placement of observers on Australia–Japan joint-venture and licensed Japanese longliners to monitor effort, catches by species, and size composition of the catches. They also collect biological samples such as otoliths, gonads, tissue samples, and stomachs on an opportunistic basis, and comment on fishing equipment and techniques. Table 5 provides details of the annual numbers of observers aboard for-

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[12] Bureau of Rural Resources, Australia. 1989. A biological study of east coast tunas and billfishes, with particular emphasis on yellowfin tuna, *Thunnus albacares*: review of results and recommendations for research. Bur. Rural Res. Working Pap. 11/89. Bur. Rural Sci., P.O.B. E11, Kingston, ACT 2604, Australia.

eign longliners[13] between 1980 and 1994 and the monitoring and biological data gathered on swordfish. Tunas and marlins have generally received higher priority than swordfish, and this is reflected by the absence of collections of hard parts and gonads. While processed weight and one or more length measurements are usually obtained for each swordfish taken during observer cruises, it is rarely convenient to weigh unprocessed fish. Sex has been recorded for many of the swordfish, but not gonad stage. Priority for observer collections of hard parts has concentrated primarily on southern bluefin tuna, then on marlins, and then on other tunas. There have been no Australian research programs focusing on age of swordfish, but it would be possible to establish the routine collection of swordfish hard parts during observer cruises.

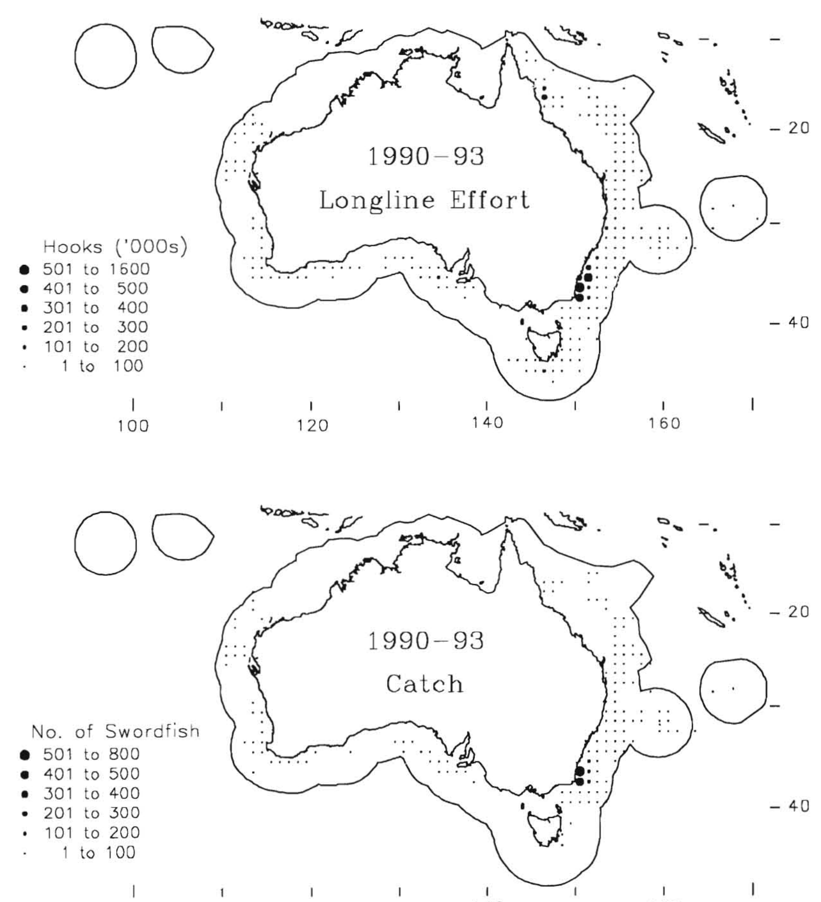

Figure 17

Distribution of longline effort (top) and catch in number of swordfish (bottom) for 1990–93 by Australian longliners in the AFZ (from Australian Fishing Zone Information System logbooks).

During processing, small fish are usually trunked[14] and large fish (>150 cm) are filleted. Relationships between OFL and processed weight, derived from observer data, are shown for fillets and trunks in Figure 18. The relationships are

$$\text{Trunked weight (kg)} = 2.0612 \times 10^{-5}\ \text{OFL}^{2.8668}\ \text{(cm)}$$
$$\text{Filleted weight (kg)} = 1.6151 \times 10^{-5}\ \text{OFL}^{2.9301}\ \text{(cm)}.$$

Sex Ratio

Observer data from foreign longline vessels (Table 5) indicate an average female to male ratio in the swordfish catch of more than 3:1. There are no data on maturity stages. Observers have recorded very few male fish larger than 200 cm OFL. Off eastern Australia, observer data indicate little change in sex ratio with size (Fig. 19). The average was 2.7 females to 1 male. Domination of females in larger fish is consistent with observations elsewhere, but it is unusual that they dominate across all sizes. For example, Mejuto et al. (1994) analyzed more than 65,000 swordfish sampled from the Atlantic and Mediterranean. They indicated that for individuals measuring less than 115 cm LJFL, the sex ratio is around 50%, whereas 90–100% of individuals larger than 200 cm are females. The accuracy of Australian observers' classification of males and females has not been checked. One of the authors (M. Scott), who is an observer, suggested that sex of small males may commonly have been recorded as indeterminate or immature because of uncertainty in identification.

Sex composition of catches by size is shown by latitude for the eastern AFZ (Fig. 16). Ratios calculated for 10-cm size groups show no indication of a trend in sex ratio with size or with latitude south of 20°S. The ratio for the most northern band is

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[13] Japanese and Australia–Japan joint-venture longliners were the main foreign longliners operating in the AFZ. However, the observer program also monitored operations by 3 Australian-chartered Korean vessels in the early 1990's.

[14] Gilled and gutted, head removed anterior to cleithrum, and tail removed posterior to caudal keels.

highly variable because of the small sample size.

The lack of data on maturity stages prevents comment on size at maturity.

Parasites

There have been no systematic studies of the parasitic fauna of swordfish in Australian waters and only a few incidental records exist (Spears[15]). These taxa include the giant trematode of the stomach, *Hirudinella marina*; cestodes, *Tentacularia coryphaenae*, *Callitetrarhynchus gracilis*, and *Bothriocephalus manubriformis*; a nematode, *Maricostula incurva*; a monogenean, *Tristoma coccineum*; and copepods, *Pennella filosa* and *Gloiopotes longicaudus*. Worldwide, numerous parasites have been recorded from swordfish (>40) and include taxa that have great potential as biological tags for stock discrimination.

Tagging

Deguara[16] reports that the New South Wales Fisheries Research Institute has managed the New South Wales Game Fish Tagging Program since 1973. The program encourages recreational fishers to tag and release fish. Competitions have developed where points are awarded for tag and release of game fish, rather than their retention. Australian releases of tagged swordfish did not commence until 1985. Since then (through June 1994), reported releases total 25. Most Australian tagged fish have been small juve-

Table 5

Observer days aboard foreign longliners and data collected on swordfish, 1980–94. (Source: Observer Programme, Australian Fisheries Management Authority.)

Year	Number of cruises	Number of observer days	Number of hooks set	Number of hooks observed	Number of swordfish	Sex		Number of weight measurements taken			Number of length measurements taken (from reference point to caudal fork)			Number of samples[2] collected
						Male	Female	Trunked	Filleted	Whole weight	Lower Jaw	Orbit	Bill	
1980	2	17												
1981	3	35												
1982	4	27			15		1							
1983														
1984	2	19			9					1	3		3	
1985	3	18												
1986	1	1												
1987	5	27			16	3	5					4	4	
1988	11	84			26	3	7			6	4	16	19	
1989	8	80			23		8			1	1	20	21	
1990	19	192			111	13	32			11	13	78	91	
1991	67	814	2,287,226	1,335,440	1,025	178	434	127	843	441	843	855	902	6
1992	63	778	2,304,812	1,612,755	1,201	124	500	236	849	303	961	697	420	7
1993	86	1,044	3,164,857	2,252,956	925	125	368	176	624	77	695	663	500	16
1994[1]	53	583	1,844,941	1,246,803	398	36	155	108	194	59	301	259	248	4

[1] to October 1994.
[2] mainly stomach samples

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[15] Spears, P. 1994. Aust. Inst. Mar. Sci., PMB No. 3, Townsville Mail Centre, QLD 4810, Australia. Personal commun.

[16] Deguara, K. 1994. N.S.W. Fish. Res. Inst., P.O. Box 21, Cronulla, NSW 2230, Australia. Personal commun.

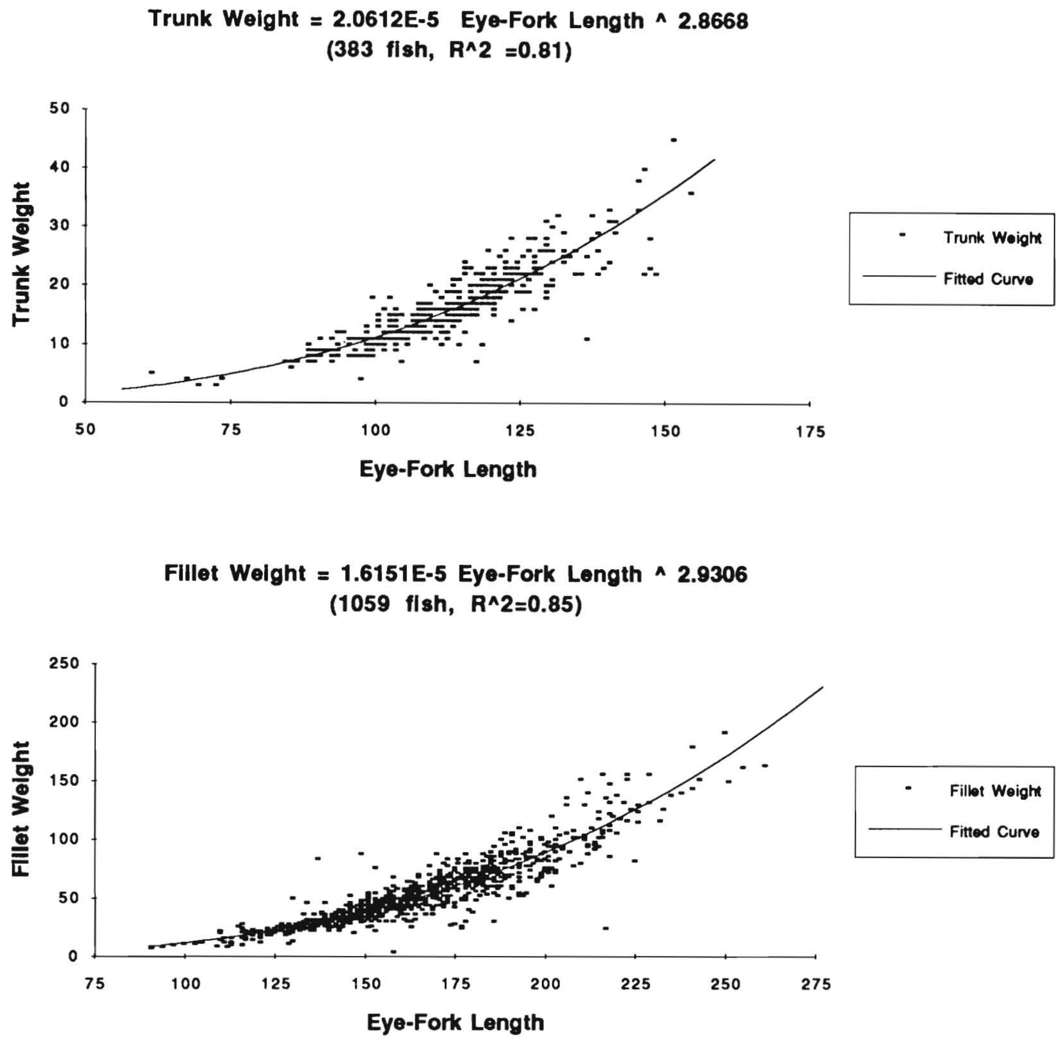

Figure 18

Relation of length (orbit-to-caudal-fork) to processed weight for trunked (top) and filleted (bottom) swordfish in the Australian Fishing Zone. Note different *x* and *y* scales. (Source: Observer Programme, Australian Fisheries Management Authority.)

niles (4–15 kg). There has been one recovery reported, of a fish released by an angler at Bermagui (375 km south of Sydney) in southern New South Wales and recovered by a domestic longliner 200 km to the north at Jervis Bay 3 months later at a size of 6 kg.

Potential for Expansion of Local Operations

Swordfish are regularly represented in longline catches from the eastern AFZ. Domestic exploitation currently remains incidental to a range of other fishing activities, probably because of marketing restrictions resulting from mercury content limits. Recent review of the limits has eased restraints sufficiently to overcome some of the wastage associated with unmarketable dead fish and may provide scope to replace some of the Japanese activity by increased domestic use of the species.

Experience in other regions suggest that swordfish are a relatively slow growing, long-lived pelagic species with a slower turnover rate and lower productivity than pelagics such as skipjack and yellowfin tunas. In that regard they are likely to be sensitive to exploitation, so that any expanded domestic use should be monitored carefully, as should exploitation in adjacent regions within the range of distribution of locally-fished aggregations.

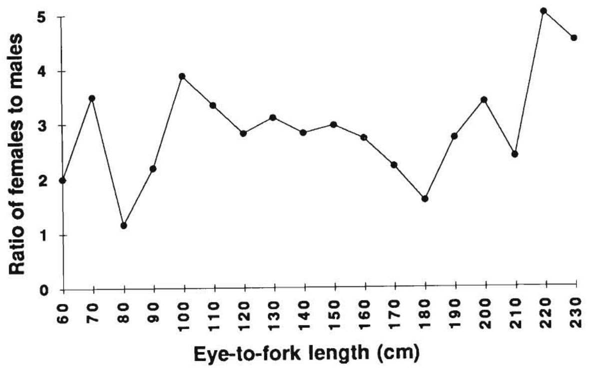

Figure 19

Ratio of female to male swordfish by length group in the eastern Australian Fishing Zone; the average ratio was 2.7:1 ($n = 1{,}366$). There was no significant trend in the ratio by length. (Source: Observer Programme, Australian Fisheries Management Authority.)

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The California Harpoon Fishery for Swordfish, *Xiphias gladius*

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ABSTRACT

We review and analyze fishery data collected from the California harpoon fishery for swordfish, which began in the early 1900's. Landings data for 1969–93, logbook data for 1974–93, and size composition data for swordfish landed in 1981–93 are analyzed. Swordfish landings peaked in 1978 (1,172,000 kg) and decreased to a record low (11,000 kg) in 1991. Landings were less than 200,000 kg in most years. Swordfish landed averaged 149 cm in length (cleithrum to fork) or 85 kg dressed weight in 1981–93.

The harpoon fishing season, typically May–December, usually concentrates in the Southern California Bight off San Diego early in the season and then shifts as far north as Oregon. Swordfish are usually sighted while basking at the surface in water of 12°–26°C. Fishing effort peaked in 1979 (12,700 days fished), decreased in 1991 (700 days), and rebounded slightly in 1993. Catch per day fished fluctuated between 0.14 and 0.93 during 1974–93, and peaked in 1974, 1978, 1985, and 1993, usually 1–2 yr after an El Niño event.

Introduction

In North America, harpoon fishing dates to the use of harpoons by Indians to catch swordfish, *Xiphias gladius,* off the California coast almost 3,000 yr ago (Kronman, 1988). Their vessels were 6.1-m (20-ft) driftwood canoes, and their gear consisted of a 1.8-m (6-ft) foreshaft tipped with a carved wooden harpoon which bore a stone point on one end and a curved barb of deer bone behind (Kronman, 1988).

California's modern-day harpoon fishery for swordfish developed in the early 1900's. The fishery was modeled after the East Coast harpoon fishery, which began almost 70 yr earlier. Vessels were small sail-powered sloops or schooners. The harpoon gear was 4.6–5.5 m (15–18 ft) in length, fashioned from hickory and tipped—with a bronze dart (Kronman, 1988). The bronze dart was backed by a tapered socket and a 0.6-m (2-ft) metal shank attached to the end of a wooden handle. The design of harpoon gear has remained unchanged except for minor modifications in the metal used in the shank.

Harpoon fishing continued as the only commercial fishery that harvested swordfish within 200 mi of the California coast until 1980, when drift gill net fishing started in waters off California. The competition from the more-efficient drift gill nets proved too great for the harpoon fishery, and many vessels converted to drift gill net gear or obtained permits to use both types of gear. Today, harpoon and drift gill net are the only commercial fishing gears operating on swordfish in the area, and only a handful of vessels continue to participate in the harpoon fishery.

This paper reviews and analyzes data collected from the California harpoon fishery. Landings data are reviewed for 1969–93, logbook data for 1974–93, and size composition of swordfish catches for 1981–93.

Data and Methods

Landings, logbook, and size composition data for California's harpoon fishery have historically been collected by California Department of Fish and Game (CDFG) biologists at landing ports as vessels returned from fishing trips. Locations of landings, logbook catches, and measured fish were recorded by CDFG blocks, which are usually 10-minute quadrangles. These were converted to latitude and longitude and summed to 1-degree quadrangles for the purposes of this report.

Landings

Swordfish landings data have been collected since the early 1900's (Bedford and Hagerman, 1983). This study includes landings data for 1969–93, to match the existing logbook and size-composition data sets. This period includes all of the 1970's, a period of relatively high catches and increased regulations that significantly impacted the harpoon fishery.

The landings data were compiled from CDFG landing receipts. Commercial fish buyers are required to fill out a landing receipt for each landing purchased in California (Hanan et al., 1993) and submit these receipts to CDFG. Therefore, coverage is very close to 100% for all landings sold commercially. Landings kept for private consumption are not recorded in the landing totals. A small number of swordfish landings may also escape the landing receipt system. The landing receipts contain information on species landed, weight landed, price paid, and fishing gear used. Other information, such as area of catch, may be included but in many circumstances is left blank.

Data for 1969–79 include landings reported as catches by harpoon, spear, and unknown fishing gear (Table 1). Data from 1980 to 1993 include only those landings specifically designated as caught with harpoon or spear gear. Landings with unknown fishing gear were included before 1980 because harpoon was the prevalent gear used during that time. After 1979, drift gill net gear accounted for a significant number of swordfish landings, and unknown gear could no longer be assumed to be harpoon.

Landings other than sharks were not included as harpoon incidental catches (Table 1). Albacore, *Thunnus alalunga*; yellowfin tuna, *Thunnus albacares*; mackerel, Scombridae; rockfishes, *Sebastes* spp.; and other species were often recorded as harpoon landings. These entries were considered errors in gear-type coding; the catches were most likely made with troll fishing gear while searching for swordfish.

Logbooks

CDFG implemented a mandatory permit and logbook system in 1974 (Bedford and Hagerman, 1983). The original logbook provided space for recording information about a single fishing day on each line. Requested information included name of skipper and boat; swordfish permit number and CDFG boat number; date (month and day) of each entry; CDFG block number; whether an aircraft was used; whether the fish was sighted underwater, finning, or jumping; whether the fish was harpooned; whether it was landed; and estimated dressed weight in pounds. Space was also included for any other pertinent remarks.

The original logbook was later modified so that each page represented a single day of fishing (Fig. 1). Fields were added to record starting and ending times of fishing, time of each entry on the form, sea-surface temperature, whether sighted fish were pursued, other CDFG blocks searched, and weather conditions, sea state, and sea color.

Size Composition

Landings of swordfish have been sampled for length since 1981 under a program originally designed to monitor gill net landings (Odemar[1]). Samples were taken by CDFG biologists as fish were unloaded at various fish markets throughout the state (Hanan et al., 1993). No formal constraints on sample size were established, and samplers selected as many fish and vessels to sample as time permitted. Since swordfish were always landed gutted, headed, and with the dorsal fins and the posterior portions of the tail fins removed, samplers recorded the cleithrum length (CL), the straight length from the anterior margin of the cleithrum to the fork of the tail. Lengths were recorded to the nearest millimeter. The samplers, whenever possible, recorded information on the weight in pounds of each fish measured, date measured, boat name and number, port and market of

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[1] Odemar, M. 1982. Inventory of California marine fisheries port sampling activities. Calif. Dep. Fish Game internal report, 157 p. CDFG, 1416 Ninth St., Sacrament, CA 95814.

Table 1

California harpoon fishery landings (kg). Landings for 1969 to 1979 include landings reported as unknown fishing gear. Unid. indicates sharks not identified to species.

		Sharks							
Year	Swordfish	Thresher	Mako	Blue	Hammerhead	Soupfin	White	Unid.
1969	459,748	0	0	0	0	0	0	5,230
1970	421,933	0	53	0	0	0	0	0
1971	68,215	0	0	0	0	0	0	0
1972	118,223	0	0	0	0	0	0	0
1973	274,779	0	0	0	0	0	0	382
1974	279,649	0	0	0	0	0	0	1,974
1975	383,658	44	0	0	0	0	0	124
1976	28,936	0	17	0	0	0	0	83
1977	219,055	1,024	192	0	0	0	0	2,839
1978	1,171,655	951	565	0	27	0	0	2,275
1979	226,625	11,857	311	348	0	0	0	4,936
1980	389,722	2,915	1,486	0	0	0	0	4,336
1981	178,660	0	157	15	69	161	0	1,184
1982	107,580	122	621	0	0	0	0	297
1983	39,796	0	82	0	93	0	0	187
1984	72,992	22	269	0	0	28	0	238
1985	145,154	0	203	0	55	0	0	0
1986	162,634	55	549	0	43	289	61	69
1987	144,954	0	1,506	0	0	0	227	39,009
1988	123,757	12	1,121	0	61	0	0	22
1989	37,197	0	404	0	0	0	0	0
1990	34,726	33	892	0	70	0	0	0
1991	11,362	29	540	0	0	0	0	0
1992	44,285	30	1,991	0	0	0	0	0
1993	116,058	0	403	0	0	0	0	0

landing, CDFG block number, and landing weights (Childers and Halko[2]). No sampling bias by vessel, market, area, or month was detected.

Vessels, Gear, and Fishing Strategies

Vessels that participate in the harpoon fishery are quite variable but very distinctive. They are usually 6–26 m (20–87 ft) in length (Holt[3]), with hold capacities up to 100 metric tons (110 short tons) and main engines of 25–1,300 horsepower. The vessels are equipped with high masts of 5–12 m (18–40 ft; Kronman, 1988) and a plank extending 6–9 m (20–30 ft) beyond the bow. The crow's nest at the top of the mast is usually equipped with controls to steer the vessel during the pursuit of swordfish. The planks, while originally made of wood, are now aluminum or steel conduit and can be raised during travel and lowered when in pursuit. At the end of the plank is a pulpit consisting of a metal stand and railing against which the harpooner can lean.

Harpoon fishing gear has changed little since the early 1900's. Current harpoon gear consists of a handle made of metal or wood and approximately 3–5 m long (10–16 ft), attached to a metal shank approximately 0.6 m long (2 ft), and tipped with a 10-cm (4-inch) bronze or iron dart. One end of a mainline, 15–46 m (50–150 ft) in length, is attached to the middle of the dart, and floats and a marker flag are attached to the other end.

Harpoon vessel fishing trips usually are from 3 to 10 days in length and vary according to fishing success, fish carrying capacity, and preservation capability. Fishing starts with the search. Fish are sighted either finning or jumping at the surface or swimming just beneath the surface. Sightings are made by the vessel's crew using binoculars or by assisting aircraft. Since sightings are of fish on or near the surface, good weather conditions

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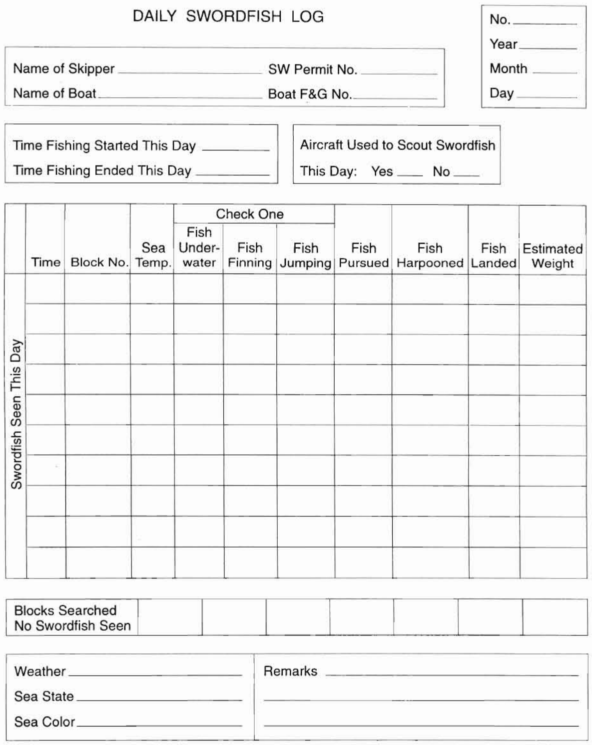
[2] Childers, J., and L. Halko. 1994. Length-frequency database description: California Department of Fish and Game gill net market samples. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Center Admin. Rep. LJ-94-01, 46 p.

[3] Holt, S. 1978. Economic analysis of the swordfish harpoon fishery. Pacific billfish management plan, 47 p. Prepared under contract no. 78-20 for PFMC. Available from Pac. Fish. Manage. Counc., 45 S.E. 82nd Dr., Ste. 100, Gladstone, OR 97027-2522.

and calm seas favor fishing. Swordfish are found in sea-surface temperatures of 12°–26°C (64°–72°F), and vessels usually start their search in areas where temperatures are within this range.

After a fish is sighted, the vessel's plank is maneuvered over the fish and the striker harpoons the fish. The handle is pulled free from the dart, the mainline, marker flag, and floats are thrown overboard, and the fish is left to tire itself. The vessel is then able to pursue other fish. After the fish has tired (approximately 2 hr) the vessel returns to retrieve it. The fish is dressed (headed, gutted, and fins removed) and stored in ice for transport to shore. During the early years of the harpoon fishery, the livers were sometimes kept for sale because of their vitamin A and D content (CDFG, 1949); this practice is no longer followed as other sources of vitamin A and D have been developed.

The use of airplanes to assist in the sighting and harpooning of swordfish started in the early 1970's. Airplanes both spot the fish and guide the vessels to the fish. Because conflicts arose between commercial fishermen who used airplanes and sportsmen and other commercial fishermen who did not use airplanes, a series of regulations was enacted to limit their use.



DAILY SWORDFISH LOG

No.______
Year______
Month______
Day______

Name of Skipper______ SW Permit No.______
Name of Boat______ Boat F&G No.______

Time Fishing Started This Day______
Time Fishing Ended This Day______

Aircraft Used to Scout Swordfish
This Day: Yes ___ No ___

				Check One						
	Time	Block No.	Sea Temp.	Fish Under-water	Fish Finning	Fish Jumping	Fish Pursued	Fish Harpooned	Fish Landed	Estimated Weight
Swordfish Seen This Day										

Blocks Searched No Swordfish Seen							

Weather______
Sea State______
Sea Color______

Remarks______

Figure 1

A page from the current California harpoon fishery logbook.

Modern-day harpoon vessels have added new technology and fishing strategies as they became available, to increase fishing efficiency. Some vessels employ state-of-the-art navigation equipment, sea-surface-temperature recorders, and sounders to help locate fish. Some have also been known to use satellite imagery to identify fishing areas. Harpoon vessel operators have also obtained multiple permits that allow them to fish both gill net and harpoon fishing gears, and have also been known to troll jigs between sightings to increase catches of swordfish and other commercial species of fish.

Regulations

Over time, several regulations have been imposed that directly or indirectly affect the California harpoon fishery (California Fish and Game Code and Title 14 Regulations; Squire and Muhlia-Melo[4]; Sakagawa[5]). The major regulations are:

1935	Swordfish may be taken with hook-and-line and harpoon gear.
1971	U.S. Food and Drug Administration (FDA) begins to enforce guideline of 0.5 ppm of mercury in swordfish.
1973	A permit is required to take swordfish commercially. California Legislature gives regulative authority over the swordfish fishery to the State Fish and Game Commission (F&GC).
1974	F&GC adopts commercial swordfish regulations including specific permit qualifications, a logbook requirement, and the notification that airplanes cannot be used to assist a vessel in capturing swordfish after 28 June 1976.
1976	F&GC allows airplane use in locating swordfish, but not within an 8-km (5-mi) radius of a vessel operated by a swordfish permittee.
1977	F&GC extends the airplane operating radius to beyond 16 km (10 mi) of a vessel operated by a swordfish permittee.
1978	FDA changes limit of total mercury in swordfish to 1.0 ppm.

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[4] Squire, J. L., and A. F. Muhlia-Melo. 1993. A review of striped marlin (*Tetrapturus audax*), swordfish (*Xiphias gladius*), and sailfish (*Istiophorus platypterus*) fisheries and resource management by Mexico and the United States in the northeast Pacific Ocean. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fisheries Science Center Admin. Rep. LJ-93-06, 44 p. (in Engl. and Span.). SWFSC, NMFS, NOAA, P.O. Box 271, La Jolla, CA 92038-0271.

[5] Sakagawa, G. T. 1994. Supply of swordfish, *Xiphias gladius*, for the United States consumer market. International Symposium on Pacific Swordfish, 11–14 December 1994, Ensenada, Mexico. Available from G. T. Sakagawa, Southwest Fisheries Science Center, NMFS, NOAA, P.O. Box 271, La Jolla, CA 92038-0271.

1980 F&GC prohibits swordfish harpoon permittees from possessing a gill net on board except for set gill nets with mesh sizes of 20 cm (8") or less if they declare on their swordfish permit that they intend to use such gear.

1984 F&GC allows unlimited airplane use to directly assist a permittee in the taking of any species of fish while operating under a swordfish harpoon permit. FDA changes its regulation to limit methyl mercury content in swordfish to 1.0 ppm.

1985 F&GC allows swordfish harpoon permittees to have set gill nets of any mesh size aboard if they declare on their swordfish harpoon permit application that they intend to use such gear.

1987 F&GC allows swordfish harpoon permittees to have drift gill nets aboard in addition to set gill nets, if they also possess a valid permit to use drift gill nets.

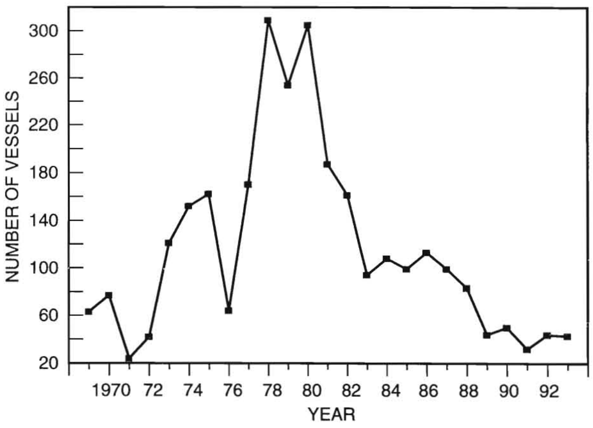

Figure 2

Number of California harpoon fishing vessels landing swordfish during 1969–93.

Numbers of Vessels and Landings

The number of California harpoon vessels landing swordfish increased from 63 in 1969, to 309 in 1978 (Fig. 2), decreased to 32 in 1991, and then increased slightly to 43 in 1993. A sharp decline in 1971 in the number of vessels participating in the fishery was probably due to the collapse of the swordfish market in that year as a result of the mercury scare—publicity about the high levels of mercury in swordfish and health problems from ingestion of mercury, which discouraged consumers from buying swordfish—and the FDA's subsequent strict enforcement of the 0.5-ppm mercury limit. The decline in 1976 was probably due to the ban on aircraft use, and the general decline since 1980 has been primarily due to increased competition from drift gill net operations.

The number of vessels landing swordfish is indicative of the harpoon fishery fleet size. CPUE during this time was relatively stable at 0.1–0.9 fish per day, and the number of harpoon permits showed a trend similar to that in number of vessels landing swordfish: 164 permits in 1984, decreasing to 43 in 1993.

Harpoon fishery landings in California have been recorded since 1918 (CDFG, 1949). Records for 1918–37 combined striped marlin, *Tetrapturus audax*, and swordfish landings, since no requirements were in place to separate the two species. Commercial landings of striped marlin in California have been prohibited since the late 1930's.

Records for 1938–68 contained swordfish landings only and are assumed to be from harpoon gear, although small amounts of catch from other fishing gears are probably included. Landings averaged approximately 330,000 kg in 1938–48 and declined to approximately 110,000 kg in 1949–68. Landings increased dramatically in 1968 to 460,000 kg, and reached a record high of 1,172,000 kg in 1978 (Table 1). After 1978, landings decreased to a record low of 11,000 kg in 1991 and rebounded slightly to 116,000 kg in 1993. In general, landings seem to be lower during El Niño events (1972–73, 1976–77, 1982–83, 1991–92) and peak 1–2 yr thereafter. The same regulations that affected vessel participation in the harpoon fishery, mentioned above, also affected annual landings.

The most prevalent incidental landings of sharks identified to species were thresher, *Alopias vulpinus*, and shortfin mako, *Isurus oxyrinchus* (Table 1). The most thresher sharks landed in a year was 12,000 kg in 1979; the most shortfin mako sharks landed was approximately 1,500 kg in 1980 and 1987. Other sharks landed by harpoon gear include blue, *Prionace glauca*; hammerhead, *Sphyrna* spp.; soupfin, *Galeorhinus zyopterus*; and white, *Carcharodon carcharias*. The most reported landings of unidentified sharks occurred in 1987 when 39,000 kg were landed.

Logbook Records

Coverage Rates

Annual logbook coverage rates were calculated as the total annual weight of swordfish reported in logbooks, divided by yearly swordfish landing weights as given in Table 1 (Fig. 3). Total annual swordfish weight reported in logbooks was calculated as the total number of fish reported in logbooks, multiplied by the average weight (85 kg) of fish recorded in market sampling of harpoon catches during 1981–93. Annual average

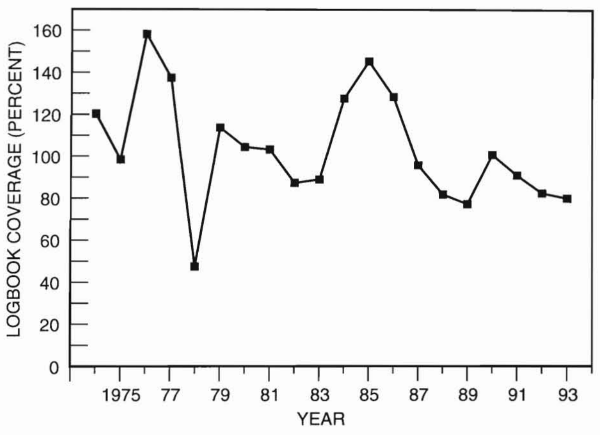

Figure 3
California harpoon fishery logbook coverage rates (logbook catch in weight divided by landed weight) for 1974–93.

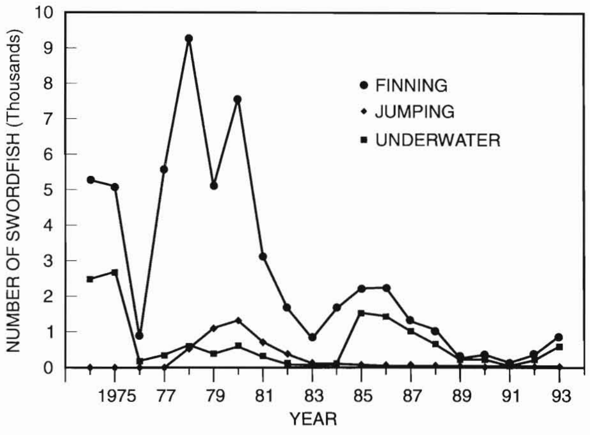

Figure 4
Number of swordfish sighted at the sea surface finning, swimming, jumping, or swimming just under the surface (underwater) by California harpoon fishery vessels and reported in logbooks for 1974–93.

weights were not used because of the low sample sizes in some years. Logbook-estimated weights were not used because they were missing for as many as 100 landings per yr, combined processed and total weights, which were difficult to separate, and produced estimates significantly higher than those produced by using average weights from port sampling.

Coverage rates were greater than 120% in 1976, 1977, and 1984–86; between 80% and 120% in 1979–83 and 1987–92; and less than 50% in 1978 (Fig. 3). Since the logbook program was mandatory during this time, vessel coverage rates should have been 100%. Coverage rates not equal to 100% can be attributed to several factors: 1) use of an average weight to convert numbers of fish to catch in weight of fish may overestimate or underestimate actual logbook catches; 2) landings underestimated due to some being classified as unknown gear; 3) fish kept for personal consumption; and 4) confusion at markets between gill net landings and harpoon landings, especially when a permittee had both drift gill net and harpoon permits. The extremely low coverage rate in 1978 is difficult to explain and may be due to a deliberate misreporting of drift gill net catches as harpoon landings, in an effort to circumvent the prohibition of drift gill net swordfish landings (Bedford, 1987).

Data on Sightings

Swordfish initially sighted by harpoon fishery vessels or spotter airplanes were reported in logbooks as either finning at the surface, swimming just below the surface, or jumping. An average of 74% of fish sighted during 1974–93 were finning at the surface (Fig. 4). The next most prevalent type of sighting was of fish just under the surface (19%), except in 1979–82, when jumping fish were sighted more often (6%). Fish were sighted finning in especially dominant numbers compared to fish seen underwater and jumping during 1976–84, when spotter airplanes were banned. Before 1976 and in 1984–88, the numbers of finning and underwater sightings were comparable, and in 1989–92 were virtually the same, probably due to the increased ability to spot fish just under the surface from airplanes.

Harpoon vessel captains recorded sightings of swordfish in three types of water color, blue/green, blue, and green. Swordfish were found most often in blue/green water in 1974–79, and in blue water in 1980–87 (Fig. 5). During 1988–93, swordfish were found with the same frequency in water of all three colors. Blue/green water is usually associated with high primary production; the records for this color water seem to parallel increased swordfish catches and abundance levels of other species of fish in the Southern California Bight during 1974–79 (Squire, 1993).

Swordfish caught in the California harpoon fishery were found in surface water temperatures of 12°–26°C (54°–79°F; Fig. 6). Over 50% of the fish were found in temperatures of 19°–22°C (66°–71°F). In El Niño years, the range of water temperatures in which the majority of swordfish are sighted narrows and favors warmer temperatures of 20°–22°C (68°–71°F). This was very evident during the strong El Niño of 1982–83 (Fig. 6). In non-El Niño years, swordfish are sighted in a broader range of water temperatures, and more are caught in colder water. This is consistent with oceanographic conditions in the Southern California Bight, where the California Current extends farther south during non-El Niño years (Miller[6]). This extension of the California Current would result in more mixing of colder water in the area and, therefore, more days when swordfish would be sighted in cooler water.

Success and Effort

When a swordfish is pursued by a harpoon fishing vessel, the fish often escapes being harpooned or, if harpooned, may never be landed. In order to measure the success of each swordfish encounter, vessel captains recorded, for each fish, whether it was pursued, subsequently harpooned, and landed. Logbook records show that when swordfish were pursued, on average 74% were actually harpooned (Fig. 7). Of those that were harpooned, 91% were actually landed. The best ratios of pursuit to landing success occurred in 1986 and 1989–92 when more than 75% of pursued fish were actually landed.

Annual harpoon fishing effort, as reported in logbooks, increased from 3,500 days fished in 1976 to a record high of almost 13,000 days in 1979, then declined to a low of approximately 700 days in 1991 (Fig. 8). Airplane-assisted fishing effort accounted for less than 30% of the total effort during 1974–79, and dropped to 0% in 1980 and 1983. Between 1984 and 1986, airplane-assisted effort increased rapidly to a peak of over 1,600 days fished (39%) in 1986, probably in response to the restoration of unlimited airplane use in 1984. The numbers of assisted and unassisted days fished since 1989 were approximately the same.

Annually, harpoon fishing effort usually peaked in August, with high levels of effort extending into the last quarter of the year (Fig. 9). In El Niño years, fishing effort peaked and concentrated in July and August, with less effort in the last quarter. Over 70% of fishing effort was expended between July and October and concentrated in the Southern California Bight during 1974–93 (Fig. 10). Fishing effort usually started in waters off San Diego early in the season, and progressed to waters sometimes as far north as Oregon later in the season. During El Niño years, fishing effort tended to compress spatially and concentrate in the Southern California Bight. In non-El Niño years, fishing effort extended to areas off Oregon, but with relatively little success. This extension of the fishery is consistent with temperature regimes during non-El Niño years, when cooler water mixes throughout the area.

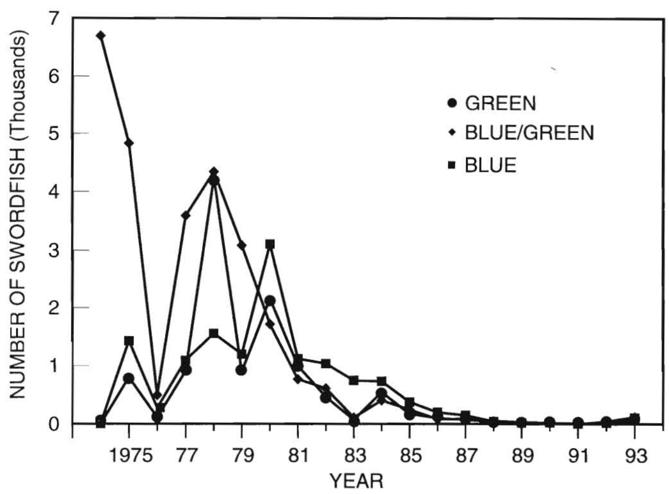

Figure 5
Number of swordfish sighted in blue/green, green, and blue water by California harpoon fishery vessels and reported in logbooks for 1974–93.

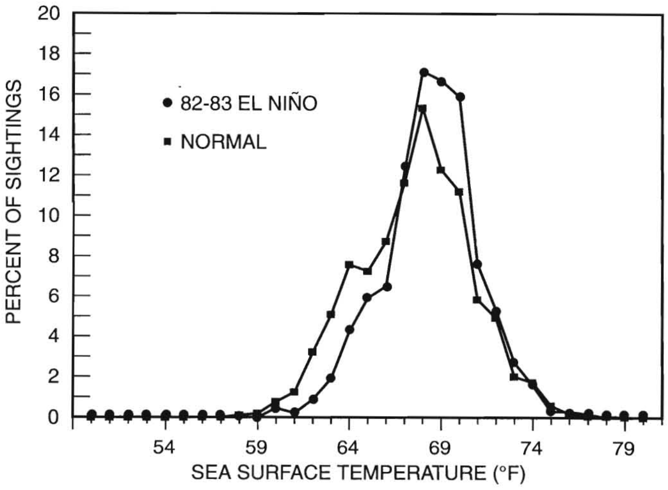

Figure 6
Proportion of swordfish sightings made at different sea-surface water temperatures (°F) from California harpoon fishery vessels and reported in logbooks for 1974–93. Normal includes all non-El Niño years. 82-83 El Niño indicates the effect of a strong El Niño on swordfish sightings.

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[6] Miller, F. 1994. Inter-American Tropical Tuna Comm., 8604 La Jolla Shores Dr., La Jolla, CA 92037-1508. Pers. commun.

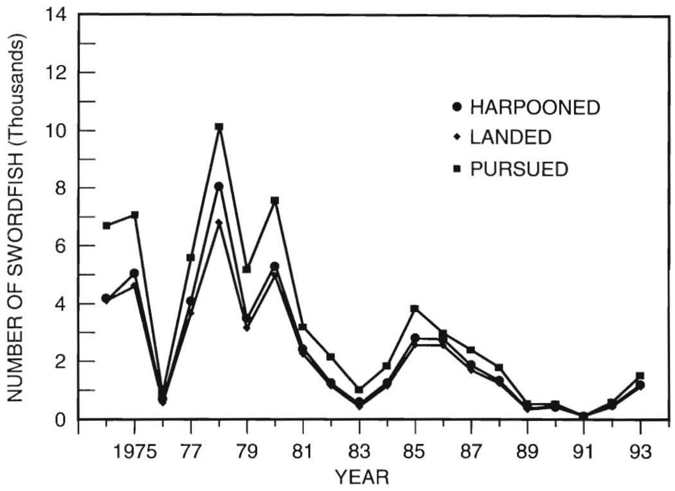

Figure 7
Number of swordfish pursued, harpooned, and landed by California harpoon fishery vessels, as reported in logbooks for 1974–93.

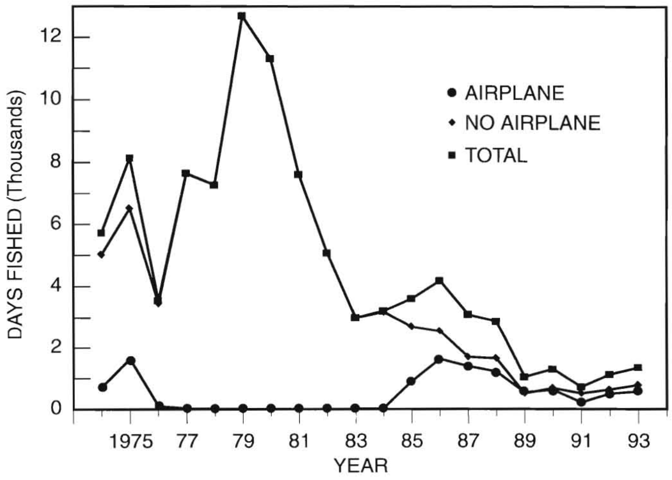

Figure 8
Total fishing effort in number of days fished, and fishing effort with and without the use of airplanes by California harpoon fishery vessels, as reported in logbooks for 1974–93.

Catches and CPUE

Trends in annual catch (in number of fish, as recorded in logbooks) closely followed trends in annual landings, with low catches of approximately 500 fish in 1976 and 1983 and a record low of 120 fish in 1991. The highest recorded catch (nearly 7,000 fish) was in 1978 . Recorded fishery catches, like effort, were also highest in the Southern California Bight, especially in waters between the California coast and San Clemente and Santa Catalina Islands (Fig. 11). Catches tended to concentrate in the Southern California Bight in El Niño years and extend farther north during non-El Niño years. Unlike fishing effort, which generally peaked in August, swordfish catches usually peaked in October, with over 70% of the catch made between July and October (Fig.

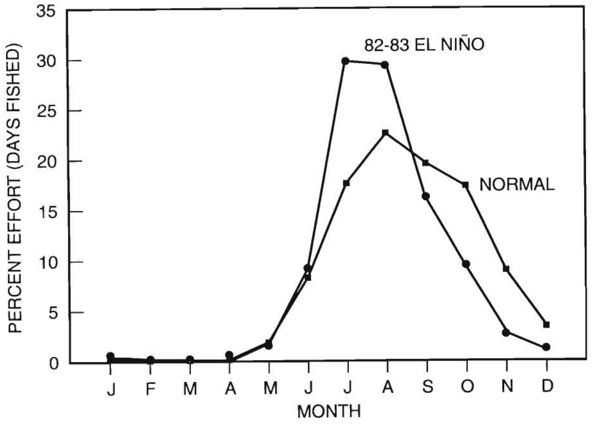

Figure 9

Proportion of fishing effort by month by California harpoon fishery vessels and reported in logbooks for 1974–93. Normal indicates fishing effort in non-El Niño years, and 82-83 El Niño indicates fishing effort during the strong El Niño of 1982–83.

12). During El Niño years, swordfish catches tended to peak earlier in the year, in July and August, with less catch in the last quarter of the year.

Catch-per-unit effort (CPUE, in number of fish per day fished) was calculated from logbook statistics for days with airplane assistance, days without airplane assistance, and for total days (Fig. 13). Airplane-assisted CPUE was higher than airplane-unassisted CPUE except in 1978–83, a period when airplane-assisted effort was less than 10 days per yr. Combined CPUE fluctuated between 0.14 and 0.93 swordfish per day fished. The trends in all estimates of CPUE were very similar: decreasing from 1978 to 1983, increasing to a peak in 1985, decreasing again until 1991, and then increasing in 1993. CPUE tended to increase 1–2 yr after an El Niño event. In comparison, drift gill net catch rates, in the same areas, ranged from 1 to 3 fish per day.

Size Composition

Sampling coverage (number of fish sampled, divided by the number of fish recorded in logbooks) for size composition of swordfish catches from the harpoon fishery sold at fish markets ranged between 0.2% and 7.0% during 1981–93 (Fig. 14). The low sampling coverage was probably due to the higher priority given to sampling gill-net-caught fish, combined with a low overall monitoring effort which did not adequately cover the various ports where harpoon vessels landed. The largest number of fish sampled was in 1984 (about 80 fish) and the smallest in 1990 (only one fish). Because of the low coverage rates, estimates of length distributions of swordfish by month and by latitudinal band could not be made. However, because of the close temporal and spatial proximity of this fishery to its drift gill net counterpart, the tendency seen in the drift gill net fishery for larger fish to be caught farther north and later in the season (Hanan et al., 1993) probably also applies to the harpoon fishery.

Average CL was calculated for each year and shows a slight increasing trend, from 140 cm in 1981 to approximately 183 cm in 1990 (Fig. 14). However, because of the small number of individuals sampled, the estimates are highly suspect during 1989–92. Fish sampled from harpoon fishery catches during 1981–93 ranged from approximately 62 to 217 cm CL (Fig. 15), with an average of about 149 cm. In comparison, fish caught in the California gill net fishery, as expected, were slightly smaller, averaging only 141 cm.

Discussion

The data collected from the California harpoon fishery are valuable for monitoring the fishery. While the data are generally of high quality, some problems can be identified and improvements made.

Landings data can be affected by various problems associated with reporting. Reported landings of fish that would be impossible to catch with a harpoon indicate a problem in the reporting of gear type used to catch those fish and possibly also swordfish. Also, since some vessels may have both harpoon and gill net per-

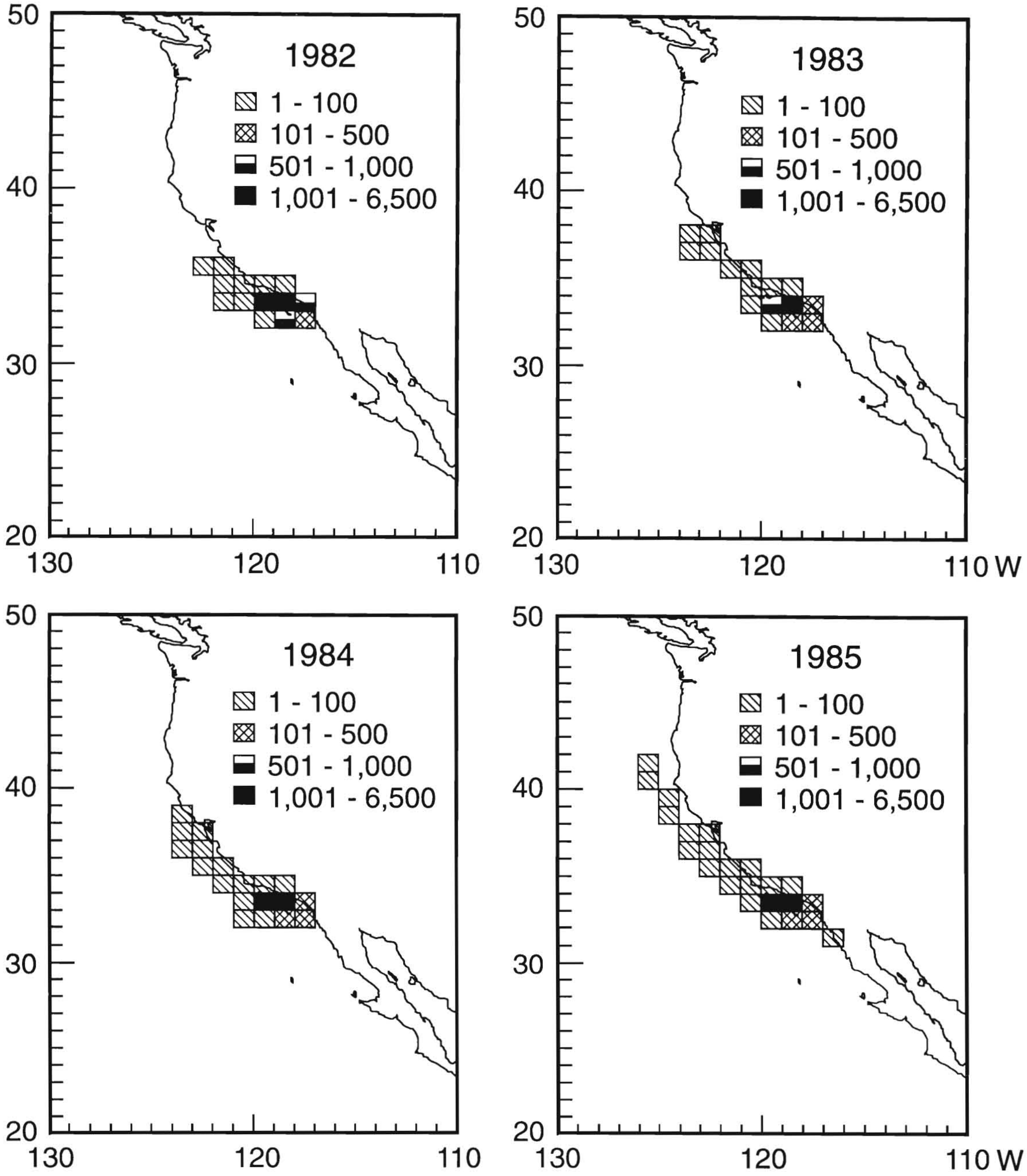

Figure 10

Typical spatial distribution of fishing effort by California harpoon fishery vessels reported in logbooks during normal fishing years, 1984 and 1985, and during a strong El Niño, 1982 and 1983. Spatial distribution of fishing effort for other years in which logbooks were collected was very similar.

mits onboard during a fishing trip, there will probably be problems in reporting of the appropriate gear. These problems could be especially frequent during periods when drift gill net swordfish landings were not allowed to exceed shark landings. Many of these problems could be alleviated and the quality of the landing statistics improved if buyers more carefully verified gear types used to capture purchased fish.

Rates of logbook data coverage are very high and therefore can be used to monitor catch rates, seasonal

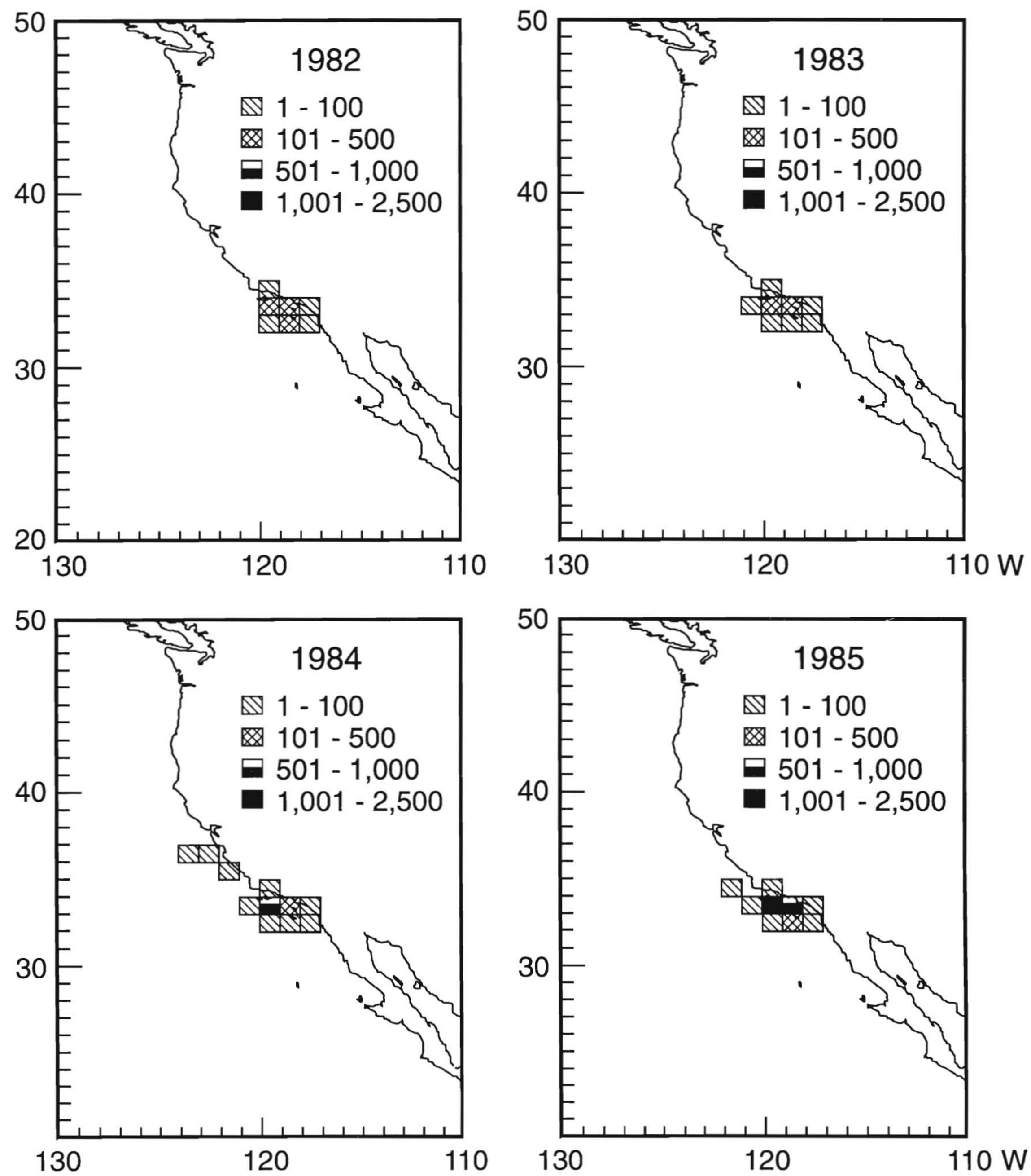

Figure 11

Typical spatial distribution of catches by California harpoon fishery vessels reported in logbooks during normal fishing years 1984 and 1985 and during a strong El Niño, 1982 and 1983. Spatial distribution of catches for other years in which logbooks were collected was very similar.

and spatial positioning of the harpoon fishery, and some environmental conditions that affect fishing success. Some confusion was noted in the reporting of weights associated with landed fish. While the vessel captains were instructed to enter their best estimates of dressed weight for each landed fish, many times these were unreasonably high and probably actually represented estimates of whole fish weight. A possible solution to this type of confusion would be to distribute an instruction section with the logbooks. An improvement in logbook recording of weights of fish landed would augment and/or verify market sampling results.

Market sampling coverage of harpoon-caught swordfish is low and leads to questions concerning the utility of size data from the sampling program. The quality of these data could be improved by establishing a formal sampling plan that began by establishing sample sizes necessary to predict lengths of swordfish caught by year, season, and geographic area.

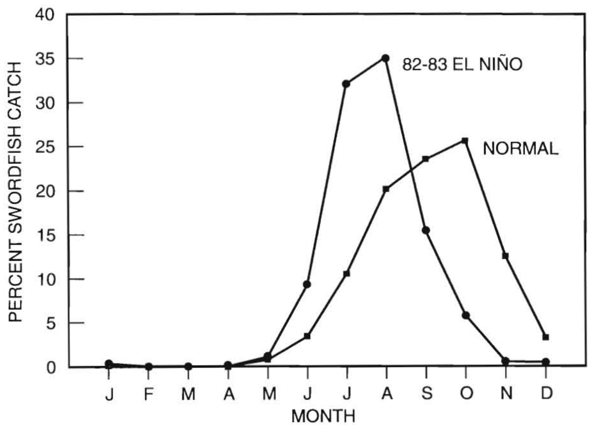

Figure 12
Proportion of swordfish catch (number of fish) by month for California harpoon fishery vessels, as reported in logbooks for 1974–93. Normal indicates fishing effort in non-El Niño years and 82-83 El Niño indicates fishing effort during the strong El Niño of 1982–83.

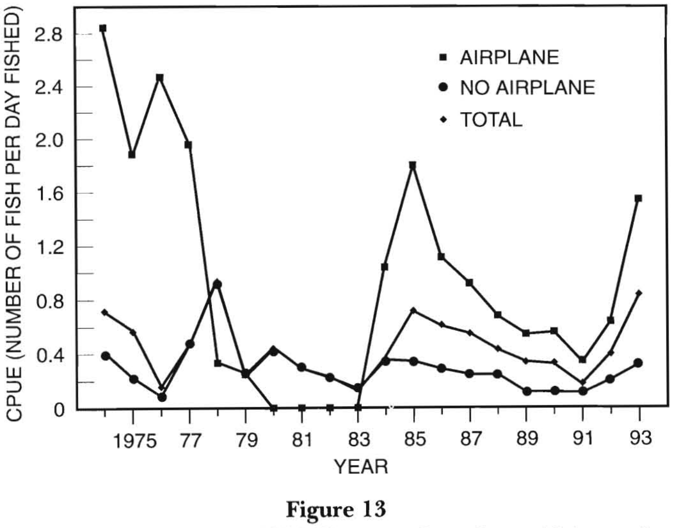

Figure 13
Catch per unit of effort (CPUE) in number of swordfish caught per day fished and per days fished with (AIRPLANE) and without (NO AIRPLANE) airplanes by California harpoon fishery vessels, as reported in logbooks for 1974–93.

The harpoon fishery is largely confined to a relatively small area, the Southern California Bight, which leaves it vulnerable to changing environmental conditions and competition from other fishing gears. The effects of environmental changes were most evident during El Niño events and resulted in decreasing catches and CPUE. Competition from the drift gill net fishery since 1980 has resulted in decreases in harpoon catches and effort. Catch rates in the drift gill net fishery are 2–3 times higher than in the harpoon fishery, drift gill net vessels use less fuel in finding and pursuing their catch, and drift gill net vessels can supplement swordfish catches with catches of sharks. It remains to be seen what effects recent increases in offshore longline fisheries will have on the harpoon fishery. Therefore, major concerns for the remaining harpoon fleet will probably be the continued availability of the resource in the Southern California Bight, and the effects of interactions between fisheries and the environment.

Because of the harpoon fishery's inability to move to other areas and increased competition from other gears, the outlook for a resurgence of the harpoon fishery seems unlikely. Recent increases in swordfish catches by the California harpoon and drift gill net fisheries (Holts and Sosa, 1994) indicate that the swordfish population may be able to support an even higher catch. However, due to the low catch rates in the harpoon fishery and the greater efficiency of the drift gill net fishery, increases in the harpoon fleet size or catch do not seem feasible (Sakagawa, 1989). Therefore, harpoon fishing will probably continue in the Southern California Bight, but as a form of fishing practiced by a handful of fishers who continue to pursue the thrill of the one-on-one hunt for swordfish.

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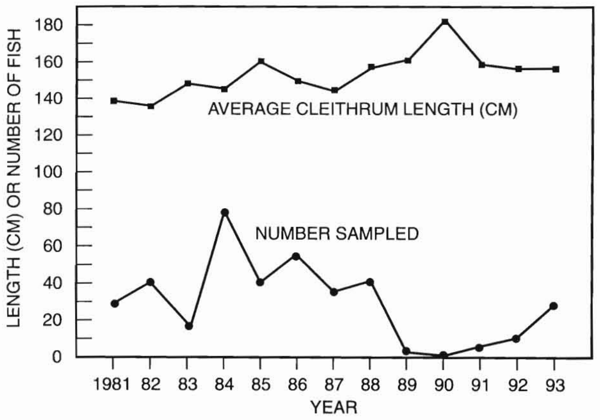

Figure 14
Number of swordfish sampled and annual estimates of average cleithrum length (cm) for swordfish caught by California harpoon fishery vessels during 1981–93.

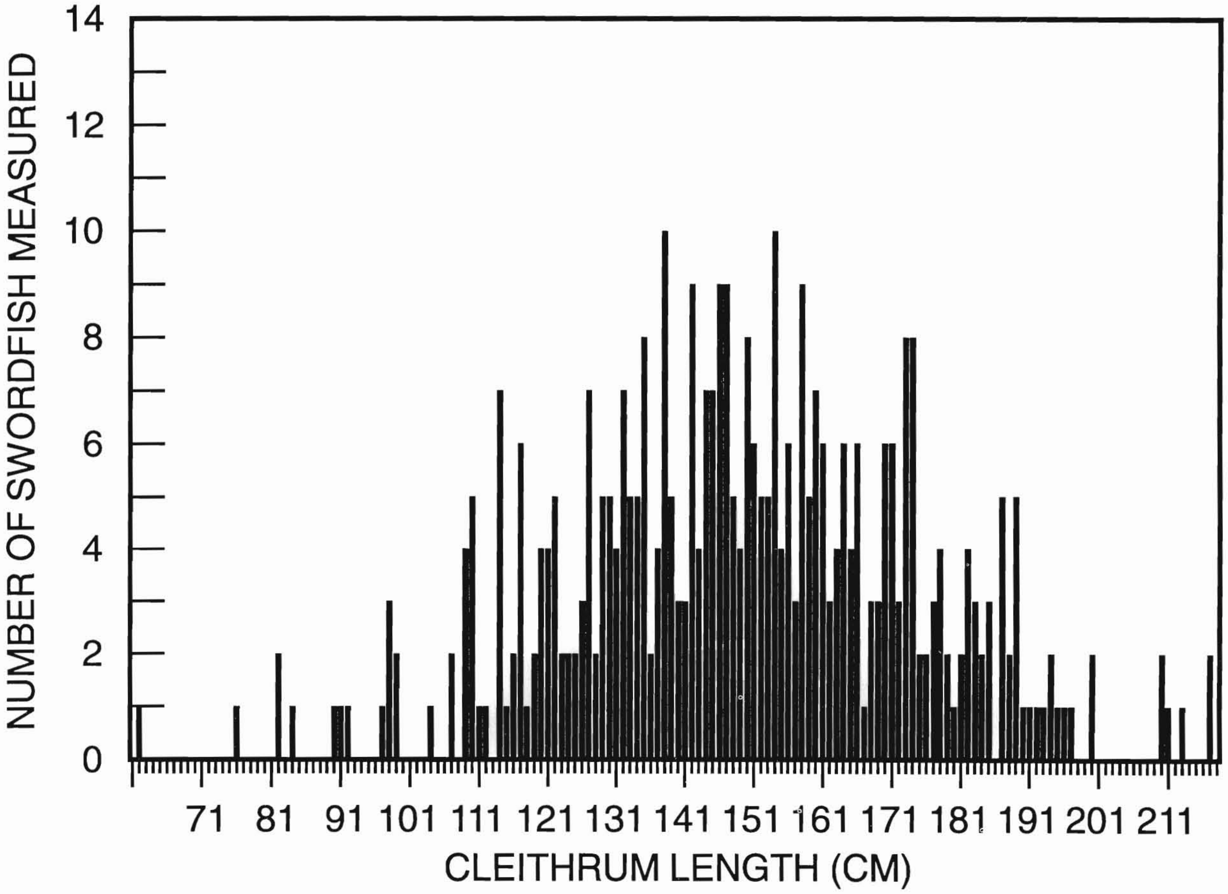

Figure 15
Size distribution (cleithrum length in cm) of swordfish sampled from California harpoon fishery vessels during 1981–93.

Spatiotemporal Dynamics of Swordfish, *Xiphias gladius*, Landings in the Hawaii-Based North Pacific Pelagic Longline Fishery[1]

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ABSTRACT

We characterize the spatial and temporal dynamics of swordfish landings in the Hawaii-based domestic North Pacific pelagic longline fishery, and develop preliminary size-based metrics of fishery performance. Between 1991 and 1993, areas of high fishing effort moved progressively north and west, concentrating in the North Pacific transition zone, along the subarctic boundary, and in the subarctic frontal zone. Annual weight-frequency distributions were characterized by high interannual variability and changing skewness and modal frequency. The observed variations in weight result from changes in fleet dynamics rather than from increasing fishing effort. The continuing decline in the number of small swordfish landed is likely confounded with changes in spatial distribution of the fleet and in landing practices. Mean swordfish weight increased and interannual variation decreased with increasing latitude.

Quarterly estimates of mean swordfish landings per unit of effort (LPUE) suggest an increasing trend accompanied by decreasing intra-annual variability and dampening of the seasonal signal. LPUE was generally higher for swordfish-targeted trips than for mixed-targeted (swordfish and tuna) trips. Between 1991 and 1993, quarterly swordfish LPUE was constant for swordfish-targeted trips (mean = 13.5 fish/1,000 hooks). Between 1991 and 1992, quarterly swordfish LPUE was constant for mixed-targeted trips (mean = 7.0 fish/1,000 hooks) before increasing to approximately 11.5 fish/1,000 hooks in 1993. In general, small swordfish contributed the least to total landings, while medium swordfish contributed the most. This pattern of size-specific contribution to total landings was generally similar in all quarters. We argue that the differences in computed performance indices are indicative of differences in fishing strategy between the two trip types.

Introduction

In this paper we characterize the spatial and temporal dynamics of swordfish, *Xiphias gladius*, landings in the Hawaii-based domestic North Pacific pelagic longline fishery (hereinafter referred to as the Hawaii longline fishery) and develop preliminary size-based metrics of fishery performance. Hawaii's longline fishery has recently experienced a period of rapid expansion and changing fishing strategy. Changes in target species, fishing methods, and areas fished characterized the recent fleet expansion.

Since its inception in the early 1900's, the Hawaii longline fishery has traditionally targeted blue marlin, *Makaira mazara*, and tunas, in particular bigeye tuna, *Thunnus obesus*, and yellowfin tuna, *T. albacares* (Boggs and Ito, 1993). However, in recent years (1989–93) the primary target of the Hawaii longline fishery has gradually shifted to swordfish, and by the end of 1990, swordfish dominated landings (by weight) in the fishery (Ito[2]).

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[1] A report of the University of Hawaii pursuant to National Oceanic and Atmospheric Administration Award no. NA37RJ0199.

[2] Ito, R. Y. 1992. Western Pacific pelagic fisheries in 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-92-15, 38 p. Honolulu Lab., SWFSC, NMFS, NOAA, 2570 Dole St., Honolulu, HI 96822-2396.

Swordfish landings increased from approximately 272 metric tons (t) in 1989 to 6,124 t in 1993 (WPRFMC[3]).

The reported increase in swordfish landings results both from a rapid increase in fishing effort directed at swordfish and from changes in the spatial distribution of fishing effort. Prior to 1989 most Hawaii longline fishing effort targeted tuna. In 1993, approximately 28.1% of Hawaii longline fishing trips exclusively targeted swordfish, 27.9% of the fishing trips targeted a mixed catch of both tuna and swordfish, and 44% of the fishing trips exclusively targeted tuna. The number of longline vessels fishing for swordfish increased from 11 in 1989 to a high of 114 in 1991 before decreasing to 88 in 1993 (Ito et al., 1998). While most swordfish fishing effort continues to occur north of the Hawaiian Archipelago, the spatial distribution of fishing effort has changed considerably. Areas of high fishing effort have continually moved farther north and west.

Albeit the magnitude of Hawaii's longline fishery is small relative to other Pacific pelagic fisheries (Neal et al., 1991), Hawaii has become a major supplier of fresh swordfish to United States (U.S.) mainland markets. Hawaii-based longliners accounted for approximately 15% of the Pacific-wide harvest and 42% of the total east-central Pacific catch (WPRFMC[4]). The rapid expansion of the Hawaii longline fishery and its increasing economic importance necessitate an understanding of the dynamics of this fishery and the sources of variability that affect indices of fishery performance. This paper is intended to address these needs by 1) describing the dynamics of the Hawaii longline fleet, 2) characterizing the size of swordfish landed in the Hawaii longline fishery from 1989 to 1993, 3) describing spatial and temporal trends in swordfish size statistics, and 4) computing size-based metrics of fishery performance and identifying factors contributing to variability in performance indices. The identification of factors affecting indices is pivotal to the estimation of standardized performance indices.

Materials and Methods

Data Collection Programs

We used data from three ongoing data collection programs in our analyses: the federal logbook program and two voluntary shoreside monitoring programs in Honolulu. Other information pertaining to changes in fishing strategy was obtained from staff of the Fisheries Monitoring and Economics Program at the Honolulu Laboratory of the National Marine Fisheries Service (NMFS), who provided important qualitative information on trends in fishing operations and fleet characteristics. A brief discussion and characterization of each data collection program follows.

Federal Logbook Program—To participate in the Hawaii longline fishery, vessels must possess a current permit and submit logbooks of daily fishing activity. The federally mandated longline fishing logbook system was implemented in November 1990 and requires fishermen to submit logbooks to the NMFS Honolulu Laboratory within 72 hr after a catch is off-loaded. Data provided by logbooks include gear configuration, fishing position (latitude and longitude), time, and catch for each longline set within a trip. When the logbook data are edited by the NMFS, each logbook trip is assigned a trip number and target-species trip type (swordfish, tuna, or mixed-species—swordfish and tuna) based on examination of the logbook data and interviews with the vessel captain or deck boss. When the captain is unavailable, trip type is determined by analyzing the times of the sets, the number of light sticks used, the area fished, type of gear fished, and previous information on trip type for that particular vessel. Operational characteristics of each trip type are outlined in Table 1. The assigned trip type designation applies to all longline sets within a trip and is indicative of a unique fishing strategy. A thorough description of the logbook system is found in Dollar and Yoshimoto.[5]

Shoreside Monitoring Programs—Voluntary shoreside monitoring is conducted at four sites on Oahu. Because

Table 1

Reported operational characteristics of the Hawaii-based North Pacific longline fishery. The ranges represent the 25% and 75% quartiles.

	Trip type		
	Swordfish	Mixed	Tuna
Hooks	650–800	900–1,020	1,000–1,560
Light sticks	400–850	120–360	0
Set duration (hr)	12–14	11–12	8–10
Sets	9–12	5–7	7–9

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[3] Western Pacific Regional Fishery Management Council (WPRMFC). 1994. Pelagic fisheries of the western Pacific region: 1993 annual report, 158 p. Western Pac. Reg. Fish. Manage. Counc., 1164 Bishop St., Ste. 1405, Honolulu, HI 96813.

[4] Western Pacific Regional Fishery Management Council (WPRFMC). 1994. Amendment 7 to the fishery management plan for the pelagic fisheries of the western Pacific region. Proposed limited entry program for the Hawaii longline fishery, 278 p. Western Pac. Reg. Fish. Manage. Counc., 1164 Bishop St., Ste. 1405, Honolulu, HI 96813.

[5] Dollar, R. A., and S. S. Yoshimoto 1991. The federally mandated longline fishing log collection system in the Western Pacific. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-91-12, 35 p. Honolulu Lab., SWFSC, NMFS, NOAA, 2570 Dole St., Honolulu, HI 96822-2396.

of rules governing the confidentiality of these data, the site identities will remain anonymous. For purposes of this study the sites have been grouped into two homogeneous categories, dealer A and dealer B.

Monitoring of dealer A for pelagic species commenced in 1987 and was initially administered by the NMFS Honolulu Laboratory. Monitoring in recent years was facilitated through a joint effort by NMFS and the State of Hawaii Division of Natural Resources (HDAR). Monitoring of dealer B commenced in 1989. Data are provided to NMFS by the dealer, and the NMFS Honolulu Laboratory is responsible for program administration.

Data collected in the shoreside monitoring programs include fishing area, date of sale, vessel identification, the weight of each lot sold, the number of fish per lot, price per pound paid for each lot (not provided in the dealer B monitoring program), and dressed condition (i.e. headed, gutted, and tailed) of fish sold in each transaction. For swordfish, a lot generally consists of one fish. In those instances when a lot is two or more fish, all fish are generally of similar size.

Data Integration and Adjustments

The federal logbook program provides fishing strategy, catch, and effort data, while the shoreside monitoring programs provide landings, size composition, and economic data. We integrated data from the data collection programs to provide a more complete description of trip events, using a two-step process. First, trips that targeted tuna were deleted. Then, by referencing on vessel permit number, the remaining strategy and economic data were integrated to create a vessel-specific transaction file. The logbook program routinely collects vessel permit numbers for each longline set, but the shoreside monitoring programs do not. However, the monitoring programs do record fishing vessel names and corresponding vessel code numbers, which enabled us to reference the vessel permit numbers. (Vessel code number is a unique vessel identification number assigned to each vessel which off-loads at either dealer A or dealer B.)

In the second step, we matched records in the vessel-specific transaction file with specific trips reported in logbooks. This was accomplished by creating vessel-specific landing intervals (time periods) from logbook data, associating a trip number with each interval, and assigning records from the vessel-specific transaction file to the appropriate intervals. A landing interval represents the window of opportunity for the landing and selling of swordfish from each trip. The beginning of the interval was assigned the hauling date of the last longline set of trip *n*, and the end of the interval was assigned the date of the first longline set of trip *n* + 1. Records from the vessel-specific transaction file assigned to an interval assumed the interval trip number, *n*.

Table 2

Monthly sampling coverage of pelagic species landings at dealer A, 1989–93.

	Sampling coverage (%)				
	1989	1990	1991	1992	1993
January	82.6	78.3	81.8	52.2	17.4
February	79.2	79.2	79.2	52.0	16.7
March	85.2	92.6	80.8	50.0	18.5
April	80.0	92.0	84.6	46.2	15.4
May	81.5	92.6	81.5	57.7	15.4
June	84.6	96.2	80.0	53.8	19.2
July	88.0	96.0	84.6	57.7	15.4
August	85.2	96.3	81.5	38.5	38.5
September	80.0	91.7	83.3	52.0	28.0
October	84.6	96.3	77.8	51.9	30.8
November	84.0	88.0	76.0	45.8	36.0
December	84.6	88.9	92.6	28.6	36.0

The average position of a trip, used as a measure of fishing position, was calculated from logbook data by weighting reported longline set position (latitude and longitude) by the reported catch of swordfish. All records from the vessel-specific transaction file were matched with logbook data; the maximum time between date of last haul and sales date was 10 days.

For purposes of this study, fishery performance, expressed as mean landings per unit of effort (LPUE; number of fish landed/1,000 hooks), and weight-based performance indices were computed using data collected at dealers A and B. While data sufficient to compute catch-per-unit-effort are collected in the logbook program, we chose not to use this measure of fishing performance.

We restricted our analysis to those samples in which swordfish were sold either whole or dressed, i.e. headed, gutted, and tailed. These two market conditions accounted for approximately 95% of all swordfish sold. Dressed weight (DW) in kg was converted to round weight (RW) in kg using the formula $RW = 1.877(DW)^{0.925}$, developed on the basis of measurements of 172 decked swordfish collected during voluntary swordfish longline observer and research vessel cruises between 1990 and 1993.

Sampling coverage at dealer A decreased over time. Accordingly, length frequency data were adjusted upward to reflect a coverage rate of 100%. Between 1989 and 1991, monthly coverage at dealer A ranged from 76% to 96% (Table 2). Monthly coverage was 29%–58% and 15%–38% in 1992 and 1993, respectively. Between 1990 and 1993 annual sampling coverage at dealer B varied from 62% to 91% (Table 3).

Table 3
Annual sampling coverage of pelagic species landings at dealer B, 1990–93.

Year	Sampling coverage (%)	Year	Sampling coverage (%)
1990	90.6	1992	62.4
1991	69.5	1993	83.2

Table 4
Swordfish sampled in Hawaii shoreside monitoring program by dealer, 1989–1993.

	Swordfish samples		
	Dealer A	Dealer B	Total
1989	2,966	66	3,032
1990	17,505	5,591	23,096
1991	34,078	12,078	46,156
1992	22,263	12,194	34,457
1993	11,190	20,059	31,249
Total	88,002	49,988	137,990

RW frequency distributions of sampled swordfish were adjusted by multiplying the number of fish in the lot by either the ratio of total number of possible monitoring days to the number of days monitored for each month (dealer A), or the ratio of total number of trips offloaded to the total number of trips monitored in that year (dealer B).

Results

Fishing Effort Distribution

During 1991–93, areas of higher fishing effort continually moved farther north and west, as shown in Figure 1. Levels of fishing effort—low, medium, and high—are based on quartile decomposition of the fishing-effort frequency distribution. Low represents the first quartile, high the fourth quartile, and medium the second and third quartiles. In 1991, much of the fishing effort was oriented in a north–south direction near the main Hawaiian Islands. By 1993, fishing effort shifted to a northwest–southeast orientation, with increased fishing effort to the northwest. This shift was particularly evident in quarters 3 and 4.

Shifts in the distribution of target-species trip types were also observed (Fig. 2). Much of this shift resulted from a significant northwestward movement of vessels targeting swordfish, particularly in quarters 3 and 4 of 1993. Data collected at dealers A and B show similar differences in fishing effort by target-species trip type (Fig. 3). Vessels off-loading at dealer B primarily targeted swordfish (~93% of trips) while vessels off-loading at dealer A generally targeted a mixed catch (~75% of trips), implying a difference in fishing strategy according to dealer.

Swordfish Size Dynamics

Between 1989 and 1993, 137,990 swordfish were sampled at dealers A and B (Table 4). The percent-frequency size distribution of swordfish landed in the fishery is characterized by high intra-annual variability and changing skewness and modal frequency (Fig. 4). Whereas the descending (right) tails of the distributions appeared similar over time, the ascending (left) tails showed a declining trend in the number of small swordfish being landed, a difference that proved to be significant (2-sample Kolmogorov-Smirnov test; $P<0.05$). Between 1989 and 1993, the mean RW of landed swordfish increased from 48.0–68.0 kg (Fig. 5).

Latitudinal distribution of mean swordfish RW is depicted in Figure 6. Data between the equator and 49°N were pooled across years and stratified into 10° latitudinal bins. Mean swordfish RW decreased from 52 to 35 kg between latitudinal bins 1 (0°–9°N) and 2 (10°–19°N), then increased to a maximum mean RW of 97 kg in bin 5 (40°–49°N). Variability was minimal in latitudinal bin 1, increased to a maximum in latitudinal bin 3, than decreased with increasing latitude. Similar trends in the mean and variation of RW by latitudinal bin were observed annually.

Monthly mean RW by latitudinal bin is shown in Figure 7. Intra-annual variation in mean RW within bins decreased with increasing latitude. However, it should be noted that the number of samples also decreased with increasing latitude. The large seasonal variation of mean RW observed in bin 3 suggests seasonal movement into and out of that bin. However, temporal sampling in adjacent bins was sparse, and migration patterns could not be inferred.

Landed swordfish were generally larger for vessels targeting swordfish compared to vessels targeting a mixed catch (Fig. 8). Similar size differences by target-species trip type were observed annually and quarterly.

Swordfish Landings Per Unit of Effort

Quarterly swordfish mean LPUE (hereinafter referred to as LPUE) from 1991 to 1993 is shown in Figure 9. An increasing trend in LPUE is suggested, accompanied by

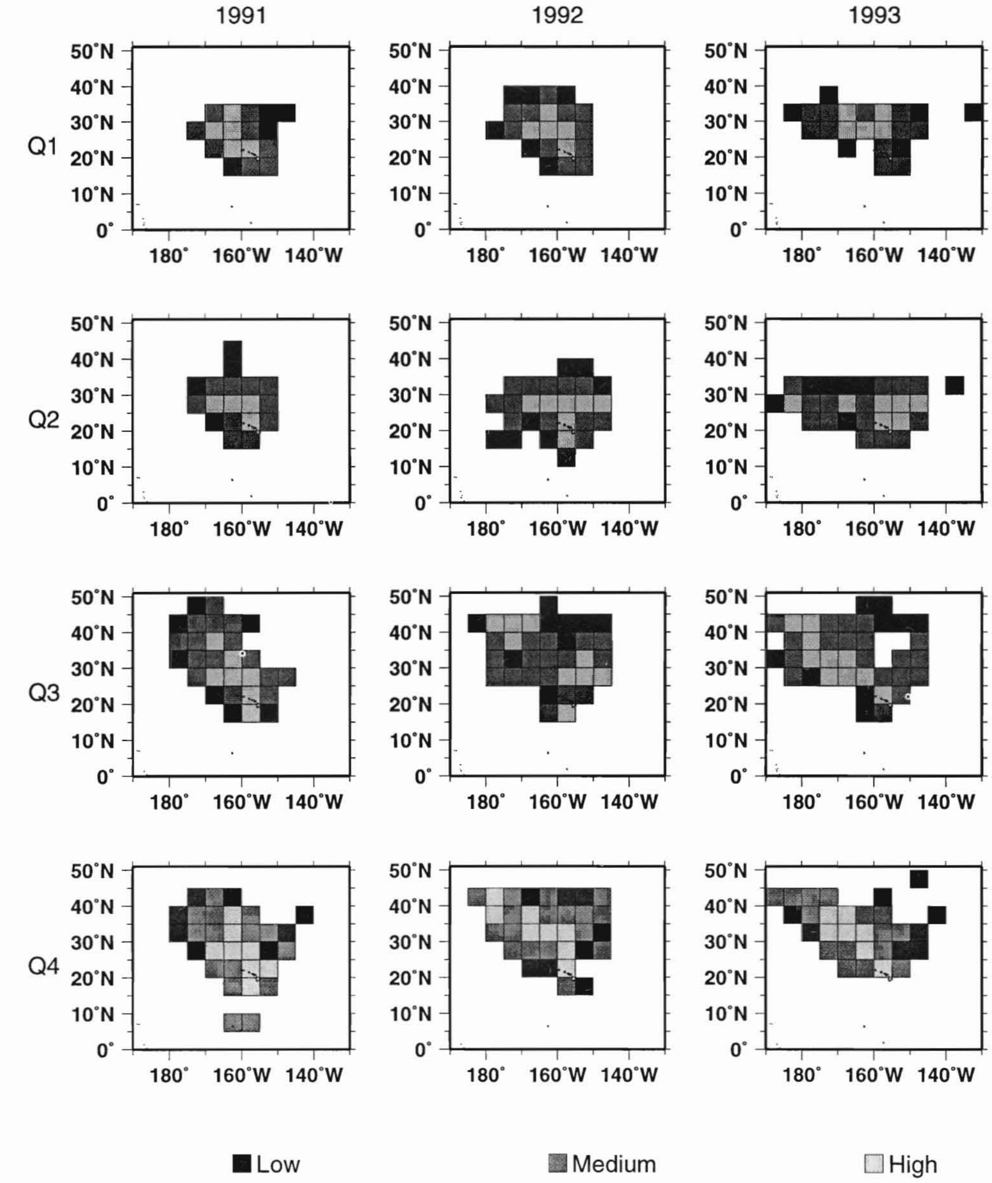

Figure 1
Quarterly (Q1–Q4) distribution of fishing effort by 5° × 5° square in the Hawaii longline fishery, 1991–93.

decreasing intra-annual variability and modulation of the seasonal signal. During 1991 and 1992, seasonal signals were similar: swordfish LPUE was greatest in quarters 1 and 2 and lowest in quarters 3 and 4. In 1993, quarterly LPUE's were similar, exhibiting little seasonality.

The quarterly LPUE time series was decomposed into two target-species trip type series: swordfish and mixed (Fig. 10). Quarterly swordfish LPUE for swordfish-targeted trips was generally higher than that for mixed-target trips and showed no apparent trend (mean = 13.5 fish/1,000 hooks). Between 1991 and 1992, quarterly swordfish LPUE for mixed-target trips showed no apparent trend (mean = 7.0 fish/1,000 hooks). In 1993, however, quarterly swordfish LPUE for mixed-target trips increased to 13 fish/1,000 hooks in quarter 1 before declining to approximately 9 fish/1,000 hooks in quarter 4. Seasonality was apparent in the mixed-target LPUE series, but not in the swordfish-targeted series. LPUE was higher during the first half of the year and lower in the second half of the year.

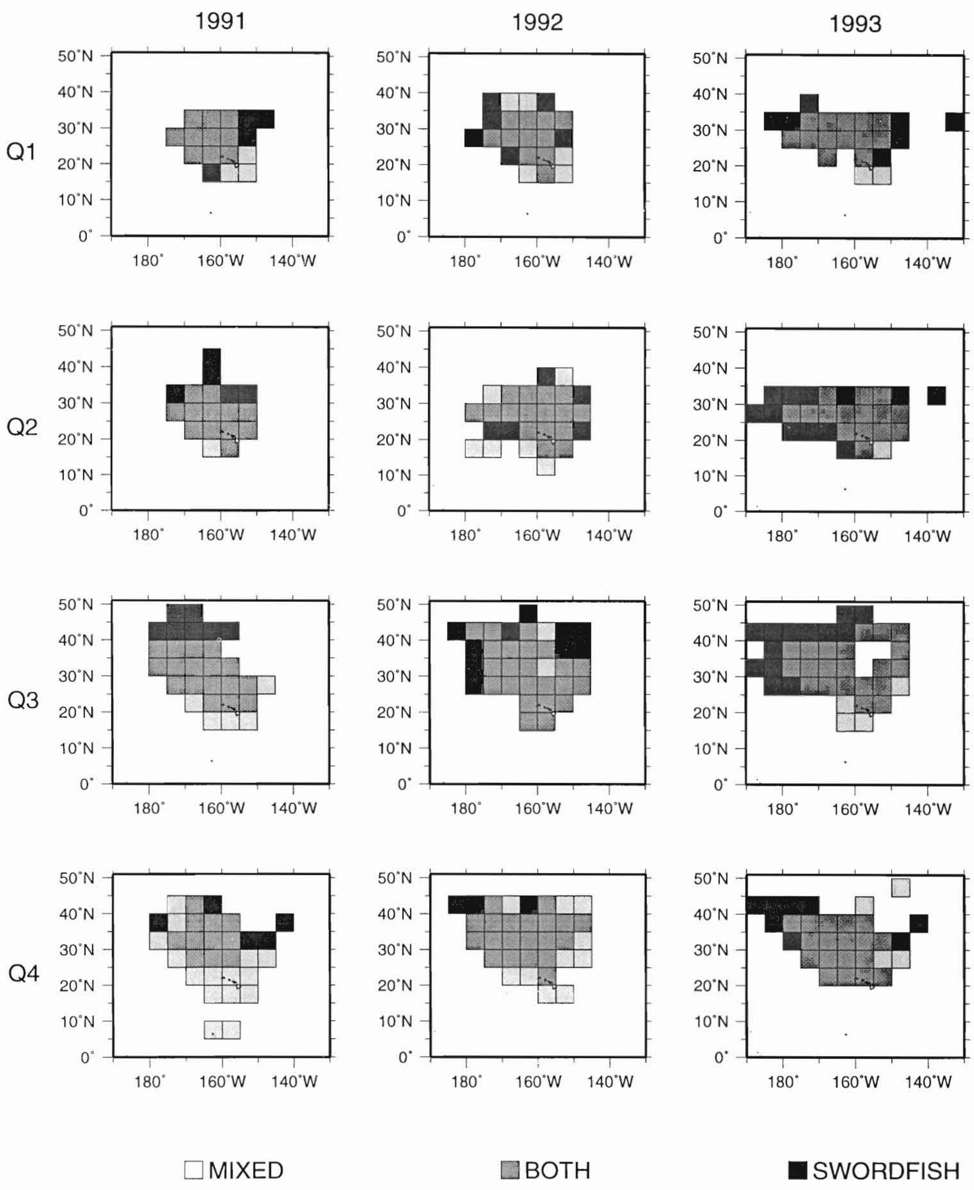

Figure 2

Quarterly (Q1–Q4) presence–absence distribution of target-species trip types by 5° × 5° square in the Hawaii longline fishery, 1991–93. Mixed = trips targeted on both swordfish and tuna; Both = both swordfish- and tuna-targeted trips.

The time series of quarterly LPUE by target-species trip type was further decomposed into three size-group series (Fig. 11, 12). The size groups small, medium, and large were identified from the cumulative distribution function (CDF) of swordfish weight data (1989–93), each representing one-third of the total swordfish sample. The small size group includes swordfish ≤30 kg, medium includes swordfish >30 kg and ≤100 kg, and large includes swordfish >100 kg. Size-group-specific LPUE series for mixed-target trips exhibit similar seasonal behavior and no apparent trend (Fig. 11). However, the relative contribution of each size group varied quarterly. During 1991 and 1992, quarterly LPUE was generally similar for different sizes of swordfish, particularly for small and large fish. In 1993, quarterly LPUE increased for medium and large fish, as did the relative contribution from medium swordfish, which dominated landings.

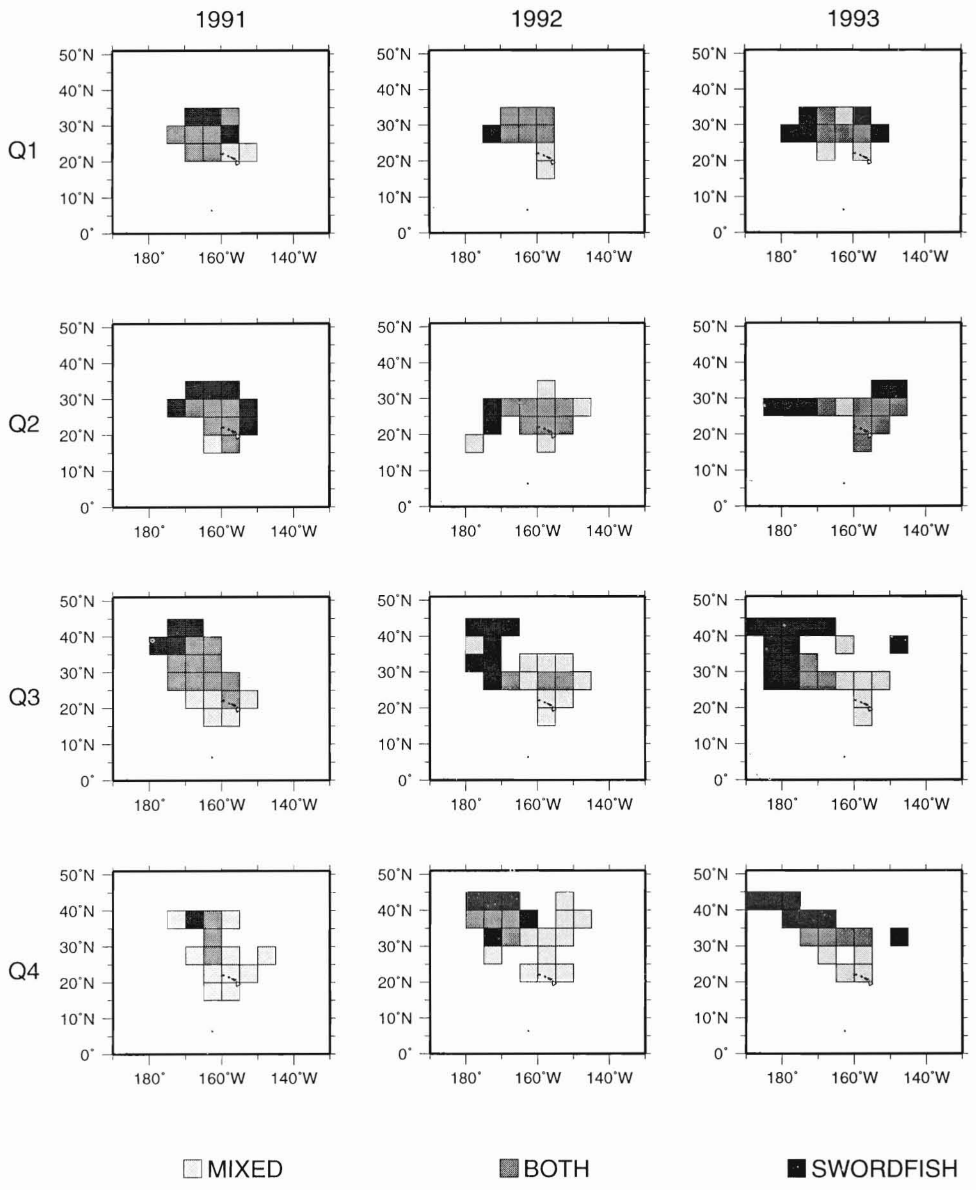

Figure 3

Quarterly (Q1–Q4) presence–absence distribution of sampled target-species trip types by 5° × 5° square in the Hawaii longline fishery, 1991–93. Mixed = trips targeted on both swordfish and tuna; Both = both swordfish- and tuna-targeted trips.

The quarterly LPUE series for medium and large swordfish caught on swordfish-targeted trips are similar and are characterized by high intra-annual variability and an increasing trend (Fig. 12). Quarterly LPUE's for small swordfish caught on swordfish-targeted trips are characterized by low inter- and intra-annual variability and a decreasing trend. Highest landing rates are associated with medium swordfish, followed by large and small swordfish. A comparison of size-group LPUE series suggests that swordfish-targeted trips generally have higher landing rates for medium and large swordfish. In contrast, LPUE for small swordfish is similar for the two target-species trip types.

These size groups (small, medium, and large) do not have biological meaning, but were derived from the CDF of swordfish RW. To help determine biological impacts of the fishery, we estimated quarterly LPUE series for mature and immature swordfish. We assumed a size at maturity of 60 kg for both sexes (Skillman, 1998). Sixty kg is the reported size at maturity for

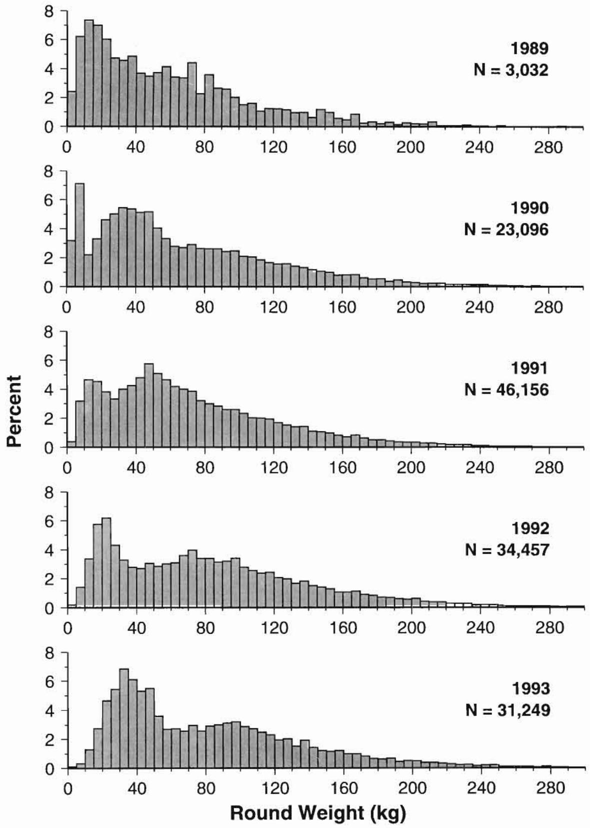

Figure 4
Annual percent-frequency distribution of round weight of swordfish landed in the Hawaii longline fishery, 1989–93.

female swordfish in the Pacific Ocean; male swordfish mature at a smaller size. Therefore, 60 kg represents an upper limit.

Quarterly swordfish LPUE by stage of maturity is shown in Figure 13 for all trips combined. The series for mature swordfish suggests an increasing trend. Quarterly LPUE for immature swordfish decreased from 1991 to 1992, before increasing in 1993.

Quarterly LPUE's for mature and immature swordfish caught on mixed-target trips are characterized by similar increasing trends and seasonal signal (Fig. 14). LPUE was generally higher during the first half of each year. Quarterly LPUE for mature swordfish caught on swordfish-targeted trips is characterized by high intra-annual variability and increasing trend; it was generally higher than that for immature swordfish (Fig. 15). Quarterly immature LPUE decreased from approximately 8.5 fish/1,000 hooks in 1991 to 3.25 fish/1,000 hooks in 1992, before increasing to a mean of 5.0 fish/1,000 hooks in 1993.

Quarterly mature swordfish LPUE was generally higher for swordfish-targeted trips than for mixed target

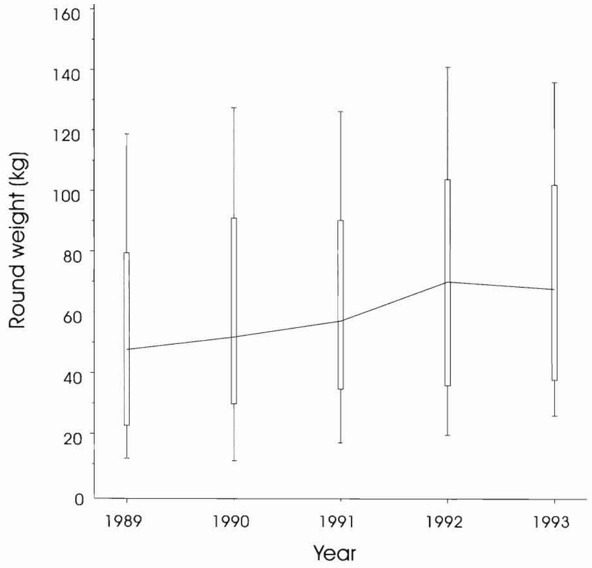

Figure 5
Annual mean round weights of swordfish landed in the Hawaii longline fishery, 1989–93. The bottom and top edges of the boxes mark the sample 25th and 75th percentiles. The whiskers extend to the sample 10th and 90th percentiles. The line connecting the box plots is drawn at the means.

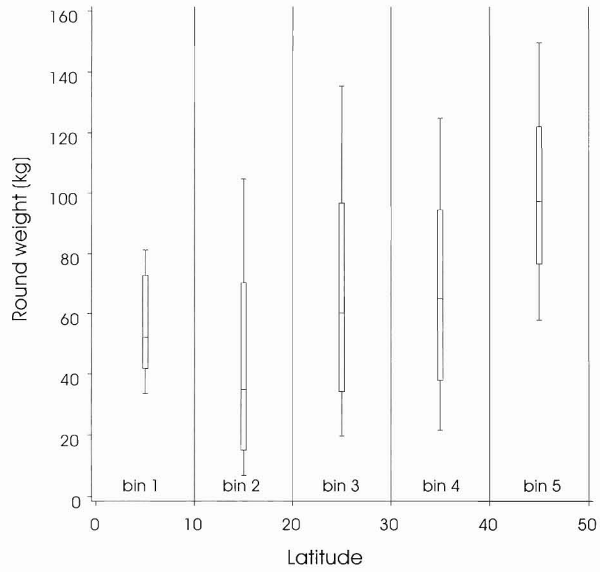

Figure 6
Latitudinal distribution of swordfish round weight. The bottom and top edges of the boxes mark the sample 25th and 75th percentiles. The whisker ends mark the sample 10th and 90th percentiles. The horizontal lines are drawn at the means.

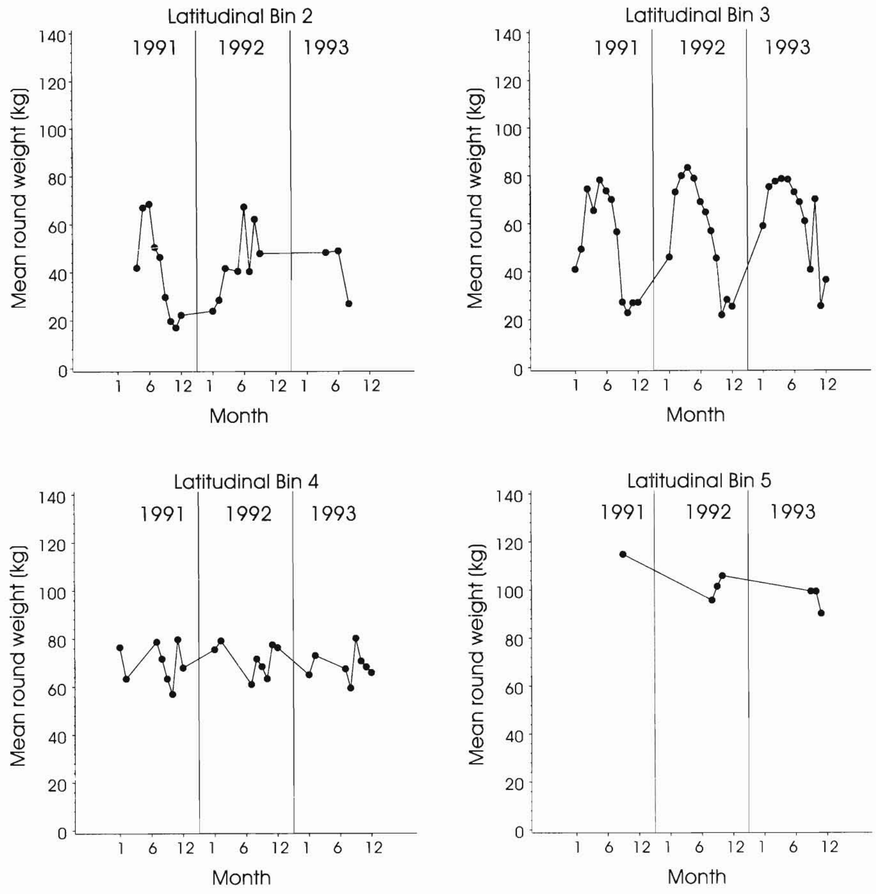

Figure 7

Monthly mean swordfish round weight by latitudinal bin.

trips (Fig. 14, 15). In contrast, quarterly LPUE for immature swordfish was similar for the two target-species trip types.

Discussion

Fleet and Fishing Effort

Changes in the spatial distribution of fishing effort characterized the recent expansion of the Hawaii longline fishery. Areas of high fishing effort moved progressively north and west, concentrating in the North Pacific transition zone, along the subarctic boundary, and in the subarctic frontal zone. Much of this change likely resulted from a combination of factors including vessel characteristics and learning. Vessel characteristics relate to a vessel's capacity for distant-water operations, i.e. self-sufficiency, on-board technology, and seaworthiness. During the summer and fall months when vessels are fishing in the northwestern areas, a fishing trip could last from 4 to 8 weeks, with 10 days for travel to and from the fishing grounds. Because of the long distances traveled and extended periods away from port, only vessels able to produce ice, that have advanced on-board technology for navigation and locating fish, and capable of performing most emergency repairs at sea tend to fish in the northwestern areas.

The observed difference in spatial distribution of trips targeted on different species illustrates the effects of fleet characteristics on spatial distribution of fishing effort. We have shown that vessels targeting swordfish accounted for much of the northwestward movement of fishing effort. Prior to participating in the Hawaii longline fishery, many of these longline vessels fished for swordfish in the Atlantic Ocean and for salmon and crabs in the northwest Pacific Ocean. These vessels are generally capable of producing saltwater ice at sea, are equipped with a full array of electronics equipment such as radar and Doppler, carry spare parts for most

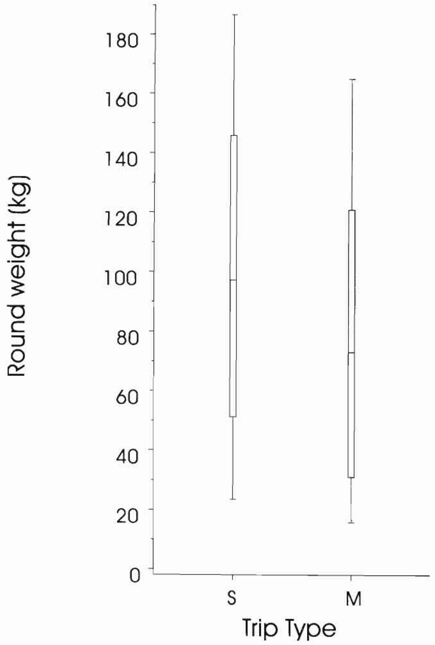

Figure 8
Swordfish round weight by target-species trip type for all years combined, 1991–93. Box plots as in Figure 6. S = swordfish-targeted trip, M = mixed-target trip.

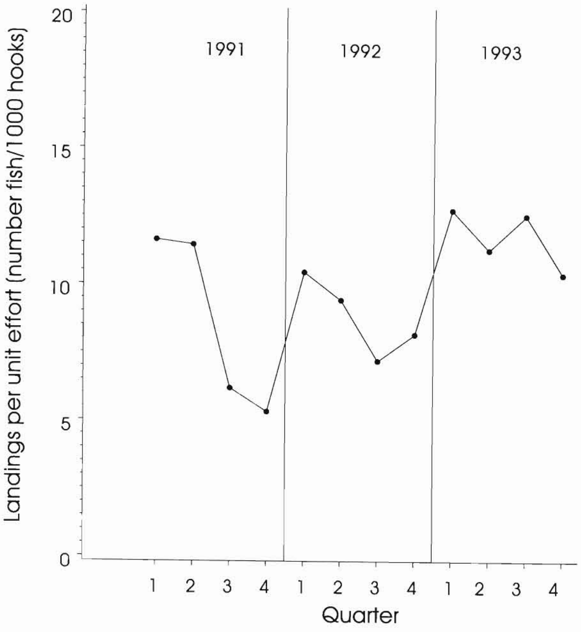

Figure 9
Quarterly swordfish landings per unit effort in the Hawaii longline fishery, 1991–93.

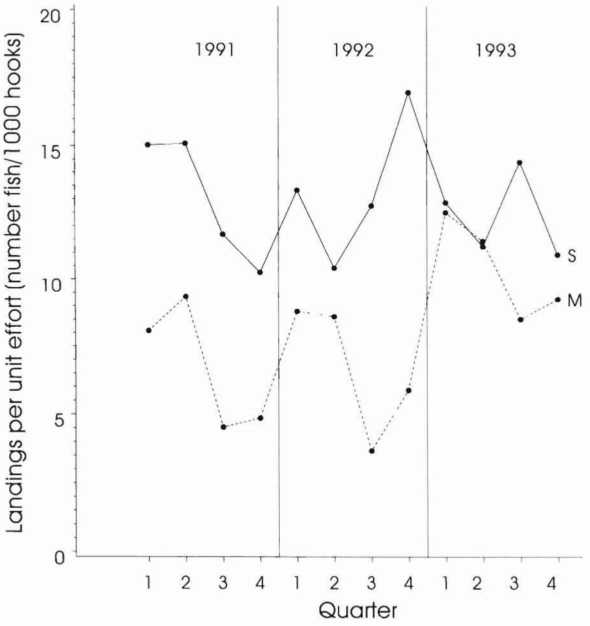

Figure 10
Quarterly swordfish landings per unit effort by target-species trip type in the Hawaii longline fishery, 1991–93. S = swordfish-targeted trip and M = mixed-target trip.

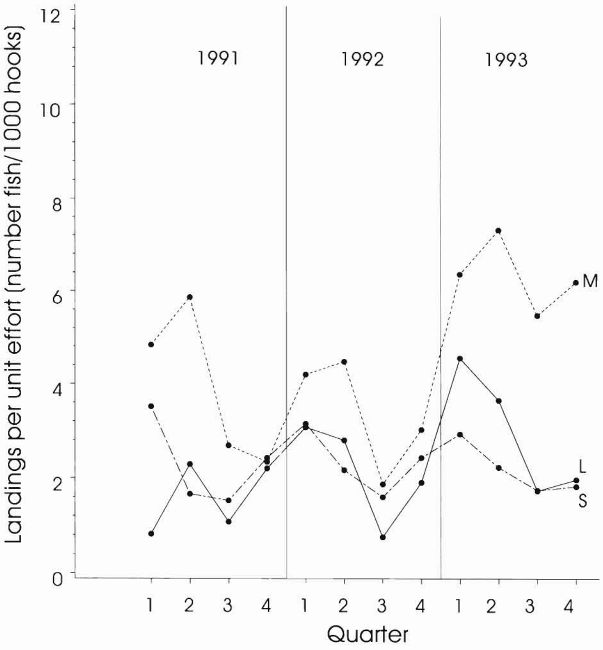

Figure 11
Quarterly size-specific swordfish landings per unit effort for mixed-target trips in the Hawaii longline fishery, 1991–93. L = large swordfish; M = medium swordfish; S = small swordfish.

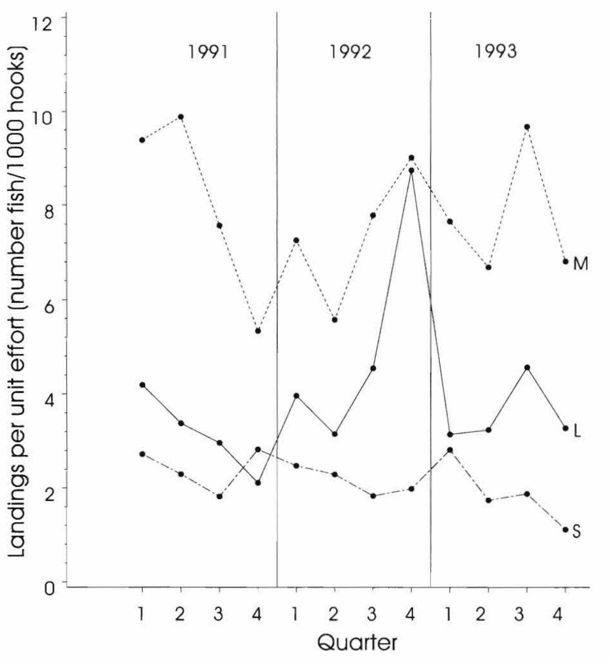

Figure 12
Quarterly size-specific swordfish landings per unit effort for swordfish-targeted trips in the Hawaii longline fishery, 1991–93. L = large swordfish; M = medium swordfish; S = small swordfish.

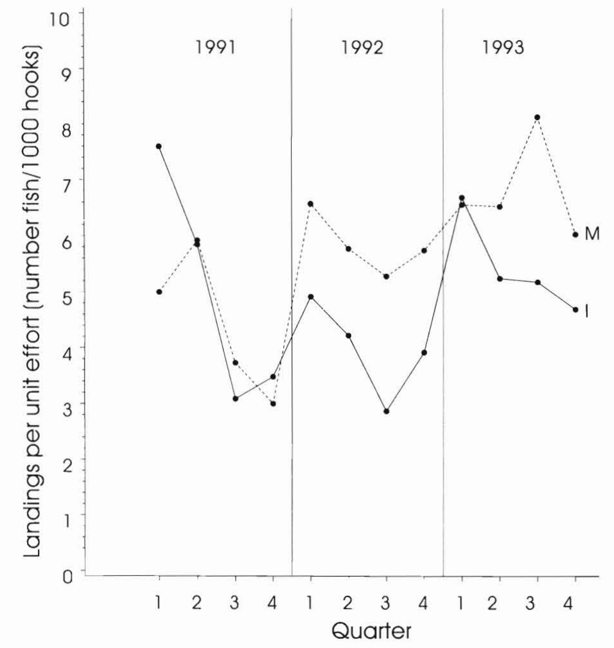

Figure 13
Quarterly swordfish landings per unit effort in the Hawaii longline fishery, 1991–93, by maturity phase. M = mature and I = immature swordfish.

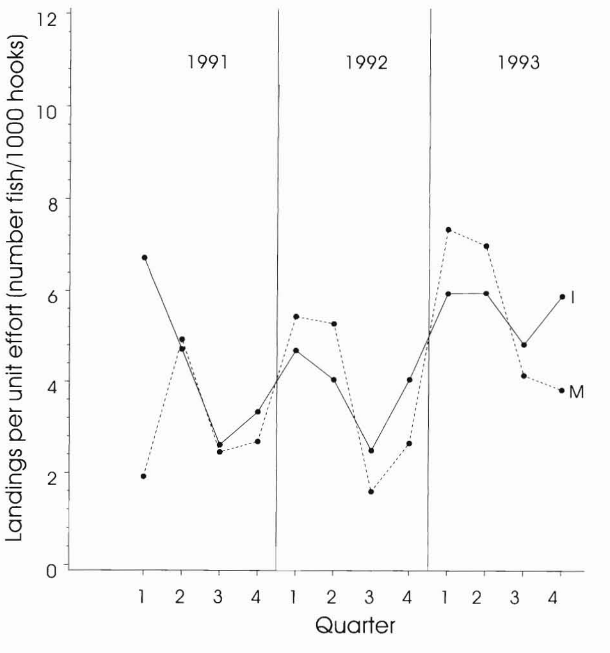

Figure 14
Quarterly swordfish landings per unit effort for mixed-target trips in the Hawaii longline fishery, 1991–93, by maturity phase. M = mature and I = immature swordfish.

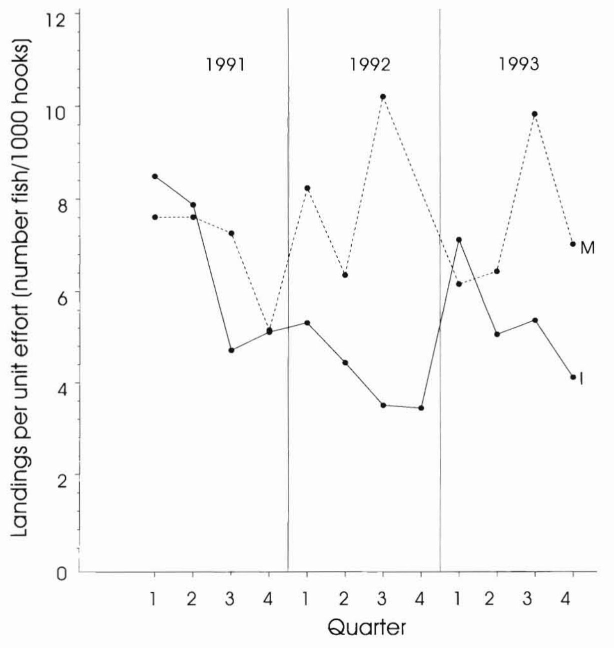

Figure 15
Quarterly swordfish landings per unit effort for swordfish-targeted trips in the Hawaii longline fishery, 1991–93, by maturity phase. M = mature and I = immature swordfish.

on-board electronics and mechanical equipment, and are more seaworthy than vessels targeting a mixed catch (Dollar[6]). In contrast, many of the vessels targeting a mixed catch are converted shrimp trawlers from the Gulf of Mexico or small and medium-sized local vessels, and are generally not designed for distant water operations. Many of these vessels are not capable of producing ice and lack on-board electronic equipment (Ito[7]). Some exceptions nonetheless exist.

Distributional changes in fishing effort based on learning result from longliners becoming increasingly familiar with large-scale persistent oceanographic features. The North Pacific transition zone, subarctic boundary, and subarctic frontal zone are three such features. These areas are characterized by multiple fronts (rapid changes in sea-surface temperature or salinity) with high productivity and distinct endemic species of nekton (Mishima, 1981; Pearcy, 1991; Roden, 1991). Squid, the primary prey of swordfish (Stillwell and Kohler, 1985; Bello, 1991), are known to form dense seasonal concentrations in these areas (Sinclair, 1991). One of the more abundant species of squid endemic to the North Pacific Ocean is the neon flying squid, *Ommastrephes bartramii* (Pearcy, 1991).

Between 1991 and 1993, longline fishing effort gradually moved north and west, with high concentrations in the North Pacific transition zone, along the subarctic boundary, and in the subarctic frontal zone. The seasonal distribution of fishing effort in 1993 was similar to the typical seasonal distribution of neon flying squid (Sinclair, 1991; Gong et al., 1993; Murata and Hayase, 1993).

While the similarity in seasonal distributions suggest a possible biological link, Hawaii longliners at best indirectly target squid concentrations. Longline vessels actively search for thermal fronts, where they set the gear.[8] Podestá et al. (1993) found higher swordfish catch rates in the vicinity of thermal fronts, but did not have enough data to link the higher catch rates to other physical or biological factors associated with frontal regimes. However, concentrations of neon flying squid are higher near thermal fronts (Gong et al., 1993) which in turn may attract swordfish.

It has been suggested that spatial targeting by Hawaii longliners may have been influenced by interactions with vessels participating in the North Pacific high-seas drift gillnet fishery (Travis[9]). Reportedly, some longliners would observe the operations of drift gillnet vessels and set their gear in areas associated with large catches. Presently it is not clear if longliners used drift gillnet vessels to identify concentrations of squid, swordfish, or the location of thermal fronts, but the reported commensalism represents an interesting form of fishery interaction.

Swordfish Size Dynamics

The observed annual variations in swordfish weight composition (Fig. 4) most likely result from changes in fleet dynamics rather than from increased fishing effort. The continuing decline in the number of small swordfish landed is probably confounded with changes in spatial distribution of the fleet and in landing practices. As the fleet moved farther west and north, the size of landed swordfish increased. Because larger swordfish receive a higher unit price than smaller swordfish, there is an economic incentive to land only the larger fish (Ito et al., 1998). Thus, small swordfish, which were traditionally landed, are caught less frequently due to the northwestward movement of the fleet, and are often discarded for economic reasons.

Although data to compute swordfish discard rates are collected through the logbook program, weight of each swordfish caught is not recorded. Only average annual discard rates, pooled over all sizes, can be estimated (4.4%–6.6%). However, these rates will be confounded with recent changes in fishing strategy (increased targeting of larger swordfish by longliners and shifting spatial distribution of fishing effort) and most likely underestimate discard rates for small swordfish.

The northwestward movement of fishing effort, and subsequent increase in size of swordfish landed, will affect the sex ratio of landed swordfish. Results from Kume and Joseph (1969) in the Pacific Ocean and Lee and Arocha (1993) in the Atlantic Ocean show that larger swordfish tend to be female. While there are no recent swordfish sex-ratio data from the Pacific Ocean, we have no reason to believe that larger swordfish landed in the Hawaii longline fishery are not mainly females.

We have shown that intra-annual variation in mean RW decreases with increasing latitude (Fig. 6). Moreover, intra-annual variability in monthly mean RW within latitudinal bins decreased with increasing latitude, with significant seasonal variation in mean RW in bin 3 (Fig. 7). These results, although limited in scope, suggest seasonal movement of swordfish in the North Pacific Ocean. However, the direction of movement (north–

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[6] Dollar, R. 1994. Honolulu Lab., SWFSC/NMFS/NOAA, 2570 Dole St., Honolulu, HI 96822-2396. Personal commun.

[7] Ito, R. Y. 1994. Honolulu Lab., SWFSC/NMFS/NOAA, 2570 Dole St., Honolulu, HI 96822-2396. Personal commun.

[8] Fishery Monitoring and Economics Program, Honolulu Lab., Southwest Fisheries Science Center, NMFS, NOAA, Honolulu, HI 96822-2396. Unpublished data.

[9] Travis, M. 1994. JIMAR, Univ. Hawaii, 1000 Pope Rd., Honolulu, HI 96822. Personal commun.

south, east–west, or some combination) cannot be inferred from existing data. While tagging studies in the Atlantic Ocean suggest north–south movement patterns (Berkley, 1989), additional data are required before migration patterns in the Pacific Ocean can be identified.

Indices of Fishery Performance

Fishing for swordfish in the Hawaii longline fishery is a recent phenomenon. The increasing trend in quarterly LPUE (Fig. 9), accompanied by decreasing intra-annual variability and modulation of the seasonal signal, exemplifies the effects of learning by longliners in a developing fishery. Prior to 1993 the catch of swordfish was seasonal: higher landing rates in the first and second quarters, followed by lower rates in the third and fourth quarters. By 1993, however, seasonality in swordfish landings disappeared. Swordfish were being landed at similar rates throughout the year, suggesting a change in fishing strategy. We hypothesize that change in strategy to be the exploitation of temperature breaks which are frequently associated with persistent large-scale oceanographic features by longliners, the same oceanographic features important in the seasonal distribution of swordfish.

The quarterly LPUE's computed for the Hawaiian longline fishery are among the highest reported for swordfish in the North Pacific Ocean. Estimates of swordfish catch-per-unit-effort (CPUE) from the Japanese tuna longline fishery in the North Pacific Ocean ranged between 3.0 and 4.0 fish/1,000 hooks in 1952–62 (Bartoo and Coan, 1989) and were generally less than 2.0 fish/1,000 hooks between 1963 and 1980 (Bartoo and Coan, 1989; Ueyanagi et al., 1989). During earlier years (1952–62), swordfish and albacore were targeted by the Japanese longline fleet, which accounts for the higher CPUE. Between 1962 and 1963, the target species of the Japanese longline fleet changed to tunas for the sashimi market, and swordfish became an incidental catch (Sakagawa, 1989). The lower CPUE in this period most likely reflects the change in target species.

We have shown that quarterly swordfish LPUE is generally less for mixed-target trips compared to swordfish-targeted trips (Fig. 10). We argue that the differences in computed performance indices are indicative of differences in fishing strategy. Gear and vessel characteristics differ between the two target-species trip types, and these differences affect catchability (DiNardo, 1993).

As larger swordfish tend to be female, the increased targeting of larger swordfish suggests increasing selection for females. Because larger swordfish are more valuable, it is unlikely that there will be a reversal of this trend. The extent and potential impact of selecting for females must be addressed as more data become available; one potential result is recruitment failure. This necessitates the need for sex ratio data on swordfish catches and reliable estimates of age at maturity. Because of the potential consequences of selecting for females, we argue that swordfish fishery performance indicators in the Pacific Ocean need to be size-based.

Sources of Variability

Assessing the status of swordfish in the Pacific Ocean requires standardized metrics of fishery performance from fisheries targeting swordfish, as well as estimates of population dynamics parameters. Although we identified factors affecting performance indices in the Hawaii longline fishery, our list of factors is not intended to be exhaustive. Rather, the identified factors represent a point of departure for future research and collaboration. Identified factors include fishing location, time, fishing strategy, vessel characteristics, fish size, and oceanographic features.

Additional data on vessel operations and fishing strategy are being collected by fishery technicians aboard vessels of the Hawaii longline fishery. These data will be used to identify additional factors (e.g. vessel captain) that affect measures of fishery performance, and to quantify standardized measures of swordfish CPUE.

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Swordfish, *Xiphias gladius*, Fisheries of the Eastern North Pacific Ocean

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ABSTRACT

Broadbill swordfish, *Xiphias gladius*, is harvested commercially throughout the area of its distribution, with catches averaging about 78,000 metric tons per yr. In the North Pacific it is harvested in both coastal and high-seas fisheries by numerous nations. This paper provides a description of the swordfish fisheries off the west coasts of the United States and northern Mexico and summaries of other fisheries in the eastern North Pacific.

Introduction

Broadbill swordfish, *Xiphias gladius*, is a large migratory oceanic species widely distributed in all of the world's tropical and temperate oceans and most major seas. It inhabits surface waters above 13°C, but seasonally may enter cooler waters (Nakamura, 1985). The swordfish is known to descend to depths of 300–500 m, where temperatures are 5°–8°C, presumably for feeding (Carey and Robison, 1981; Holts et al.[1]). It is found in greater abundance in areas of rich production where small pelagic prey are plentiful, such as in frontal zones and where water currents merge or where temperature and salinity gradients occur (Sakagawa, 1989; Sosa-Nishizaki and Shimizu, 1991). In the Pacific Ocean there are at least four such areas: the coastal and offshore waters of the California Current, the Kuroshiro Current off Japan, the Peru Current off northern Chile, and the current systems east of Australia.

Swordfish is harvested commercially throughout its area of distribution. It is highly desired, and sold both fresh and frozen in seafood and sushi markets around the world. Individual swordfish may exceed 500 kg in the Pacific. Worldwide landings peaked at 81,000 metric tons (t) in 1988 (Table 1), and currently average about 76,400 t. Total annual catch in the Atlantic Ocean and Mediterranean Sea averages about 44,000 t, representing 56.8% of the world catch. In these areas swordfish production is declining and the stock(s) appear to be overexploited. The International Commission for the Conservation of Atlantic Tunas (ICCAT) therefore set Atlantic quotas in 1991 to gradually reduce catches to below the current estimated maximum sustained yield (MSY). Catches in the Pacific and Indian Oceans, where there is no international management regime, represent 38.7% and 4.5% of world production, respectively (Fig. 1).

The north Pacific swordfish resource was considered stable at the time of the most recent assessments (Sakagawa and Bell, 1980; Bartoo and Coan, 1989; Sakagawa, 1989; Skillman, 1989). However, the data used in these studies were complete only through 1981. The global market and product value have remained steady. In response to continued demand, and reduced supply from the Atlantic, swordfish catches in the Pacific have increased. Data assembled by the Food and Agriculture Organization (FAO) of the United Nations indicate substantial production increases in all three of its eastern Pacific statistical fishery areas (67, 77, and 87), especially from the United States (U.S.), Mexico, Chile,

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[1] Holts, D. B., N. W. Bartoo, and D. W. Bedford. 1994. Swordfish tracking in the southern California bight. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SWFSC Admin. Rep. LJ-94-15, 9 p. Available from SWFCS, NMFS, 8604 La Jolla Shores Dr., La Jolla, CA 92083.

Table 1
Swordfish catch (metric tons) for the eastern Pacific Ocean, entire Pacific, and world (data from Food and Agriculture Organization, 1986–93).

	Eastern Pacific				
Year	Northern Area 67	Central Area 77	Southern Area 87	Pacific total	World total
1970	0	6,000	3,600	9,600	40,500
1971	0	2,800	500	3,300	26,678
1972	0	3,602	800	4,402	28,417
1973	0	4,504	2,600	7,104	32,183
1974	0	2,814	904	3,718	25,911
1975	0	2,697	540	3,237	28,819
1976	0	3,908	544	4,452	31,465
1977	0	3,216	832	4,048	33,380
1978	1	3,760	1,119	4,880	39,864
1979	0	3,215	572	3,787	37,992
1980	0	4,308	896	5,204	37,489
1981	8	5,534	900	6,442	38,663
1982	14	4,926	804	5,744	43,716
1983	26	4,168	1,316	5,510	46,587
1984	35	4,794	1,073	5,902	53,517
1985	162	4,995	688	5,845	59,121
1986	25	4,927	1,239	6,191	61,036
1987	28	5,903	2,662	8,593	67,028
1988	74	5,977	5,508	11,559	81,036
1989	86	5,217	6,318	11,621	78,704
1990	30	8,463	6,072	14,565	76,235
1991	4,004	9,390	8,403	21,797	71,639

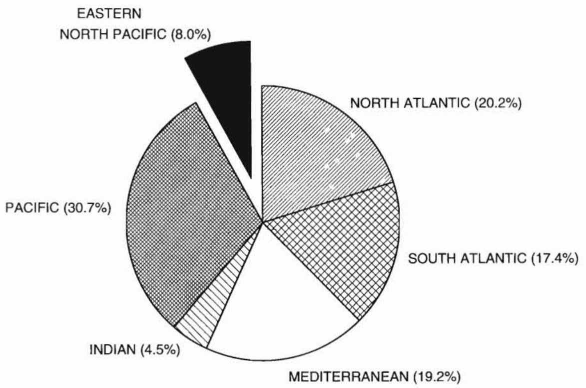

Figure 1
Worldwide swordfish production by major ocean system, 1987–92 (data from Food and Agriculture Organization, 1986–93).

and other Central and South American countries (Food and Agriculture Organization, 1986–93; Table 1). Many U.S. commercial swordfish vessels transferred their operations from the Atlantic and Gulf states to the eastern North Pacific in 1993. This increase in potential production raised fears that the Pacific stock(s) may also be vulnerable to overfishing, and created an urgent need for new assessments utilizing current data (Joseph et al.[2]).

Imports of swordfish into the U.S. have increased from less than 1,000 t prior to 1984, to over 4,000 t per yr in 1985–89. Generally priced well below domestic market prices, imports have continued to increase to more than 7,000 t per yr in recent years (1989–92) with an annual value in excess of $40,000,000 (Jacobson[3]). Imports from the Pacific Ocean are currently about 67% of total U.S. swordfish imports.

This description of the swordfish fisheries off the west coast of the U.S. and Mexico east of 140°W longitude includes the harpoon, driftnet, and longline fisheries operating out of U.S. west coast ports and the driftnet and longline fisheries of Mexico, through the 1993 fishing season (Fig. 2). Summaries of the longline fisheries of Japan, Taiwan, and Korea in the eastern North Pacific and that of Hawaii are also presented.

Fisheries

Japan

Japanese longline vessels began operations in the Pacific in 1952 and were fishing the entire eastern Pacific between 40°S and 35°N by 1968 (Nakano and Bayliff, 1992; Squire and Muhlia-Melo[4]). Directed fishing effort changed seasonally and annually to target the most lucrative species of billfish and tunas available. Japanese Pacific-wide swordfish catches varied between 10,000 and 18,000 t and accounted for at least 80% of Japan's catch of swordfish during 1952–68. The three areas of the eastern Pacific with the highest swordfish catch rates were off northern Mexico, east of 120°W; off northern Chile; and at 10°–15°S and 95°–110°W (Nakano and Bayliff, 1992). Japan has had up to 600

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[2] Joseph, J., W. H. Bayliff, and M. G. Hinton. 1994. A review of information on the biology, fisheries, marketing and utilization, fishing regulations, and stock assessment of swordfish, *Xiphias gladius*, in the Pacific Ocean. Inter-Am. Trop. Tuna Comm. Int. Rep. 24, 81 p. Available from IATTC, La Jolla, CA 92037-1508.

[3] Jacobson, R. 1994. Statistics and Market News, Natl. Mar. Fish. Serv., NOAA, Long Beach, CA 90802. Personal commun.

[4] Squire, J. L., Jr., and A. F. Muhlia-Melo. 1993. A review of striped marlin, swordfish, and sailfish fisheries and resource management by Mexico and the United States in the northeast Pacific Ocean. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin Rep. LJ-93-06. 44 p. Available from SWFSC, NMFS, 8604 La Jolla Shores Dr., La Jolla, CA 92038.

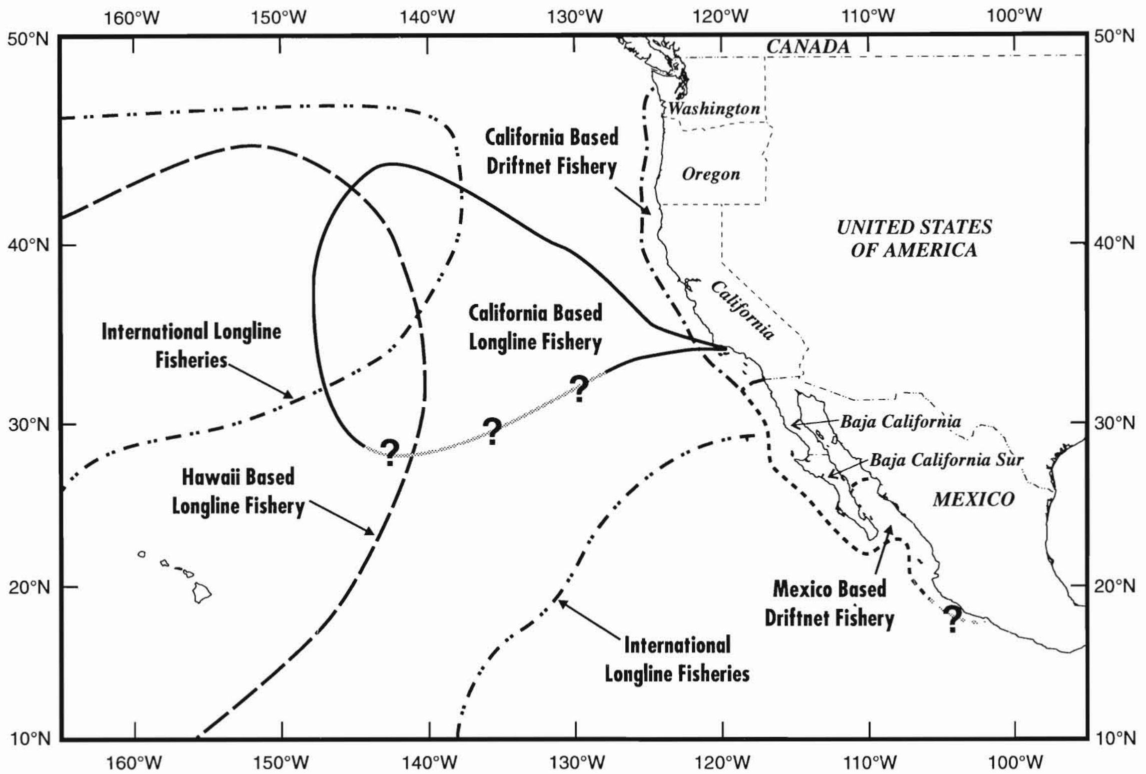

Figure 2

Swordfish fisheries operating in the eastern North Pacific.

longline vessels operating in the eastern Pacific in a single year (Sakagawa, 1989).

Japanese longline fishing effort in the North Pacific increased from 100 million hooks deployed annually in the 1950's to 230 million hooks by 1967, and has remained above 200 million since. Fishing effort in the eastern North Pacific increased from approximately 100,000 hooks during the late 1950's to over 20 million in 1968, and averaged 9.5 million (range 6.4–13.7 million) between 1970 and 1980. This effort was directed primarily at tuna, although striped marlin, *Tetrapturus audax*, and swordfish were targeted around the tip of the peninsula of Baja California, Mexico. During the late 1980's, 49%–58% of Japan's total longline fishing effort in the Pacific was concentrated in the eastern North Pacific, north of 10°N and east of 140°W.

Substantial numbers of Japanese longline vessels fished within 12 nautical miles (n. mi.; 22 km) of the coast of Baja California in 1964, targeting swordfish, marlins, and sailfish. Japan began targeting bigeye tuna, *Thunnus obesus*, in about 1975, using deep longline technology (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992). That technology employs longer floatlines and fewer floats, increasing the distance between floats and allowing the hooks to fish deeper in the water column where bigeye tuna are more abundant. Deep longlining was more commonly used south of 10°N and was used only about 25%–45% of the time off Baja California.

Conventional Japanese longline fishing effort continued off northern Mexico for swordfish, and the highest catch rates (catch per hundred hooks) were reported from 1975 to 1983 and again in 1986 and 1987 (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992). Mexico prohibited longline fishing within its Exclusive Economic Zone (EEZ) from late 1984 through most of 1985.

Catch of swordfish north of 10°N and east of 140°W peaked between 1968 and 1973 at an average of nearly 14,200 fish, and represented 9.5% of Japan's total swordfish catch in the Pacific. Between 1974 and 1980, the Japanese catch in the eastern North Pacific declined to 4,400 swordfish (3.1% of their Pacific-wide catch) as a result of targeting on other billfish and tunas. The most recent data available indicate swordfish catches in 1984 and 1985 were the lowest since the early 1960's.

Japanese longline catch rates for swordfish were highest during the mid-1960's from 10°N to 30°N, off Baja

California Sur and Mexico and east of Hawaii. Catch rates were 0.1–0.3 fish per 100 hooks off Baja California in the 1960's and 1970's and fluctuated from <0.1–0.4 as fishermen switched target species between swordfish and other billfish off Baja California in the 1980's (Nakano and Bayliff, 1992). Mexico began enforcing its EEZ in 1978, allowing foreign longline effort within the EEZ on a permit basis only. These permits were limited to joint-venture operations in 1978–91 and were withdrawn for a period in 1984–85. All longline effort, foreign and domestic, was abolished within Mexico's EEZ in 1991. During 1981–87, the greatest Japanese longline catch rates occurred at 30°–35°N and east of 135°W (off Baja California Sur) throughout the year and west of 135°W in the fall and winter.

Considerable variation exists in the length-frequency data. Swordfish less than 80 cm and greater than 200 cm, measured from posterior margin of the eye to fork in tail (EFL), were most common off Baja California Sur. Although clear trends were not identified, recruitment into the longline fishery apparently occurs throughout the year and over a broad area and wide range of sizes (Nakano and Bayliff, 1992).

Japan's high-seas driftnet fleet did not enter the eastern North Pacific, although it did fish for swordfish, billfish, and tunas in the South Pacific in 1972–92.

Taiwan

Taiwan's high-seas longline fleet began fishing in the South Pacific in the 1960's and had expanded into the North Pacific by 1967. Its fishing effort was primarily directed at albacore, *Thunnus alalunga*, and yellowfin tuna, *Thunnus albacares*, in the western Pacific. Taiwan's longline fishing effort exceeded 2 million hooks in 1976, but declined steadily through 1991. Fishing effort in the eastern North Pacific occurred in only two years (1980 and 1987) and was directed toward tunas. Incidental swordfish catches were insignificant.

Korea

Korea's high-seas longline fishery targeted on tropical tunas began in the South Pacific and had expanded into the eastern Pacific by 1975. Fishing effort in the North Pacific averaged 10 million hooks from 1975 to 1987 (range 4.5–21.0 million). Most of this effort targeted tuna between 10°N and the equator. Effort in the eastern North Pacific averaged 1.0 million hooks in 1975–87 (range 0.2–3.5 million). Effort decreased after 1984, possibly because of restrictive licensing agreements within Mexico's EEZ. Catches of swordfish were incidental, averaging only 230 swordfish per year (range 0–1,018).

United States

Harpoon Fishery—Fishing for swordfish with hand-held harpoons began off southern California in the early 1900's. Swordfish (and striped marlin) could be taken by both recreational and commercial fishermen until 1935, when harpooning for sport was banned by the California Fish and Game Commission (CFGC). Harpoon fishing remained the primary fishery for swordfish until 1980, when it was essentially displaced by the driftnet fishery for pelagic sharks and swordfish.

Traditionally the swordfish harpoon fishery extended seasonally north as far as Oregon and south well beyond the U.S.–Mexico border. It was, however, concentrated in warmer waters (18°–22°C) within the Southern California Bight from about Santa Barbara to the Mexican border and out about 60 n. mi. (110 km). The harpoon season peaks in the summer and fall, when generally mild weather conditions exist. Changes in climate and current patterns have influenced the catch distribution (Coan et al., 1998). Fishing vessels search for swordfish "finning" or basking at or near the surface. Because fish are usually sighted from the vessel's mast or from airplanes, calm weather and sea conditions are critical to locating the fish.

Harpoon vessels average about 6–26 m in length, with a bow plank of about 6–8 m. They normally operate with a crew of at least two, who search with binoculars for swordfish. When a swordfish is sighted, one crew member maneuvers the vessel's bow plank over the fish while the other throws the harpoon from the end of the bow plank. The catch is often stored on ice during short trips of a few days.

The number of vessels with harpoon permits remained fairly steady prior to 1970. In 1971, levels of total mercury in swordfish exceeded the allowable level of 0.5 ppm. Local demand dropped for two years, but recovered in 1973. Imports of swordfish were severely restricted for several years, but domestic swordfish, sold locally, was not subject to inspection. The level of methyl mercury legally allowable in swordfish was increased to 1.0 ppm in 1978. With reduced competition from imports and renewed consumer acceptance, the number of permits increased from 150 to over 1,200 by 1980 (Bedford and Hagerman, 1983), although the number of vessels landing harpooned swordfish exceeded 300 only in 1978 and 1980.

Harpoon vessels began using aircraft to assist in locating swordfish at or near the surface in 1970. In 1973, the harpoon was designated the only commercial gear for swordfish by the CFGC. Aircraft proved extremely efficient in locating swordfish and improving catches for those vessels employing their use (Bedford[5]). Air-

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[5] Bedford, D. W. 1985. Pelagic shark/swordfish drift gill net fishery. Calif. Dep. Fish Game Manage. Info. Doc., 74 p. Available from CDFG, 1416 Ninth St., Sacramento, CA 95814.

craft use was prohibited for a short time in 1976, but its effectiveness had been demonstrated by both increased catch rates and landings. Use of aircraft was resumed but only to locate areas of fish, and aircraft were required to remain at least 5 mi. from the fishing vessel with which they were working. Legislation was passed in 1980 allowing swordfish taken in the driftnet fishery to be landed and sold in California. Competition between the two fisheries became intense, and harpoon fishers lobbied for and received, in 1984, unrestricted use of aircraft (Squire and Muhlia-Melo[4]).

Many of the owners of harpoon and driftnet vessels obtained dual permits for taking both harpooned and net-caught swordfish during the same trip. These dual permittees set their nets at night and spent their days searching for swordfish to harpoon (Hanan et al., 1993).

Fishing effort for the harpoon fleet peaked in 1979 at nearly 13,000 fishing days, and then fell rapidly in 1980–83 as competition from the driftnet fishery increased. Days fished by the harpoon fleet have averaged about 1,000 per yr since 1989 (Coan et al., 1998).

The first sizable harpoon catch, landed in 1927, was 59 t. Landings fluctuated between 100 and 500 t throughout the 1930's and 1940's, then declined to 10–200 t, where it remained throughout the 1950's and 1960's. Catches averaged about 320 t in 1970–80 and peaked at 1,172 t in 1978 (Table 2). Between 1981 and 1992 catches of harpooned swordfish averaged 92 t, and they increased to 116 t in 1993 with a fleet of less than 40 vessels.

Measured swordfish from the harpoon fishery ranged between 64 and 217 cm alternate length[6] (AL) and averaged 85 kg dressed weight (Coan et al., 1998). Dressed weight of swordfish is estimated at 55% of whole body weight for tax purposes by the California Department of Fish and Game (CDFG, 1995, Chap. 371, p. 2).

Driftnet Fishery—The driftnet fishery off the coast of southern California began in 1978, primarily for pelagic sharks. Major changes have occurred in almost every aspect of this fishery including vessels, gear, fishing techniques, regulations, fishing areas, seasons, and targeted species. By 1980, Pacific broadbill swordfish was the target of the fishery. The early success of the fishery was attributed to the abundance of Pacific swordfish and pelagic sharks (thresher, *Alopias vulpinus*, and shortfin mako, *Isurus oxyrinchus*) in coastal waters, popular consumer acceptance of both swordfish and sharks, and lower operating expenses than in the swordfish harpoon fishery, primarily due to greater fuel efficiency.

Table 2

Reported landings in metric tons by the California swordfish fisheries, 1970–93, by fishery type. DGN=drift gillnet.

Year	Harpoon	DGN	Other	Total
1970	199.3		229.3	428.6
1971	45.2		24.6	69.8
1972	86.4		34.2	120.6
1973	194.9		83.5	278.4
1974	193.7		101.1	294.8
1975	297.8		94.9	392.7
1976	22.4		15.7	38.1
1977	187.1		44.6	231.7
1978	1,171.7		9.2	1,180.9
1979	222.4		43.8	266.2
1980	389.7	110.2	42.9	542.8
1981	178.6	319.7	20.0	518.4
1982	107.6	629.9	29.4	766.9
1983	39.8	922.4	250.9	1,213.1
1984	73.0	1,488.8	430.4	1,992.2
1985	145.0	1,659.4	552.5	2,356.8
1986	162.6	1,169.1	412.4	1,744.2
1987	145.0	895.7	202.4	1,243.0
1988	123.7	759.2	243.6	1,126.5
1989	37.2	730.1	530.1	1,297.5
1990	34.7	717.4	96.8	849.0
1991	11.3	577.8	120.7	709.7
1992	44.2	898.9	110.8	1,053.9
1993	116.1	905.0	67.3	1,088.4

Continued market demand encouraged development, and fishers began exploring new areas farther offshore and as far north as Oregon and Washington, although few landings were made outside California. Both effort and catch expanded, reaching highs in 1984 and 1985.

Several fishery-related conflicts emerged in the early years of this fishery. Commercial swordfish harpoon fishers feared reduced catches of swordfish and lobbied against netting, as did recreational anglers, who were concerned about striped marlin. A related problem was the incidental bycatch of marine mammals (Hanan et al., 1993; Hanan and Scholl[7]; Diamond et al.[8]).

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[6] Alternate length (AL) for swordfish is measured from the anterior margin of the cleithrum to the fork of the tail. The regression equation to convert to EFL (length post-orbit to the fork of the tail) in centimeters is EFL = 1.09(AL) + 10.13.

[7] Hanan, D. A., and J. P. Scholl. 1985. Shark drift gill net fishery observation program (May–June, 1983). *In* D. A. Hanan (ed.), California Department of Fish and Game coastal marine mammal study, annual report for the period July 1, 1982–June 30, 1983, p. 10–12. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. LJ-85-10C. Available from SWFCS, NMFS, P.O. Box 271, La Jolla, CA 92038-0271.

[8] Diamond, S. L., D. A. Hanan, and J. P. Scholl. 1986. Drift gill net observations for the 1984–85 fishing season. *In* D. A. Hanan (ed.), California Department of Fish and Game coastal marine mammal study, annual report for the period July 1, 1984–June 30, 1985, p. 9–26 and 45–46. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish Sci. Cent. Admin. Rep. LJ-86-25C. Available from SWFCS, NMFS, P.O. Box 271, La Jolla, CA 92038.

Observer programs were mandated by CDFG in 1980 to address the incidental take of marine mammals. These documented incidental catches during the early years of this fishery. The CDFG observed hauls from 443 net sets during 1980–85. There were no systematic observations during the 1986–89 fishing seasons. As mandated by the U.S. Marine Mammal Protection Act (MMPA), the National Marine Fisheries Service (NMFS) established an observer program in 1990. Data were recorded by observers onboard driftnet vessels during observed net pulls (Hanan et al., 1993; Lennert et al., 1994). Coverage in observed trips has been 10%–14% since 1990.

The incidental catch of marine mammals was considered relatively high in the developing years of the fishery. Time and area closures around the Channel Islands and along the mainland were successful in reducing that bycatch. Currently, the bycatch of marine mammals in this fishery is apparently low and not compromising any stocks (Hanan et al., 1993). Bycatch of other species does not appear to be a problem, except possibly for blue sharks, *Prionace glauca*, which average 10–15 per set. Blue sharks that are not marketable in the U.S. are discarded at sea (Julian and Beeson, 1998).

The first vessels in the driftnet fishery were converted from sea bass and halibut set-net vessels, most of which had wooden or fiberglass hulls. Many harpoon fishers also converted their vessels for driftnet fishing. Effort was concentrated around nearshore banks, canyons, and escarpments, and the offshore islands. As the success of this fishery continued, many of the smaller and older vessels were replaced with larger steel and aluminum vessels with increased speed and range. Fish hold space increased, and cooling capabilities evolved from ice to brine-spray and blast freezers. Several vessels now have large-capacity ice makers and limit the length of trips to less than about 3 wk to obtain the best market price.

As the driftnet fishery prospered, the number of vessels increased and competition for available swordfish became intense. Airplanes were often hired to locate areas of fish and to observe catches of other vessels (Hanan et al., 1993). In 1980, the California legislature made the driftnet fishery a limited-entry fishery, setting the maximum number of permits at 150, but allowing those fishers already involved to continue fishing. The actual number of permits issued reached a high of 300 in 1985. Driftnet vessels landing swordfish in California numbered 173 in 1991, 169 in 1992, and 162 in 1993. There were, however, rarely more than 100 active vessels fishing throughout any one season.

Drift nets are usually fished 4–10 m below the surface to allow small vessels to pass over without entangling them and to avoid catching non-target surface-swimming species. The nets are deployed at sundown and retrieved in the early morning after a soak of 8–12 hr. The length of the drift nets is limited to 1 n. mi. (1.8 km). The nets vary in depth between 50 and 100 meshes, and fish a vertical depth of 15–30 m. The size of each mesh is limited to a minimum of 40 cm (18 in) although 48 cm (22 in) is more common. The fishing season originally started on 1 April and ended on 31 January of the following year. To reduce fishing effort and to protect thresher sharks migrating northward along the California coast, the season start was pushed back to 15 August (Hanan et al., 1993).

Swordfish are removed from the net by first cutting off the bill and removing the fins. Swordfish (and sharks) are dressed (head removed, and eviscerated), unwanted parts discarded, and the carcasses washed with sea water and placed in the hold at just above freezing (0°–2°C) until the vessel returns to port. Most swordfish are sold in local markets (Herrick and Hanan, 1988; Cailliet et al., 1993; Hanan et al., 1993). Ex-vessel price for swordfish has ranged from about $4.40 to $8.50 per kg since 1990.

Hanan et al. (1993) summarized the available driftnet data from the California logbook system, landing receipts, and market sampling program for the 1981–90 fishing seasons. Logbooks collected from driftnet skippers under a mandatory logbook system (Huppert and Odemar, 1986) include catches (number of fish) by species, date, geographical position, gear and set data, and various other information, such as vessel registration and permit numbers. Fishing effort is designated in logbooks as number of sets, a set being one deployment and retrieval of the net.

Landing receipts are collected from commercial fish brokers each time a vessel delivers its catch to a California market. The receipts report landings in pounds, along with location and date of catch and type of fishing gear used. Problems associated with reporting of gear types resulted in the development of criteria to estimate actual landings of the driftnet fishery (Hanan et al., 1993). This convention was used in the determination of 1991–93 effort data in this report. Combined logbook and landing-receipt data provided improved estimates of effort (Julian and Beeson, 1998; Beeson and Hanan[9]) and are used here to estimate effort and catch for the 1991–93 fishing seasons.

Skipper compliance with logbook reporting regulations was estimated to be greater than 90% (Hanan et al., 1993; Miller et al.[10]). The effort data reported in

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[9] Beeson, M., and D. Hanan. 1991. Effort estimates of California gill net fisheries: halibut–angel shark set net and shark–swordfish drift net for the 1990–91 fishing year (April 1, 1990–March 31, 1991). Final rep. NA90AA-HFC401 and NA86-ABD-00201 submitted to Natl. Mar. Fish. Serv., Southwest Region, Terminal Island, CA.

[10] Miller, D. J., M. J. Herder, and J. P. Scholl. 1983. California marine mammal–fishery interaction study, 1979–1981. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. LJ-83-13C, 233 p. Available from SWFSC, NMFS, 8604 La Jolla Shores Dr., La Jolla, CA 92038-0271.

Table 3
Reported and estimated swordfish catch and effort in the California driftnet fishery.

	Reported			Estimated	
	Effort (landings)	Effort (sets)	Catch (fish)	Effort (sets)	Catch (fish)
1981	2,388	6,710	3,871		
1982	3,282	10,452	12,925		
1983	3,021	11,160	21,878		
1984	2,912	9,688	25,725		
1985	2,860	9,238	23,062		
1986	2,411	11,243	23,454		
1987	2,258	8,382	12,690		
1988	1,572	6,047	11,289		
1989	1,376	6,028	11,511		
1990	1,545	4,392	9,367	4,504	15,211
1991	1,335	4,643	7,771	4,752	11,517
1992	1,119	3,898	10,460	4,504	16,360
1993	1,305	5,380	11,680	5,380	13,706

logbooks were therefore assumed accurate. The annual distribution of effort in the driftnet fishery shifted geographically from nearshore southern California to northward and offshore. Prior to 1982, fishing effort during spring was concentrated on sharks in the Southern California Bight, then shifted northward and offshore, targeting swordfish as the season progressed. During the height of the fishery, effort was concentrated around the offshore seamounts of central and northern California, and northward to Oregon and Washington. Most effort off Oregon and Washington was directed at thresher sharks, and few swordfish were caught. Because most of these vessels were based in California, their catches were likewise landed in California.

Total reported annual driftnet effort nearly doubled in the first 5 yr to a high of 11,243 sets in the 1986 fishing season, and subsequently declined to a low of 3,898 sets in the 1992 season. This effort increased in 1993 to 5,380 sets. The decline in effort resulted from increasing regulations and laws governing the fishery. Concern about possible overfishing of some pelagic sharks resulted in the fishing season being shortened in 1985 to 15 August–30 January, and in prohibition of sets within 75 n. mi. (139 km) of the coast and nearby islands to avoid the directed spring thresher shark fishery. Effort decreased almost 60% by 1993, corresponding to decreased total landings. Reported driftnet landings increased to a high of 3,500 in the 1983 season, then decreased steadily to a low of 1,500 in the 1990 season, and have averaged 1,223 during the 1991–93 seasons. Estimates of effort that incorporate NMFS observer data closely correspond to reported effort for the 1990–93 fishing seasons (Table 3).

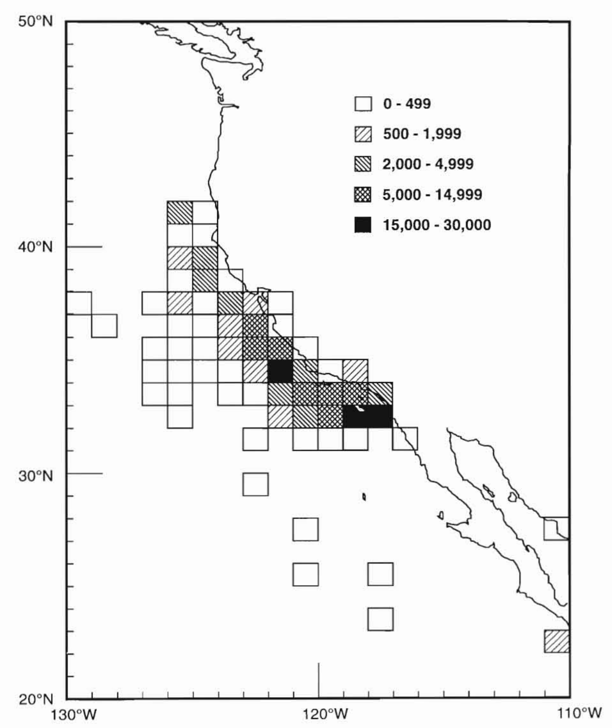

Figure 3
Geographical distribution of swordfish catch (number of fish) reported in CDFG logbooks for the California driftnet fishery, 1981–93 fishing seasons.

The driftnet fishery catches swordfish mostly in waters off San Diego to San Francisco, and within 500 km of shore. Catches of swordfish usually peak in October and November and taper off in December and January. During the 1981 and 1982 seasons, the areas of highest catch were in the Southern California Bight. Small numbers of swordfish were also caught between San Francisco and the California–Oregon border and within 200 km of shore. As effort expanded, good catches were taken offshore of Monterey and San Francisco. Few catches of swordfish occurred north of Oregon (Fig. 3).

Logbook data closely followed landings data, showing a peak catch of 25,725 swordfish in the 1984 season followed by a decrease to 7,771 swordfish in the 1991 season and then an increase to 11,680 in 1993 (Table 3). Mean annual landings were 898 t of swordfish for the 1981–93 seasons. Average landings for 1990–93 were 775 t, with improved landings in 1992 and 1993 (Table 2). Estimates that incorporate NMFS observer data indicate that swordfish catch may be under-reported from 15% in 1993 to 38% in 1990 (Julian and Beeson, 1998).

Swordfish dominated driftnet landings during 1983–93. Swordfish landings increased from 110 t in the

1980's to a high of 1,659 t in the 1985 season, and then declined to 578 t by 1991. Landings subsequently increased to 941 t and 897 t in 1992 and 1993, respectively. Shark landings are a significant product of this fishery, and actually dominated the catch prior to 1983. Shark landings have decreased steadily from a high of 1,000 t in 1981 to about 500 t in recent years (Hanan et al., 1993).

The CDFG market sampling program began in 1981 (Bedford, 1987). Market samplers made routine visits to primary California fish markets in San Diego, San Pedro, Santa Barbara, Ventura, Morro Bay, Monterey, Moss Landing, and the San Francisco Bay area. They recorded weight and AL for swordfish carcasses delivered for sale.

Swordfish sampled during the 1981–93 seasons (24,401 fish) measured 37–250 cm AL (mean 144 cm). Annual mean ranged from 128 to 152 cm (Fig. 4). Larger swordfish (150–160 cm AL) tended to be caught off northern California, north of 35°N, with smaller fish (130–145 cm AL) taken farther south (Hanan et al., 1993). At-sea measurements by NMFS observers between 1990 and 1993 indicate that fish caught north of 35°N averaged 8.6–17.5 cm AL longer than those caught south of 35°N. CDFG market samplers measured fewer swordfish after 1991, while measurements by NMFS observers increased (Fig. 4). A large proportion of swordfish measured by NMFS observers between 1990 and 1993 were caught north of 35°N. Coverage rates for NMFS observation averaged 5%–28% of reported trips.

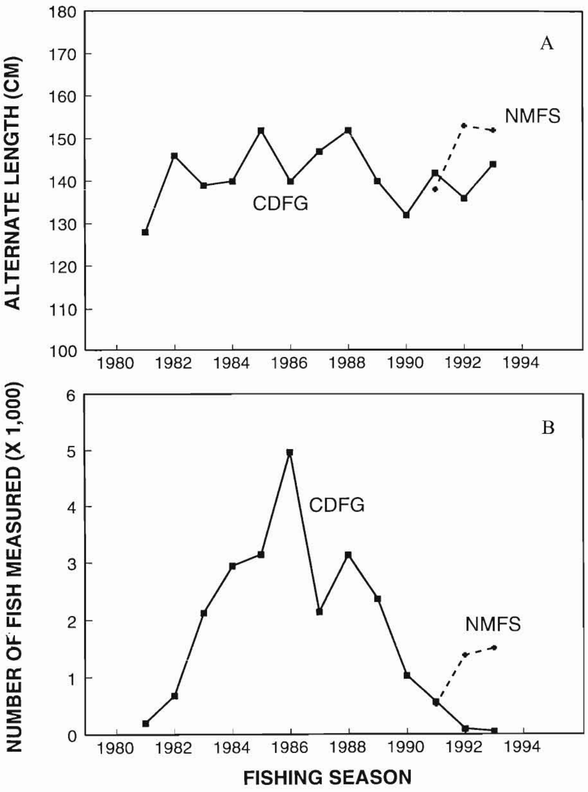

Figure 4

(A) Mean alternate length of swordfish and (B) smaller coverage in number of swordfish measured by CDFG market samplers and NMFS observers, 1981–93.

Longline Fishery—Traditionally there has been little longline effort for swordfish along the west coast of the U.S. and only moderate effort in waters around Hawaii. In California, only harpoon and driftnet fishing for swordfish were allowed within the EEZ. Catches of swordfish taken by high-seas longlining started arriving in southern California in 1991. Swordfish are rarely landed by any fishery in Oregon or Washington.

Longline vessels based in Hawaii have fished for a variety of tunas and billfish since the 1950's. In the beginning, this was primarily a near-shore, daytime tuna fishery. In 1987 the Hawaii-based fishery expanded with technology adapted from the successful longline swordfish fishery in the Atlantic Ocean, employing night fishing with chemically-activated light sticks attached near each baited hook. Expansion was encouraged by new export markets for fresh tuna in Japan and for swordfish in the U.S.

This fishery mostly operates west of 140°W, although some fishing occurs to the east. By 1990, annual swordfish landings in Hawaii had jumped from <40 t to >1,600 t (Boggs and Ito, 1993), greatly exceeding landings on the west coast of the U.S. In 1991, the longline catch of swordfish totaled 4,500 t and represented 68% of total landings in Hawaii. Landings exceeded 6,000 t in 1993 and were valued in excess of US$27 million (Ito et al., 1998; Skillman, 1998).

Hawaii-based longline vessels targeting only swordfish deployed 6–7 million hooks annually between 1991 and 1993. As the fishery expanded farther than 200 n. mi. (370 km) from Hawaii, higher catch rates were obtained to the north and east. Swordfish CPUE varied between 10 per 1,000 hooks in the most productive areas to less than 4 per 1,000 hooks nearer the Islands.

Longlining for swordfish in waters off California and Mexico began prior to 1950. This daytime effort met with little success, and was banned within California by the CFGC in 1971, when harpoons were designated the only legal commercial fishing gear for swordfish in California.

In the fall of 1993, four longliners arrived in Ventura, California, from the U.S. east-coast swordfish fishery and began longline operations for swordfish in the waters beyond 200 n. mi. They ranged north to 42°N and west to at least 135°W (Vojkovich and Barsky, 1998). These vessels had encouraging catches, and by the spring of 1994 another 15–20 vessels had departed the swordfish fisheries in the Atlantic and Gulf of Mexico for the west coast. A few local vessels also converted to longline gear, and by late 1994 nearly 30 California-based longline vessels were fishing swordfish. They set from 300 to 1,300 hooks per set, depending on location and sea-surface conditions. Like the Hawaiian fishery, they set at night with light sticks and used large squid for bait.

In 1994 it was legal to land longline-caught swordfish in California only if taken outside the EEZ. Preliminary data indicate catch was 100 t for the last part of 1993 and nearly 543 t for 1994 (Barsky[11]). These fish ranged between 73 and 226 cm AL, and averaged 63 kg dressed weight (Vojkovich and Barsky, 1998).

In 1994 the CFGC approved a regulation to require all longline vessels operating beyond the EEZ from California ports to complete and submit logbooks of daily fishing activity to the CDFG.

Recreational Fishery—The California recreational fishery for swordfish developed along with that for striped marlin in southern California about the turn of the century. Because of the size and strength of swordfish, anglers still consider them one of the finest of all trophy game fish. Although highly prized by the recreational community, catch is insignificant compared to the commercial catch in the same areas (Bedford and Hagerman, 1983).

Swordfish in California was first listed as a game fish in 1931, and required a sport fishing license issued by the CDFG. Recreational anglers were allowed the use of hand-held harpoons as well as sport rod-and-reel fishing tackle until 1971, when the CFGC restricted harpooning to the commercial fishery.

The rod-and-reel season for swordfish can begin as early as May and continue through December, although most fish are taken from July to September. Fishing occurs from about Santa Barbara south at least to the U.S.–Mexico border, and out to about 100 km. Most fishing is done during the day from private boats targeting striped marlin. Swordfish is a minor component of the sport catch of billfish in California, equalling only 1% or less of total marlin catch. Swordfish commonly fin or bask at or near the water's surface in the area between the Channel Islands and the coast of southern California. When anglers sight swordfish, they will offer them live bait or artificial lures, although swordfish are usually not receptive to bait presented while basking.

Catch records of swordfish are kept by the various sportfishing clubs in California. The Balboa Angling Club, San Diego Marlin Club, and the Tuna Club (Avalon) are three of the major clubs where anglers have their swordfish catches recorded and weighed. Catches have averaged 3–4 fish per yr, except for 1969–80, when they averaged 30.5 fish, and peaked in 1978 with 127 swordfish reported (Fig. 5). The increased catches in 1969–80 corresponded to a similar increase in landings from California's harpoon fishery, and may have reflected a generally higher abundance of swordfish in southern California waters during that time. Higher abundances were also reported for the northern anchovy, *Engraulis mordax*, and bluefin tuna, *Thunnus thynnus*, during the same period (Squire, 1993). There were four El Niño episodes during this time, and it is possible that increased catches occur in the years following El Niño events (Coan et al., 1998).

The whole weight of recreationally-caught swordfish is less than the weight of fish taken in the harpoon fishery. Of 45 swordfish weighed at major sport fishing clubs between 1981 and 1992, the average whole body weight was 107.5 kg (range 58.5–177 kg).

The only estimate of recreational fishing effort for swordfish is from the NMFS's Billfish Angler Survey (Squire and Muhlia-Melo[4]; SWFSC[12,13]). The survey requests individual angler data on fishing effort and catch of all billfish and swordfish in the Pacific Ocean. The survey cannot, however, identify effort directed specifically at swordfish. Effort is primarily directed at striped

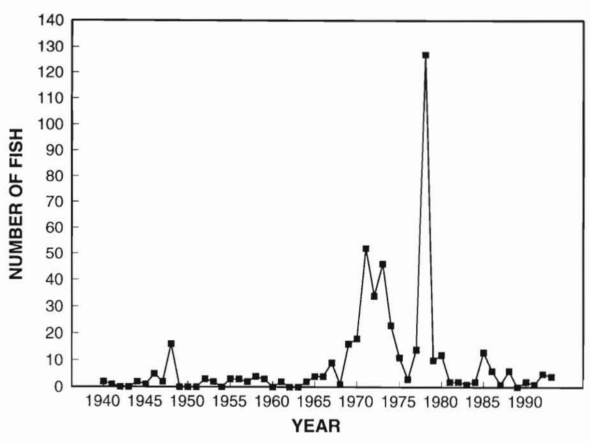

Figure 5

Recreational swordfish catch by southern California anglers, as reported by major sportfishing clubs, 1940–93.

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[11] Barsky, K. 1994. Marine Resources Div., CDFG, 530 E. Montecito St., Ste. 104, Santa Barbara, CA 93103. Personal commun.

[12] Southwest Fisheries Science Center (SWFSC). 1994. 1993 Billfish Newsletter. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SWFSC, 9 p. Available from SWFSC, NMFS, 8604 La Jolla Shores Dr., La Jolla, CA 92083.

[13] Southwest Fisheries Science Center (SWFSC). 1995. 1994 Billfish Newsletter. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SWFSC, 12 p. Available from SWFSC, NMFS, 8604 La Jolla Shores Dr., La Jolla, CA 92083.

Table 4
Reported swordfish effort and catch from the Japanese longline fishery within the Mexican EEZ, 1961–85.

Year	Hooks	Catch (number of fish)
1961	74,700	36
1962	429,198	62
1963	502,124	76
1964	10,502,535	20,624
1965	12,797,567	12,235
1966	8,524,654	10,722
1967	7,169,512	6,363
1968	14,393,695	14,770
1969	7,679,938	10,667
1970	7,754,116	14,490
1971	7,269,733	12,092
1972	8,453,797	16,575
1973	8,883,135	12,593
1974	8,365,245	6,214
1975	4,316,486	5,749
1976	7,405,134	11,441
1977	1,844,845	2,997
1978	287,515	115
1979	699,044	233
1980	2,676,935	1,790
1981	1,569,164	3,657
1982	4,601,736	9,275
1983	3,538,430	4,537
1984	1,899,067	1,994
1985	62,984	7

marlin in southern California, and is directed at all billfishes in Mexico. Effort estimates (catch per angler day) for swordfish are therefore very low. Anglers fishing in southern California and northern Mexico reported swordfish catches of 0–0.002 fish per day in 1990–93.

Mexico

Longline Fishery—In 1967, the Mexican government increased its Exclusive Fishing Zone from 9 to 12 n. mi. (from 17 to 22 km). Prior to this, foreign commercial fishing for swordfish, billfish, and tunas was essentially unrestricted beyond 17 km from the coast. Between 1967 and 1976, Mexico issued permits to Japan's longline fleet to fish for swordfish, billfish, and tunas off northern and central Mexico, 22 km and further from the coast. Fishing effort averaged 8.2 million hooks and catch averaged over 11,000 swordfish per yr during that 10-yr period (Table 4).

Mexico established its EEZ in 1976 and withheld all longline permits for swordfish, billfish, and tuna between 1977 and 1980, although some fishing continued. Between 1980 and 1984, only vessels registered in Mexico and joint-venture longline vessels fished coastal waters. Fishing effort increased within Mexico's EEZ, averaging 2.4 million hooks in 1981–83. In 1983, a 50-n. mi. (93-km) sportfishing-only zone was established along the coast of Mexico to protect billfish, swordfish, and other popular species and to manage them for the recreation and tourist industries. Longline permits were not issued from mid-1984 until late 1985, and effort decreased (Table 4). Longline permits were again issued in 1987 under stricter regulations, allowing only about 15 fishing vessels within the EEZ. Operating under new permits, the Japanese/Mexican joint-venture fleet increased fishing effort to 2.3 million hooks between 1986 and 1988 (Squire and Muhlia-Melo[4]). All longline permits for swordfish, billfish, and tunas within Mexico's EEZ were repealed in 1990. Longline fishing operations have not been conducted since.

Table 5
Reported swordfish landings and catch rates for fishing vessels landing swordfish in the driftnet fishery of Mexico, 1985–93.

Year	Landings (metric tons)	Mean catch (kg/day)	Vessels
1986	286		2
1987	471		3
1988	385	88.8	11
1989	407	250.9	14
1990	661	287.6	21
1991	831	215.5	28
1992	552	115.6	29
1993	372	105.7	31

Most of the swordfish and marlin catches from the joint-venture vessels were shipped to Japan and the U.S., while other catches were canned or used in domestic markets. The most productive area was 20°–27°N, east of 115°W.

Longline catches from Mexico's joint-venture fisheries peaked in 1982 with 9,275 swordfish (after a low of 115 in 1978). Catches of swordfish subsequently increased to at least 5,000 through 1988, before being terminated in 1990 (Squire and Muhlia-Melo[4]). CPUE fell dramatically in 1983 and 1984, possibly due to the prohibition of fishing within the 50-n. mi. sportfishing-only zone.

Driftnet Fishery—In 1986 a small fleet of driftnet vessels appeared in northern Baja California. This fishery was stimulated both by the reduction in longline permits and by the local abundance of swordfish and other marketable bycatch products, including several species of large pelagic sharks. The number of vessels had grown to 20 by 1990, and to 31 by 1993 (Table 5). These vessels operate out of Ensenada and are similar in de-

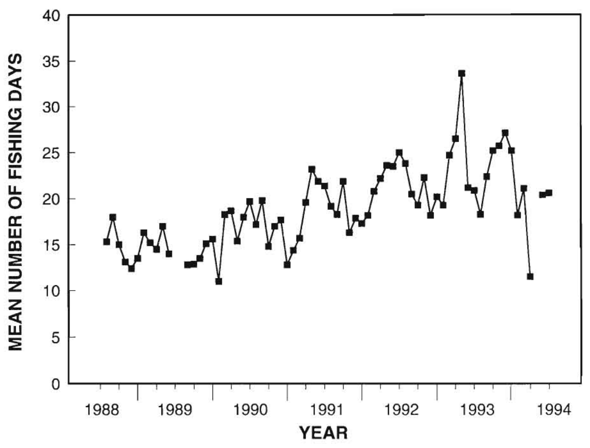

Figure 6

Total reported fishing effort for the driftnet fishery in Mexico, 1988–94.

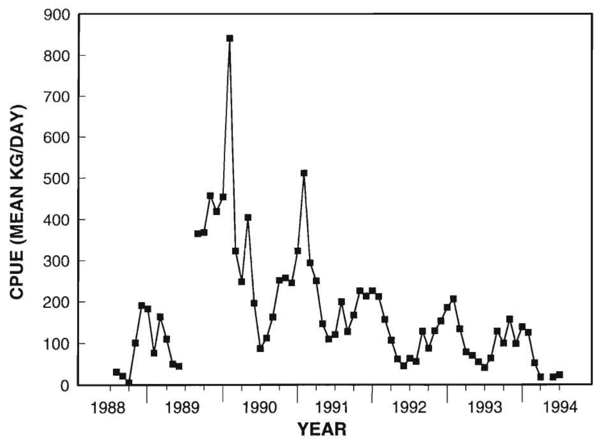

Figure 7

CPUE by month for the driftnet fishery in Mexico, 1988–94. The break in 1989 represents missing data.

sign and size (18–25 m) to the U.S. driftnet vessels operating just 100 km to the north. The nets are similar in design to the U.S. drift nets, although they may be up to 4.5 km long, whereas U.S. nets are limited to 1 n. mi. (1.8 km). Operational procedures are virtually identical to those in the U.S.

The fishing season usually begins in the waters off Ensenada in the fall and moves south to central Baja California between 25° and 27°N during December and January.

Swordfish landings from Mexican driftnet vessels were first reported in 1986. They increased steadily to a high of 831 t in 1991, and averaged 535 t in 1988–93 (Table 5). The low catch in 1993 forced some fishing vessels to look for alternate resources including coastal and pelagic sharks in the Gulf of California. The number of vessels driftnetting for swordfish in the first half of 1994 fell to 16.

Total driftnet fishing effort for swordfish increased from about 15 days per mo in 1989 to 20–30+ days per mo in 1993 (Fig. 6). CPUE increased from about 100 kg/day in 1989 to over 800 kg/day by the end of 1990, but has generally declined through 1994 (Fig. 7). The best catches occur in the winter months of October–February (Fig. 8)

A coperative program was established by commercial driftnet fishermen operating out of Ensenada and scientists at Centro de Investigación Cientifica y de Educación (CICESE), Ensenada, Mexico in 1992. Crew members and scientists measured 1,412 swordfish during the 1992 and 1993 seasons (Sosa-Nishizaki et al., 1993). Most fish were taken from the southern Baja California peninsula between 25° and 28°N. Mean length (EFL) was 164 cm and fish length ranged from 60 to 245 cm. Larger fish were reported taken during March and October, mostly in waters off Baja California Sur (Sosa-Nishizaki et al., 1993).

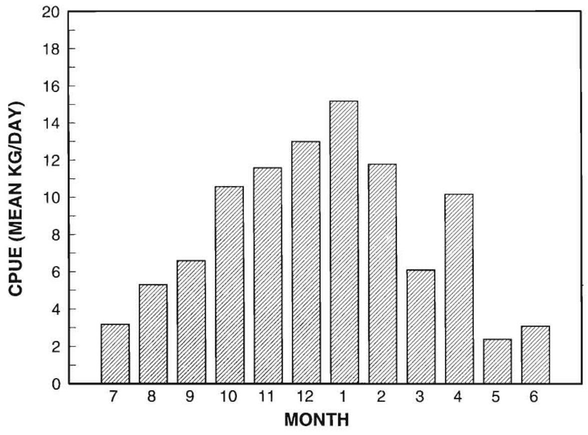

Figure 8

CPUE by month for the driftnet fishery in Mexico, 1988–94.

Recreational Fishery—Recreational fishing for marlin around the Baja California peninsula is extremely popular world-wide. Angling for swordfish in these waters is opportunistic and incidental to the large marlin catch. Although the recreational catch of swordfish is unreported, the greatest catches of swordfish appear to be off Guaymas and Mazatlan. Swordfish, like marlin, are included under the existing regulations which allow a maximum catch of one billfish per day.

Acknowledgments

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The Hawaii-based Longline Fishery for Swordfish, *Xiphias gladius*

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ABSTRACT

This report profiles the Hawaii-based domestic longline fishery for broadbill swordfish, *Xiphias gladius.* This fishery grew rapidly during 1989–91, mostly due to the arrival and participation of recent entrants. Swordfish became the dominant species landed by Hawaii's fisheries in 1990 and the most important in terms of ex-vessel revenue in 1991. In 1993, 88 longliners fishing for swordfish logged 650 trips, fished 7,533 days, set 6.6 million hooks, and landed 6,000 metric tons of swordfish with an estimated ex-vessel value of $26.5 million. Swordfish is delivered as a fresh product. Most swordfish landed in Hawaii is exported to mainland U.S. cities by air freight.

Introduction

Longlining for broadbill swordfish is a relatively new fishery in Hawaii. In 1988, the fishing vessel *Magic Dragon* began experimentally targeting swordfish using techniques based on the Florida longline fishery. During 1989, a few Hawaii tuna longline and lobster vessels experimented with longlining for swordfish for at least part of the year. Good catches by those vessels led to increased effort as well as national attention (Freeman, 1989).

Domestic U.S. longline vessels from the Gulf of Mexico (Gulf vessels) were among the first to join the growing longline fleet operating from Hawaii (Kawamoto et al.[1]). These new participants initially targeted yellowfin and bigeye tuna, but in early 1990 some vessels began targeting swordfish. Longlining for swordfish by many of the Gulf vessels was discouraging at first due to poor catches and the high cost of bait and light sticks. Catches of swordfish increased as these fishermen became more experienced.

The decline in Atlantic swordfish landings, catch rate, and average fish size in the late 1980's (Berkeley, 1989; Pollack, 1990) as well as prospects of good swordfish catches in Hawaii influenced many Atlantic swordfish longline fishermen to relocate to Hawaii. These experienced fishermen from the U.S. east coast began arriving in Hawaii in early 1990. A few longline vessels from the west coast also entered the fishery at the same time as Gulf longliners and east coast longliners. In addition, many tuna longline vessels were able to switch to targeting swordfish with minor modification to gear and operations.

By the end of 1990, swordfish were the dominant species landed in Hawaii (Ito[2]) with landings (by weight) exceeding those of any other species. By 1991, the monofilament main line, hydraulic reel, and other techniques of the swordfish fishery were widespread throughout the longline fleet. The Western Pacific Regional Fishery Management Council (WPRFMC) passed an emergency rule in October 1990 to arrest the rapid growth of the longline fishery. The emergency rule was replaced by a 3-yr moratorium on new entry in April

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[1] Kawamoto, K. E., R. Y. Ito, R. P. Clarke, and A. A. Chun. 1989. Status of the tuna longline fishery in Hawaii, 1987–88. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-89-10, 34 p. Honolulu Lab., NMFS, 2750 Dole St., Honolulu, HI 96822-2396.

[2] Ito, R. Y. 1992. Western Pacific pelagic fisheries in 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish Serv., Southwest Fish. Cent. Admin. Rep. H-92-15, 38 p. Honolulu Lab., SWFSC, NMFS, 2570 Dole St., Honolulu, HI 96822-2396.

1991. The moratorium was to provide a period of stability during which data could be collected for assessing the impacts of the increased longline effort on small-boat pelagic fisheries in Hawaii. The longline fishery is now under a limited-entry plan.

Despite the initial rapid growth, participation of vessels in the longline fishery declined slightly in 1992–93. Increasing operational costs from longer trips and lower swordfish prices were the primary reasons for decreased activity. Most of the longliners exiting the fishery were vessels originally from the Gulf and west coast. However, longlining for swordfish is still the largest commercial fishery in Hawaii.

Hawaii has gained the reputation of being an important source of fresh swordfish for U.S. mainland markets. Characteristics and operations of this segment of the Hawaii-based longline fleet, catch per unit effort (CPUE), landings, size of fish, and the swordfish market are described here, and data sources and problems reviewed. We also discuss trends and outlook for this fishery.

Data and Methods

Monitoring of longline fleet activity in Hawaii is conducted primarily by the Fisheries Monitoring and Economics Program (FMEP) of the National Marine Fisheries Service (NMFS) Honolulu Laboratory. Hawaii-based domestic longline fishing vessels either target swordfish or bigeye and yellowfin tuna, or follow a mixed-species target strategy. Trip types[3] contributing substantial amounts of swordfish are from longliners targeting either swordfish or mixed species. Longliners targeting tunas make incidental catches of swordfish and contribute only a small fraction of total swordfish catch (Yoshida, 1974; Kawamoto et al.[1]). Therefore, only data from swordfish and mixed-target longline trips are used in this report. The data originate from shore-side samples, federal longline logbooks, federal longline permit applications, voluntary observer reports, and personal interviews.

Estimates of landings were derived from shore-side sampling conducted by FMEP in conjunction with the Hawaii Division of Aquatic Resources (HDAR) during 1989–93, and from a combination of this sampling and Federal longline logbooks for 1991–93. In the sampling program, weights of individual fish were recorded along with observations on degree of processing or damage. Landed swordfish have typically been headed, gilled, and gutted. The sample weight of each fish was raised to an estimated whole weight. Raising factors, which were species-specific, varied from 1.1 to 1.5 depending on degree of processing or damage. The raising factors were based on rates used by the seafood industry in Hawaii.

Numbers of vessels and trips were derived from the shore-side sampling data for 1989–90 and from federal logbooks for 1991–93. The federal logbooks were also the source of detailed information on fishing operation: effort (i.e. vessels, trips, sets, hooks), fishing area, and CPUE (number caught per 1,000 hooks).

Landings for 1992–93 were estimated as the product of the number of each species kept, from logbook data, and the corresponding average weight from shore-side sample data (Ito[2]). Logbook data were not used to estimate landings in 1991 due to a number of problems with implementation of the logbook program in the first year (Dollar[4]). Shore-side sample data were used for 1991. Logbook data were compared for accuracy with the shore-side data for total numbers and species identification. Proper species identification for marlins and total number kept were inaccurate during the first year (1991). Accuracy in total numbers improved in 1992 and 1993, but improper species identification, especially for marlins, is an ongoing problem requiring education of fishermen.[5]

Vessel characteristics were summarized from the fishing permit applications of vessels actively longlining for swordfish. All domestic longline vessels based in Hawaii have been required to have a federal longline fishing permit since 1990. Gear and technology, fishing procedures, processing and storage of the catch, and market information were derived from voluntary observer reports (Dollar[6]; Dollar et al.[7]) and personal interviews with industry personnel.

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[3] Criteria for determining trip type from logbook data are described in Dollar, R. A. 1994. Annual report of the 1993 longline western Pacific longline fishery. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-94-06, 38 p. Honolulu Lab., SWFSC, NMFS, 2750 Dole St., Honolulu, HI 96822-2396.

[4] Dollar, R. A. 1992. Annual report of the 1991 longline western Pacific longline fishery. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-92-11, 26 p. Honolulu Lab., NMFS, 2750 Dole St., Honolulu, HI 96822-2396.

[5] Proper marlin identification has been encouraged by the distribution of informational material by FMEP staff to vessel operators.

[6] Dollar, R. A. 1991. Summary of swordfish longline observations in Hawaii, July 1990–March 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-91-09, 13 p. Honolulu Lab., NMFS, 2750 Dole St., Honolulu, HI 96822-2396.

[7] Dollar, R. A., R. Y. Ito, K. E. Kawamoto, and K. C. Landgraf. 1991. Summary of swordfish longline observations in Hawaii, July–October 1990. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-91-03, 10 p. Honolulu Lab., NMFS, 2750 Dole St., Honolulu, HI 96822-2396.

The Fishery

Vessel Characteristics

Hawaii-based longliners that fished for swordfish at least 2 yr during 1991–93 (*N*=93) were typically steel- or fiberglass-hull vessels with a mean age of 11 and 12 yr respectively (Table 1). Most vessels were 20–24 m in length, though they ranged from 8 to 30 m (mean = 20 m; Fig. 1). Steel-hulled vessels were slightly larger than fiberglass-hulled vessels. All vessels had diesel engines, with an average of 460 horsepower (hp; range 200–700 hp).

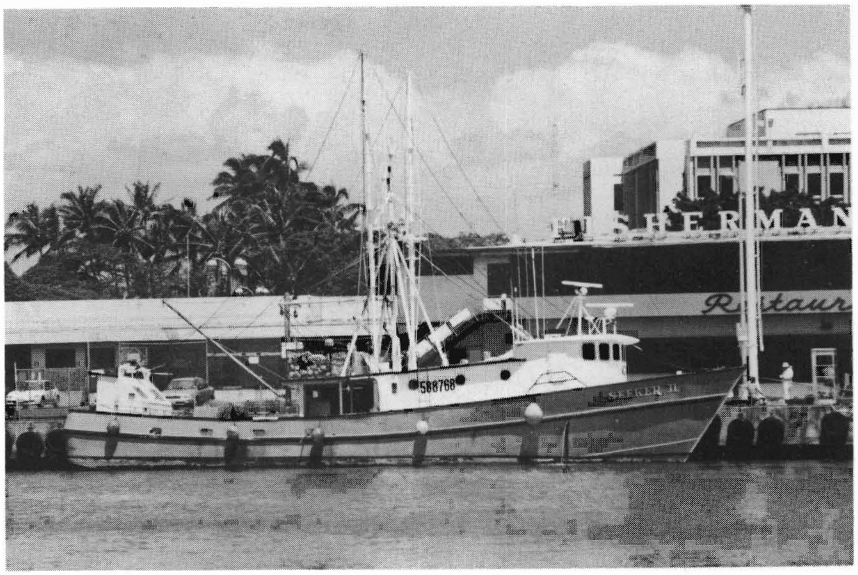

Figure 1
A typical Hawaii-based swordfish longline vessel.

Fishing Gear and Technology

Longlining for swordfish employs hundreds of branch lines attached to a single main line set horizontally below the ocean's surface. The monofilament main line is stored on a large hydraulic-powered reel (Fig. 2A); over 80 km of main line can be stored on one reel. Larger vessels may also have an additional main-line reel to store spare main line or to sometimes set more than one reel of main line. Monofilament branch lines are stored in plywood boxes or plastic bins (Fig. 2B). Alternatively, small spools (hand carts) are sometimes used to store monofilament branch lines and float lines (Fig. 2C). The most commonly used float is an orange high-density foam buoy (Fig. 2D). Large polyethylene floats, floats with radar reflectors, radio buoys, and strobe-light buoys are also used. These buoys and floats support the main line and aid in locating the gear. Gear characteristics are detailed in Table 2. With minor modifications to gear and techniques, vessel operators can set gear to target swordfish, bigeye tuna, or yellowfin tuna.

Table 1
Characteristics of Hawaii-based swordfish longline vessels (from National Marine Fisheries Service, Pacific Area Office permit data).

Hull type	Number	Mean age (yr)	Length (m) Mean	Maximum	Minimum
Steel	84	11	23	30	16
Fiberglass	9	12	19	24	8

Many of the larger vessels use temperature probes, satellite or global positioning system (GPS) navigation, automated track plotting, satellite weather imaging, and communications systems to aid in locating fish. However, some longliners take a low-technology approach to keep capital and operating costs down.

Longline gear is deployed by spooling the main line off the reel while maintaining a slight tension on the drag. A few vessels are equipped with a line shooter to maintain tension on the main line from the reel to the point where it leaves the boat. The depth of fishing is controlled by a number of factors including branch line and float line length, weights attached to branch lines, length of main line set between floats, and amount of tension or slack in the main line. The high frequency of floats used in longlining for swordfish keeps the main line close to the surface. The shape of the catenary formed by the main line is not as deep as that formed when longline gear is set to target bigeye tuna (Suzuki and Warashina, 1977; Berkeley et al., 1981; Sakagawa et al., 1987; Boggs, 1992).

Light sticks greatly increase efficiency in catching swordfish (Freeman, 1989) either by attracting swordfish directly or by attracting swordfish prey (Berkeley et al., 1981). A chemical light stick is attached to the branch line about 2 m above the hook (Dollar[6]). Chemical light sticks glow for up to 12 hr.

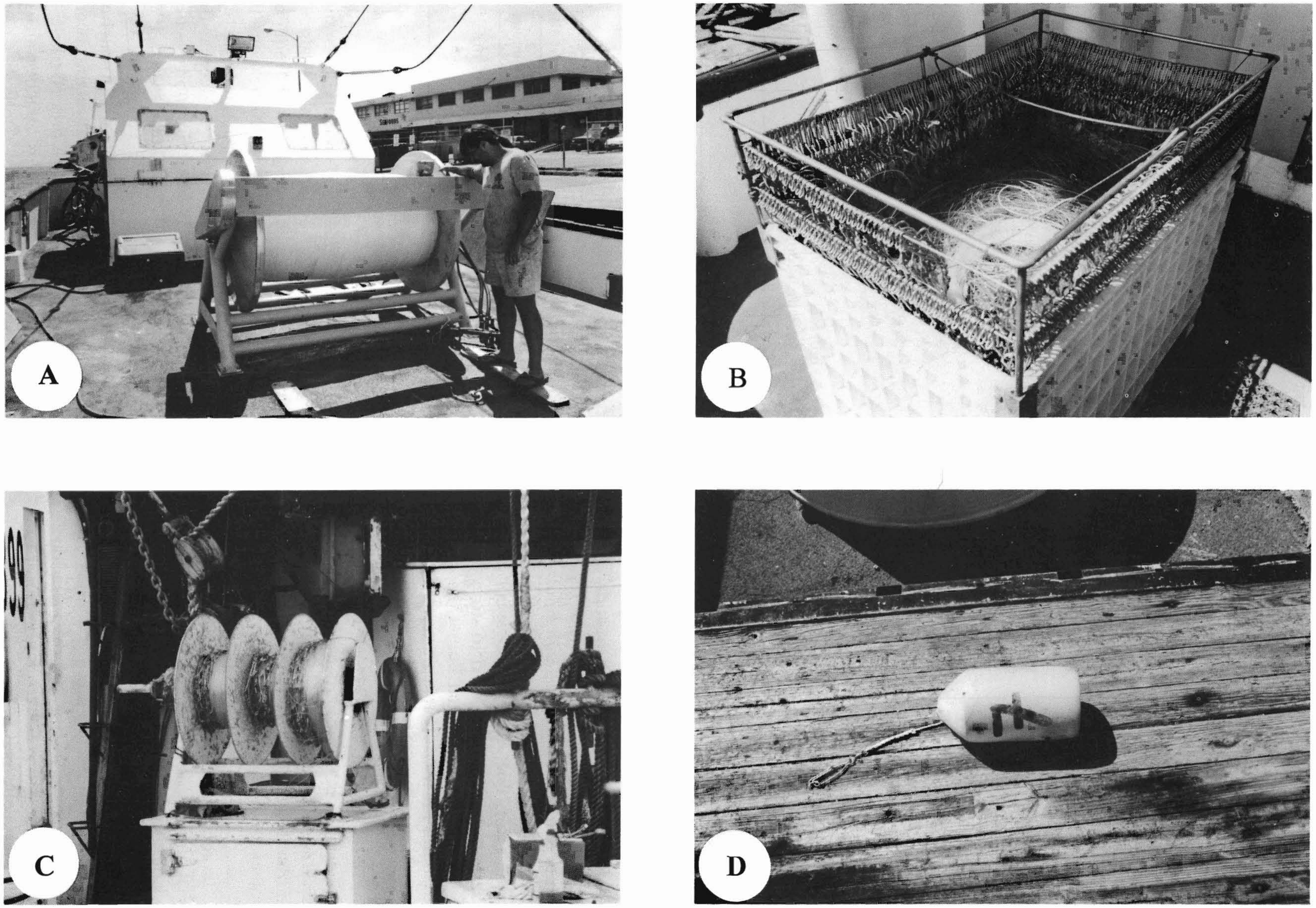

Figure 2

Main components of swordfish longline gear: (A) hydraulic reel with main line, (B) leader bin with branch lines, (C) hand cart with branch lines, and (D) orange high-density foam buoy.

Table 2

Characteristics of swordfish longline gear used on Hawaii-based longline vessels (Dollar[1]).

Gear	Characteristics
Lines	Monofilament stored on hydraulic reels
Main line length	30–80 km
Main line diameter	3.0–4.0 mm
Estimated distance between floats	90-160 m
Branch line length	13 m
Branch line diameter	2.1 mm
Hooks	8/0–10/0 Mustad[2]
Hooks per set	Range 450–1800, mean 724
Lightsticks	Cyalume[2] (break-activated) and World Plastics (thaw-activated)
Bait	Argentine shortfin squid, *Illex argentinus*

[1] Dollar, R. A. 1991. Summary of swordfish longline observations in Hawaii, July 1990–March 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-91-09, 13 p. Honolulu Lab., NMFS, 2750 Dole St., Honolulu, HI 96822-2396.

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

Large high-quality Argentine shortfin squid, *Illex argentinus*, was the preferred bait, with whole squid hooked in the mantle. Dyes were sometimes used to color the squid in an attempt to make them more appealing.

Longline gear, technology, and fishing techniques used by the Hawaii-based longline fishery for swordfish originate from the U.S. east coast and the Gulf longline fisheries. The major differences between the east coast and Gulf styles are the number of hooks set between floats and the frequency at which the light sticks are attached (Fig. 3). The east coast style of swordfish longlining is similar to the Florida style, in which 2–3 hooks are set between floats (Berkeley et al., 1981); a light stick is attached to each branch line with a rubber band. The Gulf style is similar to the method of longlining for yellowfin in the Gulf of Mexico (Wilson, 1988). The Gulf longliners set about 3–5 hooks between floats and attach one light stick for every 3–5 branch lines. Both styles of gear configuration are utilized by Hawaii-based longliners fishing for swordfish, and both styles are effective.

Fishing Area

Most effort by Hawaii-based longliners fishing for swordfish occurred north of the Hawaiian Islands. Fishing extended from 50 mi. off the main and northwestern Hawaiian Islands to far outside the Hawaii Exclusive Economic Zone (EEZ), with some trips in excess of 2,000 mi. from Honolulu. The northern range of the fishery approached 50°N, the northernmost distribution of swordfish as described by Bartoo and Coan (1989). The fishery extended latitudinally from 5° to 48°N and longitudinally from 175°E to 140°W (Fig. 4). In general, area fished expanded westerly from 1991 through 1993.

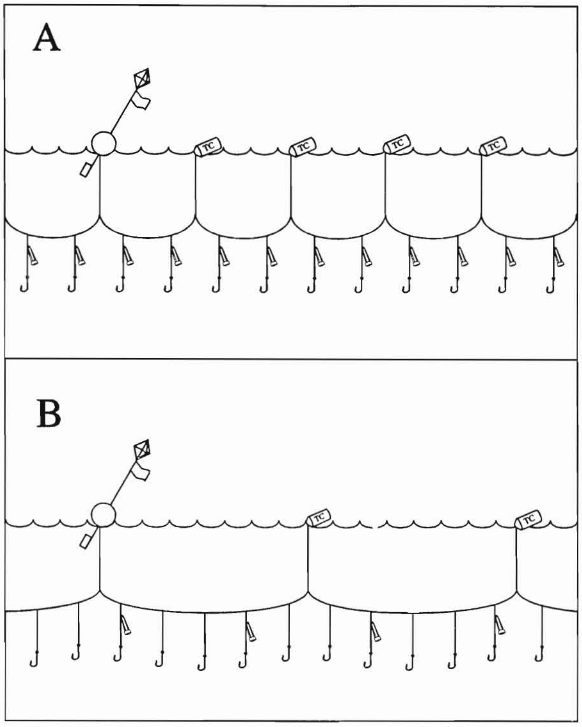

Figure 3

(A) East coast and (B) Gulf style longline gear configurations used by Hawaii-based longliners fishing for swordfish.

As a vessel approaches the fishing grounds, fishermen look for frontal zones where a rapid change in sea-surface temperature occurs (Sakagawa, 1989), and exploratory fishing for swordfish is focused in these areas. Concentrated fishing follows if a productive area is located. Fishing activity is also affected by moon phase. Fishermen have remarked that swordfish catch is better near the full moon, so more fishing occurs then.

The most seaworthy Hawaii-based longline vessels have the capability to fish in the North Pacific throughout the year. However, the majority of longliners fishing for swordfish traveled farther to fishing grounds during the summer, when seas were calm, and tended to fish closer to the Hawaiian Islands in the fall and winter, when seas become rough. Many longliners also fish close to Hawaii during the spring months, when swordfish abundance near the Islands exhibits a seasonal peak (Uchiyama and Shomura, 1974; Dollar[8]). The high price and increased abundance of bigeye tuna influences many vessel operators to target tunas during the winter season.

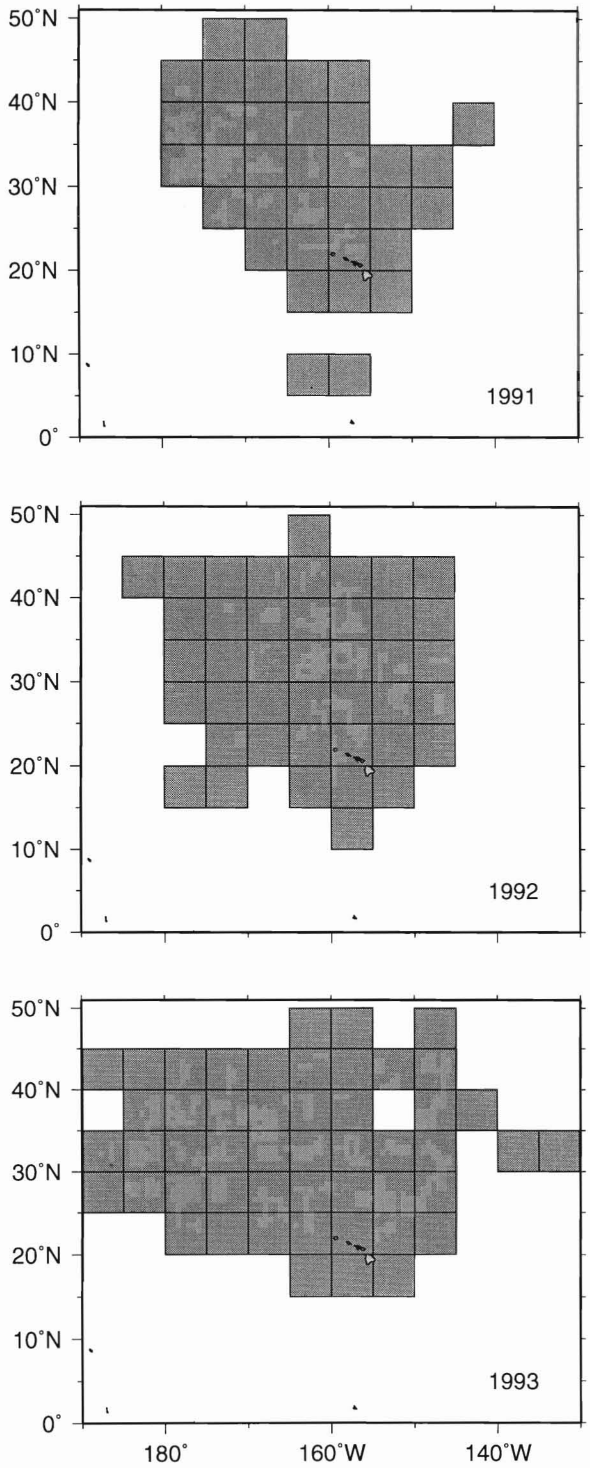

Figure 4
Geographic area fished by the Hawaii-based longline fleet fishing for swordfish, 1991–93.

Fishing Procedures

Swordfish longline gear is usually set during the late afternoon or evening (Table 3). Setting the gear takes about 4–6 hr depending on the amount of gear and sea conditions. Typically, about 48–64 km of longline gear is set. After setting the gear the vessel either idles near the end of the longline or travels back to the starting point of the set. The boat maintains visual and radio contact with the longline by attaching a strobe buoy and a radio buoy at the end of the gear. The longline gear is soaked overnight for 6–10 hr.

Retrieval begins early in the morning. The vessel approaches and hauls aboard the strobe and radio buoys. The main line is tied to the main line reel and the haulback process begins. Branch lines are coiled in the bins or on hand carts. The vessel slows down to haul fish aboard. Fish are processed and iced down soon after they are caught. Bait for the next day of fishing is removed from the freezer and allowed to thaw midway through the haul-back process. Retrieval time can vary considerably depending on number of fish caught and on sea conditions.

Table 3
Typical operating schedule of a Hawaii-based longline vessel fishing for swordfish.

Time	Activity
1630–1730	Gear preparation for setting longline.
1730–1930	Start setting gear (start time varies daily).
2130–2330	End set and clean up (approximately 4 hr to set gear).
2330–0500	Soak gear overnight and sleep.
0500–0600	Search for light/radio buoy.
0600–1430	Haul gear, process and store fish (approximately 8 hr to haul gear; however, the time to complete hauling gear depends on amount of gear set, number of fish caught, and tangles and breakage in the main line).

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[8] Dollar, R. A. 1993. Annual report of the 1992 longline western Pacific longline fishery. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-93-12, 25 p. Honolulu Lab., SWFSC, NMFS, 2570 Dole St., Honolulu, HI 96822-2396.

Processing and Storage of the Catch

Swordfish are headed, gutted, and finned immediately upon capture. The kidneys are removed and the visceral cavity scraped to remove any remaining slime or tissue. In general, marlins, tunas, and other fishes are left whole. Tunas and other pelagic species deteriorate in quality faster than swordfish, so bycatch is sometimes released alive or discarded early in the trip. Another reason for releasing or discarding bycatch is to conserve space for swordfish in the fish hold.

Most vessels have well-insulated, refrigerated fish holds. In addition, some have on-board saltwater ice makers. Saltwater ice, which is colder than freshwater ice, is used to chill and store the swordfish. To prevent tunas and other bycatch from freezing, they are packed in freshwater ice.

Effort

Number of Vessels

The number of Hawaii-based longliners that fished for swordfish increased more than 10-fold during 1989–93, from 11 in 1989 to a high of 114 in 1991, and then decreased to 88 vessels in 1993 (Fig. 5). Of 93 longline vessels that fished for swordfish in 1991–93, 50 were originally from the Gulf, 18 from the east coast, 15 from the west coast, and 10 were Hawaii longline vessels.

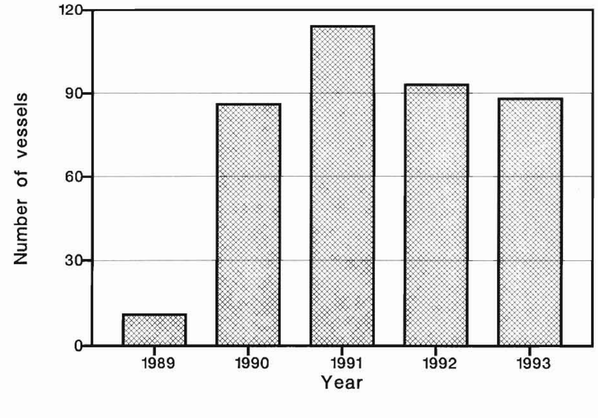

Figure 5
Hawaii-based longline vessels fishing for swordfish, 1989–93.

Trips and Sets

The number of swordfish-targeted and mixed-target trips increased dramatically from an estimated 43 in 1989 to 1,115 in 1991, and then declined to 650 in 1993 (Fig. 6). The total number of sets directed at swordfish and at mixed species including swordfish also decreased from 8,331 in 1991 to 7,533 in 1993. However, sets inside the Hawaii EEZ decreased dramatically, while sets outside increased (Fig. 7). The main reasons for the shift in fishing areas were higher swordfish catch rates outside the EEZ, and emergency federal regulations implemented in 1991, which closed areas around the Hawaiian Islands.[9]

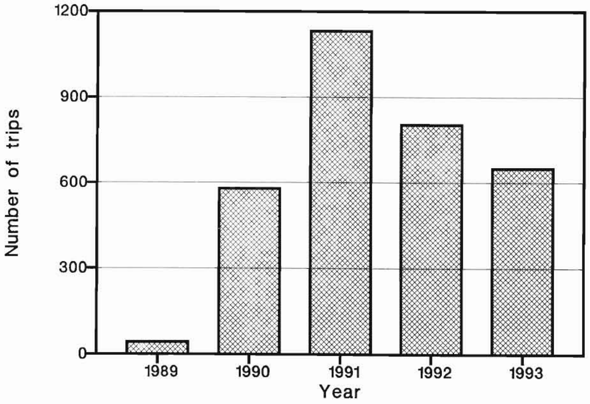

Figure 6
Trips by Hawaii-based longline vessels fishing for swordfish, 1989–93.

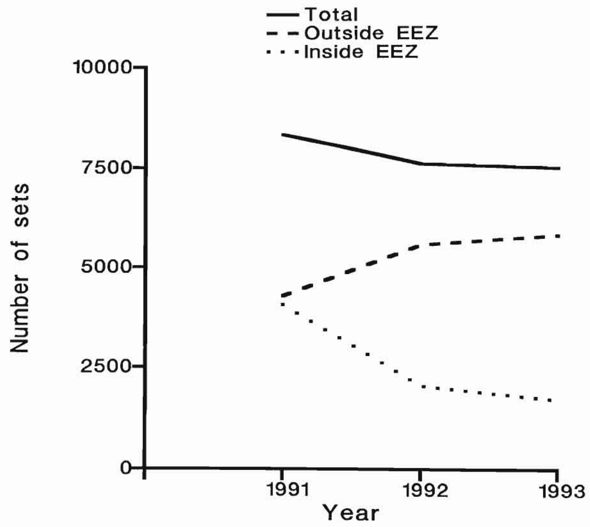

Figure 7
Sets made by Hawaii-based longline vessels fishing for swordfish, 1991–93, inside and outside the Hawaii EEZ.

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[9] The area around the northwestern Hawaiian Islands was closed due to interactions with the Hawaiian monk seal, *Monachus schauinslandi*, and near-shore areas around the main Islands were closed due to gear conflicts with small trolling and handline vessels (Western Pacific Fishery Management Plan amendments #3 and #5 respectively).

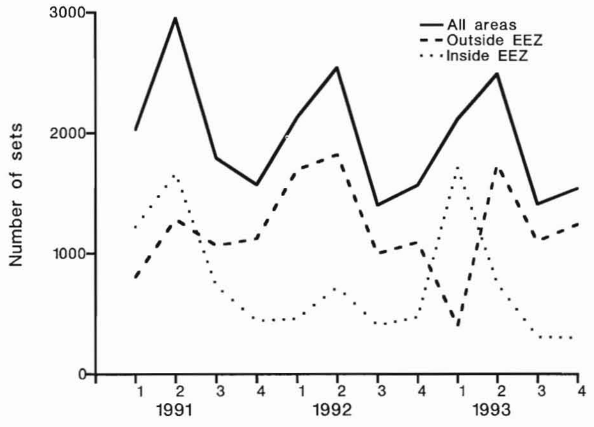

Figure 8
Quarterly number of sets made by Hawaii-based longline vessels fishing for swordfish inside and outside the Hawaii EEZ, 1991–93.

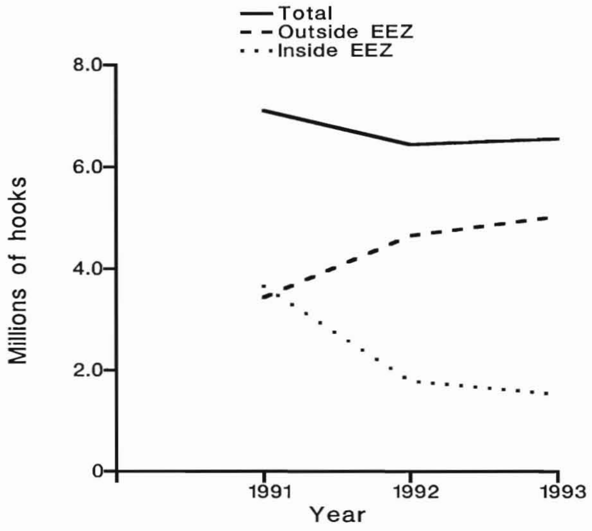

Figure 9
Hooks set by Hawaii-based longline vessels fishing for swordfish inside and outside the Hawaii EEZ, 1991–93.

Average number of sets per trip increased from 7.5 in 1991 to 11.6 in 1993. Sets per trip ranged from 5 to 27. The distance covered on trips and the number of fishing days increased. Transit time to the fishing grounds varies throughout the year, increasing during spring and summer (10–12 days) and decreasing during winter (5–7 days). The number of sets was highest during the second quarter and lowest in the third or fourth quarter of each year (Fig. 8).

Hooks

The total number of hooks set by longliners fishing for swordfish in 1991 was 7.1 million. Hooks set decreased to 6.5 million in 1992 and remained about the same in 1993 (Fig. 9). The decreased effort was a direct result of fewer vessels fishing in 1992 and 1993. Slightly more hooks were set inside than outside the EEZ in 1991, but more hooks were set on the high seas outside the EEZ in 1992 and 1993. The average number of hooks set per vessel per day changed little during 1991–93 (range: 842 hooks in 1992 to 868 hooks in 1993).

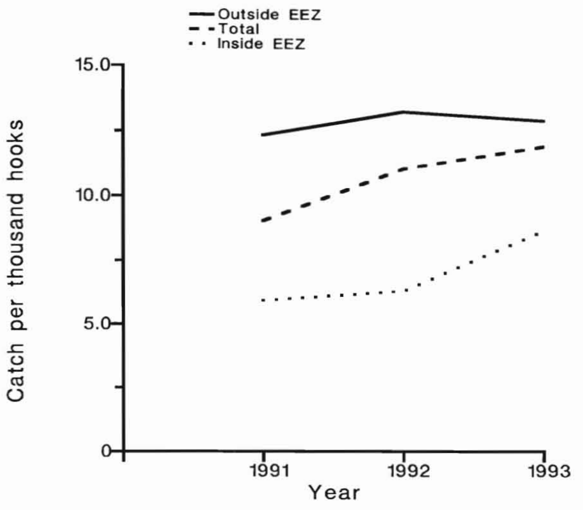

Figure 10
Hawaii swordfish catch per 1,000 hooks inside and outside the Hawaii EEZ, 1991–93.

CPUE

Swordfish CPUE (catch per 1,000 hooks for swordfish and mixed-target trips) rose from 9.0 in 1991 to 11.9 in 1993 (Fig. 10). Swordfish catch rates were much higher outside than inside the EEZ. However, fishermen commented that they had to travel farther from Hawaii to sustain high catch rates.

Swordfish CPUE varied considerably throughout the year (Fig. 11). CPUE outside the EEZ was consistently higher than CPUE inside; it peaked in the first quarter and was lowest in the second or third quarter. CPUE within the EEZ was highest in the second quarter and lowest in the fourth quarter. Peak CPUE outside the

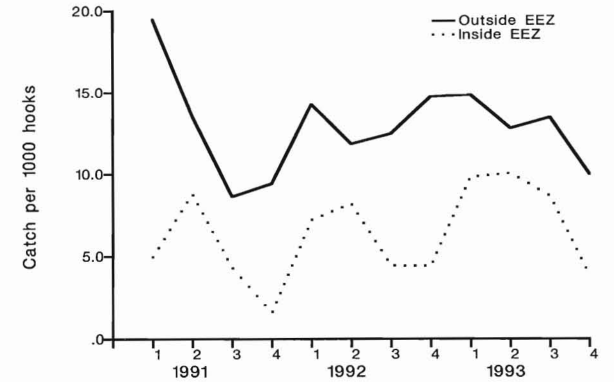

Figure 11
Quarterly swordfish catch per 1,000 hooks by Hawaii-based longline vessels, 1991–93.

EEZ occurred one quarter earlier than peak CPUE within the EEZ throughout 1991–93.

Landings

Swordfish

It has been estimated that Hawaii-based longliners accounted for about 15% of the Pacific-wide harvest and about 42% of the total eastern central Pacific catch (WPRFMC[10]). Hawaii-based longline landings of swordfish increased dramatically between 1989 and 1992. In 1990, swordfish became the dominant species landed in Hawaii's pelagic fisheries (Ito[2]). Estimated landings of swordfish by longliners fishing for swordfish increased from about 200 t in 1989 to 6,000 t in 1993 (Fig. 12). Much of the increase during the past 3 yr is a result of fishermen acquiring more knowledge of the fishery, modifying fishing techniques, and expanding the area of fishing.

Species Composition

The swordfish component of total longline landings (by weight) ranged from 60% in 1989 to 74% in 1992, and averaged 68% over the 5-yr period (Fig. 13). Tunas were the next largest component of total landings. Bigeye tuna (10.8%), yellowfin tuna (6.0%), and albacore (2.4%) were the most important tuna species represented. Marlin landings were composed mostly of striped marlin (3.3%) and Pacific blue marlin (2.8%). Other marketable species, mainly mahimahi (dolphin), moonfish, ono, pomfrets, and sharks, contribute a small portion of the landings (all species combined, 6.1%).

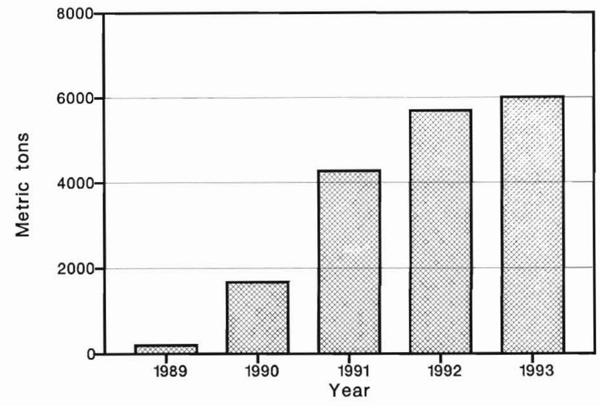

Figure 12
Swordfish landings by Hawaii-based longline vessels fishing for swordfish, 1989–93.

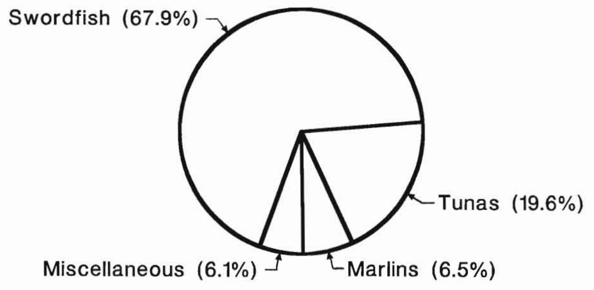

Figure 13
Species composition of landings by Hawaii-based longliners fishing for swordfish, 1989–93.

Sharks are the largest portion (by number) of longline catch in Hawaii (Dollar[4,8,11]), but relatively few are landed. The estimates of sharks landed were of those sold fresh, and do not include sharks that had been finned. Mako and thresher sharks were sold as a fresh product but nearly all blue and other sharks were released. Since shark fins were not observed in the shoreside sample, the volume and value of shark fins could not be estimated. The names of pelagic species

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[10] Western Pacific Regional Fishery Management Council. 1994. Amendment 7 to the Fishery Management Plan for the Pelagic Fisheries of the Western Pacific Region. WPRFMC, 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

[11] Dollar, R. A. 1994. Annual report of the 1993 western Pacific longline fishery. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-94-06, 38 p. Honolulu Lab., SWFCS, NMFS, 2750 Dole St., Honolulu, HI 96822-2396

commmonly caught by longliners fishing for swordfish are listed in Table 4.

Size of Fish

Small and badly damaged (i.e. eaten by sharks or whales) swordfish have little or no commercial value and are often discarded at sea or given away to friends at port upon the vessel's return. Data on these fish were not available based on the current sampling protocol, and therefore the shore-side sample was biased towards a higher number of larger, more marketable fish.

Mean weight of whole swordfish showed a slight net increase in 1989–93 (Table 5), increasing from 67.0 kg in 1989 to 81.3 kg in 1992, then decreasing to 80.0 kg in 1993. Weights of individual fish were broadly distributed, with standard deviation exceeding 45 kg. Swordfish landed in 1989–93 (Fig. 14) appeared to have a higher frequency of large fish than those landed in 1987–88 (Ito^2), prior to the exploitation of swordfish by Hawaii-based longliners. The weight-frequency distributions were bi-modal in most years, but uni-modal in 1990. The modes of these distributions were below the 71–80 kg size class in all years except 1993, when a mode was observed at 81–90 kg. The modal peaks shifted by 1–2 size classes each year.

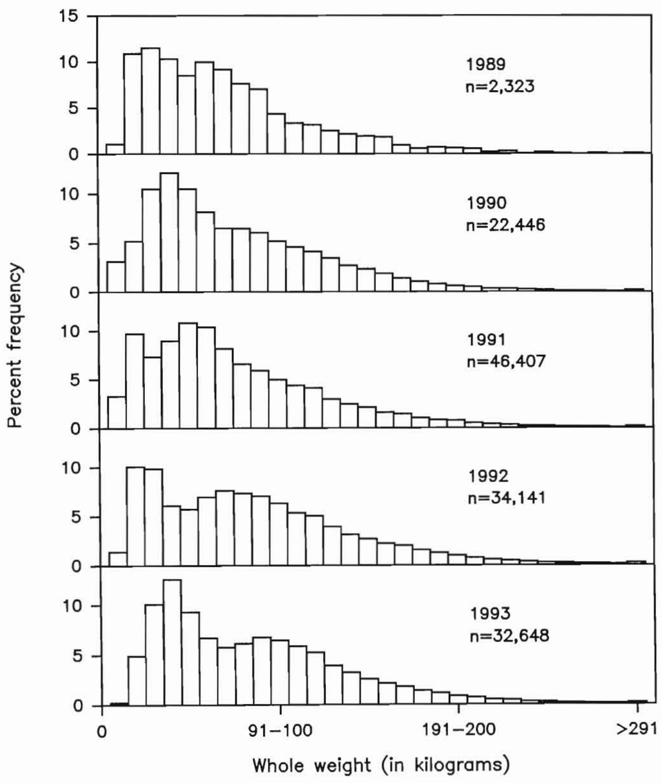

Figure 14
Annual weight-frequency distribution of swordfish landed by Hawaii-based longliners fishing for swordfish, 1989–93.

Market

U.S. swordfish consumption increased dramatically during the early 1980's (Lipton, 1986). Swordfish landed in Hawaii are either sold by open auction or brokered by Hawaii seafood dealers; almost all are exported to the U.S. mainland. Swordfish are chilled with gel ice packs placed in the gut cavity, individually wrapped in plastic bags, packed in insulated air freight containers (LD-3's), and exported via air freight. The cost of freight and handling ranges from $0.25 to $0.50 a pound. Some of the more common destinations are Boston, New York, Los Angeles, and San Francisco.

Currently, the volume of swordfish consumed in Hawaii is low. Local consumers are not familiar with swordfish, and the demand for the product is low. Most local sales of swordfish are to restaurants.

Ex-vessel Revenue

Estimated annual ex-vessel revenue generated by swordfish rose dramatically from 1989 through 1993, from $980,000 to $26.5 million (Fig. 15). Ex-vessel revenue for swordfish has been the highest of all fish species in Hawaii since 1991.

Average Prices

Estimated ex-vessel prices were based on dressed weights. The swordfish size categories used by the seafood market industry are: rats (<22.7 kg), pups (22.7–44.9 kg), and markers (>44.9 kg). Larger fish receive a higher unit price than smaller fish (Table 6). In general, mean prices for all sizes of swordfish were depressed in 1992–93. Estimated prices for rats and pups decreased from 1990 to 1992–93. Estimated price for markers declined from a high in 1990 to a low in 1992 and increased slightly in 1993.

Protected Species Interactions

Allegations of incidental takes of the Hawaiian monk seal, *Monachus schauinslandi*, in the proximity of certain islands and atolls of the northwestern Hawaiian Islands (NWHI), and a rapid

Table 4

Common and scientific names of common pelagic species caught by Hawaii-based longliners fishing for swordfish.

Common name	Scientific name
Billfish	
Swordfish	*Xiphias gladius*
Pacific blue marlin	*Makaira mazara*
Black marlin	*M. indica*
Striped marlin	*Tetrapturus audax*
Shortbill spearfish	*T. angustirostris*
Sailfish	*Istiophorus platypterus*
Tunas	
Bigeye tuna	*Thunnus obesus*
Yellowfin tuna	*T. albacares*
Albacore	*T. alalunga*
Northern bluefin tuna	*T. thynnus orientalis*
Skipjack tuna	*Katsuwonus pelamis*
Sharks	
Bigeye thresher	*Alopias superciliosus*
Shortfin mako	*Isurus oxyrinchus*
Oceanic whitetip shark	*Carcharhinus longimanus*
Blue shark	*Prionace glauca*
Miscellaneous requiem sharks	Carcharhinidae
Miscellaneous species	
Mahimahi (dolphin)	*Coryphaena hippurus*
Ono (wahoo)	*Acanthocybium solandri*
Moonfish	*Lampris guttatus*
Escolar	*Lepidocybium flavobrunneum*
Lancetfishes	*Alepisaurus* spp.
Pelagic stingray	*Dasyatis violacea*

Table 5

Mean whole weight and standard deviation (kg) of swordfish landed by Hawaii-based longline vessels fishing for swordfish, 1989–93.

	1989	1990	1991	1992	1993
Mean	67.0	73.8	71.3	81.3	80.0
S.D.	45.9	51.1	49.8	54.9	51.6

Table 6

Hawaii ex-vessel swordfish prices (dollars per kg), 1989–93.

	1989	1990	1991	1992	1993
Rats (<22.7 kg)					
Mean	2.98	4.87	3.33	2.58	2.58
S.D.	1.23	1.15	1.21	1.21	0.95
Pups (22.7–44.9 kg)					
Mean	4.67	5.36	5.14	4.28	3.77
S.D.	1.12	1.39	1.12	1.41	1.08
Markers (>44.9 kg)					
Mean	5.34	5.47	5.40	4.94	5.07
S.D.	1.17	1.39	1.19	1.39	1.15

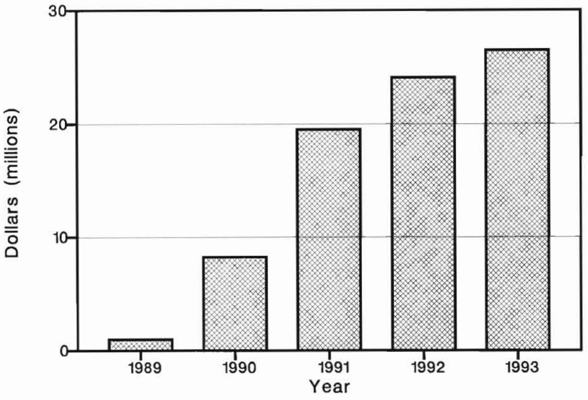

Figure 15

Swordfish ex-vessel revenue from the Hawaii-based longline fishery, 1989–93.

increase in the number of longline vessels in Hawaii prompted the WPRFMC to take regulatory action (55 FR 49285, on 27 November 1990). Regulations required longline vessels to maintain a fishing logbook, to have permits, and to take an observer if an operator intended to fish in the study zone around atolls and islands of the NWHI. Based on further reports of monk seals taken by the fishery, the study zone was closed permanently to longlining on 18 October 1991 (Regulation 56 FR 52214). According to logbook data, the area closures around the NWHI appear to have eliminated interaction incidents with Hawaiian monk seals. The area closure resulted in the loss of several banks where swordfish congregate during the spring months, a loss felt by many of the smaller longline vessels.

Due to uncertainty over the frequency of turtle interaction with longline gear based on logbook reports, the low level of authorized incidental take, and greater than anticipated level of longlining effort, an observer program was initiated.[12] The main objective of the observer program was to document incidental take of sea turtles and to verify logging of interactions by vessel operators. Observers began embarking on longline vessels whose captains volunteered to host them in the last quarter of 1993 (Dollar[11]). A regulation issued by the Secretary of Commerce in January 1994 made it mandatory for all permitted Hawaii-based longline vessels

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[12] Endangered Species Act Section 7 Biological Opinion Consultation, conducted by NMFS in 1993.

to give notification 72 hr in advance of departure and to accommodate an observer. The initial authorized level of total turtle take and mortality was modified upward in light of the uncertainty regarding the actual level of incidental take.

The first objective of Amendment 7 to the Fishery Management Plan (FMP) for the Pelagic Fisheries of the Western Pacific Region is to regulate effort "... by limiting potential increases in effort in order to minimize the risk of adverse impacts on the longline fishery, other fisheries, the stocks, and protected resources such as sea turtles" (WPRFMC[10]). The limited entry and observer regulations reduce the chance of much higher levels of effort which might affect turtles, allow NMFS to more accurately estimate the impact of longlining on protected sea turtles, and may temporarily dissuade NMFS from imposing conservation measures either under regulations implementing the pelagics FMP, or under the Endangered Species Act based on the earlier authorized level of incidental take of sea turtles.

Conclusions

The Hawaii-based longline fishery for swordfish grew at a rapid pace beginning in 1989 and is now the largest commercial fishery in Hawaii. This growth has raised concern regarding over-utilization of the swordfish stock (WPRFMC[10]). However, the rate at which the fishery has grown in the past 2 yr has slowed in comparison to 1989–91. The number of vessels decreased in both 1992 and 1993. Total fishing effort, in number of sets and hooks, remained about the same during 1991–93 but the effort shifted to outside the EEZ. Swordfish CPUE changed little during 1991–93, but fishermen were making longer trips and fishing farther from Hawaii.

Swordfish landings, ex-vessel revenue, and size of fish have not declined in this new fishery. Indicators presented in this report are helpful in understanding the swordfish in the central Pacific. However, monitoring of the Hawaii-based longline fishery must be continued to see what kind of long-term impact it has on swordfish of the North Pacific.

Acknowledgments

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Recent Development of Swordfish, *Xiphias gladius*, Longline Fisheries near Reunion Island, Southwestern Indian Ocean

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ABSTRACT

A substantial increase in French longlining activity targeted on swordfish has been observed between 5°S and 35°S in the western Indian Ocean since 1992. The domestic fleet increased from one unit in 1991 to 15 in 1994. Other countries active in the area are Taiwan, with an estimated 150 longliners, and Spain, with five 45-m longliners. Initially concentrated near the island of Reunion, French activity presently extends to the entire French Exclusive Economic Zone surrounding Reunion and southward to 26°S.

The catch of the Reunion fleet increased from 41 metric tons (t) in 1992 to approximately 700 t in 1994. In 1994, swordfish represented 65% of the catch (in number); mean catch was 14 fish per 1,000 hooks, and mean weight of fish was 50 kg. Sales on the local market are low. The high-quality product is transhipped fresh by air to Europe, and the lower grade is frozen.

The development of this fishery stresses the need to develop a program in cooperation with other countries in the southwestern Indian Ocean to improve knowledge of the biology of swordfish, its relation to the environment, and fishing activity, in order to assess and manage the stocks in the long term.

Introduction

The domestic swordfish, *Xiphias gladius*, fishery was virtually nonexistent a few years ago around the island of La Reunion, an overseas department of France in the southwestern Indian Ocean. Beginning in 1991, two factors promoted the rapid development of this fishery. First, the favorable conditions for swordfish in the southwestern Indian Ocean and the success of the Asian fleet based on the island inspired a local fisherman to begin longline trials with a 12-m boat. Second, new tax regulations offering exemption for certain investments in French overseas departments encouraged fishing companies from the mainland to come to Reunion. Four 16-m longliners based at Pointe des Galets harbor started operating in 1992, targeting bigeye tuna destined for the Japanese market. Information on the success of this fishery spread rapidly. There have since been significant changes in various aspects of the swordfish fishery, including the evolution of boat and gear characteristics, fishing techniques, fishing grounds and seasonal activity, target species, and markets.

In 1993, the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) began a program in Reunion to study and monitor the swordfish fishery, analyse the catch, and improve knowledge on the biology of swordfish and billfish from the southwestern Indian Ocean. The Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) contributes to this program, specifically by producing weekly surface temperature charts from satellite images. These charts, which are produced for the Regional Tuna Project, Phase 2, of the Commission de l'Océan Indien (COI), are distributed to participating countries: Comoros, France, Madagascar, Mauritius, and Seychelles.

This paper describes the swordfish fisheries in the southwestern Indian Ocean and the data which have been collected on them, and presents an analysis and evaluation of geographical swordfish distribution, catches, and catch per unit effort. Along with brief histories of the fisheries, we describe the fishing strategies of the various fleets operating in the zone, to examine their fundamental differences and to draw out the positive developments of the emerging fishery based at Reunion Island.

The Fisheries

Vessels

Domestic Fleet—The characteristics of the vessels composing the Reunion fleet are summarized in Table 1. Four companies are represented, operating a total of 15 vessels.

Taiwanese Fleet—The Taiwanese longline fishery is very active in the Indian Ocean, with probably 150 longliners operating in the French Exclusive Economic Zone (EEZ) around Reunion Island. In 1994, 28 vessels received licenses to fish in the EEZ, on condition that the catch is landed in Reunion. These vessels are 35–45 m long, between 145 and 380 horsepower, and have a capacity of at least 100 metric tons (t), with 18–30 men on board. A large proportion are equipped with freezing holds (–60°C).

Spanish Fleet—There is little or no information available on the Spanish fleet. Five 45-m longliners operate occasionally in international waters in the southwestern Indian Ocean. These vessels were redeployed from the Spanish fleet of longliners in the northeast Atlantic. They arrived on an exploratory cruise at the end of 1993 and in early 1994.

Fishing Gears and Methods

All the Reunion vessels use a system of drifting longline which utilizes a main spool and a line shooter. The main line is a nylon monofilament 3.5 or 4 mm in diameter and approximately 45–80 km long. The line can be weighted to control its depth in strong currents. The leaders with hooks (size 8/0 or 9/0) are 10 m long and 2 mm diameter, and are attached to the main line with snaps. Depth is controlled by a series of intermediate floats attached to the main line with leaders of 5–25 m. In addition a larger float is used to separate the various sections of 60–100 hooks. Between 500 and 1,400 hooks are utilized for each set. The buoys at the end of the longline are equipped with a strobe light and a radio system to assist in retrieval. There may be various modifications to the fishing gear, these being determined by the requirements of individual skippers.

Because swordfish is the target species, the longline is always set in the evening. Kume and Joseph (1969) have shown that lines set at night are more productive for capturing swordfish than lines set during the day. A line shooter draws the line from the main spool and controls its setting speed. Clipping of the leaders on the main line and baiting of the hooks takes place progressively during each set. Squid is generally used as bait in addition to a light stick (Cyalume[1]) placed 1 m above the hook. This whole operation requires three crew-

Table 1
Specifications of the longliners of the Reunion fleet.

	Company					
	Compagnie des Longliners			Sopesud	Pointe de la Table	Creole
Number of units	3	1	8	1	1	1
Length (m)	25	20	16	12	12	12
Bunker capacity (m^3)	48	23	13		2.5	2
Crew	9	7	6	5	4	4
Horsepower	600	2 × 350	350	200	250	213
Insulated hold (m^3)	120	50	28	20	12	9
Ice machine	yes	yes	yes	no	no	no
Regulated hold (0°C/–20°C)	yes	yes	yes	no	no	no
Regulated hold (–40°C)	yes	yes	yes	no	no	no

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

men on deck and one at the helm. The longline is set in 4–6 hr cruising downwind.

The line is hauled after sunrise. The duration of the haul depends on the catch and sea conditions. The number of days at sea varies according to vessel size and capacity, and weather conditions. Small vessels stay at sea from 2 to 8 days, while vessels longer than 16 m stay at sea 7–18 days.

Very little information is available on the fishing techniques of the Taiwanese fleet. It is known, however, that the Taiwanese do not use a monofilament longline and therefore require a large crew. At least 2,000–2,500 hooks are utilised for each set. The target species are albacore and bluefin, bigeye, and yellowfin tuna. Mackerel is generally utilized as bait.

No information is available concerning techniques utilized by the Spanish fleet. These are most likely as described by Rey and Alot (1984).

Onboard Catch Processing

Handling and treatment of the catch depends on the type of vessel and market requirements. Two processing techniques are utilized: swordfish are headed and gutted (H&G): head, guts, gills and fins are discarded; or the fish are gutted only: guts are discarded and the head is left on, with the gill discarded. The latter treatment is generally carried out on pieces of less than 20 kg. In Reunion, fish destined for export are carefully and individually processed on board on ice in order to conserve quality.

On Taiwanese albacore longliners, the entire catch is placed in –45° or –60°C holds after processing (H&G). Billfishes are not subject to any particular special treatment. On Taiwanese longliners targeting bluefin, bigeye, and yellowfin tuna ("sashimi boats"), the entire catch is placed in –60°C holds. Fish are carefully treated taking into account the special requirements of sashimi buyers.

Marketing

Reunion Longliners—In an effort to control the regional market, only local companies are presently allowed to sell on the Reunion market. The portion of the catch destined for export is processed by a specialized company. Swordfish and tuna loins of 3 kg are vacuum-packed in temperature-controlled packaging and air-freighted to Europe.

The Compagnie des Longliners exports its entire catch, for which purpose it has established a joint venture with an American company which specializes in the marketing of fresh swordfish and high-quality tuna. Quality control is carried out before export. The fresh products are primarily exported to Europe (90%) and the United States (10%). Fresh fish that are not of export quality are frozen and exported at a later date to other markets.

As the result of a flooded market following the first year of production, there was a sharp drop in the price in Spain, France, Italy, and Germany. The world demand for fresh swordfish allowed profitable returns of around US$4 per kilo.

The various strategies for exporting fresh fish by air from Reunion, including techniques of preservation and controlled packaging, have been determining factors in the evolution of the industry and have added value to this limited resource.

Taiwanese and Spanish Vessels—The Star Kist company purchases the catch of the Taiwanese albacore longliners, which is exported in bulk-freezer vessels to canneries in Puerto Rico. The sashimi boats transship their catch in Japanese shuttle vessels equipped with bulk deep-freezers; it is purchased by traders in Japan. The marketing of the catch from the Spanish fleet is undocumented.

Data Collection

Domestic Fleet

Logbooks were distributed to all Reunion longliners to collect information on fishing positions, number of hooks per set, light sticks used, fishing gear techniques, times that line is set and hauled, number of fish caught by species, and their estimated weights. Environmental and weather conditions (sea-surface temperature, wind speed and direction, etc.) are also recorded. The logbooks are collected regularly from the skippers or company managers.

Fishing statistics for Reunion's fleet are determined on the basis of voluntary declarations of catches by skippers and companies to the Fisheries Administration. Available data on catches represent the comprehensive results of fishing operations by all registered companies. The companies must declare the date of the departure and arrival of each of their vessels as well as the total catch by species (13 species). In order to confirm the information received, port sampling and on-board observer programs are also conducted.

Other Fleets

Authorization to fish in the French EEZ for a period of one year was granted to 28 Taiwanese longliners in

November 1993. This agreement requires that Star Kist hand over logbooks completed by captains and indicating precise fishing positions, number of hooks per set, and total catch transhipped at the port of Pointe des Galets.

Fishing statistics on the Asian fleet are organized and published by the Indo-Pacific Tuna Development and Management Programme (IPTP) of the FAO, based on declarations from individual countries. No data are available on the Spanish fishery.

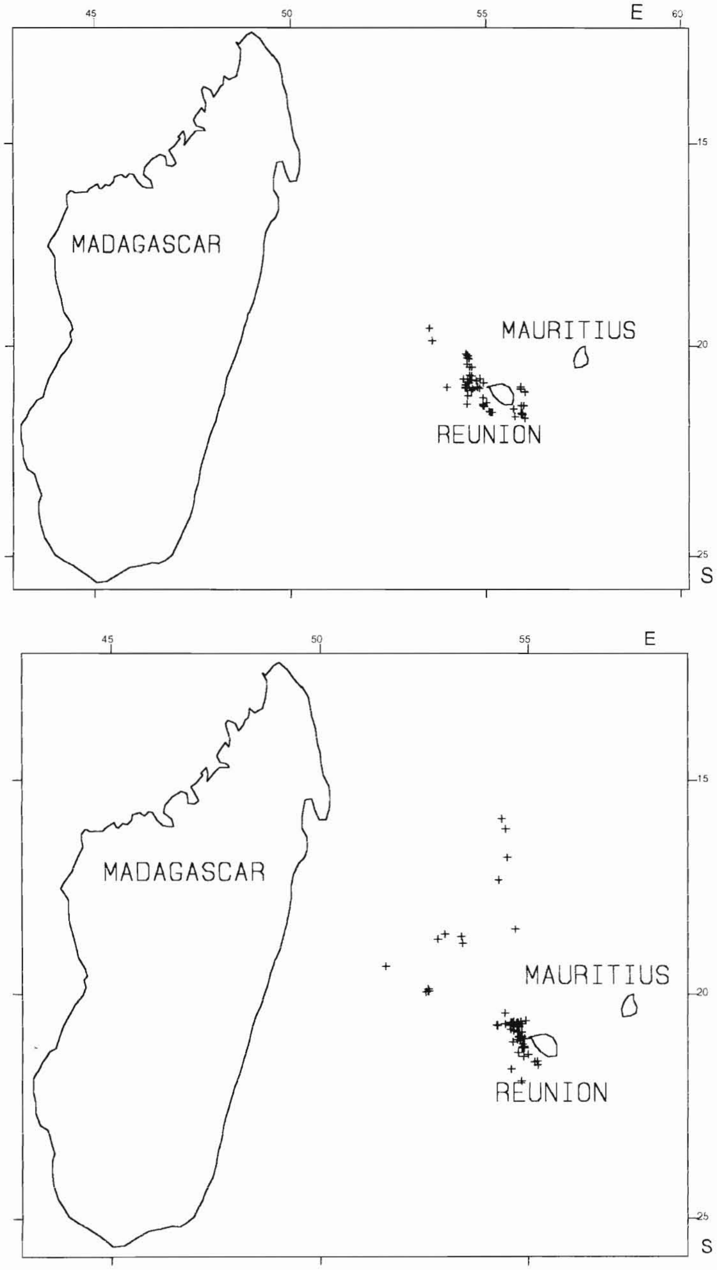

Figure 1

Distribution of the Reunion longliner fleet in 1993 in summer (upper) and winter (lower).

Results and Discussion

Because the logbooks only cover a portion of fishing activities, a coverage rate has been established, defined as the ratio between the number of trips listed in the logbooks and the estimated number of total trips by the entire Reunion fleet. The coverage rate was 24% in 1992, 40% in 1993, and 95% in 1994.

Fishing Grounds

Figures 1 and 2 show the distribution of the Reunion longliner fleet in 1993 and 1994. Each cross represents the starting position of a set during one fishing day. Figure 3 shows the fishing operations of the 21 Taiwanese longliners in winter 1993 and summer 1994.

Species Caught

An exhaustive list of species caught was begun by compilation of fishing logbooks and was completed by scientific observers during trips onboard longliners based in Reunion (Table 2). The processing carried out on the catch by the Taiwanese longliners makes species identification difficult; however, *Lampris guttatus* was detected in the catch.

Quantities Caught

Figure 4 shows swordfish catches by the major countries fishing for swordfish in zone 51 of the FAO (30°–80°E) during 1984–93 (IPTP[2]). The increasing catches of swordfish and albacore by the Reunion fleet during 1991–94 are depicted in Figure 5. Increasing targeting on swordfish by the Reunion longliners during 1992–42 is reflected in Figure 6, which shows the proportions of major species caught during that time. The

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[2] Indo-Pacific Tuna Development and Management Programe (IPTP). 1994. Indian Ocean and Southeast Asian tuna fisheries data summary for 1994.

monthly variation by species of catch by Taiwanese longliners is presented by number of fish in Figure 7, and by percentages in Figure 8.

Effort

Not only the number, but the size of French longliners based in Reunion have increased since 1991 (Fig. 9). Between 1991 and 1994, both the number of boat days at sea and the amount of effort, estimated as the number of hooks set, increased more than 20-fold (Table 3). The seasonal distribution of effort by the Taiwanese fleet from July 1993 to February 1994 is presented in Table 4.

Catch Per Unit of Effort

The 1993–94 spatial distribution of swordfish catch per unit effort (CPUE) of the Reunion longliner fleet is illustrated in Figure 10, and that of the 21 Taiwanese longliners in Figure 11. CPUE by species for the Reunion longliners (in weight per boat-day at sea) from March 1992–September 1994 is shown in Figure 12. Monthly CPUE (fish caught per 1,000 hooks) for swordfish, albacore, and other species) caught by the Reunion and Taiwanese longliner fleets is presented in Figure 13.

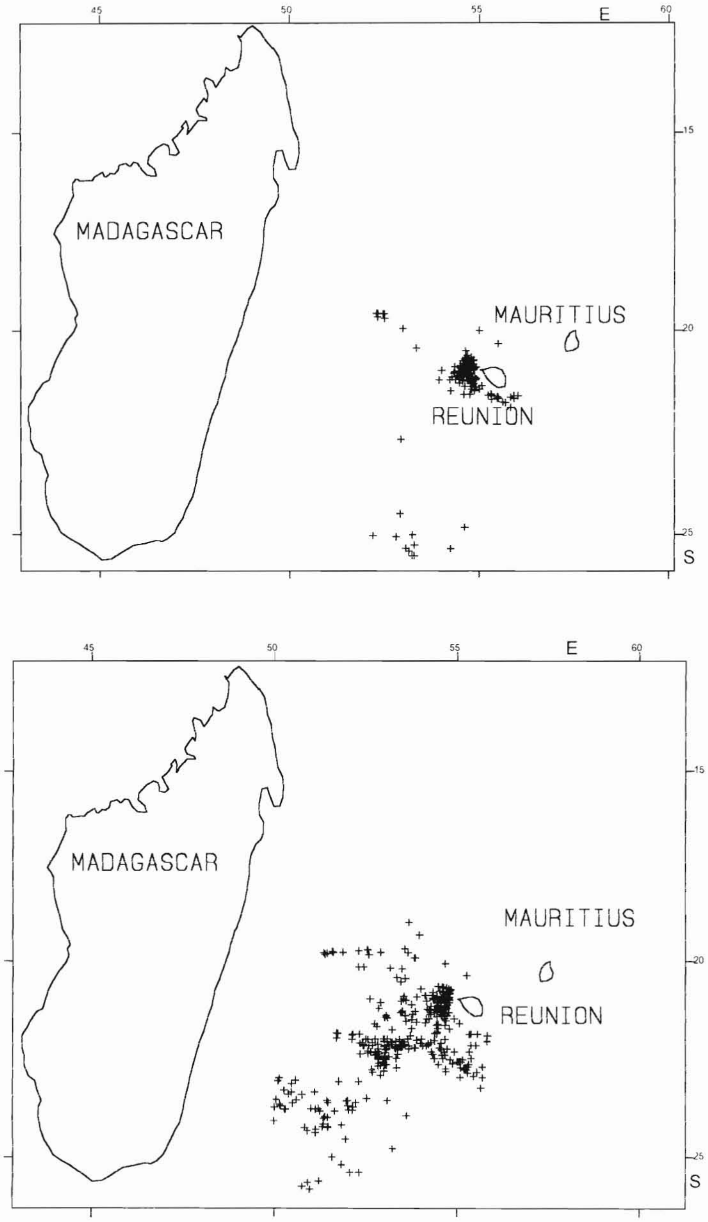

Figure 2
Distribution of the Reunion longliner fleet in 1994 in summer (upper) and winter (lower).

Discussion

Reliability of the Data

Most companies and skippers have cooperated well with the new system of collecting catch logbooks, introduced in November 1993. In exchange for the data, complete confidentiality is guaranteed. Raw (unaggregated) data are not disclosed or published. These logbooks provide very solid information on the position of sets, techniques used, environmental conditions, and number of fish caught by species.

Analysis of the data has shown some limitations to this system. When total daily catch is compared with the actual transshipment figures, differences of up to 20% appear; therefore, the catch estimates provided by the skippers must be viewed cautiously. There was also discrepancy between data on fishing periods collected by the Fisheries Administration and by ourselves, for example, the dates of the start and end of fishing trips were different.

It would be useful in the future 1) to include a recapitulation table in the declaration forms, in which the number and weight of fish unloaded would be summarized by species; 2) to furnish a size–weight conversion table to each skipper in order to improve estimates; and 3) to add to the declaration forms further required information, such as number of sets per trip and number of each species caught.

Concerning the catch declarations of Taiwanese longliners, two types of information are provided, the number of fish caught and the total tonnage of each species unloaded. There are many inconsistencies, probably as a result of transshipment at sea and at other ports. In order to improve the quality of the data it would be necessary to place observers aboard and to monitor this fishery on a regional level, over the entire Indian Ocean.

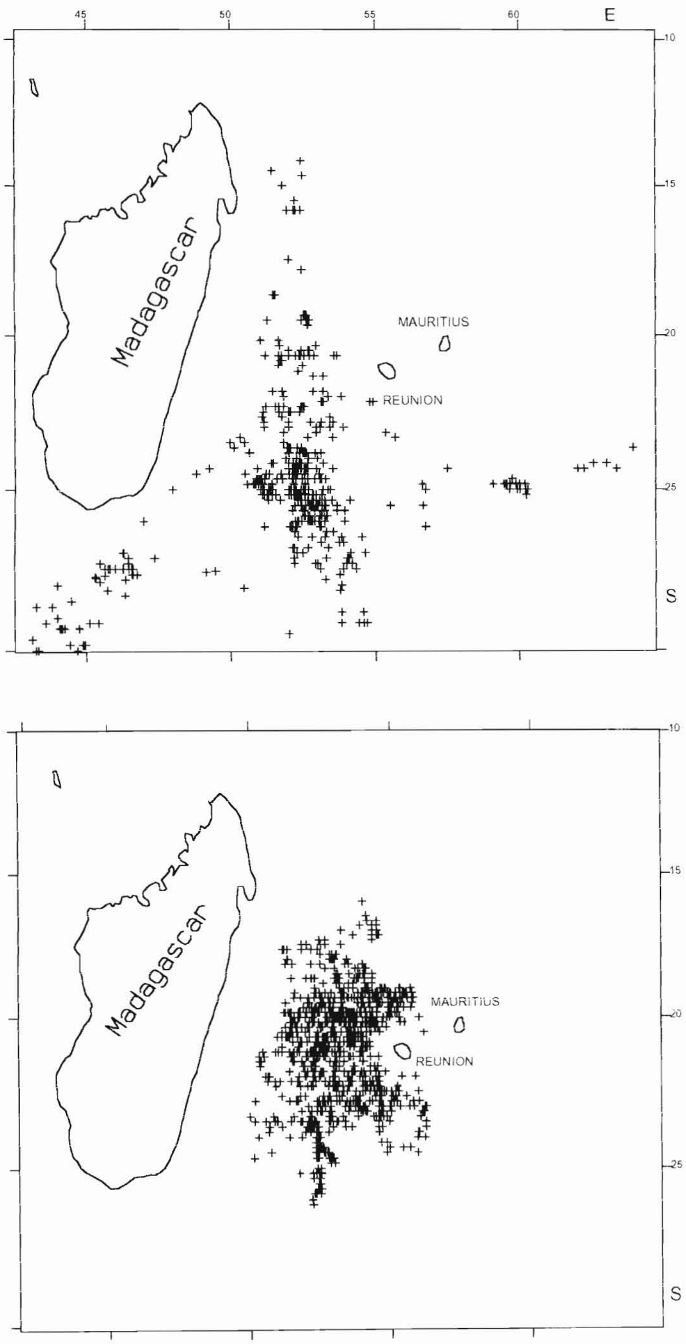

Figure 3

Distribution of 21 Taiwanese longliners during winter 1993 (Jul. 93–Oct. 93; upper) and summer 1994 (Nov. 1993–Feb. 1994; lower).

Fishing Grounds and Seasons

Domestic Fleet—The fishing grounds of the Reunion longliners are to the west and south of Reunion in the French EEZ and in international waters. No longliners are authorized to fish within a zone of 30 nautical miles (n. mi.) from Reunion, in order to avoid conflicts with the artisanal tuna fishery.

The period of the most intensive fishing activity corresponds to austral summer. It appears that the seasonal abundance around Reunion could be related to the migration of mature fish, which congregate in this zone during summer.

The youngest females observed, stage 6 on the scale of maturity (Uchiyama and Shomura, 1974), were observed in the month of November; females in the phase of atresia have been observed in April near Reunion Island. During the month of January, swordfish larvae have been observed in the Mozambique Channel (Kondritskaya, 1970) as well as off the east coast of Madagascar (Gorbunova, 1969).

The violent trade winds that characterize the southern winter limit boats of the domestic fleet, which are not designed for distant water operations. In addition, the smaller vessels are incapable of manufacturing ice. Thus during the winter 12-m vessels prefer to pursue demersal fishes on banks off the Mauritian islands of Rodrigues and Soudan.

The activity of the domestic fleet has significantly evolved in the last 3 years. This is illustrated by Figures 1 and 2, which show the progressive spatial extension of fishing. The catch zone west of Reunion in 1993 expanded to the southwest in 1994, with maximum catches between 30 and 60 n. mi. to the west and southwest, extending southwestward beyond the 200-n. mi. zone. Figure 12 illustrates changes in the monthly average catch per unit effort, which displayed strong seasonal trends. In 1994 there was no winter decrease in catch rate, a consequence of progressive mastery of fishing techniques by the crews. This promoted a positive balance of accounts for companies in 1994 and ensured a constant

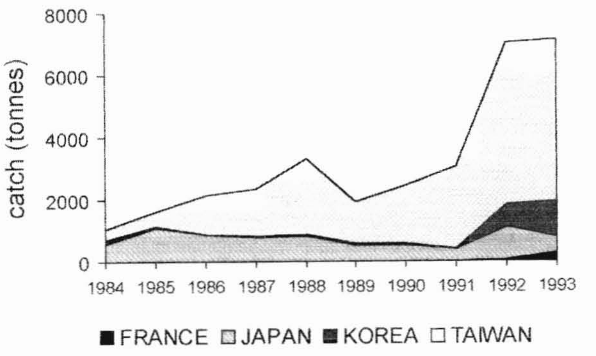

Figure 4
Swordfish catch by longliners of the main countries fishing swordfish in FAO zone 51, 1984–93 (from IPTP[1]).

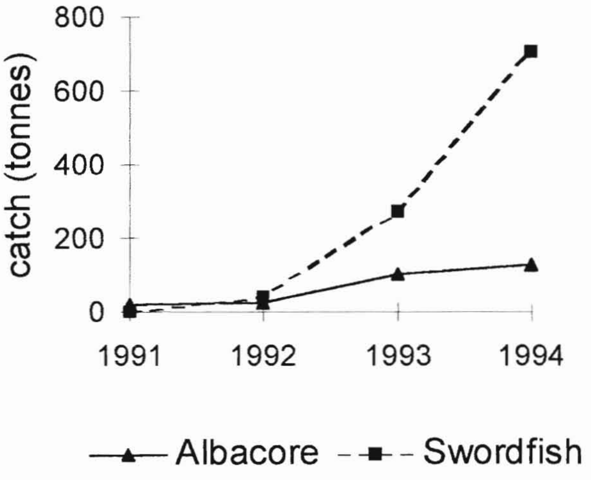

Figure 5
Catches of albacore and swordfish by Reunion longliners, 1991–94.

supply of exports to penetrate international markets. The arrival of more powerful vessels, improvement and mastery of fishery techniques, and the discovery of new zones of exploitation could all bring further notable changes to current strategies.

Taiwanese Longliners—The seasonality and fishing grounds of the Asian fleet are not precisely known. These vessels are constantly on the move, searching for bigeye, albacore, and bluefin tuna. It seems that this fleet operates during the austral summer between 10°N and 25°S, and between 25°S and 35°S during the winter, when they target juvenile albacore. No precise data

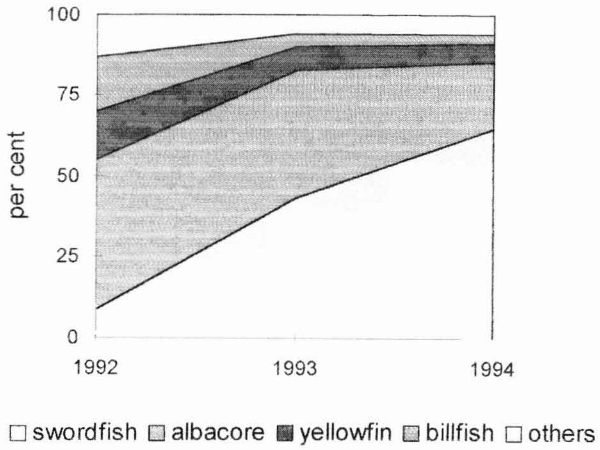

Figure 6
Proportions (by number of fish) of main species caught by Reunion longliners, 1992–94.

is available on their activity in the EEZ between 35°S and 40°S. The movements of this fleet are known only from a sample of 21 boats out of a total fleet of 150 in the EEZ around Reunion Island and Mauritius between July 1993 and February 1994. It would appear, according to information obtained by scientists from Seychelles, Mauritius, Madagascar, and the Comoros, that at least 300 vessels were listed during 1994 in the region southwest of Reunion.[3]

Spanish Longliners—Contacts have been established with the Spanish Oceanographic Institute (IEO) and the European Economic Community (EEC), which financed the redeployment of vessels from the Atlantic to the Indian Ocean, to obtain more information on this venture. These 5 vessels seem to obtain excellent results to the south of Madagascar and in the Mozambique Channel, but no data are available to date.

Catch

Reunion Fleet—A considerable and progressive increase in swordfish landings by the domestic longline fleet was recorded during 1992, 1993, and 1994, from approximately 1 t in 1992 to 600 t in 1994 (Fig. 5). The number

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[3] Statistical meeting of the Regional Tuna Project, phase 2 (PTR2) of the Indian Ocean Commission. Albion, Mauritius, July 1994.

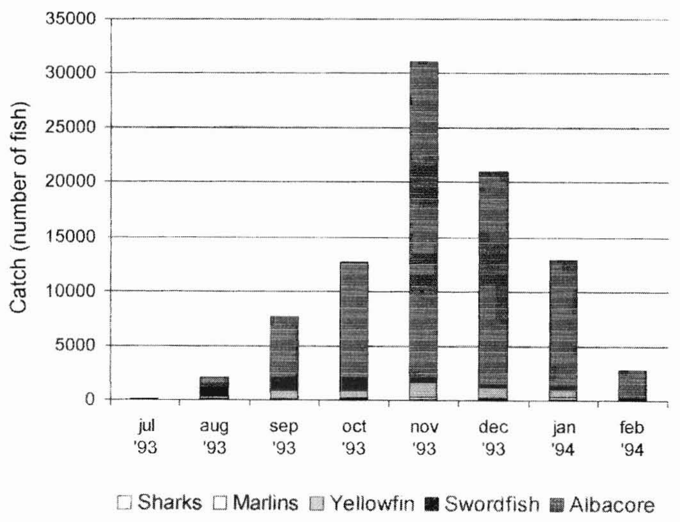

Figure 7
Catch (number of fish) by species of the 21 Taiwanese longliners between July 1993 and February 1994.

Table 2
Fish species caught by the longliners of the Reunion fleet.

Target species	Bycatch species
Swordfish, *Xiphias gladius*	Skate, unidentified
Albacore, *Thunnus alalunga*	Ocean sunfish, *Mola mola*
Yellowfin tuna, *Thunnus albacares*	Snoek, *Thyrsitoides* sp.
Bigeye tuna, *Thunnus obesus*	Oilfish, *Ruvettus* sp.
Dolphin fish, *Coryphaena hippurus*	Remora, *Remora* sp.
Sailfish, *Istiophorus platypterus*	Crocodile shark, *Pseudocarcharias kamoharai*
Blue marlin, *Makaira nigricans*	Silky shark, *Carcharinus falciformis*
Shortbill spearfish, *Tetrapturus angustirostris*	
Shortfin mako, *Isurus oxyrinchus*	
Oceanic whitetip shark, *Carcharinus longimanus*	
Scalloped hammerhead, *Sphyrna lewini*	
Smooth hammerhead, *Sphyrna zygaena*	
Blue shark, *Prionace glauca*	

of swordfish caught from March 1993 to December 1994 can reasonably be estimated at 8,000, corresponding to 410 t dressed weight. This increase in the catch has made this fleet one of the major players in the Indian Ocean (Fig. 4).

Taiwanese Fleet—Changes in the Taiwanese catch by species and by month has been calculated from logbook data on fish caught by 21 vessels. In 8 mo, 4,152 swordfish were caught. Representation in weight is not useful because landing tonnage does not match the catch, due to long trips and transfers at sea.

Spanish Fleet—The Spanish catch cannot be quantified at present.

Effort

Reunion Fleet—During 1991–94 there was a regular and rapid increase of fishing effort (Table 3). This seems mainly due to an increase in the national fleet, which has grown from 1 to 15 vessels in 3 yr (Fig. 9); increased numbers of trips and sets, with a transition from a seasonal to a year-round operation; an increase in the number of hooks per set; and a major expansion of the fishing grounds.

Taiwanese Fleet—The effort of the Taiwanese fleet is known only from the declaration made by 21 vessels from July 1993 to February 1994, indicating a probable presence of approximately 150 vessels. These figures would have to be multiplied by 7 or 8 to give a more realistic indication of the Taiwanese fishing effort.

Catch Per Unit of Effort

In 1993, the best CPUE for the domestic fleet was within 70 n. mi. of Reunion (Fig. 10). The catch in this area ranged between 10 and 15 fish per 1,000 hooks. In 1994, there was an important increase in CPUE over the whole fishing grounds, with a zone of optimum catch distributed around a northeast–southwest axis 50–300 n. mi. from the island. In this zone there were 25–35 captures/1,000 hooks. For the Taiwanese fleet in 1993–94, the best CPUE on the entire fishing grounds was 20 fish/1,000 hooks. This was in a zone situated on a northeast–southwest axis in the Madagascar EEZ, 100 n. mi. to the southwest of the most productive area identified by the domestic fleet. Another productive zone (5–20 fish/1,000 hooks) appears in the Mozambique channel southwest of Madagascar.

Table 3
Fishing effort of Reunion longliners, 1991–94.

Year	Trips	Boat days at sea	Hooks (× 10^3)
1991	20	43	28
1992	59	155	70
1993	142	841	549
1994	173	1,048	690

Table 4
Fishing effort of Taiwanese longliners (21 vessels) off Reunion, July 1993–February 1994.

Year/quarter	Sets	Hooks (× 10^3)
1993/3	155	505
1993/4	841	3,586
1994/1	1,048	1,386

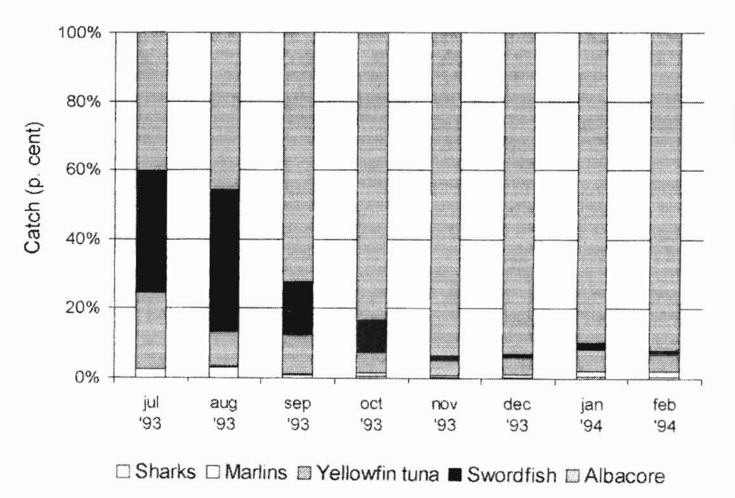

Figure 8
Monthly proportions of species caught by the longliners of Taiwan.

Analysis shows that these zones of high CPUE are all situated in the southern tropical convergence zone next to the Agulhas Current in the Mozambique channel and the Malagasy Southeast Current off Madagascar. Oceanographers have found several vortices and meanders in the surface circulation, which can generate a succession of divergence and convergence zones (Donguy and Piton, 1991; Marsac, 1994). Even if it is not possible to model these and to explain them at the

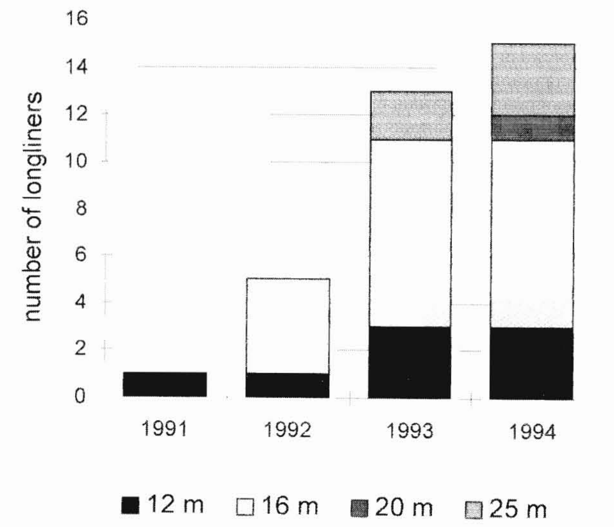

Figure 9
Longliners based in La Reunion, 1991–94, by boat length.

present time (Petit, 1991), fishermen are successful in reducing search time and increasing catch rate by using satellite temperature data to locate convergence zones.

The spectacular increase in catch rate of the domestic fleet (Fig. 12) is largely due to the ability of crews to improve on American techniques; accurate targeting of swordfish with techniques including light sticks, setting at night, adaptation of gear according to the lunar cycle, and utilization of XBT profiles and bathymetric data; and more systematic utilization, since July 1993, of satellite thermal charts, allowing boats to locate thermal fronts and to position their gear accordingly. These charts are now considered crucial by the skippers.

Comparison between the domestic and Taiwanese fleets shows that the catch rates of the domestic fleet are clearly superior for all species (Fig. 13).

Targeting and Bycatch

Figures 5 and 6 reveal a change in targeting by the domestic fishery. Swordfish accounted for only 7% of the catch (in number) in 1992, but 65% in 1994. One will also notice a progressive drop in the catch of billfishes (marlins, sailfish, and spearfish; Fig. 6) which underscores the specificity of the techniques employed. This confirms that it is possible to exploit swordfish without prejudice to recreational game fishing activities based on billfish in nearby countries. As for sharks, by reason of their current weak market value, only dead individuals are preserved and posted as catches. Live ones, which are usually more numerous, are released. Capture of sharks remains marginal.

Predation after Capture

Predation is weak (<1%) and seasonal. Nevertheless, the catch of a set can be totally destroyed by predation, mainly by sharks, short finned pilot whales, *Globicephala macrorhynchus*, and false killer whales, *Pseudorca crassidens*.

Conclusion

The longline fishery has been operating in the Indian Ocean for about forty years. This activity was traditionally dominated by Asian fleets until the 1980's.

The French tuna fishery in the Indian Ocean began with the arrival of a purse seiner fleet from tropical Atlantic waters. Reunion Island developed a domestic longline fishery, which was more suited to the exploitation of pelagic resources in oligotrophic subtropical waters. In the early stages, tax exemptions and the arrival of fishermen from the mainland created the necessary incentives for the development of these activities. Today, these two factors no longer play a crucial role. The growing harvest of pelagic resources by Reunion-based fishermen and companies has involved regional participation and development in three direct ways: upgrading of the artisanal fishery using new, specially-adapted 12-m longliners; involvement of local investors; and education and training of local fishermen in longlining techniques.

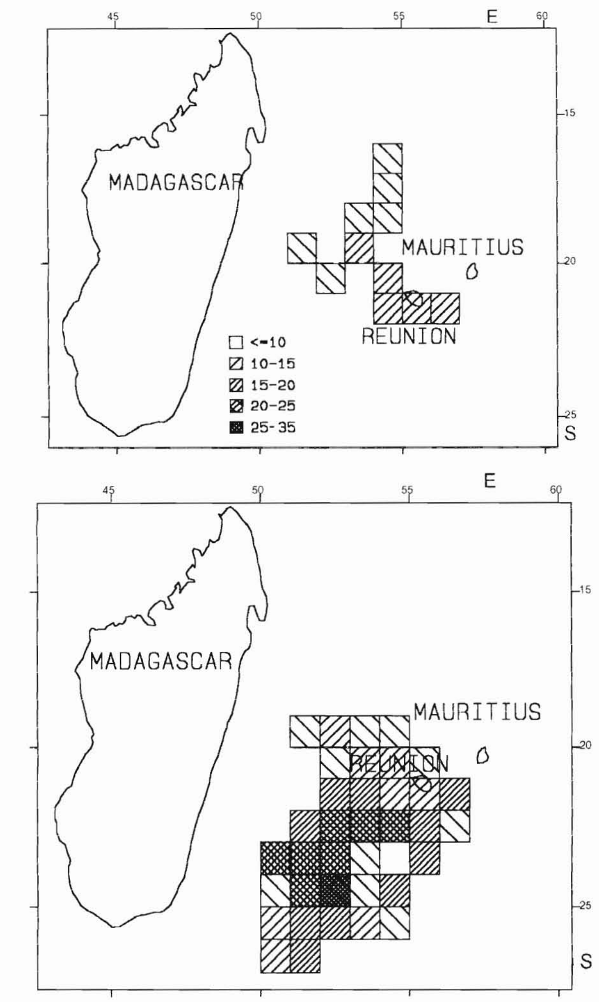

Figure 10
Average number of swordfish caught per 1,000 hooks by Reunion longliners by 1° × 1° areas in 1993 (upper) and 1994 (lower).

Some improvements have yet to be undertaken: all longliners need adequate working space on deck, and cold storage from 0°C to –60°C; and local seafood quality control services should be improved, in particular to meet the new standards established by EEC regulations.

In addition, management strategies for swordfish stocks should be developed and improved, based upon

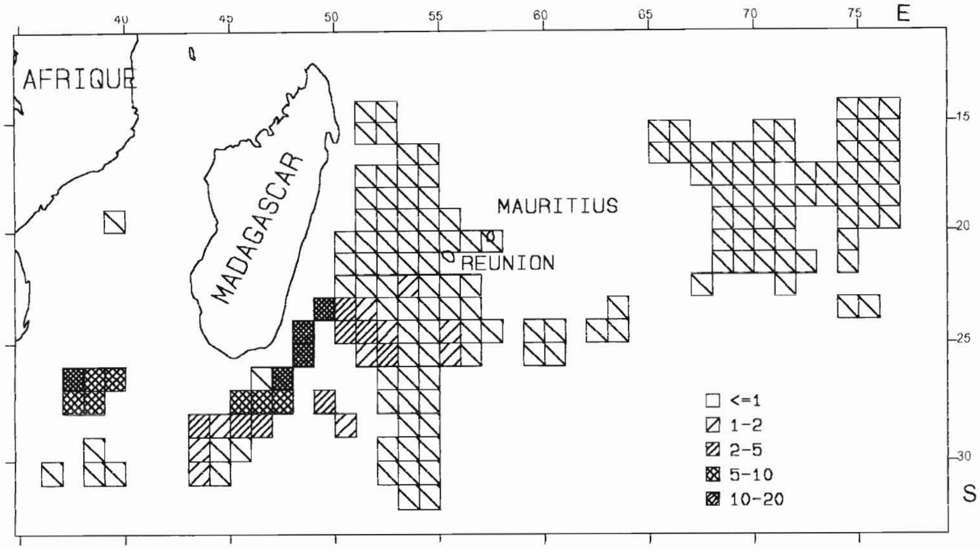

Figure 11
Average number of swordfish caught per 1,000 hooks by 21 longliners of the Tawainese fleet, by 1° × 1° areas, Jul. 1993–Feb. 1994.

the management problems faced in other geographical areas. A major program could be structured through

- data collection on catches and transshipments at all major southern Indian Ocean ports;
- estimation of an index of abundance based on catch and effort data;
- setting up a biological program to study ageing, reproduction, migration, and behavior;
- data collection on bycatch; and
- study of the potential effects of environmental conditions on the distribution of swordfish.

Typical swordfish management problems are linked with the dangers of local overexploitation (which should be controlled at a EEZ and subregional level) in conjunction with global ocean problems, which should be addressed by a future ad hoc Indian Ocean Tuna Commission.

Effective control of the longlining fleet should be set up through a number of geographically-limited subregional organizations to manage migratory and long-lived species such as swordfish. Only geographically limited organizations are likely to efficiently exert control and to be able to enforce edicts of the larger Indian Ocean Commission. Cooperation will become more crucial as the catch by the Taiwanese fleet continues to increase sharply, with no clear control either inside or outside the EEZ's of southwestern Indian Ocean countries.

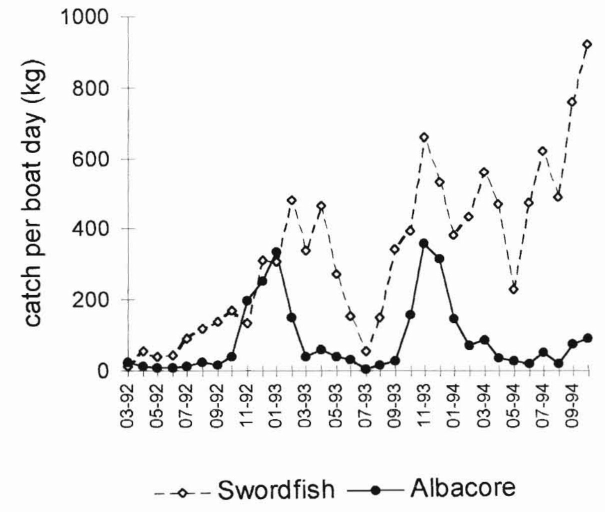

Figure 12
Catch per unit of effort of swordfish and albacore by the Reunion longliners, March 1992–September 1994.

Acknowledgments

This study was made possible by financial aid from the European Economic Community and the local assembly (Conseil Général) through the Reunion Centre d'Appui National (CAN) under PTR2. We are grateful

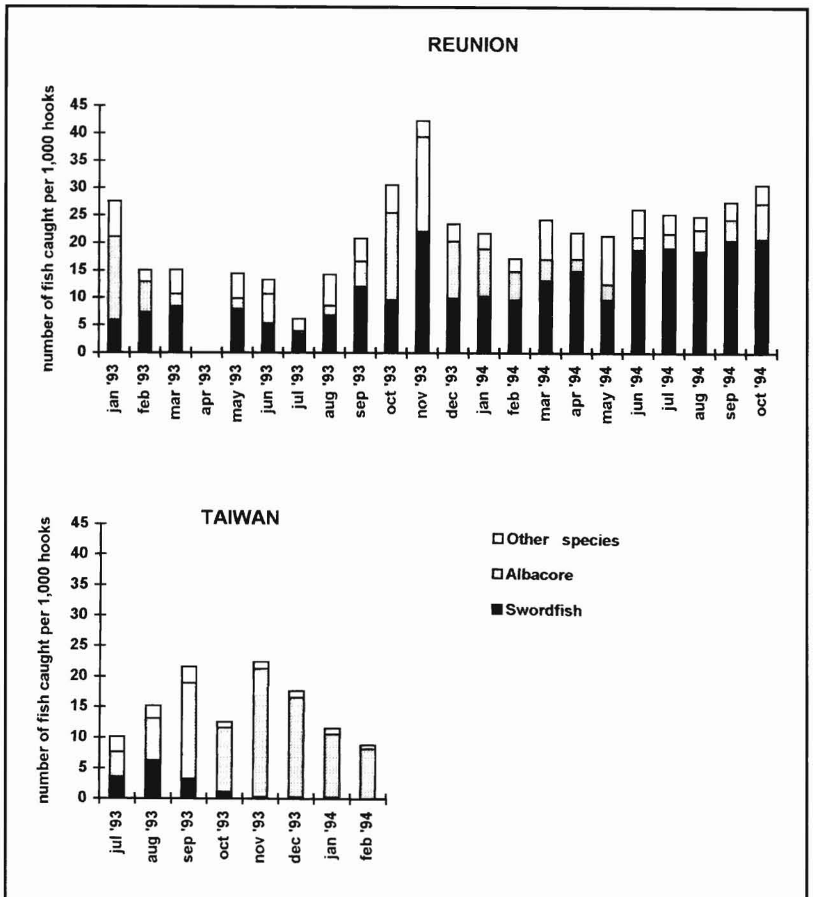

Figure 13

Average number of fish of various species caught per 1,000 hooks by the Reunion longline fleet during January 1993–October 1994 and the Taiwanese longline fleet during July 1993–February 1994.

to all Reunion companies and longlining fishermen for their active cooperation. They always have been generous in sharing their knowledge of the fishery.

The authors wish to thank M. Petit, Dominique Belleme, and Xavier Bernardet from ORSTOM Reunion for their valuable suggestions and assistance, and are also very grateful to Joel Najeon de L'Estang for his help with the English translation.

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Central Pacific Swordfish, *Xiphias gladius*, Fishery Development, Biology, and Research

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ABSTRACT

The development of the Hawaii longline fishery for swordfish, *Xiphias gladius*, in the central North Pacific, which began in 1988, is described. Swordfish landings in the Hawaii fishery reached 6,000 metric tons in 1993. To put the Hawaii fishery in perspective, swordfish fisheries and their production in the Pacific and the world are reviewed, along with swordfish biology and stock dynamics information from the Pacific and Atlantic Oceans. The fishery monitoring and research strategies of the Honolulu Laboratory are described, and potential avenues for collaboration are suggested.

Introduction

Prior to 1988, swordfish, *Xiphias gladius*, was an incidental component of the Hawaii longline fishery targeted on tuna. The fishery for swordfish expanded rapidly in 1990 and 1991 until swordfish contributed 51% of longline landings by weight and 50% by revenue (Ito[1]). The Hawaii longline fishery thus became the single largest swordfish fishery in the central-eastern Pacific (Skillman et al., 1993). A few boats based in California and Alaska have also participated in the central Pacific swordfish longline fishery. The rapid increase in the Hawaii fishery and the perception based on events in the western Atlantic fishery (Beardsley, 1978; Miyake and Rey, 1989) that the species is more sensitive to exploitation than other large pelagic fishes (e.g., most tunas) has led to concerns for the long-term stability of the Hawaii fishery and the status of the resource in the central Pacific (WPRFMC[2]).

This paper provides an overview of swordfish fisheries with emphasis on the development of the Hawaii fishery, a review of swordfish biology and stock dynamics, and a description of monitoring activities and stock assessment and research strategies at the National Marine Fisheries Service (NMFS) Honolulu Laboratory.

Swordfish Fisheries

Global

Evidence of the harvesting of swordfish dates to 3,000–4,000 B.C. in Japan (Ueyanagi, 1974) and to Aristotle's time (384–322 B.C.) in the Mediterranean (Berkeley, 1989). Commercial harpoon fishing for swordfish began off the northeast coast of North America by the 1870's (Berkeley, 1989); the harpoon fishery in California began in the early 1900's (Beardsley, 1978). Drift gill nets have today largely displaced the use of harpoons in coastal fisheries, including off California (Hanan et al., 1993). High-seas fishing for swordfish began in the early 1950's when the Japanese longline fleet began seasonal targeting in the northwest Pacific (Yamanaka, 1958). Today, subsurface longline gear remains the dominant gear for harvesting swordfish on the high seas, though much of the take is a bycatch of tuna fishing. In addition, minor catches occurred in

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[1] Ito, R. Y. 1992. Western Pacific pelagic fisheries in 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-92-15, 38 p. Honolulu Lab., Southwest Fish. Sci. Cent., NMFS, Honolulu, HI 96822-2396.

[2] Western Pacific Regional Fishery Management Council (WPRFMC). 1993. Amendment 7 to the Fishery Management Plan for the Pacific Fisheries of the Western Pacific. Western Pac. Reg. Fish. Manage. Counc., 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

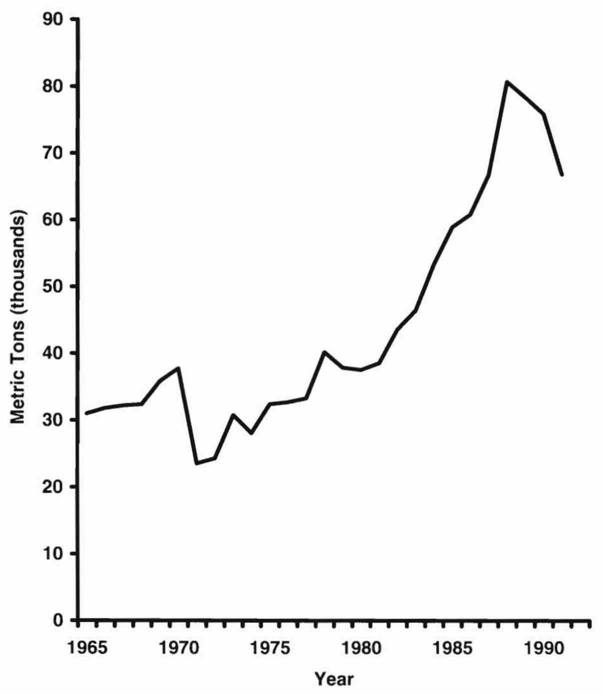

Figure 1
World swordfish landings (FAO, 1993).

the high-seas driftnet fisheries in the central North Pacific, which ceased at the end of 1992. World catches of swordfish remained fairly steady during 1965-80 at around 30,000 metric tons (t) and then increased through 1988 to a high of 81,000 t (Fig. 1). Reported landings declined during 1990–91 for the first time since 1979.

Pacific

Although the Pacific Ocean is approximately twice the size of the Atlantic Ocean, Pacific landings of swordfish in 1990 made up only 38% of the reported world catch (Fig. 2) or approximately 29,000 t (FAO, 1993). The 1990 reported catch in the Atlantic, including the Mediterranean Sea, was about 45,000 t and in the Indian Ocean only 3,000 t.

In the Pacific, 1990 swordfish landings accounted for only 1.3% of the harvest of large pelagic finfish (Fig. 3). The fishery for tuna was by far the largest at 2,155,000 t, while landings of Istiophorid billfishes at nearly 53,000 t were almost double the swordfish landings. However, there were more landings of swordfish in 1990 than of Indo-Pacific blue marlin, *Makaira mazara*, the Istiophorid with the most landings (22,000 t). The Japanese fishery (conprised of pelagic longline, driftnet, set net, and, in the early years, harpoon) accounted for 90% or more of landings in the Pacific during 1952–60 (Fig. 4). While Japanese landings, primarily from tuna longline operations, remained relatively stable after 1960, their pro-

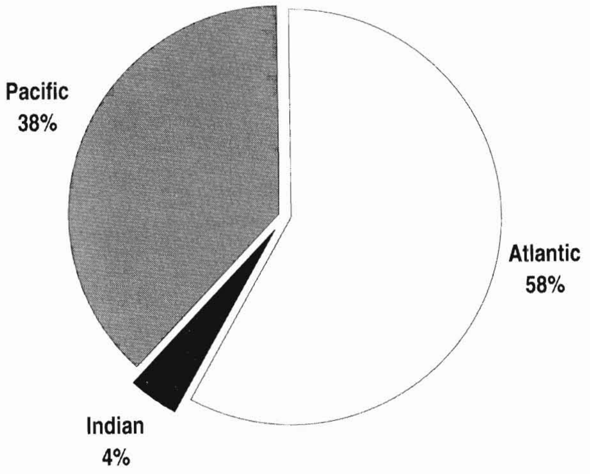

Figure 2
Swordfish landings by ocean in 1990 (FAO electronic database).

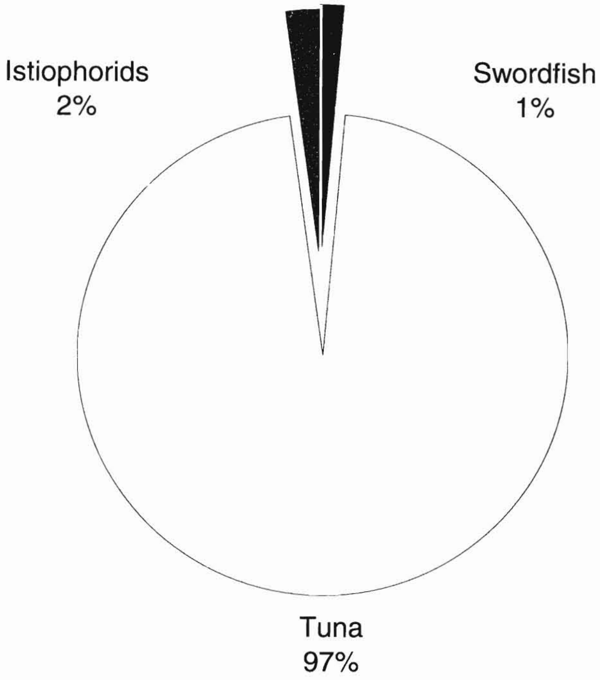

Figure 3
Catch composition of large pelagic species in the Pacific in 1990 (FAO electronic database).

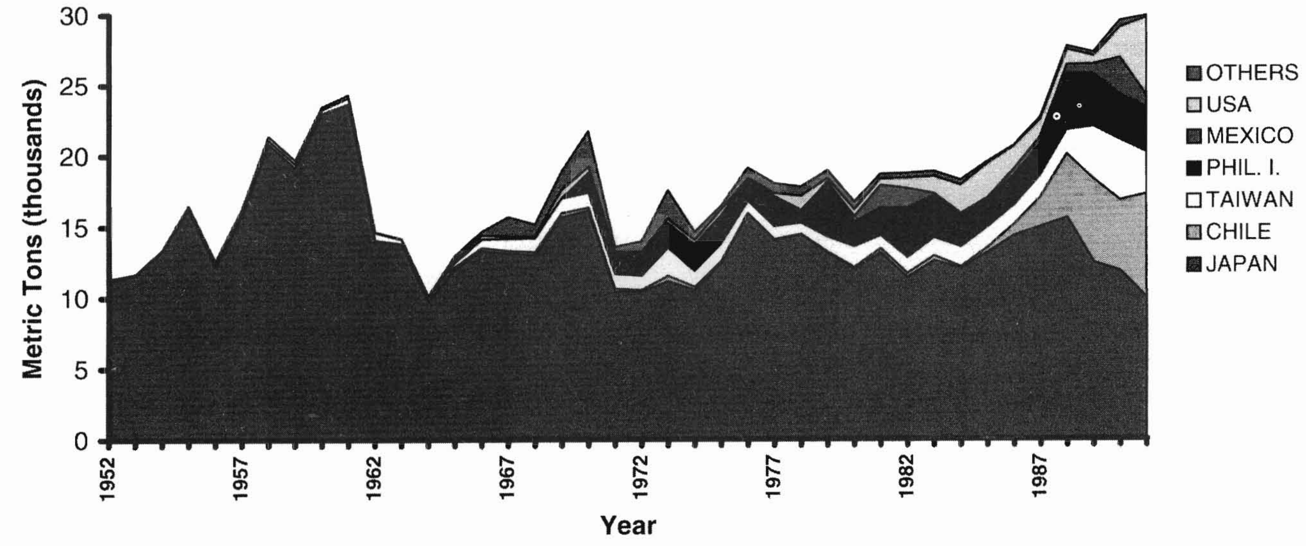

Figure 4
Area plot of Pacific Ocean swordfish catches by country, 1952–91 (FAO electronic database).

portion of the total catch declined to 40% by 1990 with the addition of other, primarily coastal, fisheries targeting swordfish. With the growth of these other fisheries, total Pacific landings since 1988 have surpassed the previous high established by the Japanese fishery in 1961. While the United States (U.S.) fishery has grown, particularly after 1982, it accounted for more than 10% of the total Pacific catch only three times through 1991 (Table 1), the most current year of summary statistics.[3]

In the central-eastern Pacific FAO statistical areas 67 and 77 (Fig. 5), Japan also dominated the fishery in the early years, accounting for >85% of the reported landings through 1979 (Table 2). The Japanese longline fishery probably was responsible for the majority of these landings, given that the large-mesh driftnet fishery targeting billfishes and tunas operated primarily in the western Pacific and generally accounted for <10% of the Pacific swordfish landings reported by Japan (Ueyanagi et al., 1989). While landings by Taiwan ranked third highest in the entire Pacific, their longline landings in the central-eastern Pacific have been less significant; those by Korea were even smaller. After 1979, landings from the driftnet fisheries based in Mexico and California increased substantially, while landings by Japan, Korea, and Taiwan remained fairly steady. Large landings in the California and Mexico fisheries have tended to occur in alternate years, possibly in response to the effects of El Niño episodes (Fig. 6). For example, while California and Mexico accounted for about 35% of the central-eastern Pacific swordfish harvests from 1981 to 1990, California's landings were half the size of Mexico's landings in 1982, 4 times larger in 1986, and one-tenth as large in 1990.

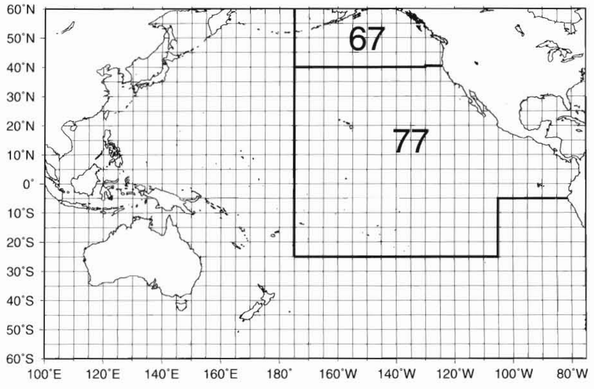

Figure 5
FAO fishery statistical areas 67 and 77 in the central-eastern Pacific.

The high-seas longline fisheries have operated throughout much of the Pacific; this has been particularly true of the Japanese fishery (Fig. 7). Species targeting in this fishery has changed over the years, which accounts for some of the change in the distribution of

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[3] Hawaii landings accounted for >10% of total Pacific landings in 1992–95.

effort. Of course, species targeting varies seasonally as well. Korean longline fishing effort was initially concentrated in the central South Pacific in association with the albacore fishery and later spread progressively into the equatorial zone, extending to the coast of Central America and into the central North Pacific (Fig. 8) because of targeting on other tuna species. Taiwanese longline fishing effort was also initially concentrated in the South Pacific in association with the albacore fishery (Fig. 9) and later spread west to Australia, along the equator, and into the central and western North Pacific.

Hawaii

The Hawaii swordfish fishery developed along with the introduction of longline fishing technology from the Atlantic Ocean in 1989. Monofilament main line replaced the fiber rope used in tuna longline gear, and hydraulic reels replaced specialized line haulers. Squid replaced finfishes as bait, consistent with the known diet of adult swordfish, although finfishes are a significant portion of the diet (Palko et al., 1981). In addition, light sticks were added to the hook droppers to improve the swordfish catch.

Table 1

Pacific Ocean landings of swordfish in metric tons, 1952–91. "Others" includes Ecuador, French Polynesia, Korea, Peru, and Tonga. From Bartoo and Coan (1989), updated using FAO's electronic database and FAO (1993). See Table 2 for updates of U.S. data.

Year	Japan	Chile	Taiwan	Philippines	Mexico	USA	Others	Total
1952	11,182					157	0	11,339
1953	11,604					85	0	11,689
1954	13,301		77			14	0	13,392
1955	16,220		185			80	0	16,485
1956	12,167		254			163	0	12,584
1957	15,771		250			222	0	16,243
1958	20,815		247			279	0	21,341
1959	19,136		262			265	0	19,663
1960	22,944		273			192	0	23,409
1961	23,636		432			218	0	24,286
1962	14,037		544			23	0	14,604
1963	13,775		300			58	0	14,133
1964	9,703		300			109	0	10,112
1965	11,955	200	300			194	300	12,949
1966	13,283	200	600			277	241	14,601
1967	13,083	200	838			181	1,347	15,649
1968	12,983	200	974			118	855	15,230
1969	15,612	300	1,023			610	1,289	18,934
1970	16,100	200	1,053	1,400	0	400	2,515	21,768
1971	10,400	200	1,033	1,500	0	100	315	13,548
1972	10,400	100	1,005	1,600	2	100	715	13,922
1973	11,100	400	1,987	1,700	4	300	2,015	17,506
1974	10,498	218	1,116	1,848	6	295	585	14,566
1975	12,361	137	1,239	1,976	0	393	273	16,379
1976	15,843	13	856	1,558	0	39	739	19,048
1977	13,997	32	902	2,103	0	220	685	17,939
1978	14,333	56	779	890	0	1,009	634	17,701
1979	13,091	40	1,060	3,845	7	249	553	18,845
1980	11,953	104	1,459	1,716	380	489	545	16,646
1981	13,078	294	909	1,940	1,575	443	348	18,587
1982	11,350	285	1,107	3,468	1,365	726	348	18,649
1983	12,511	342	1,268	2,974	120	1,195	360	18,770
1984	11,986	103	1,387	2,274	47	2,009	352	18,158
1985	13,083	342	1,429	2,036	18	2,370	148	19,426
1986	14,271	764	1,357	2,089	422	1,585	70	20,558
1987	14,867	2,059	1,540	2,137	550	1,221	194	22,568
1988	15,496	4,455	1,690	4,034	613	1,086	245	27,619
1989	12,367	5,824	3,692	3,756	690	588	263	27,180
1990	11,767	4,955	4,217	3,187	2,650	2,150	474	29,400
1991	9,889	7,255	2,933	3,139	861	5,526	151	29,754

Table 2

Central-eastern Pacific swordfish catches in metric tons, 1950–93. "Others" includes Korea, French Polynesia, and Tonga. Non-U.S. data from Bartoo and Coan (1989), updated using FAO statistics for areas 67 and 77 (FAO, 1993). Data for Hawaii from SWFSC,[1] Hamm and Kassman,[2] Hamm and Quach,[3] Ito,[4] and WPRFMC[5,6] and for the U.S. west coast from NMFS Southwest Region summaries of Pacific Fishery Information Network data.

Year	Japan	Taiwan	Mexico	U.S. west coast	Hawaii	Others	Total
1950					13		
1951					17		
1952				157	12		157
1953				85	5		85
1954				14	5		14
1955				80	17		80
1956				163	13		163
1957				222	13		222
1958				279	12		279
1959				265	9		265
1960				192	13		192
1961				218	10		218
1962				23	12		23
1963				58	10		58
1964	5,500		0	109	11		5,609
1965	2,700	0	0	194	8		2,894
1966	2,800		0	277	7		3,077
1967	1,900	0	0	181	6		2,081
1968	2,600	0	0	118	5		2,718
1969	4,400	0	0	610	6		5,010
1970	5,600	100	0	400	5		6,100
1971	2,700	0	0	100	1		2,800
1972	3,400	100	2	100			3,602
1973	4,100	100	4	300	0		4,504
1974	2,330	183	6	295	0		2,814
1975	2,139	165	0	393			2,697
1976	3,591	36	0	39	2	242	3,910
1977	2,743	113	0	220	19	140	3,235
1978	2,615	108	0	1,009	14	29	3,775
1979	2,735	181	7	249	12	43	3,227
1980	3,299	117	380	489	15	23	4,323
1981	3,381	105	1,575	443	9	38	5,551
1982	2,666	85	1,365	726	18	98	4,958
1983	2,654	131	120	1,195	16	94	4,210
1984	2,589	133	47	2,009	10	51	4,839
1985	2,578	137	18	2,370	5	54	5,162
1986	2,792	130	422	1,585	7	23	4,959
1987	3,917	150	550	1,176	45	92	5,930
1988	4,123	160	613	1,041	45	68	6,050
1989	3,566	400	690	316	272	58	5,302
1990	3,556	460	2,650	245	1,905	70	8,886
1991				1,029	4,497		
1992				1,548	5,735		
1993				1,743	6,124		

[1] Southwest Fisheries Science Center (SWFSC). 1993. Annual and average monthly trends in catch of large pelagic species in Hawaii, 1949–78. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SWFSC Honolulu Lab. Admin. Rep. H-83-24, 74 p. SWFSC, 2570 Dole St., Honolulu, HI 96822-2396.

[2] Hamm, D. C., and T. T. Kassman. 1986. Fishery statistics of the western Pacific, vol. 1. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-86-04, p. var. Available from SWFSC, 2570 Dole St., Honolulu, HI 96822-2396.

[3] Hamm, D. C., and M. M. Quach. 1988. Fishery statistics of the western Pacific, vol. 3. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-88-04, p. var. Available from SWFSC, 2570 Dole St., Honolulu, HI 96822-2396.

[4] Ito, R. Y. 1992. Western Pacific pelagic fisheries in 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-92-15, 38 p. Honolulu Lab., SWFSC, NMFS, 2570 Dole St., Honolulu, HI 96822-2296.

[5] Western Pacific Regional Fishery Management Council (WPRFMC). 1993. Pelagic fisheries of the Western Pacific Region 1992 annual report. Western Pac. Reg. Fish. Manage. Counc., 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

[6] Western Pacific Regional Fishery Management Council (WPRFMC). 1994. Pelagic fisheries of the Western Pacific Region 1993 annual report. Western Pac. Reg. Fish. Manage. Counc., 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

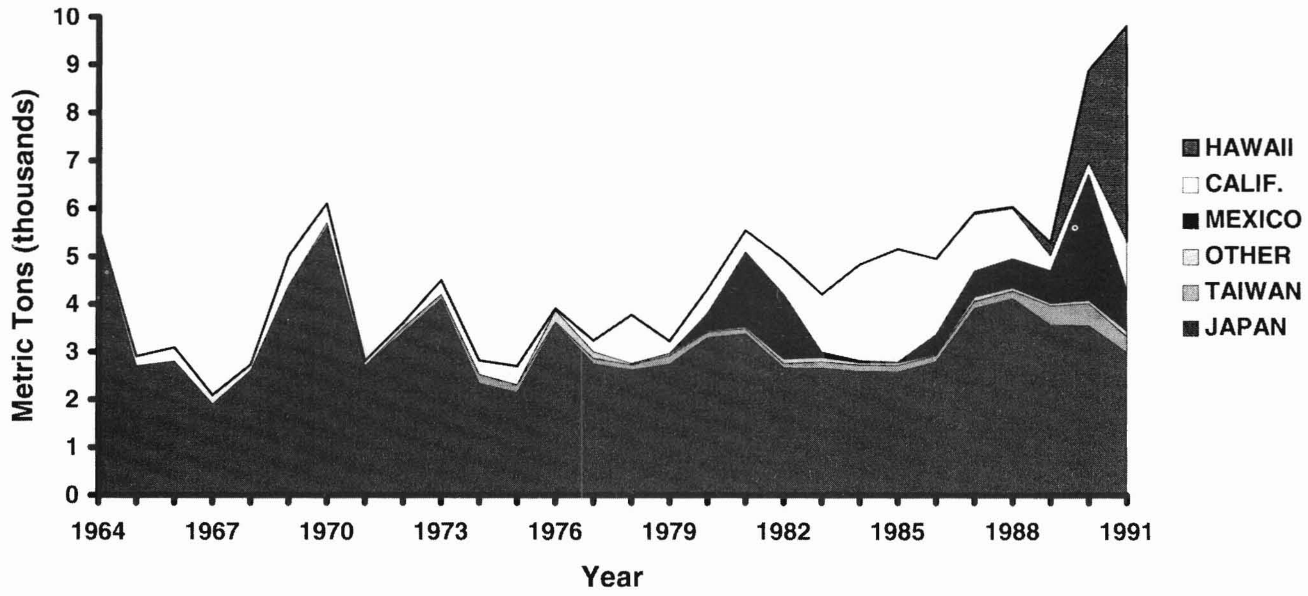

Figure 6

Area plot of swordfish landings in FAO statistical areas 67 and 77 in the northeast and east-central Pacific (FAO electronic database).

Swordfish gear is set at dusk and hauled at dawn or earlier, rather than being set at dawn and hauled at midday as is typical with tuna gear. This is consistent with the observation that swordfish in offshore waters swim near the surface at night and at depth during the day (Carey, 1990). Swordfish longline gear is configured to fish at depths of 15–25 m, with 2–3 hooks between floats, whereas tuna gear is rigged to fish at depths of 150–300 m with 5–15 hooks between floats, depending on the species being targeted.

If a concentration of swordfish is found as the gear is being hauled, some boats will cut the main line, terminate it with a float or radio beacon, set additional gear in the area, and then continue to haul the remainder of the gear. Some vessels fish for both swordfish and tuna on different portions of a trip or even by having some segments of the gear along the main line configured for swordfish, and others for tuna.

The longline fishery in Hawaii underwent a gradual decline in number of boats from the early 1950's to 1975–76, during which time the fleet was reduced by about 80% (Fig. 10). During 1977–87, the trend reversed and the number of boats roughly doubled. Then, from 1987 to 1991, the number of boats nearly quadrupled. In April 1991, a moratorium was put into effect under the authority of a new U.S. federal law, the Magnuson Fishery Management and Conservation Act. The moratorium prevented the entry of new boats into the Hawaii longline fishery and restricted the transfer of vessel permits. Consequently, in 1992 the number of boats active in the fishery declined from 140 to 123.

From a single boat in 1988, the estimated number of boats targeting swordfish on at least one trip per year increased to 114 in 1991 (Ito, 1998). The swordfish fleet increased in size when some Hawaii tuna longline and lobster boats switched to targeting swordfish, and other boats relocated from U.S. longline fisheries in the northeast coastal states and the Gulf of Mexico (Ito[1]).

Prior to 1989, swordfish were an incidental take in the tuna fishery in Hawaii, with landings averaging 10 t during 1952–86 (Table 2). Reported swordfish landings increased in 1987 and 1988 to 45 t because of the large increase in the number of longline boats. The swordfish fishery began in earnest in 1989, when 11 boats participated in the fishery and landings increased to nearly 300 t, 500% over the previous high (Fig. 11). Landings rapidly increased again in 1990 (by 600%) and then by more modest amounts in 1991, 1992, and 1993 (136%, 28%, and 7%, respectively). By 1990, the Hawaii fishery accounted for 21% of reported swordfish landings in the central-eastern Pacific. Since California landings were down in 1990, total U.S. landings accounted for only 24% of total reported landings, but Mexico and U.S. landings together accounted for 54%. With 1991 Hawaii landings increasing to 4,500 t, and assuming other catches equal to those in 1990 (more recent data were not available), Hawaii may have accounted for 40% of the landings in the region.[4] Similarly, projected total U.S. landings and combined U.S. and Mexican landings for 1991 may have accounted for 50% and 60%, respectively, of regional landings (Fig. 6).[5]

The proportion of swordfish in total pelagic landings in Hawaii has changed dramatically with the development of the swordfish fishery (Fig. 12). In 1977, the species composition in the Hawaii pelagic fishery was comparable to that in the Pacific in 1990 (Fig. 3), except that there was more marlin (9.5% versus 2.4%) and less tuna (88.2% versus 96.3%). The proportion of swordfish had not changed much by 1987, the year prior to the rapid expansion of the fleet (Fig. 12), but the proportion of marlin had increased to 22.2% and tuna had decreased to 74.9%. Subsequently, the proportion of swordfish increased substantially while the proportions of tuna and, to a lesser extent, of marlin declined.

Almost all the swordfish landed in Hawaii are transshipped fresh to the U.S. mainland. Some dealers buy only directly from fishing boats, others do so on occasion, and the remainder bid for the fish at the Honolulu fresh fish auction. Some vessel operators transship their landings under consignment to dealers on the mainland. The transshipped product has been headed, gilled, gutted, and finned (all fins). Fish below 23 kg are marketed locally only, and processing is limited to removing the lobes of the caudal fin and the bill. Shark- or bird-damaged swordfish are also generally marketed locally. The estimated dockside revenue generated from swordfish landings in Hawaii has risen in proportion to catches, reaching nearly $27 million in 1993 (Table 3).

Examination of the distribution of Hawaii longline fishing effort became possible in November 1990 when sub-

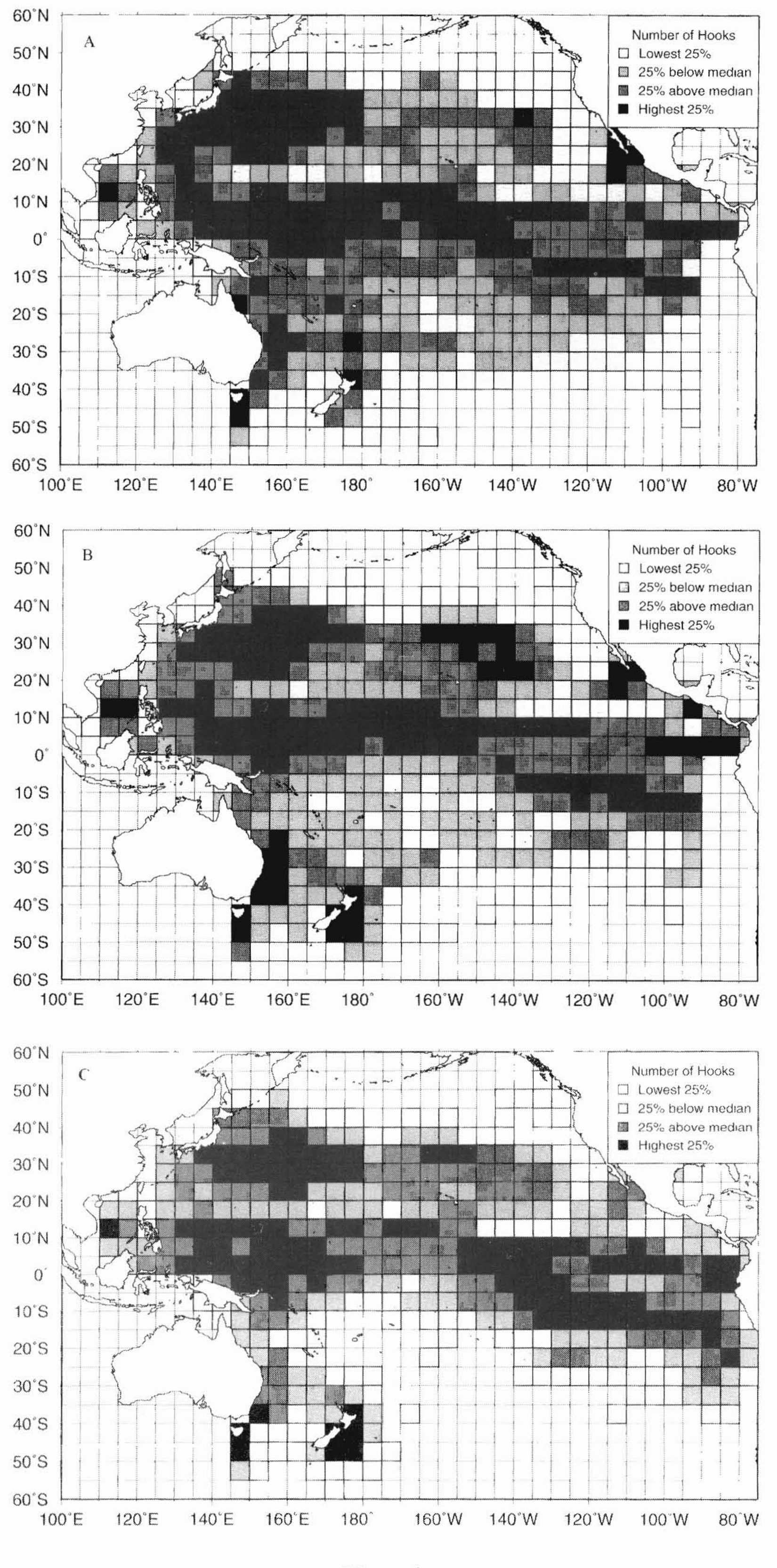

Figure 7

Distribution of Japanese longline fishing effort in (A) 1962–69, (B) 1970–75, and (C) 1976–80.

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[4] In fact, Hawaii catches made up approximately 37% of regional catches in 1991–93 and then declined to 23% in 1995.

[5] In fact, U.S. and combined U.S.–Mexican landings accounted for 38% and 45%, respectively, in 1991; they stayed at about this level through 1994, then declined to 28% and 32%, respectively, in 1995.

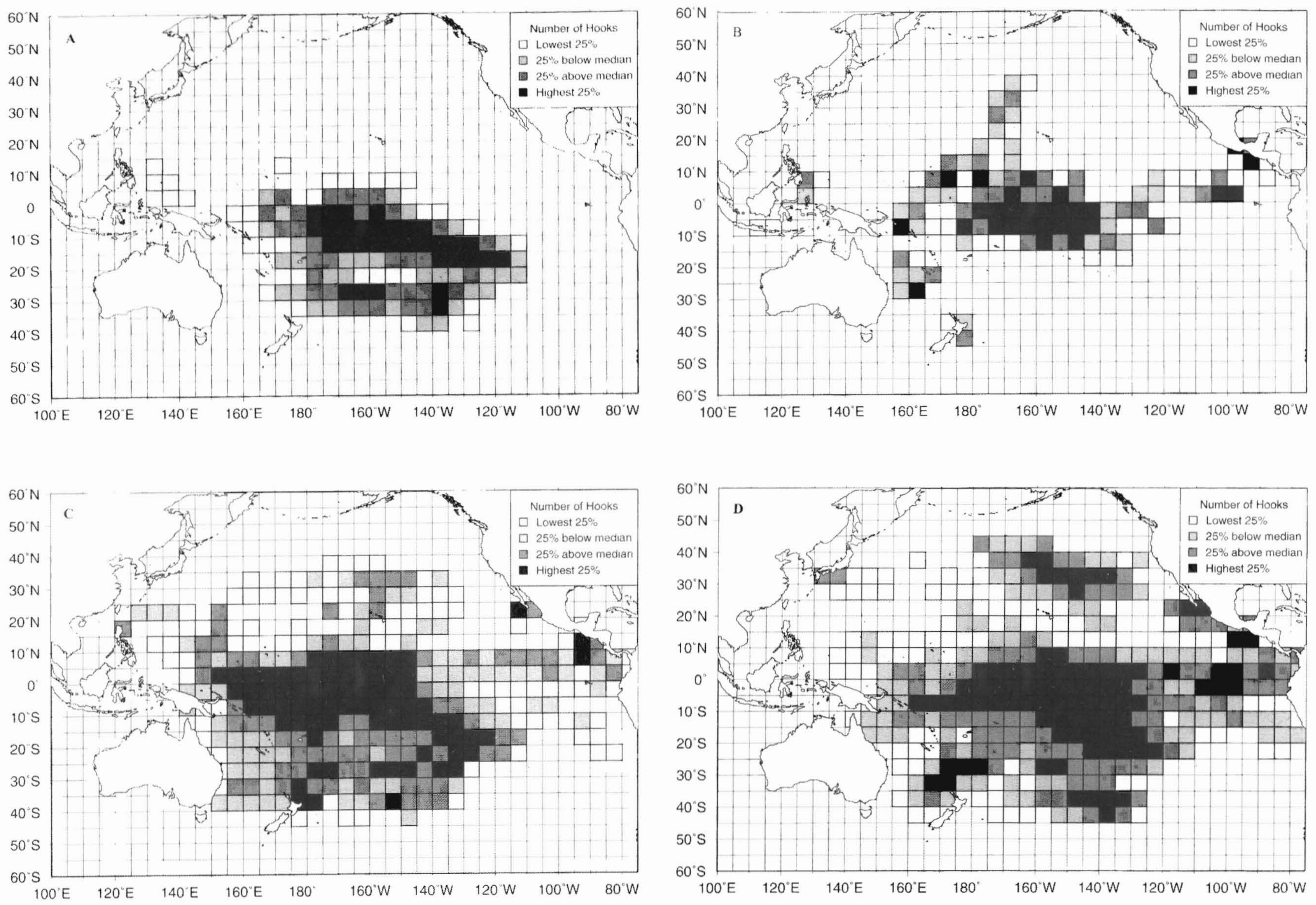

Figure 8

Distribution of Korean longline fishing effort in (A) 1966–69, (B) 1975, (C) 1977–80, and (D) 1981–87.

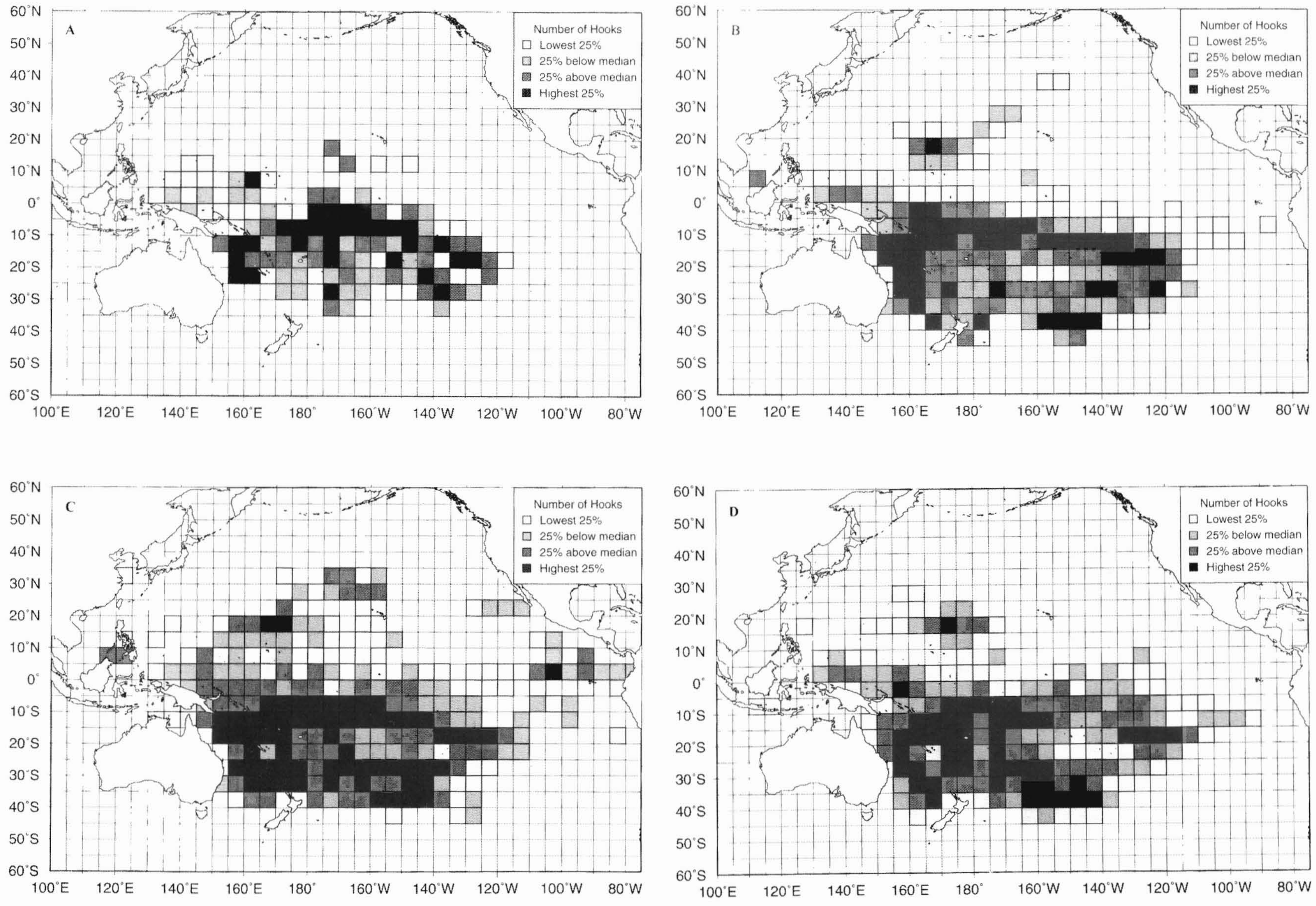

Figure 9

Distribution of Taiwanese longline fishing effort in (A) 1967–69, (B) 1970–75, (C) 1976–80, and (D) 1981–86.

mission of logbooks became mandatory. During November and December 1990, the fleet was limited to waters around the main Hawaiian Islands and the southernmost of the northwestern Hawaiian Islands (Fig. 13). In 1991, effort occurred from latitude 0° to 50°N and from longitude 140°W to 180°. While the highest level of effort was again in waters around the main islands and the northwestern islands, considerable effort was expended south and especially north of the archipelago. During 1992 and 1993, higher concentrations of effort extended into the northwestern Hawaiian Islands and waters to the northwest. Also, the limits of the Hawaii longline fishery expanded to the north, west, and east. Effort by the Hawaii fishery reached as far east as Japanese effort through 1980 (Fig. 7), but fell 5° in longitude short of the eastward extent of Korean effort (Fig. 8).

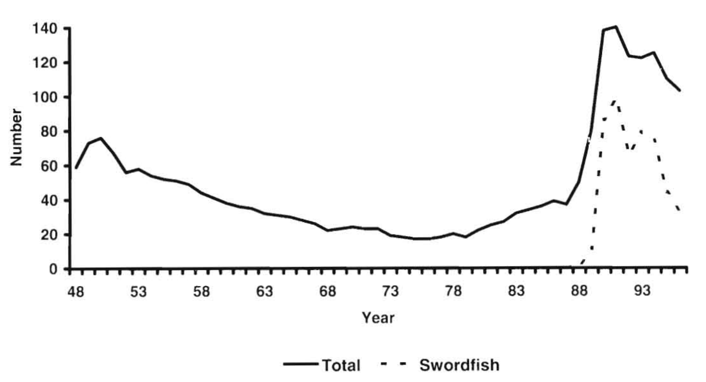

Figure 10

Estimated number of Hawaii longline boats, including those exclusively targeting swordfish. Data from Hawaii Division of Aquatic Resources, 1948–53, and NMFS logbook data, 1991–93.

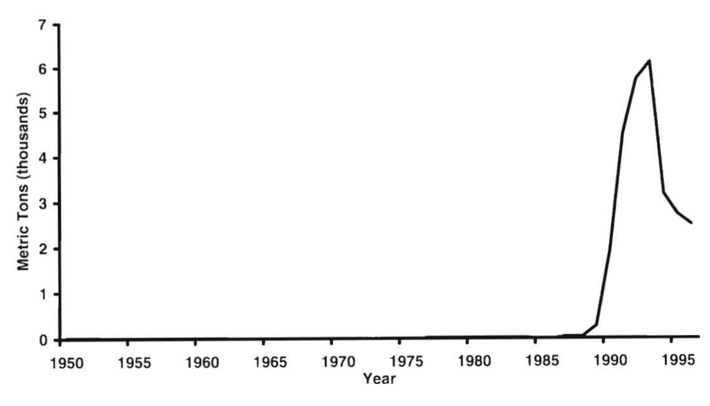

Figure 11

Annual Hawaii swordfish catches, 1950–96. Data from Hawaii Division of Aquatic Resources and NMFS shoreside monitoring.

The highest catch rates of swordfish in the Hawaii longline fishery (Fig. 14) occurred in the farthest northwestern and northern areas into which the fishery expanded (Fig. 13). As will be shown in the section on resource distribution, the areas of high catch rate by the Hawaii fleet coincide with the central Pacific portion of a region of high catch rate extending from the western to the central Pacific (Fig. 15). Thus, it appears that the Hawaii swordfish fishery developed in a region of resource abundance and that the expansion of the fishery to the northwest and north was due to the portion of the Hawaii longline fleet targeted on swordfish. It is also apparent that a considerable portion of the fishing effort of the Hawaii fleet is still being expended near the main Hawaiian Islands in the pursuit of tuna. An examination of indicators of species targeting and possibly Gulland's (1955) concentration index could demarcate specific locations of segments of the fleet targeting swordfish or tuna.

Population Biology and Dynamics

Effective management requires knowledge of various basic aspects of swordfish biology so that the dynamics of the resource and the impacts of the fishery and management actions can be assessed.

Range and Distribution

Swordfish distribution was inferred from the distribution of Japanese longline catch rates because the fishing effort for this fishery is distributed more widely than any other (Fig. 7, 8, 9). These catch rates are for the most part a measure of the availability and vulnerability of swordfish adults to gear not used to target swordfish. As always, the real abundance and thus distribution of the resource may differ from what the fishery statistics indicate. Information about fisheries targeting swordfish is also used here.

Swordfish has a wide distribution in the Pacific, from latitude 50°N to 45°S and from the western margin of the Pacific to the west coasts of the American continents, based on swordfish catch rates for the Japanese longline fishery during 1962–80 (Fig. 15). In the South Pacific, catch rates declined toward the southern limit of the effort distribution (Fig. 7), but in the North Pacific, high catch rates generally continued up to the northern limit of the effort distribution. The reasons for this differ-

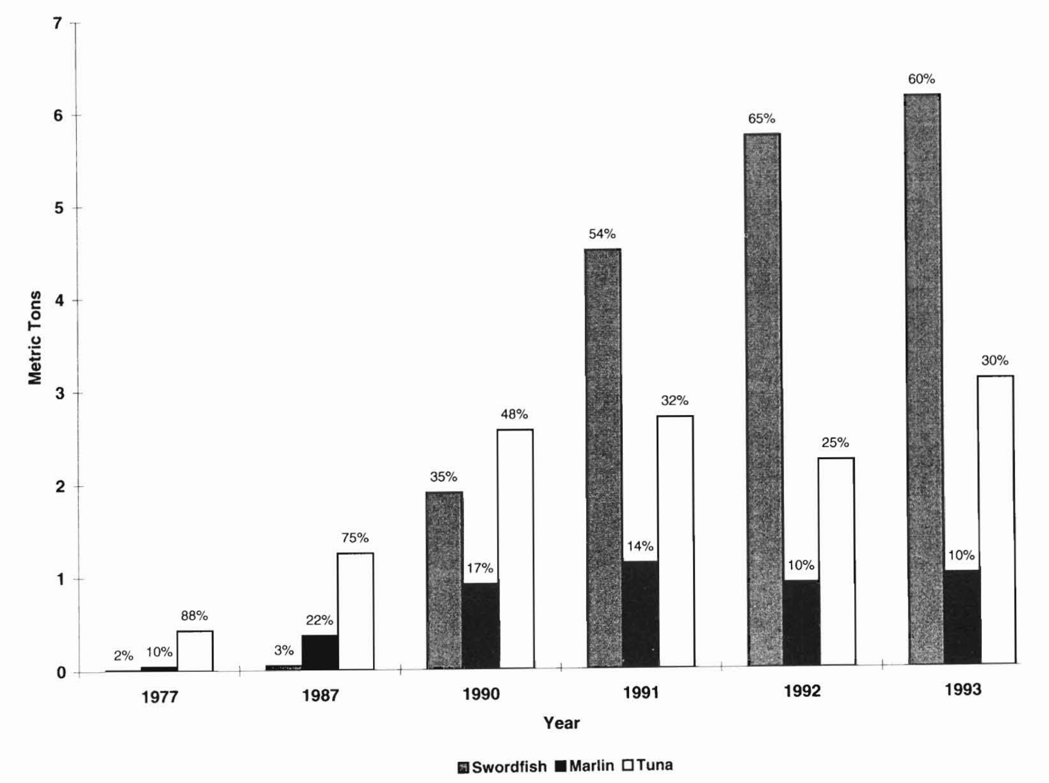

Figure 12
Species composition by weight and by percentage weight of catches by the Hawaii longline fishery, 1977–93.

ence are not clear; it may be due to the occurrence of the resource north of the fishery limits, to data aggregation by 5° latitudinal sections, to strong ecological boundaries, to fleet licensing restrictions, or to some combination of these.

Table 3
Revenue from longline-caught swordfish in Hawaii, 1987–93 (Ito[1]; WPRFMC[2]).

Year	U.S. Dollars (thousands)
1987	200
1988	200
1989	1,100
1990	9,700
1991	22,000
1992	24,270
1993	26,830

[1] Ito, R. Y. 1992. Western Pacific pelagic fisheries in 1991. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-92-15, 38 p. Honolulu Lab., SWFSC, NMFS, Honolulu, HI 96822-2396.

[2] Western Pacific Regional Fishery Management Council (WPRFMC). 1994. Pelagic fisheries of the Western Pacific Region 1993 annual report. Western Pac. Reg. Fish. Manage. Counc., 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

There were high catch rates in several areas, with considerable variation in their extent. The largest, most consistent region of high catch rates was a broad band across the North Pacific from Japan eastward to about 140°W. High catch rates also occurred along the western margin of the Pacific from the equator to the coast of China; this region extended northeast to Japan and connected with the North Pacific region in the earlier periods summarized. Coastal fisheries using harpoon and other gears also operated in this area. The second largest region of high catch rates was off Australia, extending variable distances into the central South Pacific at different times. There appeared to be several regions of high catch rates off the west coast of the Americas; one off the coast of California and Mexico did not extend far enough to the northwest to connect with the west-central North Pacific region or far enough south along the coast to connect with another small region off central America. Drift net fisheries are also conducted in these coastal waters off California and Mexico. A region appeared off South America with

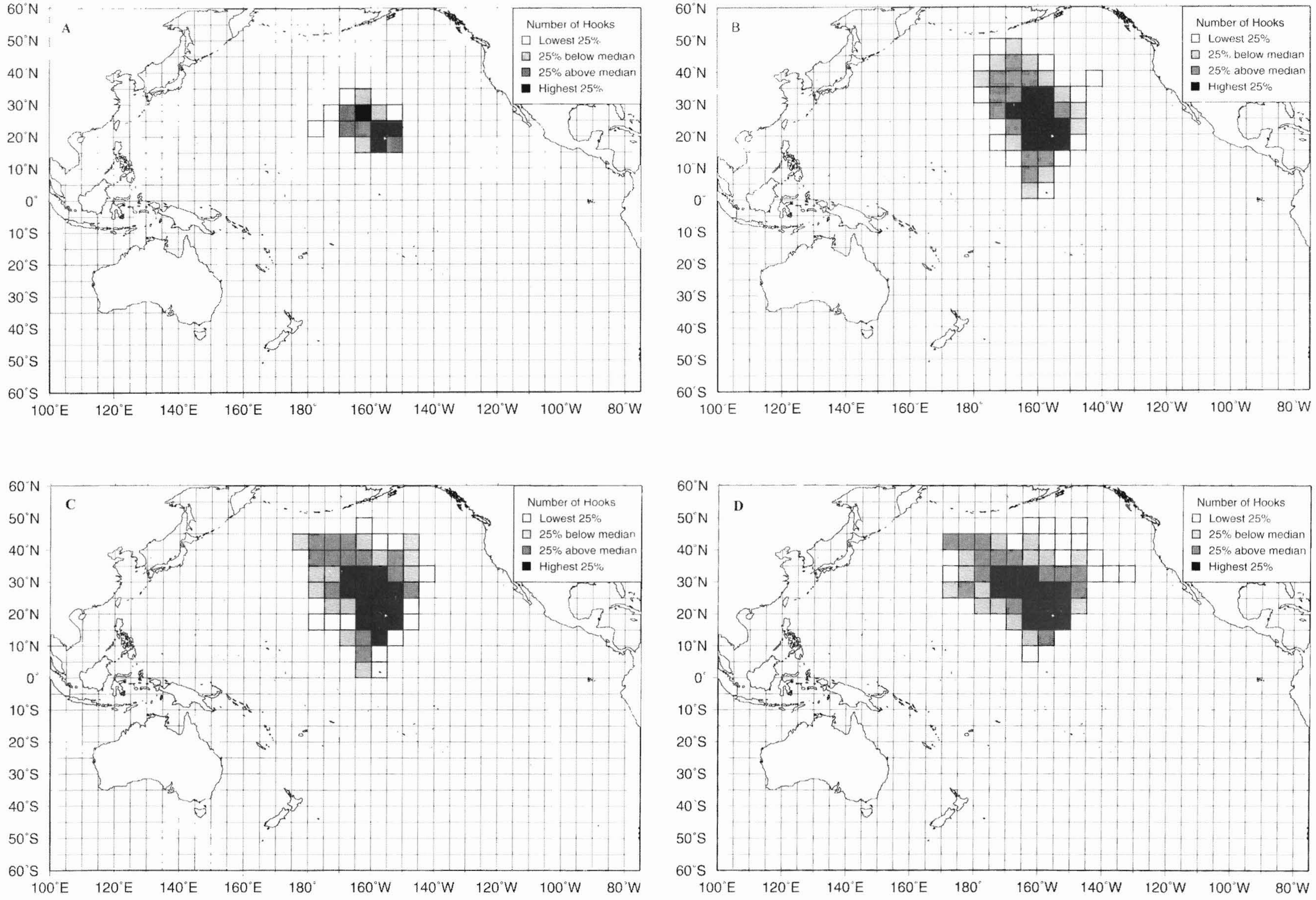

Figure 13

Distribution of Hawaii longline fishing effort in (A) November–December 1990, (B) 1991, (C) 1992, and (D) 1993.

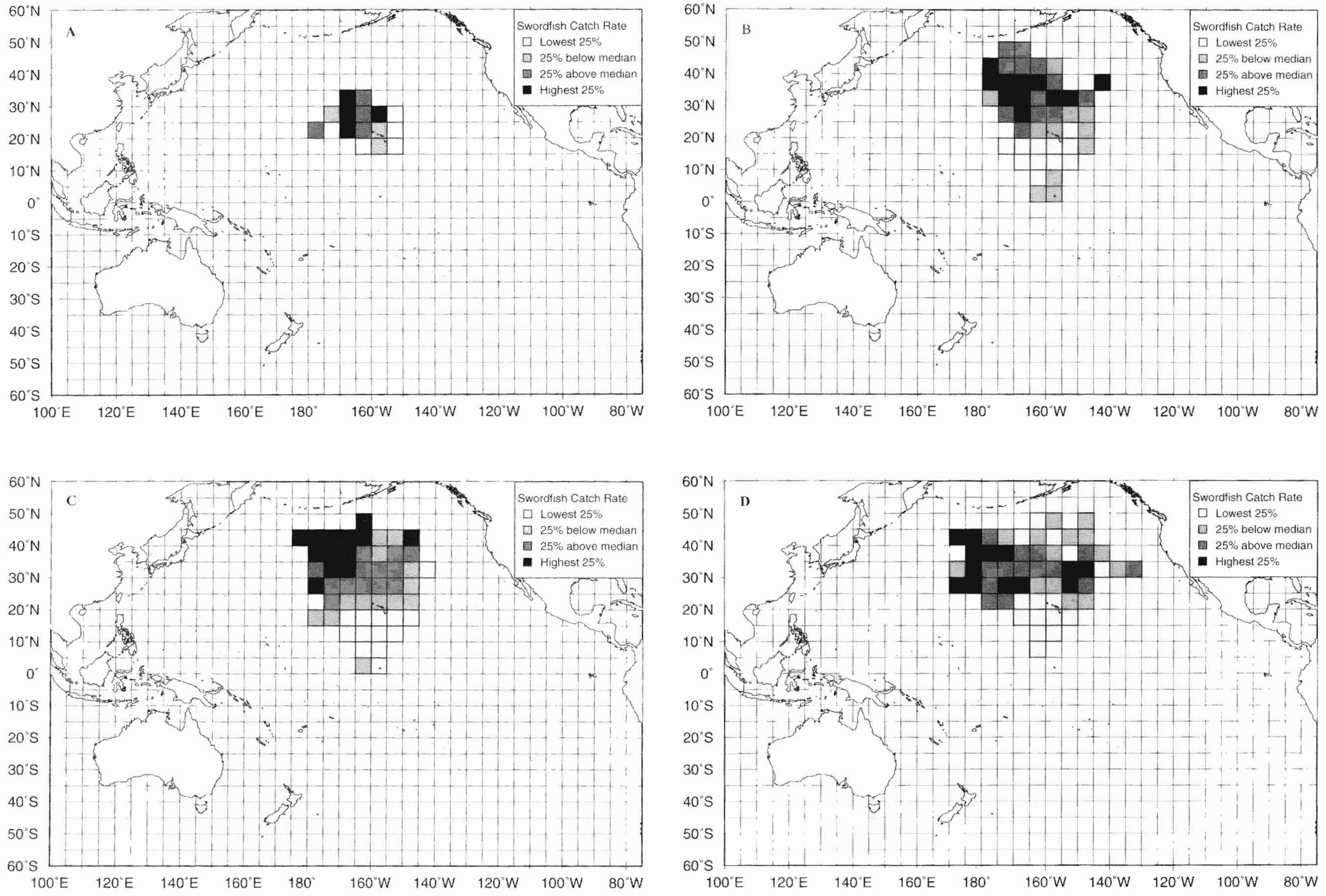

Figure 14

Distribution of catch rates (swordfish per 1,000 hooks) for the Hawaii longline fishery during (A) November–December 1990, (B) 1991, (C) 1992, and (D) 1993.

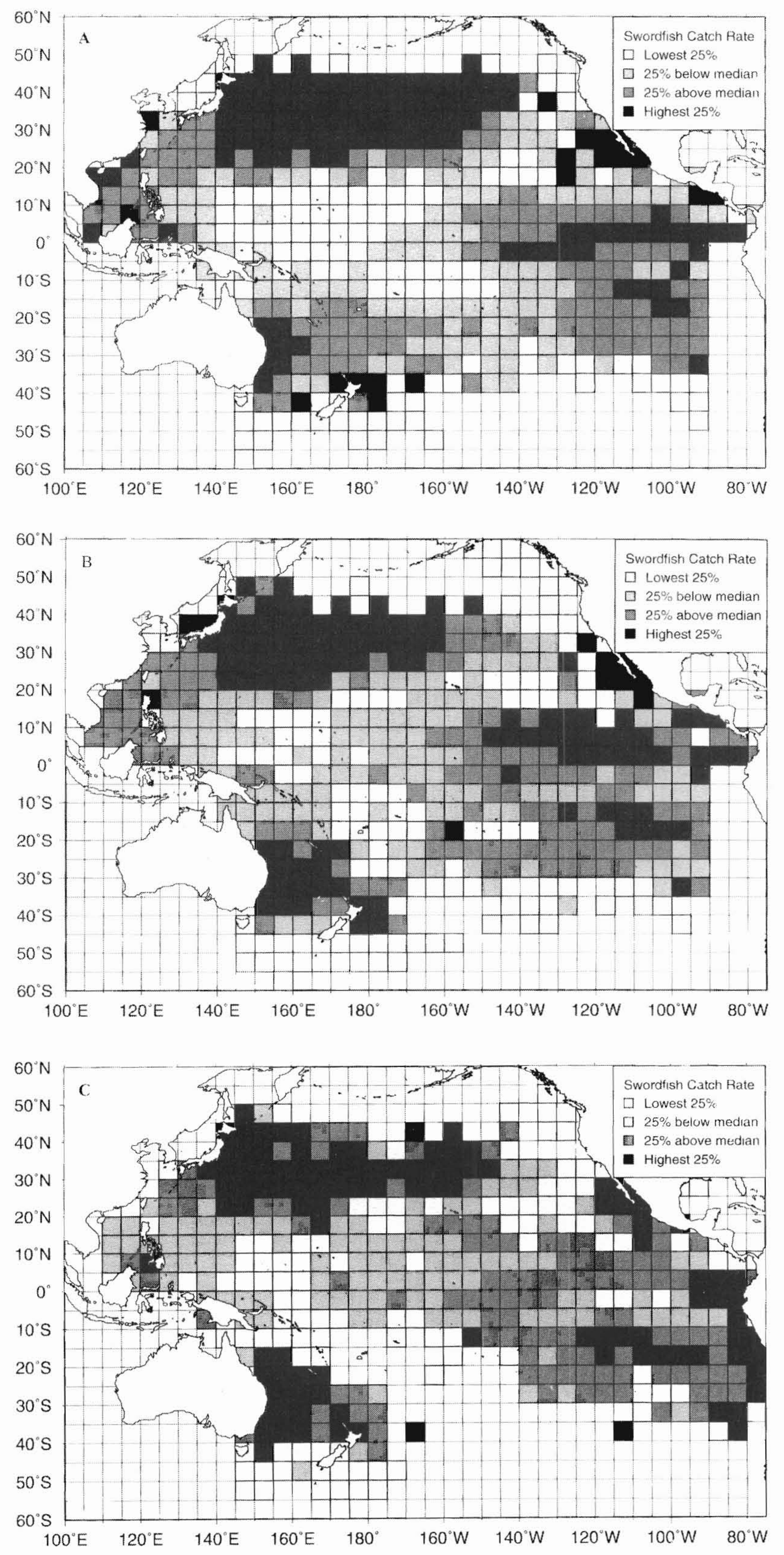

Figure 15

Distribution of catch rates (swordfish per 1,000 hooks) for the Japanese longline fishery during (A) 1962–69, (B) 1970–75, and (C) 1976–80.

extensions into the central Pacific along the equator and at middle southern latitudes, but it never quite joined with the region extending eastward from Australia. The Chilean fishery also takes place in these coastal waters off South America.

Stock Structure and Movement

The stock structure of swordfish is poorly understood. For stock assessment purposes, a single, Pacific-wide stock generally has been assumed, with the possibility that there are separate stocks associated with known fishing grounds in the western-central North Pacific, eastern Pacific, and western South Pacific (Sakagawa and Bell, 1980; Bartoo and Coan, 1989; Skillman, 1989). Only a single swordfish tag recapture has been recorded in the Pacific. This fish, which weighed approximately 11 kg when it was tagged and released from a commercial fishing boat at 29°N, 154°W on 24 April 1992, was recaptured in the same general area 11 months later at a weight of 32 kg. Tagging results in the Atlantic have indicated that swordfish movement is primarily latitudinal (Berkeley, 1989) and that fish tagged in the summer tend to return to the same locale in subsequent summers (Beckett, 1974).

Progress on the use of genetics to determine swordfish stock structure is reported by Grijalva-Chon et al. (1996) and in the present publication (Alvarado Bremer, Leclerc, and Ely, 1998; Chow, 1998).

Size at Maturity and Spawning

U.S. federal law (the Magnuson Fishery Management and Conservation Act) requires the prevention of recruitment overfishing. Thus, an estimate of size at maturity is necessary to assess trends and the dynamics of the mature, spawning component of the stock. All of the published estimates (Table 4) are based on small

Table 4

Estimates of swordfish size at maturity. Values are in the units published by the authors: EFL = eye–fork length, LJFL = lower jaw–fork length, and RWT = round weight.

Ocean	Sex	Smallest mature	All mature	Size at maturity	Units	N[1]	Source[2]
Pacific	Female	140		170	cm EFL	362	1
		83.0		156.5[3]	kg RWT	15	2
		150		170	cm EFL	~58	3
Atlantic	Female	70			cm LJFL	NG	4
		74			kg RWT	NG	5
		160	235	171	cm LJFL	NG	6
	Male	100			cm LJFL	NG	4
		21			kg RWT	NG	5
		90	165	113	cm LJFL	NG	6

[1] NG = not given.

[2] 1 = Kume and Joseph (1969), 2 = Uchiyama and Shomura (1974), 3 = Yabe et al. (1959), 4 = Ovchinnikov (1970), 5 = Palko et al. (1981) referencing personal communication from E. Houde, 6 = Hoey et al. (1989) referencing personal communication from R. Taylor.

[3] Median between the smallest and largest mature fish in the sample.

sample sizes, and none are based on modern histological techniques necessary to determine maturity in indeterminate spawners, which swordfish may be, and to estimate fecundity.

For the eastern tropical Pacific, Kume and Joseph (1969) classified ovary samples collected from the Japanese longline fleet using values of the gonado-somatic index (GSI), the ratio of gonad weight to the cube of eye orbit–fork length (EFL). While they stated that there was no established relationship between GSI and state of maturation for swordfish, they observed that there was a cluster of samples with low ovary weights and GSI values <3.0, which they classified as immature or undeveloped. Mature fish were defined as having GSI values ≥3.0.

For the central Pacific, Uchiyama and Shomura (1974) classified, according to the most mature ovum stage present, a small sample of ovaries collected from commercial longline boats operating in the vicinity of Hawaii. The ovum stages identified were primordial, early developmental, developing, early ripe, ripe, and residual. Taking the occurrence of early ripe or later stages as indicating maturity, I determined that the mature fish in their samples ranged from 83.0 to 246.3 kg round (unprocessed or whole) weight (RWT), with the median at 156.5 kg RWT.

For the western Pacific, Yabe et al. (1959) plotted ovary weight versus EFL of samples collected from the swordfish fishing grounds (30–45°N, 140°E–180°). They observed a cluster of points with small ovary weights, which they interpreted as immature fish, and a length range in which ovary weight increased rapidly with body size. They interpreted this range (150–170 cm EFL) as the size at maturity, and also gave age at maturity as 5–6 years. Sosa-Nishizaki (1990) indicated a similar range (150–160 cm EFL) using samples collected from across the Pacific in all seasons.

For the Atlantic Ocean (Table 4), Palko et al. (1981) provided estimates of size at maturity for female and male swordfish, referencing Ovchinnikov (1970), without any details of origin of the samples or methods used. They also provided estimates for swordfish taken off the southeast coast of the U.S., referencing a personal communication from E. Houde. Also, Hoey et al. (1989) provided estimates from gonads collected off the coast of Florida, referencing a personal communication from R. Taylor. These estimates for female and male swordfish were for the size at which mature fish were first found, the size at maturity (size at which 50% of the specimens were classified as mature), and the size when all specimens in the spawning season were mature. Miyake and Rey (1989) stated that swordfish age 4 and above were mature.

Since these estimates were reported in different units of measure (EFL, lower jaw–fork length, and RWT; Table 4), I converted them to EFL using research data collected in the central Pacific to facilitate comparison. For females, all the estimates except that by Ovchinnikov (1970) clustered around 150 cm EFL. For males, a smaller size at maturity was indicated, around 100 cm EFL, but fewer estimates were available and only for the Atlantic.

Uchiyama and Shomura (1974) found that sexually mature swordfish with developed gonads occurred in Hawaiian waters from April through July. Swordfish were rarely present at other times and were generally small, immature fish. Kume and Joseph (1969) found that sexually immature female swordfish were present in the eastern Pacific in all months, whereas females in spawning condition were most abundant during March–

July north of the equator and around January south of the equator.

To evaluate the occurrence of mature swordfish captured with longline gear, Sosa-Nishizaki (1990) divided the Pacific into five areas, one spanning the equator from 10°N to 10°S, and two areas each in the North and South Pacific, divided at longitude 150°W. In the northwest area, spawning appeared to be concentrated in waters from the Hawaiian Archipelago southward and occurred during April–July. Spawning was not apparent in the northeast area. In the southeast area, spawning occurred in noncoastal pelagic waters during October–January. In the southwest area, spawning was concentrated in the Coral Sea during November–February and in waters around Fiji during May–July. Mature fish were found in all months in the equatorial area and exhibited no seasonal trend. Sosa-Nishizaki (1990) believed the equatorial area to be an area of mixing of stocks from north and south.

Growth

The ability to establish the age of fish allows us to classify landings by age-class and to model fish growth. Estimates of growth model parameters can be used in various age-based and age-structured stock assessment models (Table 5). Current efforts to age central Pacific swordfish are described in Uchiyama et al. (1998).

All the studies cited in a recent summary of growth model parameters (Sakagawa and Bell, 1980; updated by Boggs, 1989) are based on very few samples, and the estimates should be regarded as provisional. The only reference for the Pacific was Yabe et al. (1959; Table 5); from the data they present, the fifth and largest modal size used to fit the growth model was 148 cm EFL. Thus, their model is not representative of growth of larger, older fish. The Japanese swordfish longline fishery in the 1950's was conducted at night, north of 30°N from 140° to 160°E (Kume and Morita, 1966), and caught mostly small swordfish.

Similar problems due to lack of data for large fish exist with several models presented for the Atlantic (Caddy, 1976, 1977; Berkeley and Houde, 1983; Wilson and Dean, 1983; Tsimenides and Tserpes, 1989). Models by Radtke and Hurley (1983) and the International Commission for Conservation of Atlantic Tunas (ICCAT, 1989) were fit with data from large fish, but data from small fish were not available for the tag recapture model (ICCAT, 1989). The models from these two sources provided quite different estimates of length at age. If the tag recapture model were accepted as the most reliable, it would suggest that the otolith ridges used by Radtke and Hurley (1983) to age fish were formed less often than once a year.

Table 5

Estimates of von Bertalanffy growth parameters and mortality rate for swordfish. Natural mortality rates (*M*) calculated from *K* using the equation of Murphy and Sakagawa (1977). Table derived from Sakagawa and Bell (1980) as updated by Boggs (1989) and again here using sources 4 and 7.[1]

Ocean	Method	*N*	Sex[2]	Size range[3] (cm)	Source[1]	*K*	t_0 (yr)	L_∞	*M*
Pacific	Length modes		U	61–245	1	0.124	–1.169	309	0.22
Atlantic	Length modes and vertebrae		U	50–260	2	0.230[4]		365[4]	0.21–0.43[5]
	Anal ray	275	M	70–270	3	0.19	–2.04	217	0.35
	internal zones	164	F			0.09	–2.59	340	0.15
	Anal ray	427	M	54–215	4	0.34	–1.22	194	0.64
	internal zones	455	F			0.25	–1.52	220	0.47
	Otolith	39	M	79–209	5	age estimates, no model			
	internal zones	39	F	102–290					
	Otolith	73	M	88–208	6	0.07	–3.94	277	0.12
	ridges	195	F	80–270		0.12	–1.68	267	0.21
	Tag recapture	84	U	90–260	7	Gompertz growth model[6]			

[1] 1 = Yabe et al. (1959), 2 = Caddy (1976, 1977), 3 = Berkeley and Houde (1983), 4 = Tsimenides and Tserpes (1989), 5. = Wilson and Dean (1983), 6 = Radtke and Hurley (1983), 7 = ICCAT (1989).

[2] M = male, F = female, U = unknown or unreported.

[3] Pacific and Atlantic size ranges are for eye–fork length and lower jaw–fork length, respectively.

[4] These estimates of *K* and L_∞ from Caddy (1977) do not match the size-at-age groups given in Caddy (1976).

[5] Total mortality, $Z = 0.12–0.65$ and 0.16–0.59 using data from the harpoon and longline fisheries, respectively.

[6] Dressed weight (lbs) = 305.56 exp (–4.6235 exp (–0.305815 · Age)), with Age in yr.

In more recent reports, Prince et al. (1988) described the reading of presumed annual increments on anal fin rays. However, they could not verify their interpretation of the annual increments using mean monthly marginal increment widths or mean marginal increment ratios. Ehrhardt (1992), in a reanalysis of the same data, provided statistical evidence that verified the use of annual increments by Prince et al. (1988). Miyake and Rey (1989) indicated that the model derived from tagging returns (SEFC, 1987) is the most accurate available and has been used by ICCAT for stock assessment. Two problems occur in gathering tag and recapture data for swordfish: it is difficult and dangerous to determine fish size prior to release, and sex of the recaptured fish must be determined when the fish are dressed at sea. ICCAT (1989) presented an updated model based on tag recaptures, a Gompertz growth model (Table 5).

Mortality

Few estimates of the instantaneous rates of swordfish total mortality, Z, natural mortality, M, and fishing mortality, F, have been published, especially for the Pacific. All available estimates are based on small sample sizes and many use approximate methods; thus, the estimates are very preliminary. Using the model of Beverton and Holt (1956), which requires estimates of the von Bertalanffy growth coefficients K and L_∞, the size of swordfish when recruited to the fishery, and the mean size of swordfish in the catch, Caddy (1977) estimated Z using data from the Canadian harpoon (0.12–0.65) and longline (0.16–0.59) fisheries. Tagging studies, according to Caddy, could also be used to estimate Z, but these estimates would be subject to considerable variation caused by immigration and emigration.

All available estimates of the instantaneous rate of natural mortality, M, were obtained by indirect means. One estimate of M (0.2–0.4) was inferred from estimates for tunas and considerations of life expectancy (Caddy, 1977). All other estimates of M were based on estimates of the von Bertalanffy growth parameter, K, and an empirical relationship between M and K from Murphy and Sakagawa (1977). This regression was computed using three data points for bluefin tuna, *Thunnus thynnus*, albacore, *T. alalunga*, and yellowfin tuna, *T. albacares*. Given the concerns about bias in the estimation of growth discussed in the previous section, similar concerns should be held for estimates of M based on K from these growth models. Estimates of M using this procedure were first provided by Caddy (1977); were recomputed utilizing several published estimates of K by Sakagawa and Bell (1980); were updated by Boggs (1989); and are updated again here using estimates of K in Tsimenides and Tserpes (1989) and ICCAT (1989) (Table 5). Separate estimates of M for males and females are given by Berkeley and Houde (1983), Radtke and Hurley (1983), and Tsimenides and Tserpes (1989). An estimate of M could not be computed for the growth model from tagged fish in the Atlantic because the Gompertz model does not include the parameter K. The single estimate for the Pacific ($M = 0.22$) was computed by Boggs (1989) using K estimated from data in Yabe et al. (1959). Most of the estimates in Table 5 fall within the range inferred from tunas, in spite of the use of different tissues and size ranges of specimen in determining the growth models.

Caddy (1977) mentions two methods to estimate M directly, but no estimates using these techniques have been published. First, he discussed using the catch-curve method, which requires data collected before heavy exploitation has occurred, but he pointed out that the method would be difficult to apply because swordfish stocks are spatially structured by sex and age. Second, he discussed Suda's method utilizing estimates of Z and fishing effort at two or more levels of fishing (Morita, 1977), but no estimates using this procedure were provided.

No estimates of the instantaneous rate of fishing mortality, F, have been published for the Pacific. For the Atlantic, estimates of F by age/size classes have resulted from stock assessments conducted using virtual population analysis (VPA; Swordfish Assessment Group, SCRS, 1992). Caddy (1977) suggested using length-based analysis to estimate fishing mortality, which requires estimates of L_∞, M/K, and exploitation rate, E, and the existence of a stable size frequency (Jones[6]). He also discussed the use of tagging data but provided no estimates using either of these methods.

In summary, no reliable estimates of Z, F, or M exist for Pacific swordfish fisheries. While rates can be inferred from studies conducted in other areas, those estimates also suffer from some of the same problems described above.

Stock Assessment

In both the Pacific and Atlantic Oceans, the first attempts to assess the status of swordfish stocks used Schaefer's (1954) equilibrium stock-production model or similar models (Pella and Tomlinson, 1969; Fox, 1970). Production models were used because they inte-

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[6] Jones, R. 1974. Assessing the long-term effects of changes in fishing effort and mesh size from length composition data. ICES Meeting Doc. C.M. 1974/F:33, 12 p. Demersal Fish (Northern) Comm., Int. Counc. Explor. Sea, Palaegade 2-4, DK-1261, Copenhagen, K., Denmark.

grate the effects of growth, natural mortality, and recruitment into a rate of stock increase that is dependent only on mean stock size. Therefore, production models have modest data requirements, requiring only two of the three commonly available fishery statistics, namely catch, effort, and an index of stock abundance (e.g., catch rate). Also, the results from such a model are simple to understand and to convey to resource managers. Production models do estimate maximum sustainable yield (MSY) accurately until MSY is exceeded.

Those attempting to assess the resource in the Pacific have noted that the predominant fishery, the Japanese longline fishery, underwent a number of changes in species targeting, bait, and gear configuration (Bartoo and Coan, 1989; Skillman, 1989). Prior to 1962 most swordfish catches resulted from a night-set longline fishery in the western Pacific targeting swordfish and using squid as bait. Over the next two years, the Japanese fishery changed to a predominately day-set fishery targeting tunas and using mixed bait. The tuna fishery has since undergone considerable expansion, and deep longlining was introduced in the 1970's to target bigeye tuna (Suzuki and Warashina, 1977). In 1976, nylon branch lines began to be used on small longline boats and by 1989 had become the dominant type of main line on these boats (Warashina, 1991). Problems have been experienced with the durability of monofilament-nylon main lines on Japanese distant-water longline boats (Katsuo-Maguro Tsushin, 1993), but their use appears to be expanding (Katsuo-Maguro Tsushin, 1994a, b). Data on these changes in gear efficiency and targeting were not readily available to standardize statistics on the Japanese longline fishing effort, and the stocks were probably not in equilibrium given the expanded level of fishing. Thus, little confidence has been placed in the results of equilibrium production models even when such modeling was attempted, e.g. an MSY of 18,000–20,000 t (Sakagawa and Bell, 1980; Skillman, 1989). The conclusion in the latter two papers and in Bartoo and Coan (1989) was that the fishery had not overexploited the stock, catch rates had remained relatively stable over time, and the resource was in good condition. It should be noted that Pacific landings (Table 1) have increased considerably and by 1991 had exceeded previous estimates of MSY by some 8,000–10,000 t.[7]

Similar problems with time series of nonstandardized fishing effort were encountered in attempting to assess Atlantic stocks using equilibrium stock-production models (Kikawa and Honma, 1981; Farber and Conser, 1983). Therefore, Atlantic researchers turned in 1985 to the use of age-structured assessment models, because these depend only on age-composition data and estimates of growth, natural mortality, and fishing mortality in the terminal year of the fishery (Conser et al., 1986). A VPA model was used to estimate stock size and fishing mortality at age, with the best estimates in the earlier years of the time series, because VPA is a backward-sequencing procedure. With the addition of average weight-at-age data, estimates of stock biomass, surplus production, and female spawning-stock biomass also became available. Such information helped in the evaluation of whether the Atlantic fishery in the course of its development had a significant impact on the stock.

Estimates from VPA were often analyzed with age-based models, e.g. estimated yield per recruit was used to estimate spawning-stock biomass per recruit. Over the next several years, different formulations of the VPA model and different means of tuning the model were used to deal with uncertainties in estimates of growth (particularly for older fish and also by sex) and natural mortality (Restrepo, 1991; Restrepo and Powers, 1991; Hiramatsu, 1992; Restrepo et al., 1992). These assessments were also used to deal with differences in size composition estimation among different fisheries and the lack of data on sex composition of landings. Since so much ancillary information was being incorporated to tune the VPA to handle these problems and obtain better estimates, an integrated approach called ADAPT was employed with the VPA (Conser and Powers, 1990; Restrepo et al., 1991; Mohn, 1992; Powers and Restrepo, 1992; Hiramatsu, 1993; Gavaris[8]).

However, Conser et al. (1992) noted that the abandonment of stock-production models for the ADAPT-VPA approach may not have been wise for several reasons. First, growth models that adequately modeled the growth of older age groups had not been developed. Second, logistical sampling problems had precluded the development of age–length keys, thus requiring the use of cohort slicing to estimate catch-at-age using size-frequency data, landings data, and growth models. Third, since the causal mechanism for the observed preponderance of females at larger sizes had not been determined, it was unclear whether to incorporate sexually dimorphic growth, differences in natural mortality by sex, differences in availability by sex, or some combination of these or other possible causes in the assessments.

Because of these problems, interest in the use of stock-production models was renewed, but this time in nonequilibrium (or dynamic) versions. In contrast to VPA, time-series estimates (e.g. biomass) from a stock-production model are estimated more accurately at the

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[7] By 1995, Pacific catches exceeded these MSY estimates by 10,000–12,000 t.

[8] Gavaris, S. 1988. An adaptive framework for the estimation of population size. Can. Atl. Fish. Sci. Adv. Comm. Res. Doc. 88/29, 12 p. Marine Fish Div., Dep. Fisheries and Oceans, St. Andrews, N.B., E0G 2X1 Canada.

end of the time series because a forward-sequencing computational procedure is used. Vaughan and Scott (1991) compared the performance of three models: the equilibrium logistic production model (Schaefer, 1954); the Pella and Tomlinson (1969) generalized model, with an adjustment for nonequilibrium (Fox, 1975); and Schnute's (1977) dynamic logistic model. While catch in a given year is a function of effort in the same year in the equilibrium stock production model, catch in the current year is a function of effort in the same year plus catch and effort in the previous year in Schnute's model. Vaughan and Scott (1991) found that an MSY estimate was highest for the equilibrium model and lowest for the dynamic model, as expected. Estimates based on the model with nonequilibrium adjustment were close to the dynamic model, but generally higher. Conser et al. (1992) proposed using Shepherd's[9] nonequilibrium stock-production model and provided a statistical basis for estimating the parameters. The dynamic nature of this model is based on biomass in a given year as a function of biomass at the start of the previous year, plus net production and catch. Another nonequilibrium model (ASPIC, a surplus-production model incorporating covariates) has been developed that is similar to the Pella and Tomlinson (1969) model but uses an analytical solution to the yield equation rather than a numerical solution (Prager, 1992, 1993b; Prager[10]). Prager (1992) noted that since the model is a forward solution, it can be modified to handle different patterns of fishing or data collection as easily as with simulation models, which is a benefit also noted by Methot (1989, 1990) in discussing his stock-synthesis model. Thus, ASPIC can use several data series, e.g. catch-and-effort data from different gears or different periods in a fishery. Auxiliary population-biomass estimates or other information can be used to tune the model. Also, bootstrapping can be used to construct approximate nonparametric confidence intervals (Prager, 1993a).

Issues and Problems

With the recent development of swordfish fisheries in the Pacific, a number of issues and problems have arisen pertaining to fishery management, biological research, and data collection.

Fishery Management

Under U.S. federal law, fishery management actions for U.S. waters are initiated by regional councils and implemented by the NMFS. Deliberations and resultant management actions taken by the Western Pacific Regional Fishery Management Council (WPRFMC) and the NMFS indicate three primary fishery management concerns associated with the swordfish fishery in the central Pacific:

Stock Dynamics and Overfishing—The size of the harvest of the expanding central-eastern North Pacific longline fishery directed at swordfish could possibly cause overutilization (harvesting beyond MSY) or even recruitment overfishing. The expansion of this fishery and coastal fisheries also targeting swordfish has changed the nature of the Pacific swordfish fishery; previously, the vast majority of swordfish were taken incidental to tuna fishing operations. A species targeted by a number of fisheries is more likely to become overfished than one taken incidentally, although bycatch can result in overfishing. Harvesting of subadults by some segments of the Hawaii fishery, and probably other fisheries as well, could lead to yield-per-recruit concerns, but this issue has not been raised, at least formally, in the Hawaii fishery. Relevant U.S. domestic management actions are the Fishery Management Plan for Pelagic Species in the Western Pacific Region and the first amendment to the plan, which specified an objective definition of recruitment overfishing.

Incidental Take of Protected Species—In U.S. fisheries, this is regulated by domestic law (Endangered Species Act). The take of marine turtles reported by the Hawaii-based longline fishery exceeded the allowable limits set for the fishery before the expansion in fleet size or targeting on swordfish had occurred. Because of this, consultations under the Endangered Species Act were conducted in 1994. The impact of such bycatches on protected species and their prevention is increasingly becoming a fisheries management issue.

Bycatch—Sharks (primarily blue shark, *Prionace glauca*) comprise the largest catch of the Hawaii-based swordfish longline fishery, although landing numbers have been low. Some finning of blue shark occurs, but estimates of landings in round weight are not currently available. Reported landings of whole sharks have consisted primarily of mako, *Isurus* spp., and thresher, *Alopias* spp., but have been a very small proportion of total longline landings. The incidental hooking of sharks may become a management issue if the take becomes large and if fishery or ecological impacts become significant.

The Pacific Regional Fishery Management Council (PRFMC) and the North Pacific Regional Fishery Management Council have not developed a fishery manage-

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[9] Shepherd, J. G. 1987. Towards improved stock-production models. Int. Counc. Explor. Sea (ICES) Working Group on Methods of Fish Stock Assessment, Working Pap. 6, 16 p. ICES, Palaegade 2-4, DK-1261, Copenhagen, K., Denmark.

[10] Prager, M. H. 1993. User's manual for ASPIC: a stock-production model incorporating covariates, program version 3.30. U.S. Dep. Commer., NOAA, Natl. Mar. Fish Serv., Southeast Fish. Sci. Cent., Miami Lab. Doc. MIA-92/93, no. 55, 31 p. SEFSC, NMFS, Miami, FL.

ment plan for swordfish or similar pelagic species. The states of Washington and Oregon do not allow driftnet- or longline-caught fish to be landed, while California allows driftnet fishing but not longline fishing in waters off its coast. However, Oregon is in the process of permitting driftnet fishing (Hanan[11]).[12] At present, there is no administrative mechanism for coordination of U.S. swordfish management in the central and eastern Pacific, although the PRFMC could serve that role on the U.S. west coast. In the North Pacific there is no regional fishery management body with the authority to manage swordfish.

Biological Knowledge

As discussed above, swordfish biology in the Pacific is poorly known, and estimates of population parameters necessary for stock assessment are generally lacking. Although some of these shortcomings are addressed in this symposium, no formal or informal arrangement exists for assessing priorities and facilitating the coordination of research among nations and scientists to improve our knowledge of this species.

Fishery Monitoring

Data collection activities are driven by local interests and historical practices. Landings data on the U.S. west coast are maintained in a database by the Pacific Marine Fisheries Commission, but data formats are not standardized between states supplying the data. Alaska does not routinely collect landings data from the longline boats fishing in the central North Pacific. The Honolulu Laboratory, in collaboration with American Samoa, Hawaii, Guam, and the Northern Mariana Islands, maintains a landings database, but it contains little data on swordfish other than for Hawaii. No regional or more broadly based arrangement between nations exists to coordinate data-collection activities for swordfish or provide a forum for exchanging or accessing data. Thus, in general, statistics necessary to assess the status of swordfish in the Pacific are either unavailable or inaccessible on a timely basis.

Honolulu Laboratory Research

Fishery Monitoring

The Honolulu Laboratory's swordfish fishery monitoring program aims to estimate production from the Hawaii fishery and collect data on the associated fishing and marketing sectors. This program is briefly described here.

Production—The weight of individual swordfish landed, ex-vessel revenue, and price are collected as part of a shoreside monitoring program conducted in conjunction with the State of Hawaii's Division of Aquatic Resources (Ito et al., 1998).

Interaction with Endangered Species—A mandatory observer program for the Hawaii longline fishery was established in 1994 by the NMFS Southwest Region to collect data on interactions of marine turtles with longline gear.

Biological Sampling—Observers from the mandatory program also collect swordfish otolith, fin, gonad, and stomach samples; determine the sex of swordfish retained; collect detailed data on catches and discards; and record length measurements for all fishes brought on board. Biological sampling also takes place on Honolulu Laboratory research cruises.

Cooperative Efforts—The following possible cooperative efforts have been discussed:

- Establish an ad hoc working group to facilitate and coordinate the collection and exchange of fishery data (weight of landings, effort and catch data, and fish sizes) for the swordfish fisheries based in Hawaii, California, Oregon, and Alaska.
- Establish a regional ad hoc working group with members from Japan and other distant-water fishing nations, Mexico, and the U.S. to facilitate sharing of data for stock assessment purposes.

Vessel Specifics—For Hawaii longline boats, data on vessel specifications, crew size, and the type and amount of gear carried are obtained from federal fishing permit applications. Personal interviews provide additional information (Ito et al., 1998).

Effort and Catch—Submission of logbooks became mandatory for Hawaii longline boats in November 1990, according to the second amendment to the Fishery Management Plan for Pelagic Species of the Western Pacific Region. These logbooks provide data on fishing effort expended daily by latitude and longitude, resulting catches by species, discards, fishing gear, and vessel operations. In addition, for longline boats fishing out of California ports, an industry association has developed a voluntary logbook which is being considered for adoption by California and the PRFMC (Hanan[4]).[13] The La Jolla

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[11] Hanan, D. A. 1996. Marine Resources Division, California Department of Fish and Game. SWFSC, P.O. Box 271, La Jolla, CA 92038-0271. Personal commun.

[12] In 1996, regulatins were passed in Oregon allowing both the use of drift nets and the landing of longline-caught fish.

[13] As of 1996, California requires the submission of logbooks by longline boats landing in the state.

Laboratory obtains summary logbook data for the high-seas Japanese, Korean, and Taiwanese longline fisheries, although data after 1990 are not available from Japan.

Oceanography Research

The goal of the Honolulu Laboratory's biological research on swordfish is to provide estimates of parameters needed for stock assessment modeling and to model the effect of gear characteristics on swordfish catch rates. Fishery oceanographic research will examine the effect of major oceanographic phenomena, e.g. El Niño, on swordfish distribution and catch rates.

Age and Growth—Efforts to refine estimates of age will continue by evaluating alternative light and electron microscope procedures and by attempting to validate ageing procedures. Sampling protocols will be revised to improve coverage of the size range of swordfish harvested by the Hawaii fleet and of the spatial range of the fishing fleet.

Size at Maturity—Sampling protocols will be developed to improve the collection of samples from the commercial longline fishery so that the precision of size-at-maturity estimates may be improved.

Fishery Oceanography—One approach will examine the effect of temperature gradients, as deduced from satellite data, on swordfish distribution and catch rates. Another will involve the use of satellite altimetry data on a mesoscale. Timely access to high-quality fisheries data and satellite oceanographic data will facilitate such research.

Stock Structure—The Honolulu Laboratory will continue to facilitate genetic research on swordfish by providing opportunities to scientists from across the Pacific to use the Laboratory's research vessel and to obtain samples.

Possible Cooperative Research—The following cooperative research has been proposed:

- Comparison of ageing techniques used by different scientists by exchanging swordfish hard parts collected from different segments of the Pacific fishery. This would also facilitate the identification of differences in regional growth, if they exist, better than independent research efforts.
- Archival tagging in fisheries across the range of the species would provide an opportunity for experiments to compare the effects of different oceanographic environments on movement.
- Joint acoustical tracking of swordfish in geographically-separated fisheries with differing oceanographic regimes would provide for more extensive testing of swordfish habitat preferences than tracking in any single fishery location.

Stock Assessment

The Honolulu Laboratory's stock assessment strategy involves a series of assessment techniques designed to progressively improve our understanding of resource dynamics. Almost all studies would benefit from, and in many cases require, cooperation and collaboration with researchers from across the Pacific to improve the quality of biological and fishery information and improve access to information.

Production Modeling—Once current, comprehensive statistics are available, initial efforts to assess the status of swordfish will employ dynamic stock-production modeling.

Yield per Recruit—Yield-per-recruit models will be employed to provide preliminary estimates of the effect of harvesting young fish, particularly by some segments of the Hawaii fleet.

Simulators—Stock and harvest simulators should be developed early on to guide stock-assessment and data-collection activities by predicting potential impacts of continued fishery development on stock dynamics.

Age-structured Modeling—Age- (or length-) structured stock-assessment models will be used to determine in more detail the impact of the fishery on the stock, e.g. the spawning component.

Spatial–Temporal Dynamics—The spatial and temporal variation of swordfish size in the catches of the Hawaii fleet will be compared to the results from the landings-based report in this symposium (DiNardo and Kwok, 1998). This and possibly other types of research will make it possible to standardize fishing effort statistics for the Hawaii longline fleet.

Possible Cooperative Research

- Cooperation between nations will be required to standardize effort statistics, due to changes in the high-seas longline fisheries of Japan, Korea, and Taiwan, the expansion of coastal fisheries, and the development of new fisheries using longline and other gear. A standardized time series of fishing effort statistics is needed to conduct unbiased production-model assessments.

- The use of nonequilibrium production models capable of including geographically-separated fisheries in a single model should provide better understanding of stock dynamics and more useful parameter estimates than fits using composite data.
- Because age- and length-structured models are dependent on age- or size-composition data from all geographically-separated segments of the fishery, at least cooperative development of the data sets is needed. Collaborative utilization of these data in fitting the models would be the best way of resolving data problems and would facilitate a common understanding of the resource status.
- Examination of the spatial and temporal dynamics of swordfish size distribution (DiNardo and Kwok, 1998) could best be extended by collaboration among investigators with access to comparable size data from other geographically-separated or overlapping fisheries.

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Standardized CPUE of North Pacific Swordfish, *Xiphias gladius*, in the Japanese Large-mesh Driftnet Fishery

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ABSTRACT

The CPUE of swordfish, *Xiphias gladius*, caught by the Japanese large-mesh driftnet fishery in the North Pacific in 1977–92 was standardized using a General Linear Model to obtain an index of annual abundance. The factors included in the analysis were year, quarter, area, and catch rates of albacore, *Thunnus alalunga*, skipjack tuna, *Katsuwonus pelamis*, and striped marlin, *Tetrapturus audax*. The catch rates of striped marlin and swordfish were highly correlated. No trend in abundance over time was found.

Introduction

The Japanese large-mesh driftnet fishery commenced in the nineteenth century in the coastal waters of Japan and then expanded widely in the North Pacific. By the 1970's the fishery had reached the South Pacific. Swordfish, *Xiphias gladius*, is one of the important species caught by this fishery. The annual catch of swordfish by this fishery in the North Pacific has ranged from 1,000 to 3,500 metric tons (t) since 1973, and has constituted about 10%–20% of the total swordfish catch by Japanese North Pacific fisheries. In addition to swordfish, the Japanese large-mesh driftnet fishery harvests considerable numbers of albacore, *Thunnus alalunga*, skipjack tuna, *Katsuwonus pelamis*, and striped marlin, *Tetrapturus audax*, in the North Pacific.

Most indices of abundance are based on catch per unit effort (CPUE). To be a reliable indicator, CPUE must be standardized to account for factors that can affect the estimation of abundance. A General Linear Model (GLM) has often been used to standardize CPUE of the tuna longline fishery (e.g. Turner, 1987; Miyabe, 1988). In this study the CPUE of swordfish caught by the Japanese large-mesh driftnet fishery was standardized using a GLM in order to investigate trends in swordfish abundance in the North Pacific.

Materials and Methods

Catch and fishing-effort data used in this analysis were obtained from Japanese large-mesh driftnet fishery statistics for 1977–92, based on logbooks and compiled at the National Research Institute of Far Seas Fisheries. These data include fishing date and position, mesh size, net length, and catch in numbers by species. Mesh size was recorded to the nearest centimeter. About 54% of the fishing effort was made using nets with 18-cm mesh; about 97% of the effort was made with nets of mesh size 15–21 cm. Mesh-size data were aggregated for purposes of this study in 3 categories: <17 cm, 17–19 cm, and >19 cm. Logbook data were aggregated by year, month, 1° × 1° area, and mesh-size category. CPUE was calculated as catch in number per 10 km of net. In order to exclude outliers, records aggregated from less than four fishing days were excluded from the analysis.

Swordfish CPUE was standardized for the effects of year, fishing season, area, mesh size, and targeting (Table 1). Fishing season was categorized by the quarter of the year. Five fishing areas were defined based on the spatial distribution of nominal swordfish CPUE (Fig. 1, 2). It is known that the species targeted by the fishery change by season and area. The CPUE's for these species were used to account for targeting effects. Four

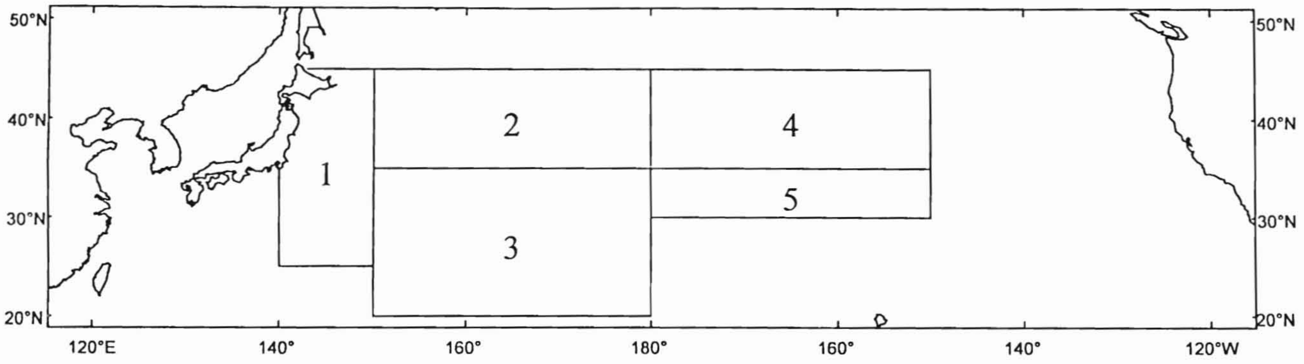

Figure 1
Fishing areas 1–5 used in the GLM analysis of swordfish CPUE in the Japanese large-mesh driftnet fishery in the North Pacific, 1977–92.

Table 1
Variables examined in the GLM for standardization of swordfish CPUE of the Japanese large-mesh driftnet fishery in the North Pacific.

Variable	Type	Description	Level
Year	classification	1971–92	16
Quarter	classification	1–4	4
Area	classification	1–5	5
Mesh size	classification	less than 17 cm, 17–19 cm, 19 cm and larger	4
CPUE of striped marlin	classification	ln(CPUE)<–1.2, –1.2–0.3, 0.3–1.5, ≥1.5	4
CPUE of skipjack tuna	classification	ln(CPUE) <1.6, 1.6–3.4, 3.4–4.6, ≥4.6	4
CPUE of albacore	classification	ln(CPUE) <–0.4, –0.4–2.9, 2.9–4.5, ≥4.5	4

categories were defined for each species such that, for each species, each category included approximately the same number of observations. It was assumed that the relative abundance and distribution of these species in the North Pacific did not change significantly during 1977–92.

The GLM used was:

$$\ln\left[\mathrm{CPUE(SWD)} + 0.05\right] = \mu + \mathrm{Y} + \mathrm{Q} + \mathrm{A} + \mathrm{M} + \mathrm{S}(i) \cdots + \mathrm{INTER} + \varepsilon$$

where SWD = swordfish;
ALB = albacore;
SKJ = skipjack tuna;
STM = striped marlin;
μ = intercept;
Y = effect of year;
Q = effect of quarter;
A = effect of subarea;
M = effect of mesh size;
S(i) = effect of species i, i = (ALB, SKJ, STM);
INTER = two-way interaction;
ε = error term ~ $N(0, \sigma^2)$.

The natural logarithm of CPUE(SWD) + 0.05 was used instead of CPUE(SWD) in order to include observations for which there was fishing effort but no catch of swordfish. The constant, 0.05, was selected based on an examination of the distribution of swordfish nominal catch rates and such that the constant would be small relative to observed values of nominal CPUE(SWD) (Fig. 3). Fitted model selection was made using Akaike's Information Criterion (AIC):

$$\mathrm{AIC} = X \ln(\mathrm{MSE}) + 2Y$$

where X is the number of observations, MSE is mean square error, and Y is the number of parameters estimated (Sakamoto et al., 1986). Model fit improves as AIC decreases. Analyses were conducted using SAS version 6.09 (SAS, 1989).

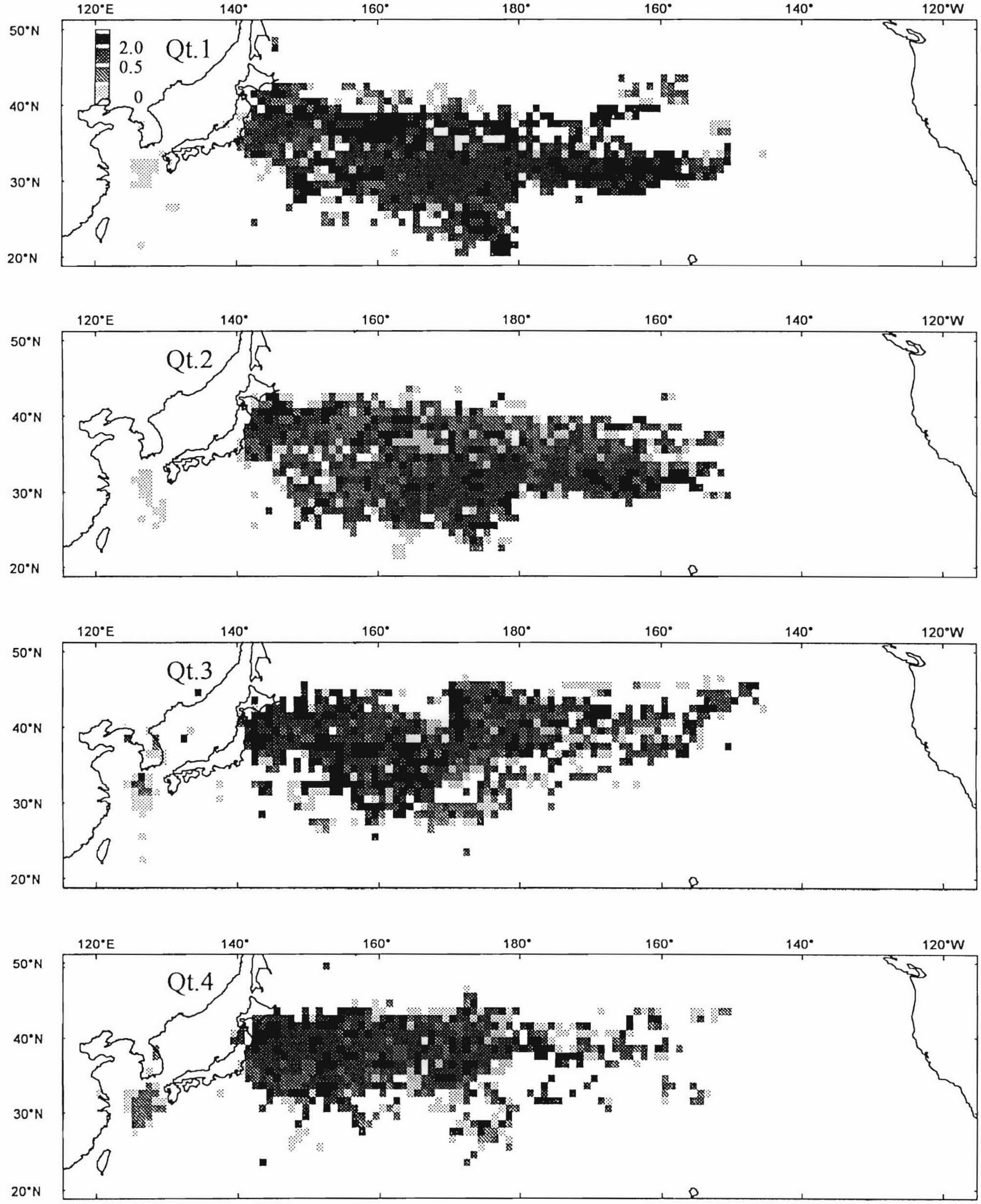

Figure 2

Distribution of the nominal catch rate of swordfish (fish per 10 km of net) by the Japanese large-net driftnet fishery in the North Pacific, 1977–92.

Results and Discussion

First the main-effects model, which included all main effects but no interaction terms, was examined to identify the effects to be considered for inclusion in the fitted model. Only mesh size was not significant (F, p=0.094). Each of the remaining main effects was then sequentially added into a model which included year effect, in the order of larger to smaller F values. A summary of the ANOVA results, with AIC values, is shown in Table 2 (A). The model that provided the best fit as measured by AIC (Model 5) included Y, Q, A, S(STM), S(SKJ), and S(ALB)

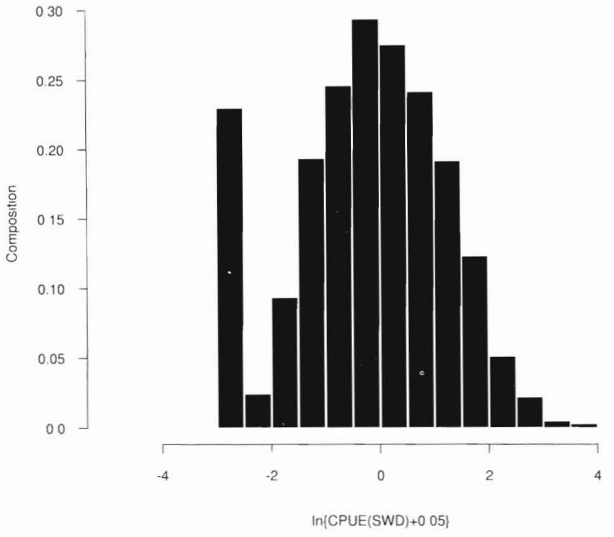

Figure 3
Distribution of ln(CPUE + 0.05) of swordfish in the Japanese large-mesh driftnet fishery in the North Pacific, 1977–92.

Next, interaction terms were added to Model 5 in a procedure analogous to that just described for main effects. All combinations of two-way interactions were attempted, except interactions with species effects. A summary of the ANOVA results, with AIC's, is shown in Table 2 (B). The results indicated that none of the models with interaction terms provided a significant improvement. Thus, the chosen model was:

$$\ln\left[\mathrm{CPUE(SWD)} + 0.05\right] = \\ \mu + \mathrm{Y} + \mathrm{Q} + \mathrm{A} + \mathrm{S(STM)} + \mathrm{S(SKJ)} + \mathrm{S(ALB)} + \varepsilon.$$

The ANOVA table for the final model is shown in Table 3, and the distribution of standardized residuals is shown in Figure 4. All terms in the model were significant at the $p \geq 0.0001$ level, i.e. at levels at least 500 times the standard p-value of 0.05. At the same time, the correlation coefficient for the final model was r^2 = 0.22. These results are not surprising given the large data set (5,633 observations) (Draper, 1984). The fact that the significance levels of the regression coefficients were so high indicates that the results may be considered not only significant but useful (Draper and Smith, 1981). In comparison, the results of GLM analyses of swordfish CPUE of the Japanese longline fishery in the North and the South Pacific had r^2 = 0.53 and r^2 = 0.47, respectively (Nakano, 1998).

Table 2
Summary of ANOVA's, with Akaike's Information Criterion (AIC). Effects Y, Q, A, S(SKJ), S(STM), and S(ALB) indicate year, quarter, area, and CPUE's of skipjack tuna, striped marlin, and albacore, respectively. Number of observations = 5,633.

Model	No. of parameters	R-square	C.V.	MSE	F value	AIC
A. Main-effects models						
(1) Y S(STM)	20	0.151	–544.69	1.771	55.58	1,438.62
(2) Y S(STM) Q	24	0.161	–541.83	1.753	51.12	1,420.84
(3) Y S(STM) Q S(SKJ)	28	0.195	–530.88	1.683	56.46	1,328.95
(4) Y S(STM) Q S(SKJ) A	33	0.216	–523.91	1.639	55.20	1,274.27
(5) Y S(STM) Q S(SKJ) A S(ALB)	37	0.222	–522.11	1.627	51.54	1,265.49
B. Models with interaction terms						
(5) + Y*Q	101	0.262	–510.42	1.555	26.34	1,282.65
(5) + Y*A	117	0.261	–511.07	1.559	23.94	1,320.90
(5) + Q*A	57	0.234	–518.48	1.605	39.79	1,271.33
(5) + Y*Q Y*A	181	0.298	–500.31	1.494	18.52	1,344.80
(5) + Y*Q Q*A	121	0.276	–506.15	1.530	24.31	1,281.58
(5) + Y*A Q*A	137	0.273	–507.68	1.539	22.08	1,328.35
(5) + Y*Q Y*A Q*A	201	0.315	–494.49	1.460	18.34	1,327.57

The GLM for standardizing catch rate of swordfish by driftnet might be further improved by addition of factors related to the environment and/or characteristics of the gear other than mesh size. For example, it is known from acoustic telemetry (e.g. Carey and Robison, 1981) that during hours of darkness swordfish spend significant periods of time at shallow depths. It is also known that swordfish are, not surprisingly, effectively targeted with longline gear that is fished with shallow hook depths at night. Therefore, including factors that account for the vertical distribution of swordfish, as well as the time of day of sets and the fishing depth of the net, might improve the model.

It was somewhat surprising that the effect of mesh size was not significant. In general, fishermen select mesh size to effectively target specific species. In the case of the Japanese large-mesh driftnet fishery, it was believed that gillnets with larger mesh sizes were selective for billfish, and smaller, for tunas. However, these results did not support that hypothesis.

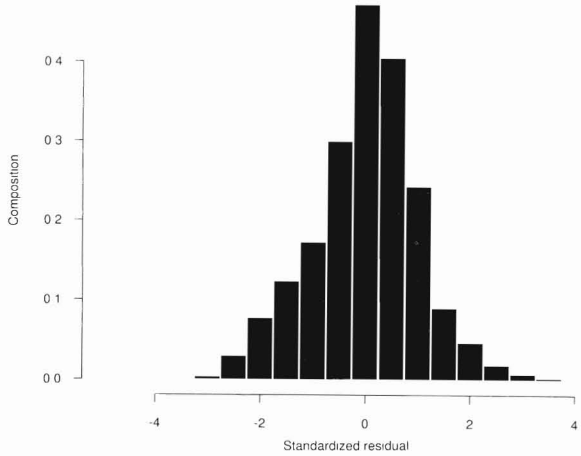

Figure 4
Distribution of standardized residuals of the fitted GLM.

Relationships between standardized swordfish CPUE and Q, A, S(STM), and S(SKJ) are shown in Figure 5. It is apparent that swordfish CPUE was greatest in the third quarter, moderate in the first and fourth quarters, and lowest in the second quarter. It is also apparent that CPUE in Area 5 was remarkably higher than in the other areas. Swordfish CPUE increased with S(STM) and S(SKJ), but not with S(ALB). This suggests that swordfish, striped marlin, and skipjack have similar distribution patterns and tend to be caught in the same times and places.

Standardized swordfish CPUE, with upper and lower 95% confidence bounds, is shown by year in Table 4. Annual CPUE has varied widely during 1977–92. It was highest (1.2–1.3) during 1978–80, but declined significantly in 1981 and 1982, and stayed at around 0.55 during 1982–84. After that, CPUE fluctuated between about 0.50 and 1.16. Based on these analyses, the relative abundance of swordfish in the North Pacific during 1990–92 was about 54% of that seen during the period of highest abundance (1978–80).

Nominal and standardized swordfish CPUE, scaled by 1977–92 average nominal and standardized CPUE, respectively, are shown in Figure 6. As expected, due to the reduction of variance provided by the GLM, fluctuations in standardized CPUE are smaller than those in nominal CPUE. The nominal and standardized CPUE series were tested for trend using regression analysis; no trend in relative abundance was found (df = 14, Student's $t = -1.10$ and -1.80, $p = 0.29$ and 0.093, respectively).

Nominal CPUE values include noise and may include bias caused by variation in artificial and natural factors

Table 3
ANOVA for the fitted model for standardization of swordfish CPUE in the Japanese large-mesh driftnet fishery in the North Pacific, 1977–92. R-square = 0.222; C.V. = –522.11

Source	DF	Sum of Squares	Mean Square	F value	*P* > F
Model	31	2,600.52	88.89	51.54	0.0001
Error	5,601	9,115.60	1.63		
Corrected total	5,632	11,716.12			
Source	**DF**	**Type III SS**	**Mean Square**	**F value**	***P* > F**
Y	15	366.94	24.46	15.03	0.0001
Q	3	223.23	74.41	45.72	0.0001
A	4	258.36	64.59	39.69	0.0001
S(STM)	3	624.80	208.27	127.97	0.0001
S(SKJ)	3	185.19	61.73	37.93	0.0001
S(ALB)	3	67.66	22.55	13.86	0.0001

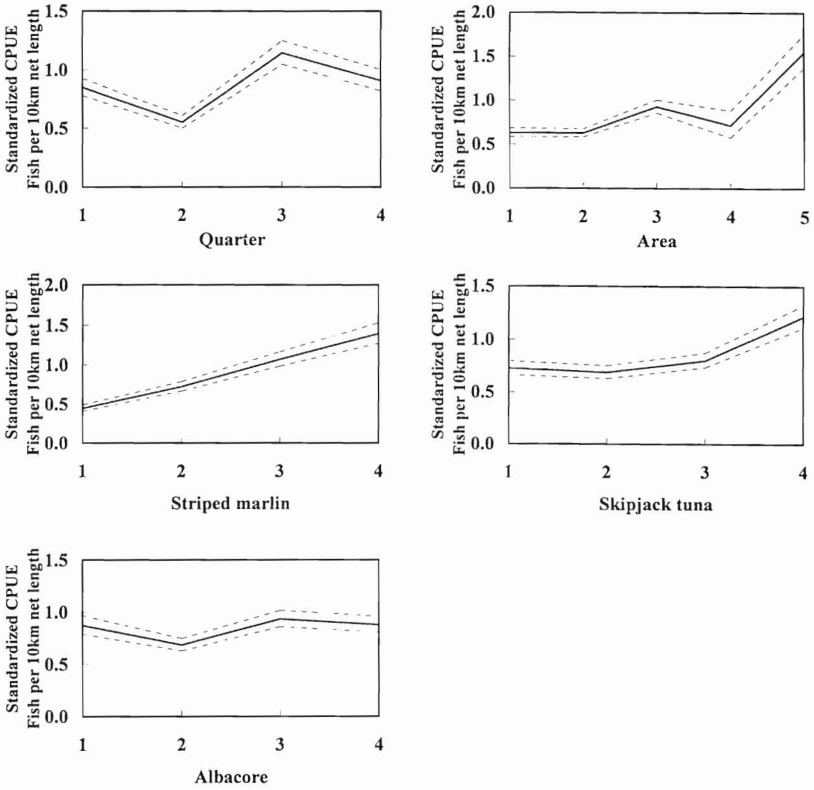

Figure 5

Relationships between standardized CPUE of swordfish and Q, A, S(STM), S(SKJ), and S(ALB). Dotted lines indicate 95% confidence bounds.

Table 4

Standardized CPUE and 95% confidence bounds for North Pacific swordfish caught by the Japanese large-mesh driftnet fishery, 1977–92. Unit is fish per 10-km net length.

	Standardized CPUE	Upper bound	Lower bound		Standardized CPUE	Upper bound	Lower bound
1977	1.02	1.27	0.82	1985	0.97	1.14	0.82
1978	1.21	1.43	1.01	1986	0.79	0.93	0.68
1979	1.21	1.48	0.98	1987	1.04	1.23	0.87
1980	1.32	1.58	1.09	1988	0.78	0.89	0.68
1981	0.83	0.95	0.72	1989	1.16	1.33	1.01
1982	0.57	0.67	0.48	1990	0.75	0.84	0.66
1983	0.57	0.66	0.49	1991	0.54	0.62	0.47
1984	0.50	0.58	0.43	1992	0.73	0.84	0.64

that affect the fishing event. Standardizing CPUE with a GLM may remove biases that result from variations such as those in fishing seasons and fishing grounds. In order to ensure that reliable estimates of the relative abundance and status of swordfish stocks in the North Pacific are available, the results of this study should be compared with the results of other such investigations to ensure that any conflicts in results may be further investigated and the reasons for any noted differences resolved.

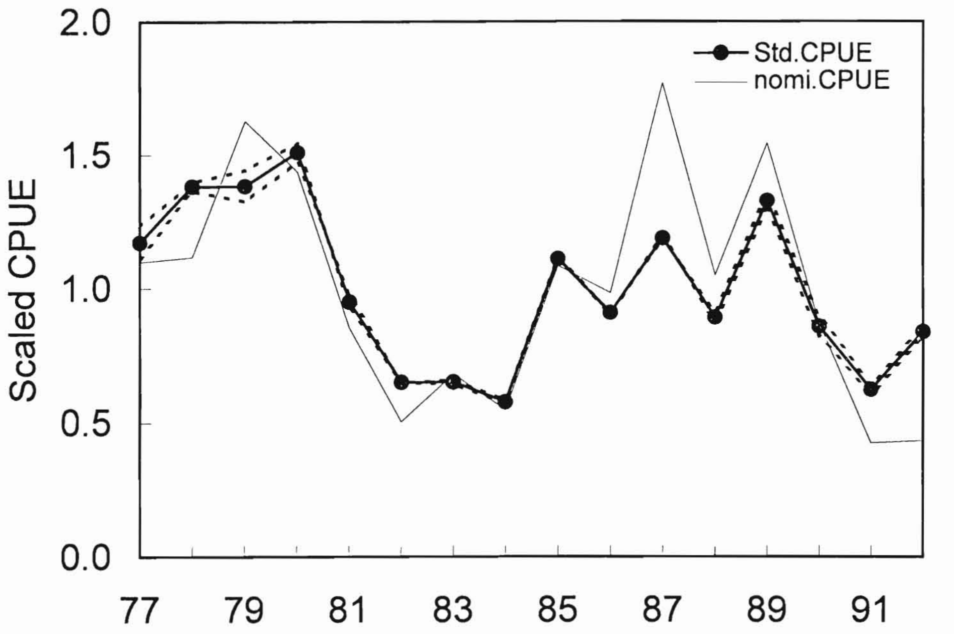

Figure 6

Nominal and standardized CPUE of swordfish, scaled by average 1977–92 nominal and standardized CPUE, respectively, for the Japanese large-mesh driftnet fishery in the North Pacific. Dotted lines indicate 95% confidence bounds for standardized CPUE.

Acknowledgments

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Review of the Japanese Swordfish, *Xiphias gladius*, Fisheries in the Pacific Ocean

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ABSTRACT

The Japanese catch of swordfish peaked at about 24,000 metric tons (t) in 1961; thereafter the catch decreased sharply to about 10,000 t in 1964. Since the mid-1960's it has been stable at 10,000–15,000 t. The catch by the Japanese longline fishery represents more than 90% of the total Japanese swordfish catch. The driftnet and harpoon fisheries accounted for a small portion of the total catch.

Over the same time period, the Japanese longline fishery expanded operations widely in the Pacific Ocean, but most of the swordfish catch was from the northwest Pacific. A minor portion was from the waters off California, Peru, and the Tasman Sea. The driftnet fishery operated mainly in the central North Pacific, but stopped operations in the high seas after the UN resolution in December 1992 for a moratorium on large-scale drift net in the high seas. The harpoon fishery operated in the coastal waters around Japan; its catch continues to decrease.

Introduction

The swordfish catch by Japanese fisheries accounted for more than 80% of the total swordfish catch in the Pacific Ocean in the 1950's and 1960's. The Japanese swordfish catch has remained stable, but other countries such as U.S.A., Philippines, and Chile have increased their catch in recent years (Table 1). Therefore the percentage of the total catch represented by the Japanese catch has declined, especially in the 1990's, when it decreased to 30–45%. However, the Japanese catch is still the largest by a single country. Catch and effort data from the Japanese fisheries, especially the longline fishery, have been used for the stock assessment of swordfish in the Pacific Ocean because of their wide areal coverage and long history (Sosa-Nishizaki and Shimizu, 1991).

This paper offers a description of the historical catch of swordfish by Japanese fisheries and its geographical distribution of catch, effort, and CPUE, based on annual statistics published by the Statistics and Information Department of the Japanese Ministry of Agriculture, Forestry, and Fisheries, as well as on logbook data compiled by the National Research Institute of Far Seas Fisheries.

Price of Swordfish and Other Billfishes in Japan

Figure 1 shows the historical changes in average price for some tunas and billfishes (frozen and round fish) at major fishing ports in Japan from 1967 to 1992. The prices of bluefin and southern bluefin tunas were much higher, but the prices of albacore and skipjack much lower than those shown here. Average prices of frozen tunas and billfishes increased markedly during the 1970's, mainly due to technological improvement in freezers which increased the quality of fish meat used for sashimi. Japanese longliners began outfitting their vessels with freezers capable of quick-freezing fish to below –55°C. The fish are then stored in holds at below –40°C (Ueyanagi et al., 1989). The prices of tunas and billfishes kept under these conditions were higher in the sashimi market. Prices stabilized after 1980, except for bigeye tuna.

The price of swordfish was less than 300 yen/kg before 1970, increased rapidly to around 700 yen/kg in the late 1970's, peaked at about 900 yen/kg in 1984, and has since decreased gradually. Its price was about average among the species of billfishes and tunas shown in Figure 1.

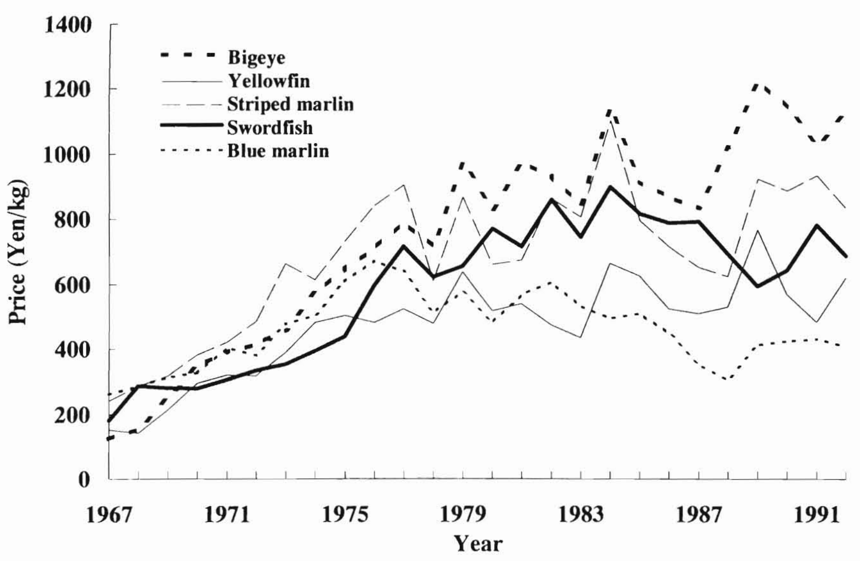

Figure 1
Average price of tunas and billfishes (for frozen and round fish, per kg) at major fishing ports in Japan, 1967–92.

Major Japanese Swordfish Fisheries

The Japanese swordfish catch in the Pacific Ocean increased during the 1950's and peaked at about 24,000 metric tons (t) in 1961 (Fig. 2). The catch decreased sharply to about 10,000 t in 1964, then fluctuated between 10,000 and 15,000 t in the 1970's and 1980's. The catch by the longline fishery represented more than 90% of the total throughout the years observed. The driftnet and harpoon fisheries accounted for only a small portion of the total swordfish catch. Catch by other fisheries such as the purse seine and baitboat fisheries was negligible and incidental.

Longline Fishery

The total effort of the Japanese longline fishery in the Pacific Ocean increased rapidly from the late 1950's to the mid-1960's and remained stable until the mid-1970's (Fig. 3). The effort increased again in the late 1970's, but has been stable since about 1980, with some fluctuations.

Albacore and yellowfin tunas dominated the longline catch during the 1950's and 1960's, but the catch of albacore decreased rapidly during the late 1960's and early 1970's (Fig. 3). After about 1970 the catch of bigeye tuna increased gradually, with some fluctuations.

The catch of swordfish by the longline fishery increased rapidly in the 1950's, then decreased drastically until 1964. Since then the catch has been stable. The catch of striped marlin also increased rapidly in the 1950's and was at record levels from 1964 to 1970, a decade after the swordfish catch had begun its decline. The striped marlin catch decreased during the early 1970's and has fluctuated until the present. The catch of blue marlin followed a trend intermediate between those of swordfish and striped marlin. The catch of swordfish has been the largest of the billfish catches since 1983, though only 10% the size of the bigeye tuna catch. Generally swordfish has been caught as a bycatch species, especially in waters distant from Japan, except for a minor local longline fishery which targets swordfish in Japanese coastal waters.

By the 1960's, Japanese longline fishery had expanded throughout the tropical and subtropical Pacific; efforts were concentrated in the waters off Japan and in western tropical waters (Fig. 4). In the 1970's, technological improvements in freezing made it possible for longliners operating in distant waters to target southern bluefin and bigeye tunas and to sell them in the Japanese sashimi market. As a result, efforts were concentrated in eastern tropical Pacific waters to target bigeye tuna and in New Zealand–Australian waters to target southern bluefin tuna, in addition to former fishing grounds. In the 1980's and 1990's (up to 1992), effort increasingly concentrated in the eastern tropical Pacific and New Zealand–Australian waters. The most striking feature of the recent two decades was the significant increase of efforts in the eastern tropical Pacific, which is

Table 1

Catch (metric tons) of swordfish in the Pacific Ocean by country, 1952–93. Numbers in parentheses are percentage of the total which the Japanese catch represents. Data from IATTC (1994) and FAO (1995).

Year	Japan	Chile	Philippines	USA	Taiwan	Mexico	Other	Total
1952	11,182 (98.6)			157				11,339
1953	11,604 (99.3)			85				11,689
1954	13,301 (99.3)			14	77			13,392
1955	16,220 (98.4)			80	185			16,485
1956	12,167 (96.7)			163	254			12,584
1957	15,771 (97.1)			222	250			16,243
1958	20,815 (97.5)			279	247			21,341
1959	19,136 (97.3)			265	262			19,663
1960	22,944 (96.1)	456		192	273			23,865
1961	23,636 (95.8)	394		218	432			24,680
1962	14,037 (94.2)	297		23	544			14,901
1963	13,775 (96.8)	94		58	300			14,227
1964	9,703 (93.2)	300		109	300			10,412
1965	11,955 (92.3)	200		194	300	0	300	12,949
1966	13,283 (91.0)	200		277	600	0	241	14,601
1967	13,083 (83.6)	200		181	838	0	1,347	15,649
1968	12,983 (86.3)	135		118	974	0	833	15,043
1969	15,612 (82.9)	300		610	1,023	0	1,289	18,834
1970	11,301 (66.4)	200	1,400	558	1,053	0	2,515	17,027
1971	9,182 (73.8)	200	1,500	91	1,149	0	315	12,437
1972	8,846 (70.7)	100	1,600	157	1,095	0	714	12,512
1973	9,644 (62.6)	400	1,700	363	1,278	0	2,015	15,400
1974	9,517 (70.4)	218	1,848	383	1,170	0	385	13,521
1975	11,274 (73.3)	218	1,976	510	1,120	0	273	15,371
1976	15,843 (83.0)	13	1,558	49	886	0	738	19,087
1977	13,997 (78.2)	32	2,103	301	789	0	684	17,906
1978	14,333 (89.0)	56	890	1,536	693	0	634	18,142
1979	13,091 (69.8)	40	3,845	346	873	7	553	18,755
1980	11,953 (73.2)	104	1,716	706	932	380	544	16,335
1981	13,078 (69.9)	294	1,940	674	803	1,575	347	18,711
1982	11,350 (61.3)	285	3,468	726	984	1,365	347	18,525
1983	12,511 (67.7)	342	2,974	1,195	979	120	360	18,481
1984	11,986 (67.2)	103	2,274	2,009	1,056	47	352	17,827
1985	13,083 (69.7)	342	2,036	2,370	775	18	148	18,772
1986	14,271 (71.7)	764	2,089	1,585	692	422	69	19,892
1987	14,867 (65.9)	2,059	2,137	1,221	1,540	550	195	22,569
1988	15,496 (56.1)	4,455	4,034	1,086	1,690	613	246	27,620
1989	12,367 (45.5)	5,824	3,756	588	3,692	690	265	27,182
1990	11,341 (39.3)	4,955	3,187	2,150	4,097	2,650	447	28,827
1991	9,936 (35.6)	7,255	3,139	4,597	1,645	861	501	27,934
1992	15,619 (44.5)	6,379	4,256	5,948	1,300	1,160	446	35,108
1993	15,458 (45.2)	4,712	4,633	6,981	1,525	806	97	34,212

one of the most important fishing grounds of bigeye tuna in the world.

The geographical distribution of swordfish catch is shown in Figure 5. In the 1960's, the catch was concentrated in waters off Japan. In later decades, the swordfish catch was increasingly concentrated off California and Peru, and in the Tasman Sea. The catch in the North Pacific was more than 90% of the total in the 1960's, but decreased gradually to around 70% in the 1970's and 1980's. In the 1990's (up to 1992), it decreased to 60%.

Figure 6 shows the distribution of nominal mean CPUE for swordfish (catch in number per 1,000 hooks) in each decade. High CPUE's were observed between 25° and 45°N in the North Pacific, off California and Peru–Chile, and in the Tasman Sea. There were low CPUE's in tropical waters.

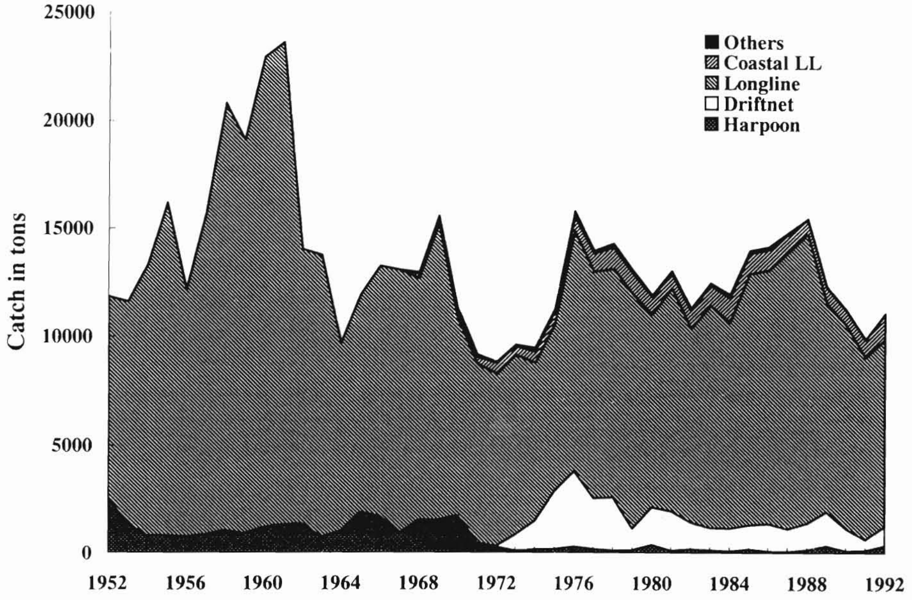

Figure 2

Swordfish catch by Japanese fisheries in the Pacific Ocean by type of fishery, 1952–92.

Driftnet Fishery

The Japanese large-mesh driftnet fishery, called "oome-ami" or "oome-nagashiami" and officially registered as "Billfishes and Others Drift Gillnet Fishery," commenced in the 19th century in the coastal waters of Japan (Watanabe;[1] Uozumi[2]). The modern large-mesh driftnet fishery started in the early 1970's and gradually expanded to offshore waters in the North Pacific. From 1983 to 1990, some of these vessels operated in the South Pacific (Nakano et al.;[3] Uozumi[2]). Swordfish has traditionally been targeted by the driftnet fishery in the coastal waters of Japan, but it has also been caught as a valuable bycatch species in the high seas of the Pacific where Japanese large-mesh driftnetters targeted albacore and/or skipjack tuna.

North Pacific—Figure 7 shows historical trends in driftnet catches of major species in the Pacific Ocean. The total catch increased rapidly in the 1970's and fluctuated between 15,000 and 23,000 t in the 1980's. In the 1990's the catch decreased rapidly, and the operations of the driftnet fishery in the high seas of the North Pacific have ended since December 1992, following a UN resolution for a moratorium on large-scale high seas driftnetting.

During the 1970's, billfishes accounted for the major part of the total driftnet catch. After about 1980, the catch of albacore increased rapidly and became the largest part of the catch. The catch of skipjack increased beginning in the mid-1980's, and became the major species in the driftnet catch after 1990.

Swordfish driftnet catch peaked at 3,500 t in 1976 and then decreased gradually through the years, with some fluctuations. The catch of swordfish has been around 1,000 t annually in recent years. It is assumed that the swordfish catch decreased substantially after 1992, since driftnet operations are now restricted to the 200 nautical miles around Japan.

The geographical distribution of the mean fishing effort (total length of fishing gear) is shown in Figure 8 by 3-yr period from 1977–91, based on logbook sampling statistics.

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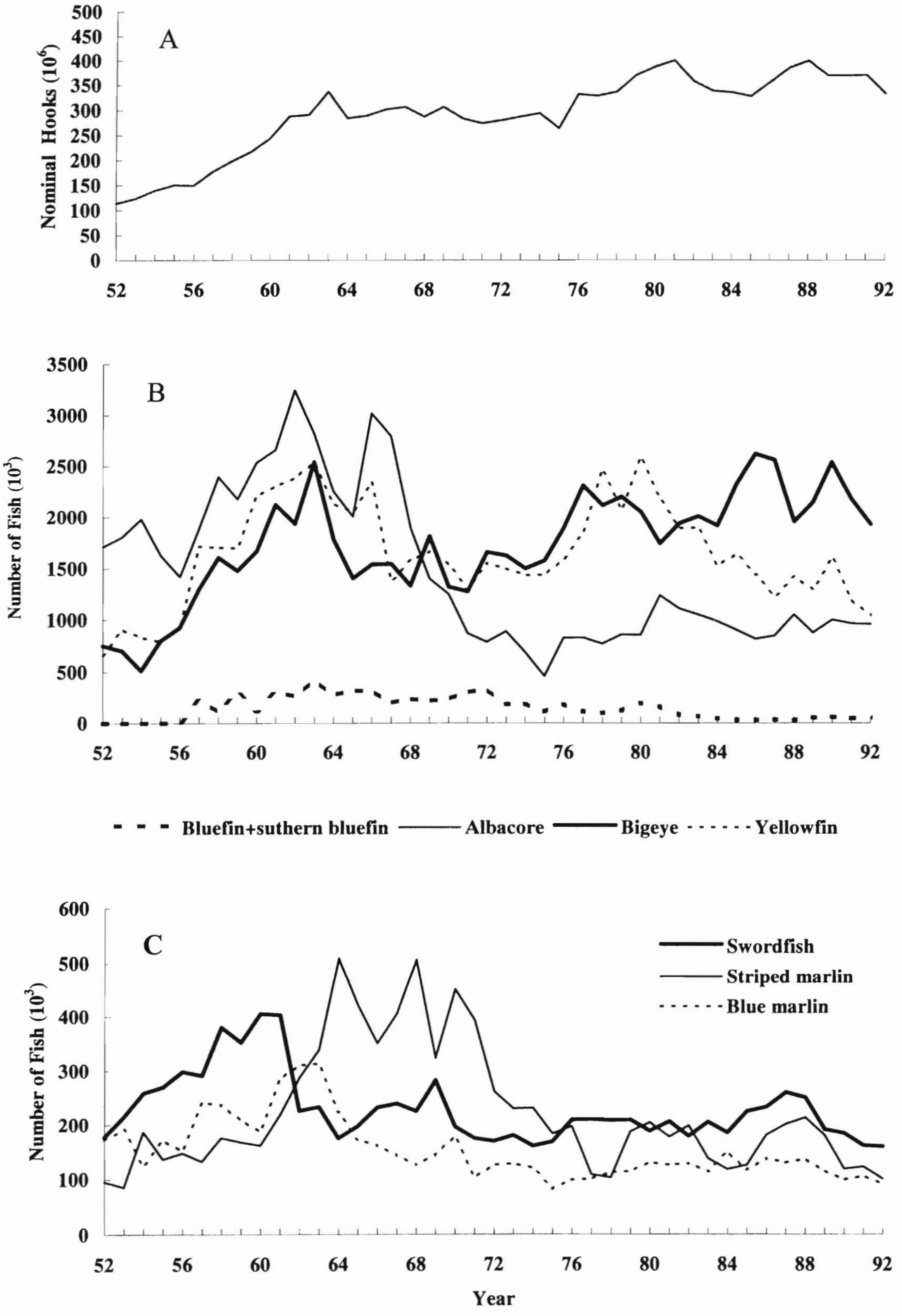


Figure 3
Catch and effort of the Japanese longline fishery in the Pacific Ocean, 1952–92. (A) number of hooks set, in millions, (B) catch of tunas, and (C) catch of swordfish and marlins. Note different scales.

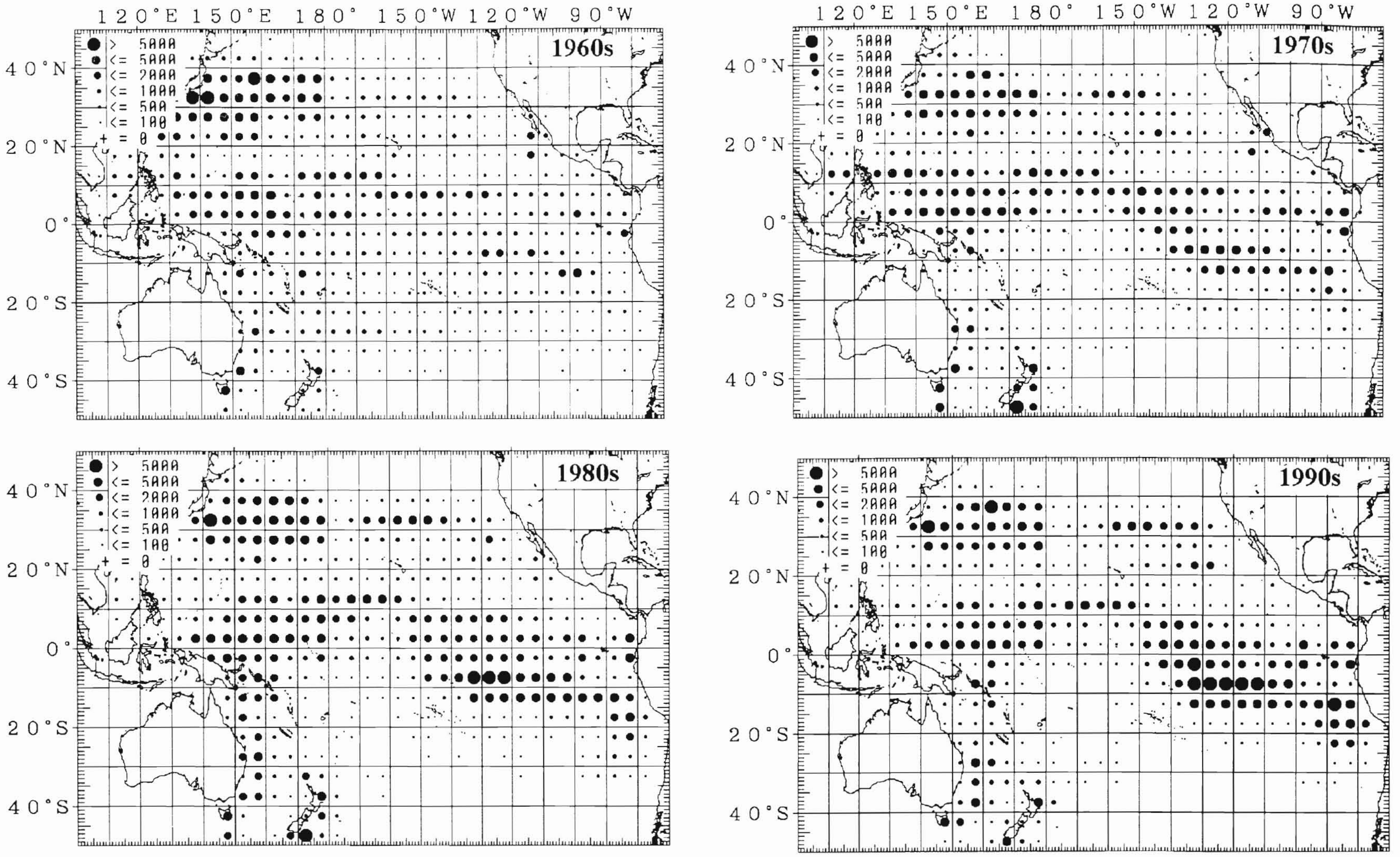


Figure 4

Geographical distribution of mean annual fishing effort (in thousands of hooks) by the Japanese longline fishery in the Pacific Ocean, by decade.

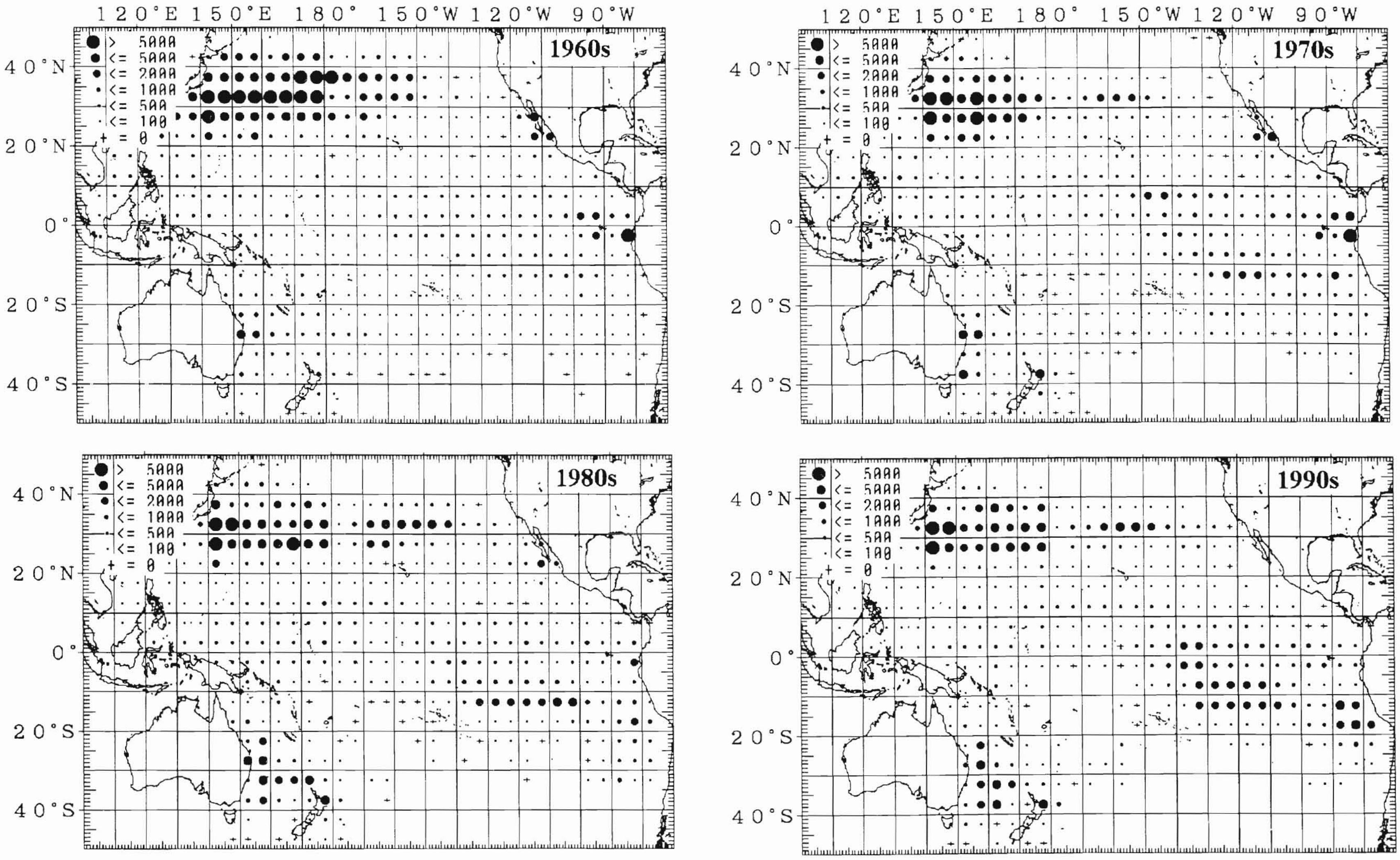


Figure 5

Geographical distribution of mean annual swordfish catch (in thousands of fish) by the Japanese longline fishery in the Pacific Ocean, by decade.

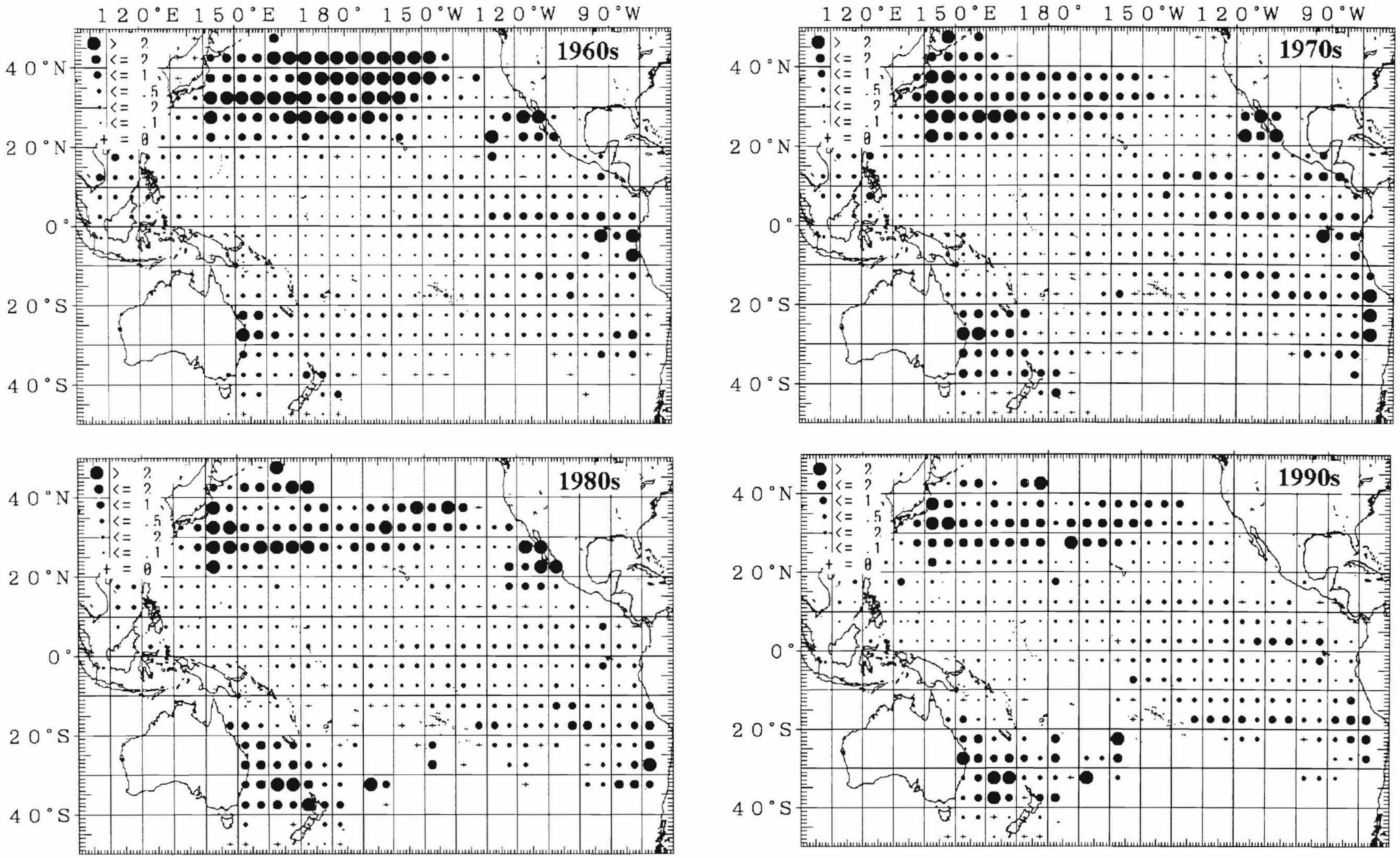


Figure 6

Geographical distribution of mean annual swordfish CPUE (number/1,000 hooks) of the Japanese longline fishery in the Pacific Ocean, by decade.

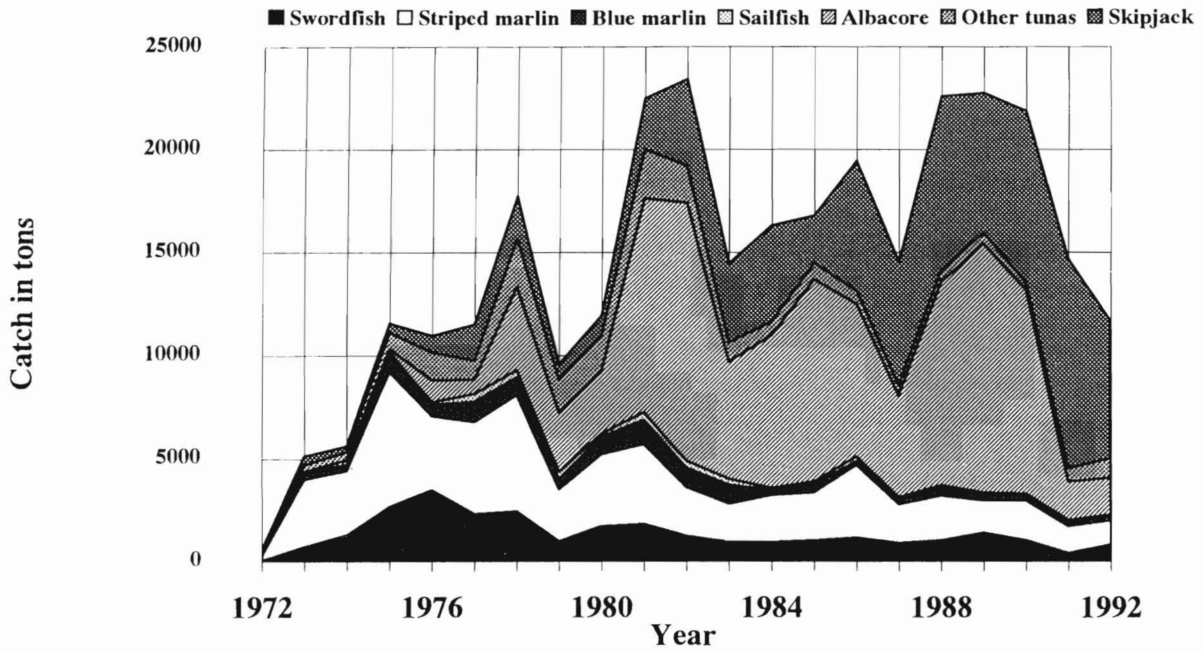


Figure 7

Catch by the Japanese driftnet fishery in the Pacific Ocean by species, 1972–92.

In 1977–79, fishing effort was mainly focused on the waters west of 180°, off Tohoku region and in the East China Sea. In 1980–82, fishing effort expanded to the eastern North Pacific, but the main fishing area was still in the western area. In 1983–85 and 1986–88, the distribution of effort was similar to that in 1980–82, but the main fishing area was shifted slightly to the east (170°E–170°W). In 1989–91, the mean distribution pattern was similar to those in previous years, but fishing effort was concentrated in the offshore waters of the Tohoku region in addition to the area between 170°E and 170°W. In this period, the interannual distribution of fishing effort changed due to socio-economic conditions. After 1991, fishing efforts in the high seas decreased rapidly and effort was again concentrated in the waters inside the Japanese 200-m EEZ.

The distribution of swordfish catch (mean catch in number/yr) by driftnetting in the North Pacific is shown in Figure 9 by 3-yr period. The catch was concentrated in the waters off Japan before 1985. In 1986–91, the concentration of catch was in waters to the northwest of Hawaii. These changes reflect the changing patterns of effort distribution.

The distribution of swordfish CPUE (number/10 km of gear) in 1989–91 is shown in Figure 10. Areas of high CPUE are scattered all over the operation area, with no area of concentration.

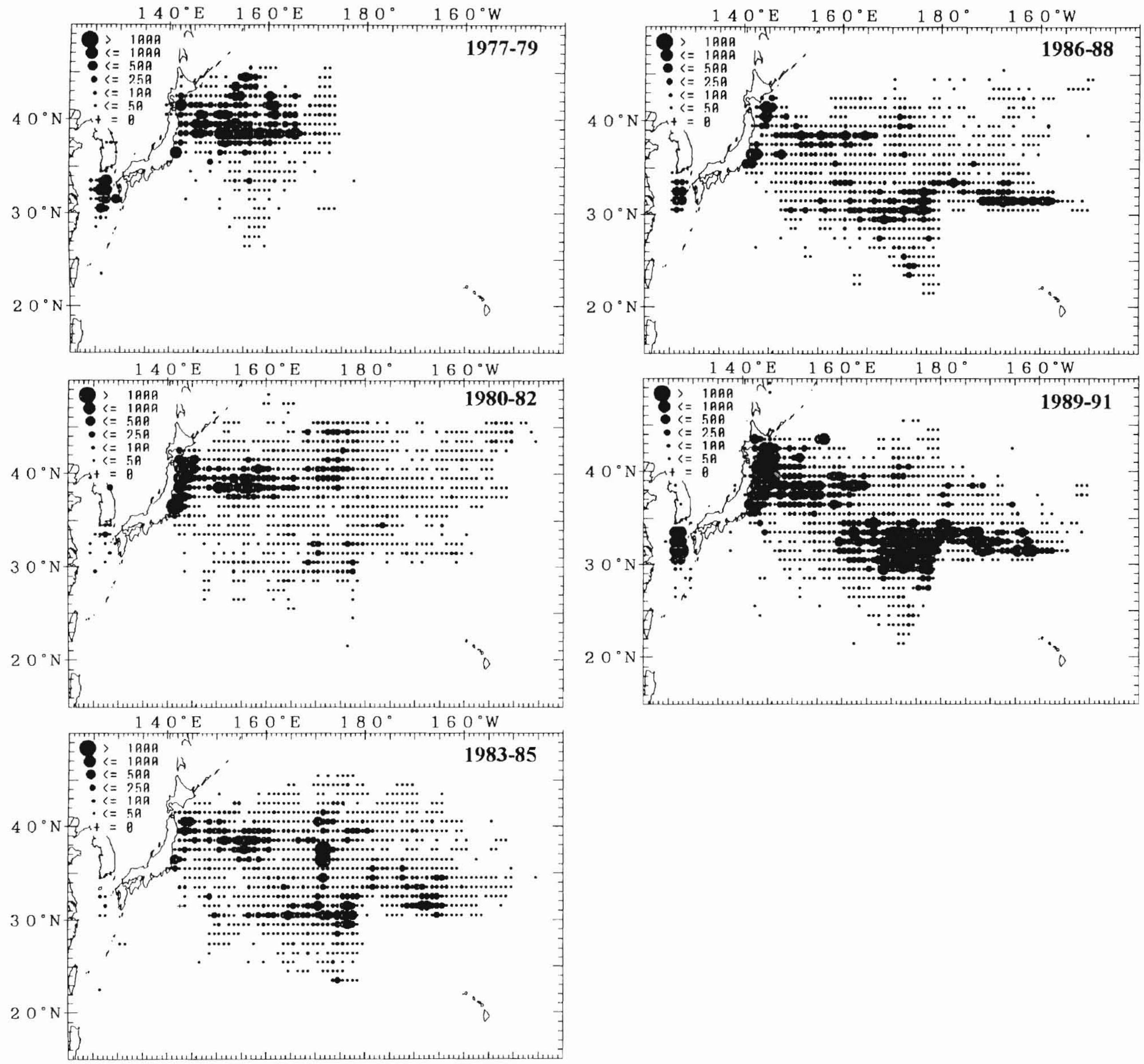
South Pacific—Driftnet operations in the South Pacific commenced in 1983. From 7 to 20 vessels operated before 1988; the number of vessels peaked at 64 in 1988, and decreased to 19 in 1989. The operations of the driftnet fishery in the south Pacific have stopped since July 1990, following the UN resolution.

The swordfish catch in the South Pacific was only 1%–2% the size of the albacore catch there. It is estimated that the swordfish catch was about 220 t in 1988, when the number of vessels peaked. In other years, the catch of swordfish is estimated at less than 50 t.

The distribution of driftnet fishing effort, swordfish catch, and CPUE in the South Pacific are shown in Figure 11. Most fishing effort was concentrated in the central area of the Tasman Sea, but some effort was expended on the eastern waters off New Zealand. Swordfish catch was also concentrated in the central Tasman Sea. But swordfish CPUE was higher in the waters east of New Zealand than in the Tasman Sea. The discrepancy between the distributions of catch and CPUE was mainly due to the fact that the driftnet fishery targeted mainly albacore, with swordfish only a bycatch species.

Harpoon Fishery

A harpoon fishery directed at billfishes operates in the coastal waters of Japan. Swordfish is one of the major target species in the harpoon fishery, next to striped



1977-79

1980-82

1983-85

1986-88

1989-91

Figure 8

Geographical distribution of mean annual fishing effort (mean total length of gear in km) for the Japanese driftnet fishery by 3-yr period, 1977–91.

marlin. The fishing grounds are located around Izu and off the Sanriku area of northern Honshu Island. The average fishing vessel is less than 20 gross t.

Total annual catch from the harpoon fishery fluctuated between 2,500 t and 4,500 t during the late 1950's and 1960's (Fig. 12). The annual swordfish catch was about 250 t until 1957, fluctuated between about 800 and 1,900 t until 1970, and then dropped precipitously to under 500 t, where it has remained. The decrease in catch by the harpoon fishery was mainly due to the decrease in number of fishing vessels.

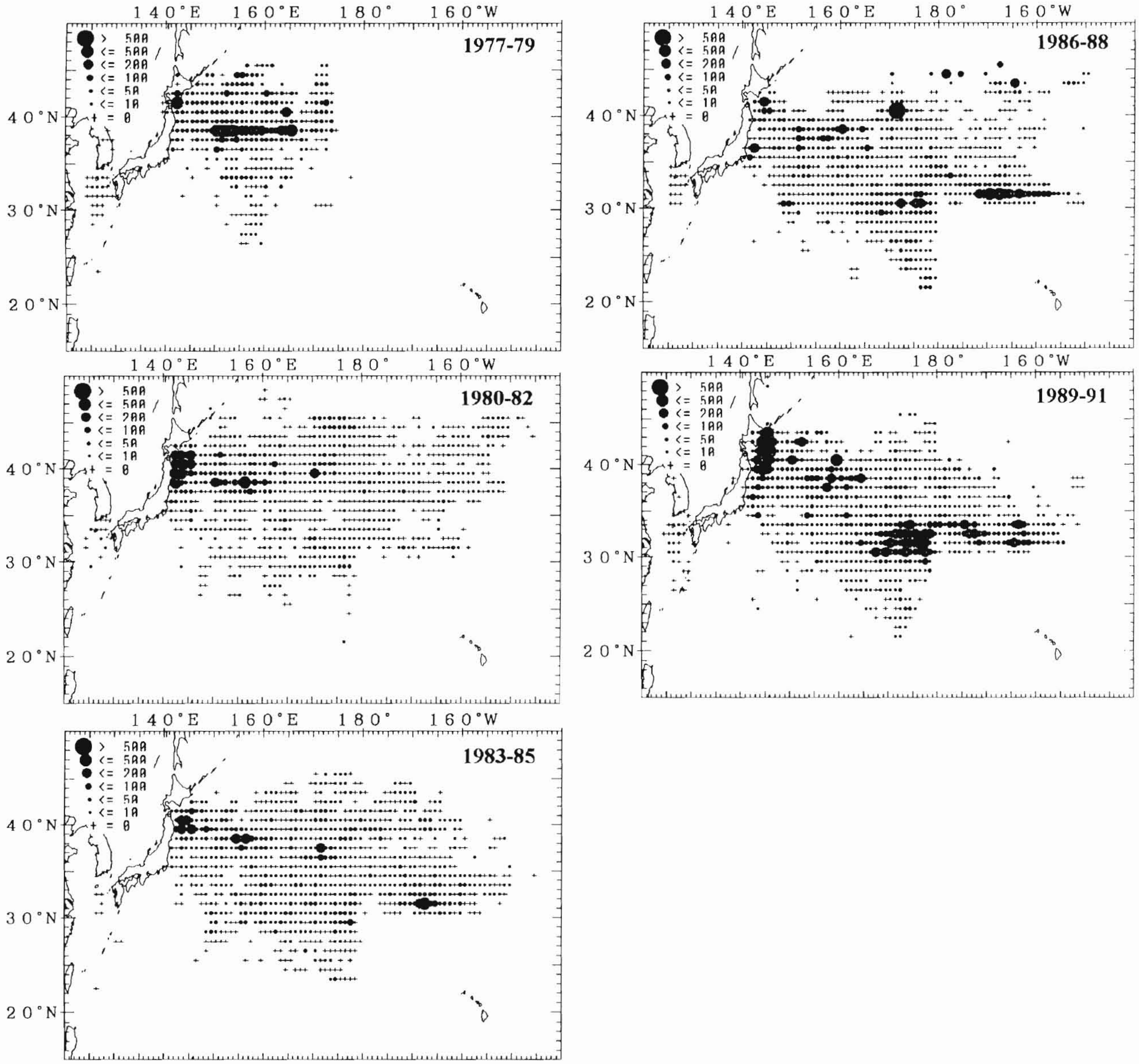


Figure 9

Geographical distribution of mean annual swordfish catch (number of fish) in the North Pacific by the Japanese driftnet fishery by 3-yr period, 1977–91.

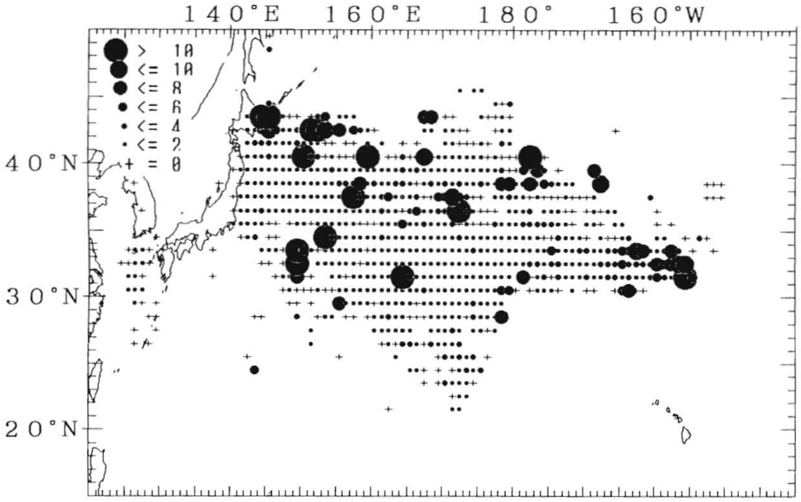


Figure 10

Geographical distribution of mean annual swordfish CPUE (number per 10 km of gear) by the Japanese driftnet fishery during 1989–91 in the North Pacific.

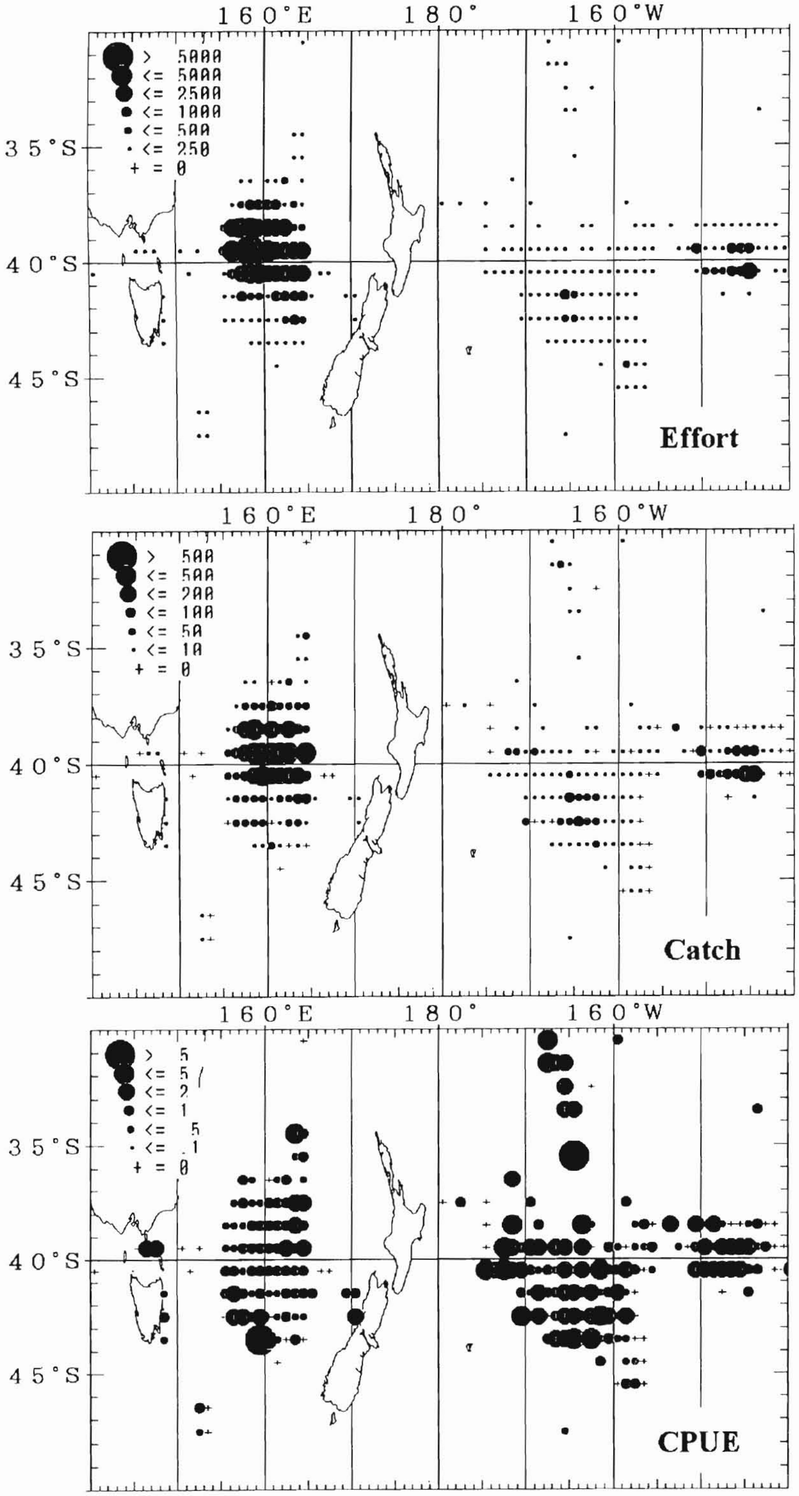


Figure 11
Geographical distribution of accumulated effort (total length of gear in km), catch in number, and mean CPUE (number per 10 km of gear) for Japanese driftnet fishery operations from 1983 to 1990 in the South Pacific.

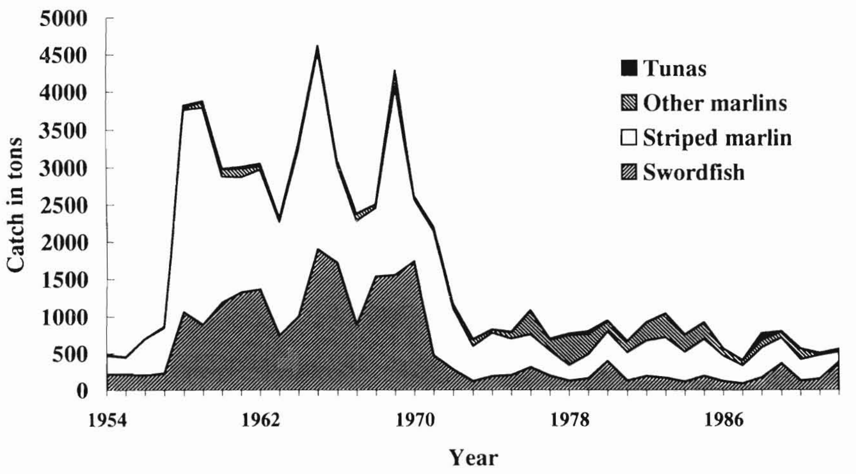


Figure 12
Annual catch by the Japanese harpoon fishery in the Pacific Ocean, 1954–92.

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The California-based Longline Fishery for Swordfish, *Xiphias gladius*, beyond the U.S. Exclusive Economic Zone

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ABSTRACT

Between 1991 and 1994, the number of California-based longliners fishing for swordfish beyond the U.S. Exclusive Economic Zone increased from 3 to 31. Recreational fishing groups raised concerns regarding the impact of the fishery on swordfish, shark, tuna, and marlin stocks. The California Department of Fish and Game established a sampling program to document species composition of longline landings and size composition of the swordfish catch, and collected anecdotal information about fishing methods and bycatch.

In 1991–94, swordfish accounted for 59%–79% by weight of all landings by the fishery. Tunas were 11%–24% of the catch, and the remainder was pelagic sharks, opah, dolphin, and escolar. Sampled swordfish were 6–277 kg dressed weight (13–611 lb). Fish <50 kg (<110 lb) accounted for nearly 48% by number, those >100 kg (>220 lb) only about 17%. Bycatch included striped marlin, turtles, birds, and marine mammals, although there are no estimates of take.

The State of California is the current management authority for this fishery; regulations comprise requirements for commercial fishing licenses, provisions governing prohibited species (striped marlin), and logbook reporting requirements similar to those for the Hawaii-based high-seas longline fishery. Discussions among the Fishery Management Councils for the Pacific, North Pacific, and Western Pacific Regions have not yet resulted in a fishery plan for Pacific swordfish.

Introduction

Swordfish, *Xiphias gladius*, provides a popular seafood which is recognized worldwide. Known for its white meat and mild taste, swordfish is the focus of many commercial fisheries. Approximately 22% of the world supply of swordfish is purchased by consumers in the United States (Sakagawa, 1990). Imports of swordfish into the U.S. have risen from nearly 500,000 lb in 1980 to over 15 million lb in 1989 (Bouchelle et al., 1991). To meet a portion of this market demand, fleets from Japan, Taiwan, and the United States target swordfish and tunas (Scombridae) year-round in the northeastern Pacific.

California-based fishermen have harvested swordfish in nearshore waters since the early part of this century. Hand-held harpoon was the predominant gear type until the late 1970's, when drift gill nets were found to be effective in catching large quantities of swordfish. Until 1979, swordfish landings in California averaged about 200 metric tons (t) annually. Since 1983 California swordfish landings have averaged approximately 1,200 t annually; in 1985 they peaked at 2,400 t (Dewees, 1992).

Recently, a California-based high-seas longline fishery has developed. While these vessels do not fish in local waters, they unload their catch and reprovision in California ports. In 1993 the California Department of Fish and Game (CDFG) began dockside sampling and tracking of longline landings, and began to develop a logbook program. This paper provides a description of the California-based longline fishery, landings, species composition, size composition of landed swordfish, and anecdotal bycatch information. The defacto management scenario is also presented. We do not discuss the health of the Pacific swordfish stock(s) or the implica-

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[1] Now the Marine Region of the CDFG.

tions of catching protected species and slow-growing, low-fecundity sharks, nor do we consider the cumulative effects of multinational exploitation on any of these stocks. These issues are important, complex, and beyond the scope of this paper.

The Fishery

From 1991 until late 1993, only 3 high-seas longline vessels fished in waters beyond the U.S. Exclusive Economic Zone (EEZ) for swordfish and tunas and landed their catch in southern California. In late August 1993, longline vessels from the Gulf of Mexico began arriving in southern California. They quickly established a local infrastructure that supplied fuel, bait, gear, ice, and fish offloading and transportation services. In 1994 a total of 31 vessels landed swordfish and tunas taken beyond the U.S. EEZ.

The California-based longline fleet operates far offshore, precluding small vessels from participating. Vessels are mostly steel hulled and at least 18 m (60 ft) in length. Vessels are of both forward and stern cabin design. Crew sizes range from 5 to 7 depending on vessel size and operating procedures.

Generally, fishing trips are 3 wk in duration, although accidents and breakdowns may cause much shorter trips. Most vessels do not have built-in refrigeration equipment and are thus limited in their time at sea. The fish are iced and are sold as "fresh".

From 1991 through 1994, it was difficult to gather information about longline fishing areas. Because there was no formal reporting requirement, exact locations of sets could not be ascertained. Discussions with captains or their representatives generated only very general geographic information. One vessel captain indicated that he usually fished around latitude 21°N and longitude 121°W, and others reported fishing as far north as 42°N and as far west as 135°W. Comments like "we are fishing in the same area as the Hawaii-based longline fleet" were common. We assumed that the vessels fished beyond the U.S. EEZ wherever they found promising signs of fishing success, within an economically feasible radius of port. Seasonal patterns of landings were unclear due to the short tenure of this fishery in California (Table 1).

Table 1

Landings by California-based longline vessels fishing beyond the U.S. EEZ, by month, 1991–94.

	1991	1992	1993	1994
January	1	2	1	3
February	1	3	1	9
March	0	1	2	19
April	1	1	1	13
May	1	1	0	15
June	0	0	1	17
July	0	2	1	6
August	0	1	4	16
September	1	0	4	5
October	3	0	5	17
November	1	1	6	17
December	3	1	10	17
Total	12	13	36	154

Vessels in the California-based longline fleet target both swordfish and tunas, especially bigeye, *Thunnus obesus*. Typically, vessels fish 24–72 km (15–45 mi) of 600-lb to 1200-lb test monofilament mainline per set. Mainlines are rigged with 22 m (72 ft) swiveled gangions at approximately 61-m (200-ft) intervals, and buoyed every 1.6 km (1 mi). Anywhere from 800 to 1,300 hooks are deployed in a set. Large squid, *Illex* spp., are known to be used for bait; variously colored light sticks are also used. The mainline is deployed in 4–7 hr and left to drift unattached for 7–10 hr. Radio beacons are attached to the gear for recovery. Retrieval requires 7–10 hr. Fishing takes place primarily during the night, when more swordfish are available in surface waters (Carey and Robison, 1981).

Longline-caught fish are sold both to wholesale fish dealers and to an auction house. Local California fisheries, distant offshore fisheries, and imports from Hawaii, Chile, and Taiwan all influence the ex-vessel price of swordfish. Longlined swordfish landed in California averages $8.00 per kg ($3.65 per lb). This compares to nearly $11.00 per kg ($5.00 per lb) for harpooned swordfish, and roughly $6.00 per kg ($2.75 per lb) for gill-netted fish. Swordfish, like most other commercially-landed fishes, are often graded by size and quality, and the price adjusted accordingly.

Landing Data

Information for this paper was derived from two sources: the CDFG Marine Fisheries Statistical System,[2] which compiles data from landing receipts, and dockside sampling. Data from the landing receipt system include date of landing; vessel, captain, and dealer identification; port of landing; gear type; fishing area; species; pounds; and price paid.

Swordfish landings in California (from all gear types) have fluctuated between 500 t and 2,400 t since 1980 (Fig. 1). Landings of longline-caught swordfish ranged from 28 t (61,000 lb) in 1991 to 497 t (1,095,000 lb) in

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[2] Marine Fisheries Statistical Unit, California Department of Fish and Game. 330 Golden Shore, Ste. 50, Long Beach, CA. Unpublished data.

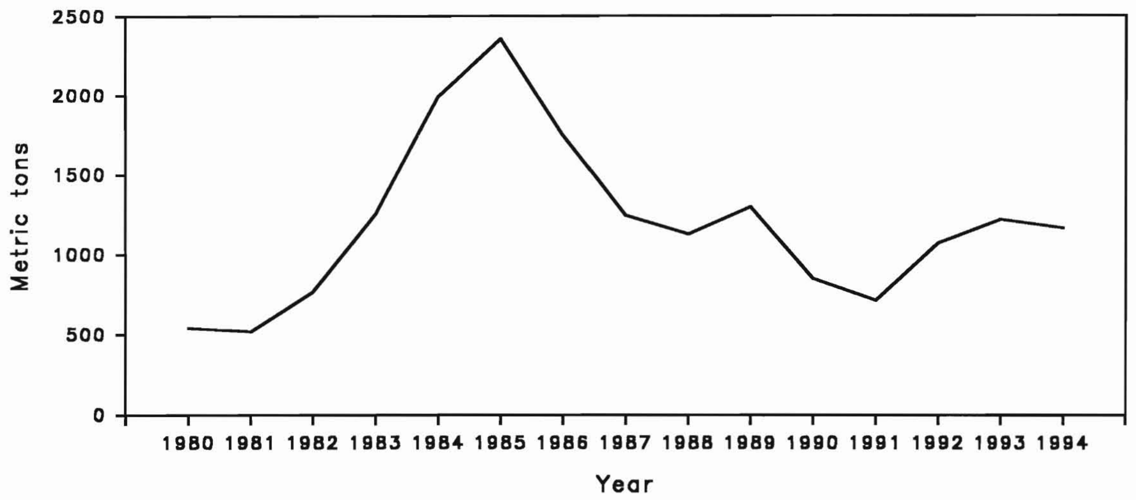

Figure 1
California swordfish landings in metric tons by all gear types, 1980–94.

1994 (Table 2). During 1991–93, longline swordfish landings grew from 4% to 8% of total swordfish landings. In 1994, longline landings were more than 5 times those in 1993, and accounted for 43% of California swordfish landings. Until recently, and since 1982, the drift gillnet fishery produced more than 90% of California swordfish landings.[2]

Species composition of longline landings was determined from landing receipt data. Swordfish were 59%–79% of landings by weight, 4 species of tunas contributed 11%–24%, and sharks represented 3%–11% (Table 3). Other marketable bycatch included opah, *Lampris regius*, dolphin, *Coryphaena hippurus*, and escolar, *Lepidocybium flavobrunneum*. Relatively few sharks (in proportion to those caught) have been marketed from this fishery. The major shark bycatch is blue shark, *Prionace glauca*, which has not been successfully marketed in the U.S., although in 1994 one large landing was purchased by a dealer on speculation.

Sampling Data

Data collected dockside included date of landing, vessel name and number, species, and individual weight and/or length. Choosing which swordfish to weigh and/or measure was done using a random number table to avoid biasing the sample, because fish were often packed in the hold by size. Length measurements (mm) of dressed fish were made with calipers from the middle of the cleithrum to the fork in the tail (CF). Individual weights (lb) were obtained as fish were offloaded and recorded for the landing receipt.

Table 2
Landings in metric tons by California-based longline vessels fishing beyond the U.S. EEZ, 1991–94.

	1991	1992	1993	1994
Swordfish	27.5	28.8	101.3	496.7
Bigeye tuna	4.0	4.7	27.0	31.5
Albacore	0.5	<0.1	2.6	20.3
Bluefin tuna	0.1	0.5	3.5	5.1
Yellowfin tuna	0.1	0.0	6.3	4.0
Unspecified tuna	0.3	0.4	0.8	4.3
Mako shark	0.9	3.6	6.3	13.3
Thresher shark	0.1	0.6	1.4	12.8
Blue shark	0.0	0.0	0.0	7.5
Unspecified shark	0.0	0.0	0.7	1.4
Dolphin	<0.1	0.7	16.1	27.6
Opah	0.8	0.5	3.9	7.3
Escolar	0.4	0.4	1.7	4.3
Total	34.7	40.2	171.6	636.1

From January 1991 through December 1994, a total of 215 landings was made by California-based longline vessels fishing outside the U.S. EEZ. Sampling coverage ranged from 8% to 50% (Table 4).

Nearly 1,500 CF length and 2,100 weight (dressed) measurements were made of longline-caught swordfish. Swordfish length ranged from 73 to 226 cm and weight from 6 kg (13 lb) to 277 kg (611 lb) (Fig. 2, 3). The mean length and weight were 136 cm and 63 kg (139 lb), respectively. Approximately 13% of the landed fish were smaller than 25 kg (55 lb), 35% were between 25 and 50 kg (110 lb), and 17% were heavier than 100

Table 3

Species composition (percentage by weight) of landings by California-based longline vessels fishing beyond the U.S. EEZ. Columns may not sum to 100% due to rounding.

	1991	1992	1993	1994
Swordfish	79	72	59	78
Bigeye tuna	12	12	16	5
Albacore	1	<1	2	3
Bluefin tuna	<1	1	2	1
Yellowfin tuna	<1	0	4	1
Unspecified tuna	1	1	<1	1
Mako shark	3	9	4	2
Thresher shark	<1	2	1	2
Blue shark	0	0	0	1
Unspecified shark	0	0	<1	<1
Dolphin	<1	2	9	4
Opah	2	1	2	1
Escolar	1	1	1	1

Table 4

CDFG sampling of California-based longline vessels fishing beyond the U.S. EEZ.

	1991	1992	1993	1994
Boats	3	2	8	31
Landings	12	13	36	153
Landings sampled	1	6	18	41
Sampling coverage	8%	46%	50%	27%

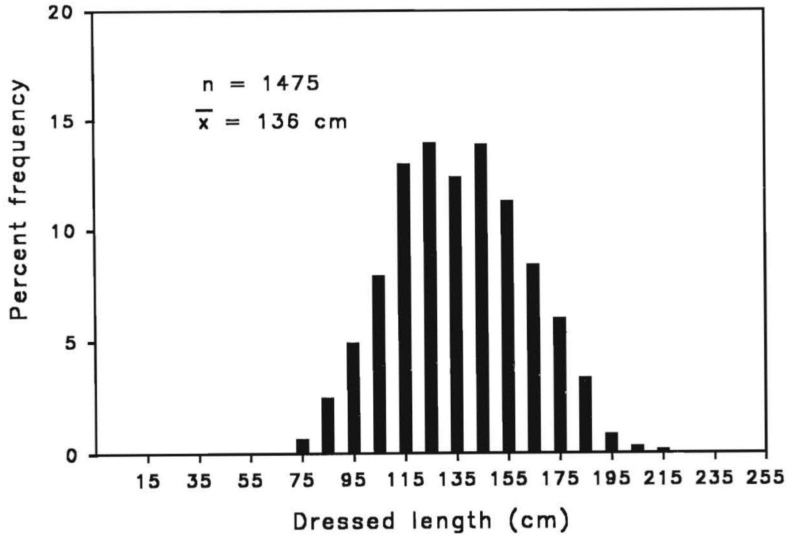

Figure 2

Length (cleithrum to fork) frequencies of swordfish sampled from the California-based longline fleet during 1991–94.

kg (220 lb). The relation between weight (lb) and length (mm) developed from those fish for which both measurements were obtained is

$$\text{Dressed weight} = 0.00000013415 \times \text{CF}^{2.87896}.$$

Bycatch

No observer program existed for the California-based longline fishery, and bycatch was not documented. However, captains and crew members reported to samplers that they caught unmarketable species, and we have seen a home videotape showing striped marlin, *Tetrapturus audax*, bird, marine mammal, and turtle bycatch.

Management

The rapid growth of this fishery captured the attention of local recreational fishing interests. They voiced concern that the longliners would increase fishing pressure on stocks of swordfish, tunas, and sharks. They were also concerned about the bycatch of striped marlin (a billfish species prohibited from commercial sale in California), birds, marine mammals, and turtles. The recreational fishing groups claimed that the west coast high-seas longline fishery would result in the same declines in swordfish, tunas, and sharks as on the Atlantic and Gulf coasts. They demanded that the Federal or State government "do something" about the increased longline fleet in California.

California commercial fishing law presently governs the California swordfish fishery. Drift longline gear is not provided for and is therefore illegal in California waters. Because the Pacific Fishery Management Council (PFMC) has not developed a Fishery Management Plan (FMP) for large pelagic species (i.e. swordfish and striped marlin) for the west coast, California fisheries jurisdiction extends beyond State waters. Thus all California gear, season, size limit, and bag limit laws apply to waters within 200 mi of the coast. If, or when, an FMP is developed for large pelagic species within the PFMC's jurisdiction, that plan would preempt California law.

Another high-seas longline fishery for pelagic species, including swordfish and tunas, is based in the Hawaiian Islands and takes place both within and beyond the Hawaiian EEZ. The Western Pacific Regional Fishery Management Council (WPRFMC) has developed an FMP for large pelagic species and has authorized a limited-entry longline fishery with a vessel cap in the Hawaiian EEZ. This prohibits non-permitted domestic vessels from fishing within the EEZ and landing fish in Hawaii. All fishing for large pelagic species by foreign vessels is prohibited in the EEZ of the Western Pacific Region.

The WPRFMC in 1994 asked the PFMC and the North Pacific Fishery Management Council (NPFMC) if it may act as lead council for the management of large pelagic species (swordfish and other billfishes) and serve as the primary repository of data for the west coast high-seas longline fleet (WPRFMC[3]). The WPRFMC feels that the swordfish stock is one of the most important components of their region's longline fishery and that they need data from all fishery sectors to effect responsible management. On the other hand, the PFMC has been petitioned by several Pacific fishermen's organizations and a fish marketing group to keep management within its own jurisdiction. The councils have not reached a decision, but are preparing a workshop on the issue for March 1995.

Although California does not allow longlining within the EEZ, it does allow longlined fish to be landed. The state requires all boats, and fishermen who land fish, to be properly licensed. In addition, striped marlin cannot be landed; that species has been set aside as a recreational-only species since the mid-1930's. In late 1994, the State of California Fish and Game Commission enacted regulations requiring all vessels participating in the high-seas longline fishery, and landing their fish in California, to fill out daily fishing logs.

Recreational fishing interests have openly expressed concerns about the longline fishery to CDFG, PFMC, and the media (Tefft, 1994). They sought legislation in 1994 to limit the number of vessels, establish a permit fee, institute an observer program, and require vessels to carry transponders (vessel-position indicators). Although they were unable to get a bill introduced during the 1994 legislative session, they are actively seeking similar legislation for 1995.

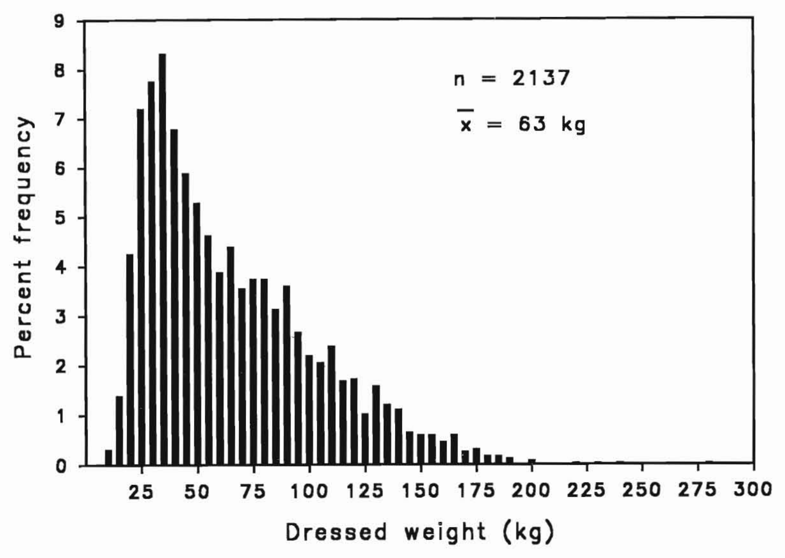

Figure 3

Weight (dressed) frequencies of swordfish sampled from the California-based longline fleet during 1991–94.

The CDFG is continuing to sample landed catch and to monitor developments within the fishery. Landings data and fleet dynamics information is being forwarded to the PFMC. Logbook implementation is scheduled for the summer of 1995.

Update—One Year Later

Many of the vessels from the Gulf and Florida coasts that were based in California during 1994 have left. During most of 1995 only 4–6 vessels fished for more than one trip from a California port, although 22 vessels did make at least one longline landing. During the latter portion of the year, five vessels from the Hawaiian fleet began operations in California. They decided to temporarily base their fishing operations in California because of the higher price realized from the sale of their fish.

Representatives from the WPRFMC and the PFMC met a number of times concerning an FMP for Pacific swordfish. At a final meeting in October 1995 the PFMC decided they could not support the WPRFMC's bid for lead council or primary data repository. The PFMC did commit to improved data collection, and fully supported international management of this highly migratory species. However, they refrained from committing to a swordfish management plan for the U.S. west coast or any additional management measures. The NPFMC initially supported WPRFMC's bid as lead council, but has since reconsidered and hasn't yet determined which management approach it will support.

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[3] Western Pacific Regional Fishery Management Council (WPRFMC). 1994. Management of U.S. Pacific fisheries: single council designation. Concept paper dated 22 September 1994, presented to the Pac. Fish. Manage. Counc. and North Pac. Fish. Manage. Counc. WPRFMC, 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

Recreational fishing interests were again unsuccessful in 1995 in getting a bill through the California legislature to control the longline fleet. They are still committed to being fully involved in the management process for swordfish.

The logbook required by the state of California was developed along the lines of the one used by the NMFS in the Hawaiian fishery. Logbooks were distributed to participants of the California-based fishery beginning in August 1995. Data on fishing locations, fishing effort and catch, and bycatch will now be available through the logbook program. No observer program has been mandated.

The California-based longline swordfish fishery remains dynamic, and we anticipate more movement of vessels in and out of the area due to changing availability of this highly migratory species and the search for new fishing grounds, reasonable port costs, and lower transshipment costs.

Acknowledgments

We thank Bill Craighead and Ken Trinh of Hi-Seas Fish Company for their cooperativeness and generous details of the fishery and markets, Bruce Mournier and Bill Irwin for their video documentation of the longlining process, and the vessel captains and crews who shared their fishing information. We also thank the many reviewers who took the time to give us constructive feedback.

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Review of Swordfish, *Xiphias gladius*, Catch in the Western Pacific Ocean

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ABSTRACT

Swordfish in the western Pacific Ocean are taken almost entirely as incidental catch by longline vessels in the tuna fishery, which is the largest anywhere in the world. Rare catches have also been reported by pole-and-line and purse-seine vessels; and there is growing interest in targeting on swordfish. This paper presents what is known of swordfish catch in the western Pacific tuna fisheries, based on data submitted to the Oceanic Fisheries Programme.

Introduction

The western Pacific Ocean (WPO) currently supports the largest industrial tuna fishery in the world; catch in the statistical area of the Secretariat of the Pacific Community (SPC; formerly the South Pacific Commission[1]) was estimated at 931,685 metric tons (t) in 1993 (Lawson[2]). Skipjack is the most important of the four major tuna species in the fishery, accounting for 59% of the 1993 catch by weight, followed by yellowfin (31%), bigeye (4%), and albacore (4%). Purse seine gear was responsible for 79% of the total catch, pole-and-line gear for 7%, longline gear 13%, and troll gear 1%.

Rare catches of swordfish have been reported by pole-and-line and purse-seine vessels. However, by far the majority of swordfish taken in the western Pacific Ocean has been incidental catch by longline vessels. The development of the Hawaiian longline fishery into a primarily targeted swordfish fishery during the past 6 yr has been well documented; this fishery has provided useful information to the developing fisheries targeted on swordfish in the SPC statistical area. There has been growing interest in targeting swordfish by longline vessels operating in the waters of Australia, New Caledonia, New Zealand and, more recently, Fiji, although this effort is very minor in comparison to overall longline effort in the region.

This paper presents what is currently known of swordfish catch in the western Pacific tuna fisheries, based on data submitted to the Oceanic Fisheries Programme of the SPC. For convenience, this paper subdivides the SPC statistical area, mainly due to the various fisheries involved, into the western tropical Pacific (10°N–10°S), the western subtropical Pacific (10°S–35°S, and the area to the north of 15°N), and the western temperate Pacific (35°–45°S) (Fig. 1). Few data have been received for the northernmost portion of the western subtropical area, which is therefore not discussed in this paper.

Western Pacific Longline Fisheries

Two types of longline vessels fish in the WPO. Large distant-water vessels (typically >100 gross metric tons) from Japan, Korea, and Taiwan are capable of fishing far from their home ports, with usual trips of >1 mo, and up to 1 yr for vessels that use at-sea transshipment. Other, smaller vessels, used specifically for shorter fishing trips, are based near their fishing areas, and make trips from a few days to 2 wk in duration. These smaller vessels have established home ports in SPC member countries and territories. They typically use ice and supply fresh, chilled fish to sashimi markets, as opposed

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[1] Renamed Secretariat of the Pacific Community in 1998.

[2] Lawson, T. 1994. South Pacific Commission tuna fishery yearbook. Oceanic Fisheries Programme, S. Pac. Comm. Available from Secretariat of the Pacific Community, B.P. D5, Noumea, New Caledonia.

to the larger distant-water vessels, which utilize on-board freezers to supply frozen fish to normally lower-priced markets. The general decline in the past 5–10 yr in the number of large distant-water vessels, and the increase in activities involving smaller vessels based in SPC member countries, are attributed primarily to efforts to capitalize on higher sashimi prices for fresh, chilled fish and to related improvements in airfreight availability.

Longline activity in the western temperate Pacific is seasonal and occurs primarily in waters off southeastern Australia and around New Zealand (Fig. 2), where southern bluefin tuna, *Thunnus maccoyii*, and yellowfin tuna, *T. albacares*, are the prime target species. Seasonality in the subtropical fisheries is less pronounced; fishing occurs off the east coast of Australia as an extension of activities in the western temperate area, in the northern waters of New Zealand, New Caledonia, Fiji, Tonga, Cook Islands, French Polynesia, and Vanuatu, and in the international waters bordering these areas. The prime target species in subtropical waters are yellowfin tuna, albacore, *T. alalunga*, and bigeye tuna, *T. obesus*. The tropical area contains the majority of western Pacific longline activity; the target species are almost exclusively bigeye and yellowfin tuna. One of the most significant developments among western Pacific longliners during the past 15 yr is the trend to set gear deeper in order to target bigeye tuna, which demand a higher price than yellowfin on the sashimi market.

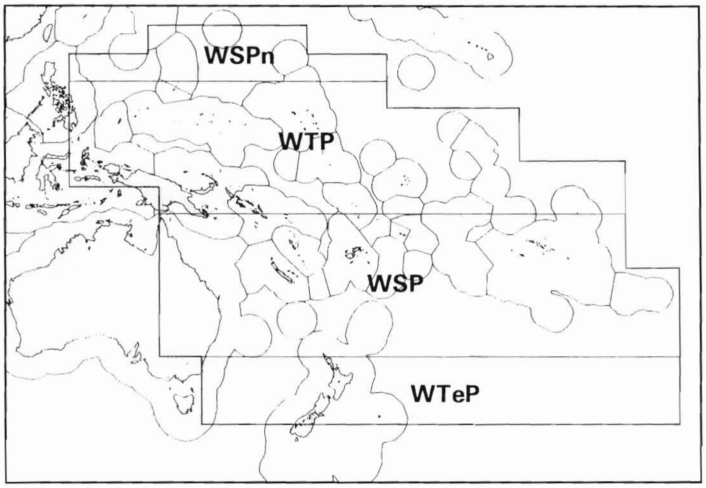

Figure 1
The SPC statistical area, showing the western tropical Pacific (WTP), western subtropical Pacific (WSP and WSPn), and western temperate Pacific (WTeP) subdivisions used in this paper, and 200-mi economic zones of SPC member countries.

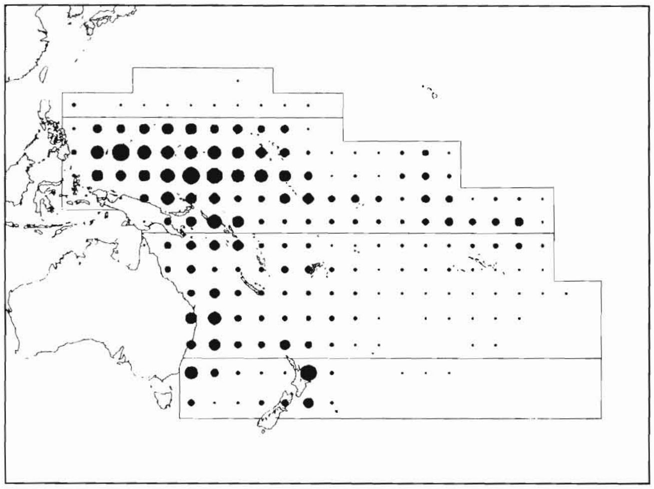

Figure 2
Spatial distribution of fishing days reported on logsheets for longline vessels in the western Pacific, 1978–92.

Data Collection

One of the prime responsibilities of the Oceanic Fisheries Programme (OFP) of the SPC is the maintenance of the Regional Tuna Fisheries Database (RTFD). The source of data in the RTFD is primarily daily catch logsheets from domestic and foreign vessels fishing in the Economic Zones (EZ) of SPC member countries. The coverage of logbook data held in the RTFD is dependent on fleet and area, and is therefore poor in some instances. Lawson[1] provides some indication of logbook data coverage.

As the prime aim of the RTFD is to gather data on catches of tuna species that are commercially important to the longline fishery, quite often data on bycatch (e.g. swordfish) has been lacking. One significant difference between the two types of longline vessel is the amount of discarded bycatch (e.g. swordfish), which is not expected to occur on the distant-water vessels, which normally have adequate freezer storage for most of their catch. The difficulty in monitoring the levels of swordfish discard via logsheets has meant that some reliance must be placed on data collected by observers, although observer data coverage is insufficient at this stage.

Table 1

Annual incidental swordfish catch and nominal CPUE (number per 1,000 hooks) from longline vessels operating in the western Pacific Ocean, 1978–94, from logbook data held in the RTFD.

	Areas of the western Pacific									
	Tropical			Subtropical			Temperate			All areas
Year	Catch (no.)	% of total catch	CPUE	Catch (no.)	% of total catch	CPUE	Catch (no.)	% of total catch	CPUE	Catch (no.)
1978	30	0.18	0.05	2	0.23	0.10	0	0.00	0.00	32
1979	668	0.10	0.02	1,095	3.01	0.55	0	0.00	0.00	1,763
1980	2,223	0.18	0.05	6,838	4.14	0.98	5,822	2.69	0.30	14,883
1981	3,123	0.26	0.05	18,422	3.40	0.78	6,469	2.73	0.28	28,014
1982	6,862	0.53	0.11	25,849	5.46	1.14	7,214	3.48	0.39	39,925
1983	3,312	0.31	0.08	14,035	2.72	0.83	4,226	2.33	0.29	21,573
1984	7,380	0.61	0.11	15,571	2.85	0.68	3,974	2.45	0.48	26,925
1985	10,466	0.79	0.14	20,049	2.75	0.82	4,056	3.44	0.67	34,571
1986	4,926	0.69	0.12	20,179	3.81	0.96	5,276	3.84	0.81	30,381
1987	5,986	0.79	0.12	21,296	3.66	1.06	4,979	3.25	0.65	32,261
1988	7,197	0.86	0.14	28,098	3.11	0.87	4,827	2.71	0.61	40,122
1989	8,399	0.78	0.12	18,333	3.07	0.73	7,498	2.53	0.55	34,230
1990	7,587	0.73	0.10	14,047	2.18	0.58	4,497	2.66	0.46	26,131
1991	5,103	0.62	0.09	12,815	2.99	0.78	5,115	3.47	0.42	23,033
1992	7,049	0.66	0.11	13,804	3.32	0.91	6,426	4.71	0.57	27,279
1993[1]	14,696	1.76	0.20	6,865	1.03	0.36	2,463	2.37	0.43	24,024
1994[1]	8,296	2.36	0.28	387	0.95	0.28	80	3.32	0.48	8,763

[1] Data incomplete.

The absence of specific questions (e.g. the use of light sticks) on logsheets has also made it impossible to determine if some primary or secondary targeting of swordfish occurs in western Pacific Ocean longline fisheries. Further, it is possible that specific fishing strategies have indirectly increased the catch of swordfish (e.g. shallow-set targeting of bigeye near the full moon), but the lack of information on logsheets has meant that such practices can not be quantified. The above-mentioned problems should be taken into account in considering the information presented in this paper.

Observer programs that have operated out of Australia (since 1979) and New Zealand (since 1986) provide some indication of the level of swordfish catch and discard in the western temperate Pacific. In the tropial waters of the western Pacific, the observer program of the Micronesian Maritime Authority of the Federated States of Micronesia currently provides the only monitoring of longline activity in an area with considerably more effort. Unfortunately, relevant data from observer programs have yet to be provided and/or compiled, so they receive limited mention in this paper.

Swordfish size-composition data have been collected from port sampling operations established in SPC member countries since 1992. Length and weight measurements of dressed swordfish have been collected from longline vessels unloading in the ports of the Federated States of Micronesia and Marshall Islands. The majority of swordfish landed at these ports have been measured from the anterior base of the pectoral fin to the caudal fork; unfortunately, there is no conversion factor available for equating these dressed weights with whole weights of swordfish taken by small-scale longline operations in the same area. In contrast, swordfish catch reported on the logsheets of distant-water vessels operating in temperate waters of the western Pacific, tends to be given as filleted rather than trunk weight; in this case, a coarse raising factor has been employed to account for this.

Swordfish Catch

Incidental Longline Catch

Table 1 shows annual swordfish catch, percentage of total catch, and CPUE for longline vessels operating in the SPC statistical area, based on logsheet data held in the RTFD, which is incomplete (for example, it excludes some fishing in international waters). Table 2 provides estimates of total swordfish longline catch in the western Pacific based on all data available, including aggregated data provided by the distant-water fishing nations of Japan (since 1962), Korea (since 1975), and Taiwan (since 1967) that have not been included in this paper. Swordfish catch data contained in the data set from Japan have already been described elsewhere (e.g. Sosa-Nishizaki and Shimizu, 1991).

The subtropical area of the western Pacific produces the highest catch rates and catch volume (Fig. 3, 4). Since the early 1980's, annual CPUE for the western subtropical Pacific has fluctuated between 3 and 11 fish per 10,000 hooks (Fig. 4; the apparent drop in swordfish CPUE and catch for 1993 and 1994 for the subtropical area is attributed to catch data for those years not having been submitted at the time of compilation). Peaks in CPUE in the subtropical and temperate areas correspond with ENSO (El Niño–Southern Oscillation) events in 1982–83, 1986–87, and 1991–92.

Table 2

Estimates of swordfish catch from longline vessels fishing in the western Pacific for 1989–92. The estimation procedure is given in Bailey et al. (1996).

	Catch	
Year	Number	Weight (metric tons)
1989	57,190	3,043
1990	82,235	4,364
1991	52,568	2,712
1992	59,270	3,213

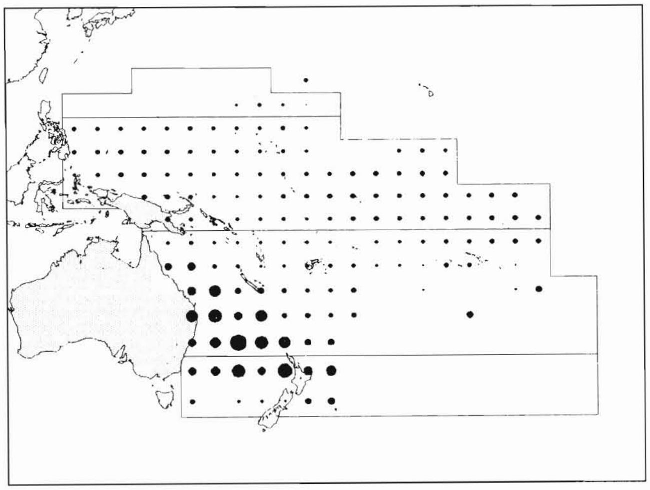

Figure 3

Distribution of nominal CPUE for swordfish taken by longline vessels in the western Pacific, 1978–92.

Catch rates for the western tropical Pacific have steadily increased during the last 10–15 yr (Fig. 4); this has coincided with a tendency for longline vessels to set their gear deeper in order to increase the catch of bigeye tuna. The marked increase in swordfish CPUE in this area during 1993 and 1994 is believed to result from 1) better reporting on logsheets by longline vessels as a result of increased observer and port sampling activities; 2) the increase in number of smaller longline vessels operating out of ports of SPC member countries; and 3) (related to 2) fishing methods that have indirectly led to increased swordfish bycatch. Unfortunately, not enough information is currently available to quantify these effects.

There is a strong seasonal pattern in the western subtropical and temperate areas, with higher swordfish catch rates during the austral winter and spring (Fig. 5). Sosa-Nishizaki and Shimizu (1991) describe seasonal trends in swordfish catch rates in other areas of the Pacific; similarities between the temperate waters of the northwest Pacific and the southwest Pacific can be expected. Analysis of Japanese longline CPUE in the Pacific Ocean using the Generalized Linear Model (GLM) method shows similar, clear seasonal changes in CPUE in the temperate areas of both hemispheres (Nakano, 1994). In contrast, there is no apparent seasonality in swordfish catch rates in the western tropical Pacific (Fig. 5).

Observer data made available to the Oceanic Fisheries Programme indicate that swordfish are rarely discarded on distant-water vessels and they appear to be the most resilient of the billfish species (Bailey et al., 1996).

Targeted Longline Catch

There has been some limited targeting of swordfish in the waters of Australia and New Zealand. In Australia, feasibility trials utilizing chemical light sticks have been successful. However, the marketing of swordfish in Australia is currently restricted by regulations prohibiting the sale of this species if it contains more than 0.5 ppm mercury.

Limited trials in targeting swordfish with longline gear have recently been conducted in American Samoa and New Caledonia. Promising catches were taken during the New Caledonia trials and a market study is currently being undertaken.

In late August 1994, some vessels that had targeted swordfish in the Hawaiian longline fishery commenced exploratory fishing in southern Fiji waters centered on 20°S. Nine vessels were operating at the end of November 1994, with average swordfish catch rates of 7 fish per 1,000 hooks during the first months of operation, plus large

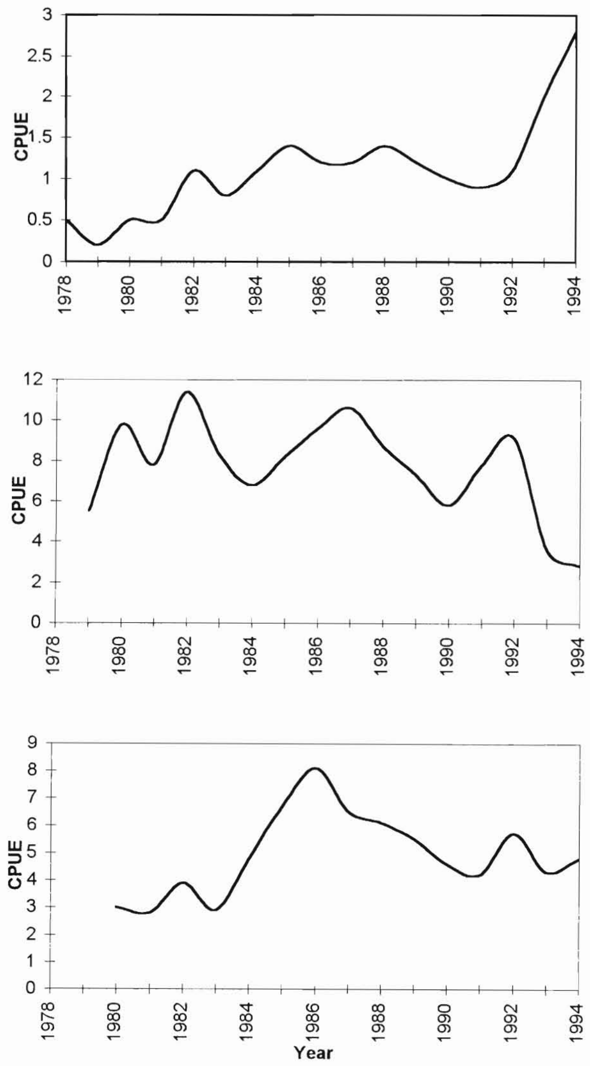

Figure 4

Annual swordfish CPUE (numbers per 10,000 hooks) for longline vessels in the tropical (top), subtropical (middle), and temperate (bottom) areas of the western Pacific, 1978–94. Source: RTFD.

incidental catches of dolphin (mahimahi) and other species. It is reported that up to 20 vessels may eventually operate in this fishery, and the potential for the development of a targeted swordfish fishery appears good.

Incidental Swordfish Catch from Other Tuna Fisheries

There has been only one report of swordfish catch by pole-and-line fishing to date. Approximately 0.1 t of swordfish were taken (presumably from one school) by a Japanese pole-and-line vessel in Kiribati waters in November 1990. The reported average weight of 2 kg is consistent with information on the expected spawning period (March–July) in the central Pacific Ocean, and with observations on the period between spawning and the appearance of juvenile swordfish in other fisheries (Nakamura, 1985).

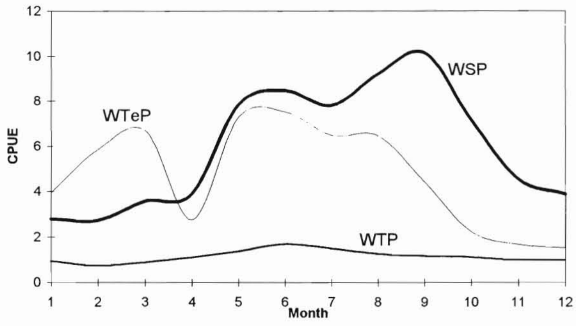

Figure 5

Seasonal swordfish CPUE (numbers per 10,000 hooks) in the longline fisheries of the tropical (WTP), subtropical (WSP), and temperate (WTeP) areas of the western Pacific Ocean, 1978–94. Source: RTFD.

A few swordfish have also been taken as bycatch in the now-defunct New Zealand purse seine skipjack fishery (Bailey et al., 1996).

Size Composition

Swordfish taken by longline vessels in tropical waters appear to have a narrower range of weights than those taken in more temperate waters (Fig. 6). Most of the dressed catch that has been sampled in the western tropical Pacific falls in the range 30–50 kg (95–125 cm pectoral fin–fork length).

Unfortunately, no data are currently available to determine whether discarding practices in the tropical area may account for the absence of smaller swordfish seen in port sampling there (Fig. 7). It is known that processing procedures are different between areas and between fleets, but it will not be possible to accurately compare size composition data from different sources until further information on the various processing procedures employed has been gathered and conversion factors for relating dressed to whole weight can be calculated. Figure 8 shows the length–weight relationship of swordfish caught in tropical waters and measured during port sampling.

Conclusions

Swordfish are an important bycatch of the western Pacific longline tuna fisheries. Logsheet programs, port sampling, and observer data provide some relevant information, and this paper provides some insight into the distribution of swordfish catch by longline vessels throughout the SPC statistical area. However, it should be noted that no attempt was made to determine standardised CPUE, and caution is advised in inferring indices of abundance.

There appears to be some potential for targeted swordfish fisheries in areas of the western Pacific (e.g. Fiji), although it appears certain that marketing logistics will be the driving force in any such implementation.

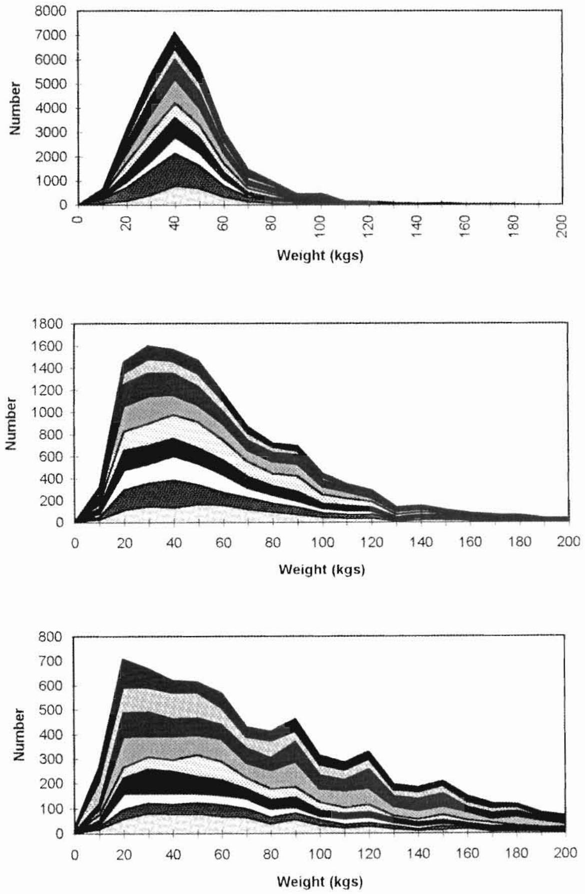

Figure 6

Weight composition of swordfish catches in the tropical (top), subtropical (middle), and temperate (bottom) areas of the western Pacific for 1984 (lowest curve) through 1992 (highest curve). Source: RTFD logsheet data for days where only 1 swordfish was recorded on a logsheet. Weights have been rounded to nearest 10 kg and no allowance has been made for weight loss due to processing.

The OFP is about to undertake a 5-yr project, funded by the European Union, referred to as the South Pacific Regional Tuna Resource Assessment and Monitoring Project (SPRTRAMP). The prime aims of this project will be to establish a regional scientific observer data collection program, and to provide assistance in further development of port sampling activities throughout the region. The project should increase our knowledge of swordfish in the western Pacific Ocean by providing

- Standardized length and weight data from port sampling operations.
- Observer-collected information on longline targeting practices, swordfish length, weight, and biology, and levels of swordfish discard.

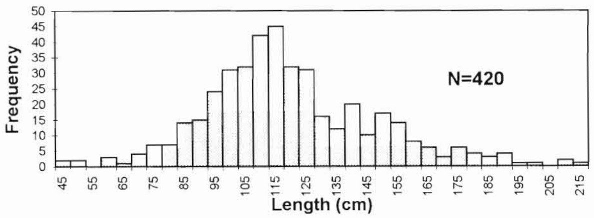

Figure 7

Length frequency distribution of swordfish taken in longline fisheries of the western tropical Pacific, 1992–94, from sampling in ports of SPC member countries. Length measured from anterior base of pectoral fin to caudal fork.

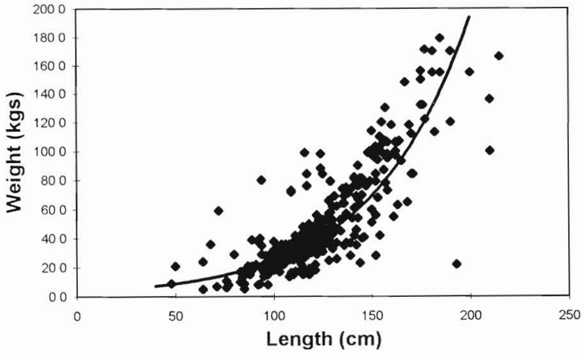

Figure 8

Length–weight relationship for swordfish taken in longline fisheries of the western tropical Pacific, 1992–94. Length measured from anterior base of pectoral fin to caudal fork. Source: size composition data collected in ports of SPC member countries.

- An improved longline logsheet form for better collection of data on targeting practices.

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Distribution and Stock Assessment of Swordfish, *Xiphias gladius*, in the Eastern Pacific Ocean from Catch and Effort Data Standardized on Biological and Environmental Parameters

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ABSTRACT

Catch and effort data for swordfish, *Xiphias gladius*, caught in the eastern Pacific Ocean (EPO) by longline fisheries in 1971–92 were standardized using a new model that incorporates biological and environmental data. Distributions of relative abundance by 2° latitude × 5° longitude areas and bimonthly periods as well as relative annual abundances (1962–92) for the entire EPO are presented. Stock structure of swordfish in the EPO was examined on the basis of biological, standardized catch rate (CPUSE), and genetic data. Results support existence of a stock with distribution centered in the southern EPO. Whether there exists a stock centered in the northern EPO is unclear. Reproductive activity was identified in the north central EPO and in the vicinity of Baja California, Mexico. Length-frequency distributions and CPUSE indicate significant migration of swordfish in the northern EPO. Thus, though there may be a stock centered in the northern EPO, the region is regularly frequented by swordfish moving across the geographical limits of this study. The Deriso-Schnute delay-difference model was used to examine stock-structure hypotheses and to estimate average maximum sustained yield (AMSY) and optimum effort (OE). Model results did not differentiate between an EPO open to or closed to migration, and the estimates of AMSY (<8,400 metric tons) and OE ($<156 \times 10^7$ average hooks) were sensitive to whether there was migration across 150°W. Independent estimates for the southern stock were not possible. Preliminary analyses of recent data indicate that catch rates are continuing to decline, but that they remain above those expected at AMSY. Further examination of stock structure and status should be conducted as more data become available.

Introduction

The first part of this study applies a new general method for standardization of fishing effort (Hinton and Nakano, 1996) to data from longline fisheries capturing swordfish, *Xiphias gladius*, in the eastern Pacific Ocean (EPO). Catch-per-unit-of-effort (CPUE) statistics provide the core knowledge of swordfish distribution and abundance, and the key source of these statistics in the Pacific is the Japanese longline fisheries. Japanese longline CPUE statistics have provided the basis of all major investigations of Pacific swordfish, and this study was no exception. CPUE is particularly valuable to fisheries investigations because it often provides the sole measure of presence and abundance. Nominal CPUE (CPUNE) is proportional to mean abundance if population or fishing effort is homogeneously distributed and if all units of effort are equal and proportional to the rate of fishing, conditions that are seldom achieved (Ricker, 1975).

The use of longline CPUE is problematic. Among the several problems encountered when standardizing longline effort across the broad geographical and temporal scales necessary for study of swordfish relative abundance and distribution patterns are 1) the fishery is directed at tunas (Ueyanagi, 1974; Suzuki, 1989); 2) small portions of the fishery were historically directed at swordfish (Kume and Joseph, 1969); 3) Japanese logbook records do not indicate target species (Squire and Suzuki, 1990); and 4) there have been significant changes in longline gear design and fishing configuration, in particular the advent of deep-longline gear, that make it necessary to standardize longline effort on a species-specific basis (see e.g. Suzuki et al., 1977;

Suzuki, 1989). Shomura (1980) noted that for longline gear, the underlying assumption that catch rate is proportional to average stock abundance is sensitive to "changes in the construction or deployment of [the] gear, shifts in fishing strategy or target species, and changes in [vulnerability] of the fish to the gear. . . ."

The underlying condition that results in violation of the assumption that longline CPUNE is proportional to average stock abundance is that longline gear is deployed across environmental conditions that limit the distribution of species caught by the gear. The fact that such limits exist has long been recognized (Blackburn, 1965; Green, 1967; Hanamoto, 1974; Sharp, 1978; Sund et al., 1981). Geographical and seasonal effects have been incorporated into models to explain variability in CPUE (e.g. Honma, 1974; Allen and Punsly, 1984; Punsly, 1987; Suzuki, 1989; Punsly and Deriso, 1991; Nakano, 1998). However, Punsly and Nakano (1992) noted that in their GLM model (used to standardize longline hook rates for yellowfin and bigeye tuna to estimate annual abundance) the "depth of the fish, resulting from variations in vertical thermal structure (Green, 1967), oxygen level, or food availability could have a greater effect on hook rates than does abundance."

While these problems may appear daunting, information on conditions limiting the distribution of a species, on distribution of limiting conditions in the environment, and on longline gear configuration, when used together, provide the means to surmount most of these problems and form a basis for effort standardization. This study illustrates the general method of Hinton and Nakano (1996) by developing standardized estimates of CPUE and presenting estimates of relative abundances for swordfish in the EPO.

The second part of this study examines the structure and status of swordfish stocks in the EPO by using biological and abundance data and applying a delay-difference model to standardized CPUE data. Published stock assessments of Pacific swordfish have been derived largely from simple production models fitted using equilibrium techniques to catch and effort data from longline fisheries, a procedure known to yield biased and unreliable results (Hilborn and Walters, 1992). Delay-difference models are in the class of biomass dynamic models, which include these simpler stock production models (Hilborn and Walters, 1992), but specifically incorporate process models, which introduce information about growth, recruitment, and survival not explicitly included in the simpler models. The parameters of delay-difference models are readily interpretable in a biologically realistic sense, which is not the case for parameters of the simpler models. Delay-difference models provide this level of interpretation and sophistication without requiring the full details of population age composition required by age-structured models such as virtual population analysis. Thus, delay-difference models represent a compromise between complex fully age-structured models and overly simplistic production models. We refer those interested to Hilborn and Walters (1992), in which each of these model categories and their applications are afforded significant description and review.

Data and Methods

The development of longline fisheries in the EPO has been documented by Joseph et al. (1974). By 1963 most of the region was being fished, and by 1968 virtually the entire area bounded by 40°N and 40°S latitudes was exploited. Suzuki (1989) noted that initially longline gear was configured to fish the upper layers of the ocean using from four to six or seven hooks per basket (HPB), and the primary target species was yellowfin tuna, *Thunnus albacares*. However, since 1974 significant portions of the effort have shifted from shallow to deeper ocean zones to more effectively target the deeper-swimming and more valuable bigeye tuna, *T. obesus* (Suzuki, 1989). Deep longline gear, which has about 8–15 HPB, fishes to maximum depths of about 200–300 m, compared with about 150 m for regular longline gear. This is a significant difference in terms of variability in hydrographic across the depth of the gear and across areas and time.

Catch and Effort Data

Catch and effort data from Japanese and Mexican longline fisheries were used in this study. The Japanese longline fishery catch and effort data were collected by the Japanese government from over 90% of registered Japanese-flag longline vessels fishing in the Pacific. These logbook data were subsequently compiled by the National Research Institute of Far Seas Fisheries, Shimizu, Japan. Formats of available fishery data were 1) total catch and effort estimates for 5° latitude by 5° longitude (5 × 5) strata by month; 2) 5 × 5 catch and effort estimates by month by HPB; and 3) catch and effort estimates for 1° latitude by 1° longitude (1 × 1) strata by month. These data were processed as described in Hinton and Nakano (1996). Note that the HPB data were used to estimate hook fishing depth (Suzuki et al., 1977; Wright, 1980; Gong et al., 1989; Hinton and Nakano, 1996), which was required to estimate vertical distribution of effort and its relationship to the distribution of swordfish in the environment.

Data from Mexican-flag longline vessels were logbook data from 1980–87 collected by the Inter-American Tropical Tuna Commission, which for each set included date and time, position, number of hooks fished, and catch in numbers and/or weight. The data did not include detailed information on HPB, as this was not recorded in the logbooks. Although several of these vessels were fishing under the direction of Korean fishing masters, the majority were under the direction of Japanese fishing masters. We also note that this fishery was previously a Japanese regular longline fishery that targeted marlins (Squire and Muhlia-Melo[1]). Thus the Japanese HPB distributions were used to estimate HPB distribution for the Mexican data. In those area/bimonthly period combinations lacking Japanese data, the regular gear configuration with HPB of 4–7 was assumed (see Hinton and Nakano, 1996). Prior to pooling with the Japanese data, the data from Mexican logbooks were summarized by 2° latitude by 5° longitude (2×5)stratum by bimonthly period (Jan–Feb, . . . , Nov–Dec) by HPB.

Estimates of the total catch of swordfish in the EPO during 1954–87 were obtained from data compiled in Joseph et al.[2] These data were used in fitting the Deriso-Schnute delay-difference model. Final estimates of total catch for more recent years were not available.

Hydrographic Data

Distributions of temperature relative to mixed layer temperature (MLT), expressed as isotherms [MLT – (1°, 2°, . . . , 17°C)] for 2×5 strata by bimonthly period during 1971–87, were developed from temperature-at-depth (TZ) data (White[3]) with depth resolution of (0, 20, . . . , 80, 120, . . . , 240, 300, 400 m), as described in Hinton and Nakano (1996). In cases where TZ data were lacking for a specific area and bimonthly period, the pertinent climatology was used. Finally, of nearly 16,850 observations in the 2×5 by bimonthly period data, in about 700 cases TZ data were not available in the White[3] database. In those cases, isotherm depths were estimated using the 5×5 by quarterly period TZ climatology of Mizuno and Yakinawa (1991). For those bimonthly periods and 2×5 areas that overlapped the quarterly periods, or overlapped the 5×5 areas in the Mizuno and Yakinawa (1991) data, the averages of the TZ data from the overlapping quarterly periods or areas were used to estimate isotherm depths.

Vertical Distribution: Time at Temperature

It was assumed that the vertical distribution of the swordfish population is limited by temperature relative to MLT (Δt). Such constraints are commonplace; for example, Δt limits marlin distribution (Brill et al., 1993), and both temperature and oxygen limit tuna distribution (Brill, 1994). Carey (1990) found that swordfish are able to regulate rates of heating and cooling of muscle tissue so that muscle cools slowly during ventures into colder waters and heats rapidly during recoveries in warmer water. The ability to control muscle temperature is also found in tunas (Brill, 1994) but not in marlins (Block et al., 1992). Swordfish eye and brain temperature are controlled by a heater organ (Carey, 1982; Block, 1990), tissue that is found in all billfishes (Block, 1991). In the case of swordfish, this heater organ is capable of maintaining elevated brain and eye temperatures over long periods in cold water. Thus, while temperature may be expected to limit swordfish distribution, other factors, such as ambient oxygen concentration and behavioral response to light levels (Carey and Robison, 1981), also may be limiting factors.

The vertical distribution of the swordfish population was estimated from plots of fish depth-at-time with overlaid isotherm profiles (Carey and Robison, 1981; Carey, 1990). These data were from five swordfish, four of which were tagged in the northwestern Atlantic (Carey and Robison's fish 7, and Carey's fishes 9, 10, and 11) and one of which was tagged off Baja California, Mexico (Carey and Robison's fish 6). They ranged in size from about 32 to 140 kg.

Japanese longline operations targeting tunas operate the gear during the day (Kume and Joseph, 1969; Ueyanagi, 1974), and the data for the Mexican fishery contained only sets made during daylight hours. The Japanese currently set longline gear at night for swordfish only in areas near Japan (Miyabe[4]). Therefore, only swordfish tracking records for the sunrise-to-sunset period were used.

Following Hinton and Nakano (1996), the data were scanned and digitized, and then pooled to obtain species-specific estimates of time at temperature relative to MLT for $\Delta t = (0, -1°, -2°, \ldots, -17°C)$. The distribution was significantly different from a uniform distribu-

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[3] White, W. 1995. Scripps Institution of Oceanography, La Jolla, CA. Personal commun.

[4] Miyabe, N. 1995. National Institute of Far Seas Fisheries, Shimizu, Japan. Personal commun.

tion ($\chi^2=17$, $p<0.0001$); the percentage of time spent within a 1°C temperature bin ranged from about 1% to 17%. The distribution thus obtained translated directly into a distribution of population in temperature–space (Fig. 1) under the assumption that the sampled fish were representative of the species.

Data not available for inclusion in this initial analysis were obtained in 1986 on a swordfish, estimated to be about 90 kg, tracked off San Clemente Island, California (Holts et al.[5]). During the 24-hr tracking period, it showed a vertical distribution with respect to temperature which was similar to the distributions of the fish for which data are included here.

Maturity

Data collected from 1,079 swordfish sampled aboard Japanese fishing and research operations during 1971–92 were examined. Summaries of the 1971–87 data have been published (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992) and procedures of data collection are detailed therein.

The gonad index (GI; Hinton et al., 1997) was estimated as

$$\mathrm{GI} = \frac{\ln(\text{gonad weight in grams})}{\ln(\text{eye–fork length in centimeters})}.$$

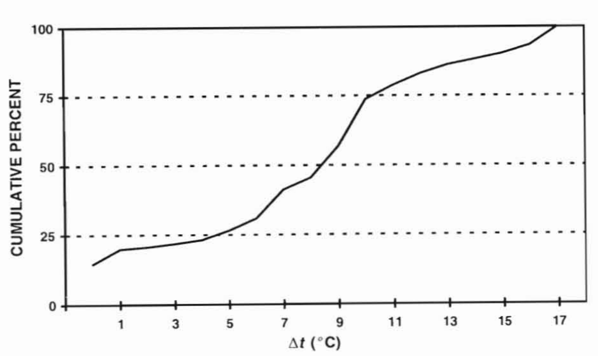

Figure 1

Cumulative percentage of swordfish at temperatures Δt below the temperature of the mixed layer, as determined by acoustic telemetry.

Effort Standardization

Fishing effort was standardized by the method developed in Hinton and Nakano (1996), which utilizes information on the distribution of habitat and on the distribution of a species within that habitat.

Let A = a region (area) of the ocean;
i = index of subregions of A, such that for $i = (1, \ldots, n_i)$, $A(\bullet) = \Sigma A(i)$;
h = depth (m) of the water column in A;
j = index of depth zones, such that for $h(i,j)$ and $j = (1, \ldots, n_j)$, $h(i,\bullet) = \Sigma h(i,j)$;
V = volume, such that $V(i) = A(i) \times h(i)$;
f_n = nominal (unstandardized) fishing effort;
f_e = effective (standardized) fishing effort;
q_v = catchability coefficient with units $[V]/[f]$;
C = catch in numbers or weight;
N = number or biomass of fish; and
p = proportion of the population in a depth zone, such that for $j = (1, \ldots, n_j)$, $p(\bullet) = \Sigma\, p(j)$.

Then catch within any depth zone (j) of subregion (i) is

$$C(i,j) = q_v \times N(i,\bullet) \times p(j) \times f_n(i,j) \times [A(i) \times h(i,j)]^{-1}$$

which, with some simplification, can be rewritten as

$$N(i,\bullet) \times A(i)^{-1} = C(i,\bullet) \times [q_v \times f_e(i,\bullet)]^{-1}$$

where $f_e(i,j) = f_n(i,j) \times p(j) \times h(i,j)^{-1}$.

As noted in Hinton and Nakano (1996), average density of the population in $A(i)$ is estimated using $C(i,\bullet)$ and $f_n(i,j)$ weighted by factors that are proportional to the fraction of the population in $h(i,j)$ and inversely proportional to volume, i.e. factors proportional to population density in volume $V(i,j)$. Effort outside the range of the population does not bias this density estimate, for example when hooks on a longline are fished outside the depth range of a species and are included in estimates of catch rates based on total hooks fished. Further, the estimate of average density is applicable not just to the sampled zones, but rather to the subregion, which is important since longline hooks often may not sample the entire depth range of a species.

In this application of the method to swordfish, the resolution was 2° latitude by 5° longitude and bimonthly period; thus these were the spatial-temporal dimensions within which $C(i,\bullet)$ and $f_n(i,\bullet)$ were estimated. The distributions of $f_n(i,j)$ were estimated from the gear configuration data. Habitat $h(i,j)$ of swordfish was delimited by 1°C increments in temperature relative to MLT, and $p(j)$ was estimated using results from ultrasonic depth telemetry studies.

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[5] Holts, D. B., N. W. Bartoo, and D. W. Bedford. 1994. Swordfish tracking in the southern California Bight. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SW Fish. Sci. Cent. Admin. Rep. LJ-94-15, 9 p. SWFSC, NMFS, Box 271, La Jolla, CA 92038.

Stock-assessment Model

We used the Deriso-Schnute delay-difference model (DSM; Hilborn and Walters, 1992) to investigate the status of swordfish stocks in the EPO. Delay-difference models have as their basis the fact that population biomass (B) at a given time t may be written as the sum of the biomass of individuals surviving from time $(t-1)$ to t, plus the biomass resulting from growth of the survivors from $(t-1)$ to t, plus the biomass of individuals that enter the population at time t:

$$B(t) = B(\text{survivors from } (t-1) \text{ to } t) + B(\text{survivors' growth from } (t-1) \text{ to } t) + B(\text{recruits at } t)$$

Incorporating process models for weight at age and recruitment, this may be written as

$$B(t) = \Sigma w(a) \times N(a,t) + w(k) \times N(k,t)$$

where $N(a,t)$ = number of individuals of age a at time t; $w(a)$ = average weight of an individual of age a; and k is the age of recruits at entry into the population.

The basic assumptions of the DSM were 1) recruitment to the population occurred over a short period (knife-edge recruitment); 2) the survival rate from natural causes (l) was a constant for all fish recruited to the population; 3) spawning occurred at the start of each year, with fishing occurring after spawning and with natural mortality negligible during that period; and 4) the average weight at age was determined by a Brody growth model:

$$w(a+1) = w(a) + \rho[w(a) - w(a-1)]$$

where ρ is the Brody growth coefficient. We applied the simplified version of this model, which has the constraint $w(k-1) = 0$, as given in Deriso (1980).

Define $S(t)$ as the biomass of adults that survive the fishery and F_B as the biomass of recruits as a function of the adult biomass. Then, substituting the Brody curve solutions for the $w(a)$ and simplifying, the full model is given by

$$B(t) = (1+\rho) \times l \times S(t-1) - \rho \times l^2 \times [S(t-1) \times S(t-2)/B(t-1)] + F_B[B(t-k)]. \qquad (1)$$

With F_B as defined, this formulation is for a closed population. An alternative formulation would include an additional term, R, added to the right side of Eq. (1) to account for net flux resulting from immigration and emigration of swordfish in the EPO. We considered the following two models for recruitment:

$$F_B[B(t-k)] = \alpha \times B(t-k)/1+[\beta \times B(t-k)] \text{ and}$$
$$F_B[B(t-k)] = \alpha \times B(t-k)/1+[\beta \times B(t-k)] + R$$

where α and β are parameters of a Beverton-Holt curve (Ricker, 1975). On the basis of length-frequency data for swordfish in the EPO (Shingu et al., 1974; Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992), individuals were considered fully recruited to the fishery at an eye–fork length of about 100 cm, which corresponds to a weight of about 10 kg and an age of about 2 yr. Thus, recruitment was lagged by 2 yr ($k = 2$) with respect to spawning stock biomass.

The Brody coefficient $\rho = 0.9999$ (~1) (Fig. 2) was estimated as follows. Length at age was first determined from a von Bertalanffy growth curve for swordfish from the Pacific (Yabe et al., 1959). These lengths at age were then converted to weights at age with the Kume and Joseph (1969) weight–length relationship for whole swordfish in the EPO. These weight-at-age estimates provided the basis for estimating ρ by the method of least-squared difference between the square roots of these estimates and the square roots of weights at age predicted by the Brody growth curve. Finally, it was considered that a reasonable range on which to consider survival rate, l, was about 0.62–0.81 (Boggs, 1989).

The parameters of the DSM were estimated by fitting model predictions of annual catch rates to "observed" rates based on catch per unit of standardized effort (CPUSE) and catch per unit of nominal effort (CPUNE) for 1962–87 (recall that the standardized data were not available prior to 1971, nor were final estimates of total catch available for the 1988–92 period). The "observed" annual catch rates are actually estimates based on the effort and weight of catch from individual 2° latitude by 5° longitude areas, $A(i)$. These areal CPUE observations were combined into an annual index of catch rate, CPUSE(t) or CPUNE(t), for the EPO using area weighting (Quinn et al., 1982).

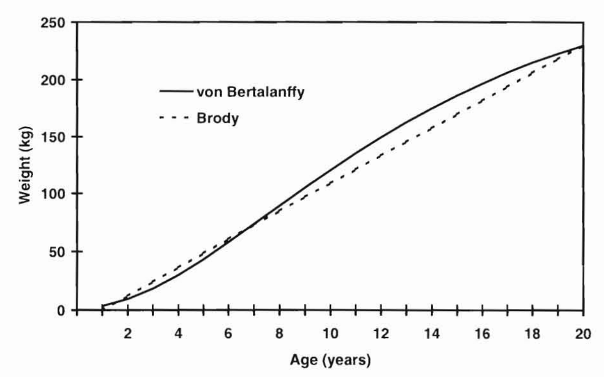

Figure 2
Brody growth model approximation of swordfish weight at age modeled by a von Bertalanffy growth function.

Fishing with deep longline gear began in the western Pacific Ocean in about 1975. During the first few years following its introduction, deep longline gear was used primarily in the western Pacific Ocean, with its use spreading over time to various other regions of the Pacific. In the first few years of the standardized series, 1971 to about 1977, there was little or no use of this gear in the EPO. The impact of effort standardization on the annual indices of CPUE was examined by first scaling the standardized and nominal CPUE series by their respective averages for 1971–87, computing the differences of the paired observations, and then testing this series of differences for trend. The Theil distribution-free test for slope (Hollander and Wolfe, 1973) indicated a significant trend in these differences (Kendall's K; n=17, p=0.003), which results from increasing values of annual CPUSE (Wilcoxon signed rank; n=11, p=0.002) starting in about 1976. When the catch rate series for 1988–92 were included in these analyses, the trend in the differences was insignificant (Kendall's K; n=22, p=0.13). The 90% confidence intervals for the annual abundance indices based on CPUSE were estimated using the bias-corrected and accelerated (BC_a) bootstrap method (Efron and Tibshirani, 1993) with 5,000 replicates and a resample size equal to the number of observations in a year, and these intervals included the observed values of CPUNE. In 1973 the difference in the scaled values of CPUSE and CPUNE was insignificant. It was therefore judged acceptable to use CPUNE for the earlier period in analyses of annual abundance. The final catch-rate series used in fitting the DSM consisted of annual CPUNE's for 1962–72 and, for 1973–87, of annual CPUSE's, scaled by the ratio of average CPUNE for 1971–92 to the respective average CPUSE. Fishing effort for this catch-rate data series is hereafter referenced in units of average hooks.

The error structure for delay-difference models involves two sources, the process error arising from the modeling of biological processes with a population dynamics model, i.e. error associated with using approximates for (true) growth, recruitment, and survival functions, and measurement error which arises from the independent estimates of catch rates (in this case the CPUSE(t) and CPUNE(t) data), against which the delay-difference model predictions are fitted during the estimation of model parameters. The process and measurement errors were assumed to have log-normal distributions with parameters $(0, \sigma^2)$. Process errors were included in the model as multipliers of annual recruitment. Measurement errors were the difference between the log-transforms of the observed and predicted catch rates. We should note that the predicted catch rate follows the assumption of Hilborn and Walters (1992, p. 345) and others that $C \times B^{-1} = 1 - e^{-qE}$.

Model fit was determined using the Microsoft Excel (version 5.0a) solver and maximizing concentrated likelihood, $CL = -(n/2) * \ln(SSE) - u$, where n is the number of observations of process and measurement error, SSE is the sum of the squared process and measurement errors, and u is a constant. Parameters estimated were l, α, β, q, and, in the open population structure, R. Prior to 1964 much of the EPO was not fully exploited by longline fisheries, so it was assumed that the biomass of swordfish in the EPO was at carrying capacity in 1962 and 1963, the first 2 yr used in fitting the model, and $B(t)$ for these years was set to the model prediction of carrying capacity.

Results

Distribution

The average annual distribution of swordfish in the EPO, as determined from relative density of CPUSE, is shown in Figure 3. Principal zones of high abundance are found from the coast of South America to 150°W,

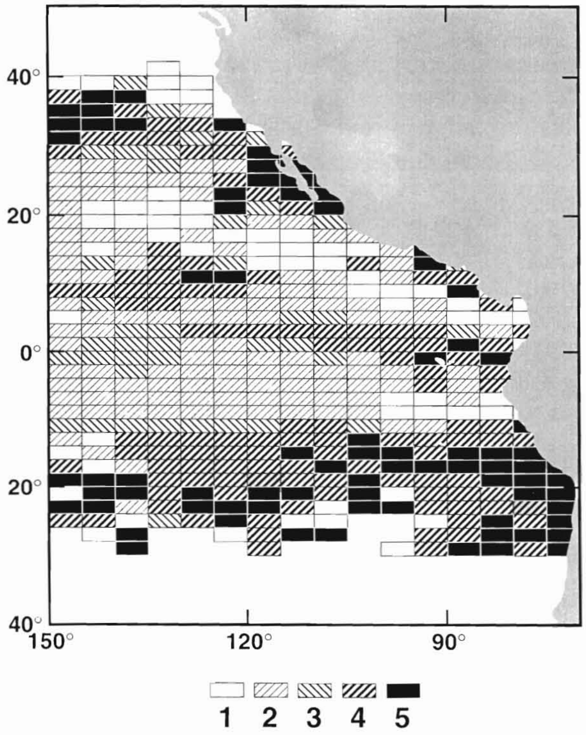

Figure 3

Annual average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

between about 10°S and the southern extent of the coverage of the longline fishery data; and from the coast of North America to 150°W along a zone of about 10° latitude bounded on the southern side by a line running from 20°N at the coast to about 28°N at 150°W. Other regions of high average annual abundance are located near the coast of Central America, from about 8°N to 16°N; westward from the coast of South America to about 90°–95°W between about 6°S and 2°N; and in a region of about 6° latitude along the Inter-Tropical Convergence Zone between about 120° and 135°W.

Underlying this picture of zonal distribution of swordfish in the EPO are seasonal distributions that vary significantly from the annual average. Average distribution during January–February (Fig. 4) is similar to the average annual distribution just described, but differs in several key respects. The southernmost zone of high abundance was shifted westward by about 5°–10° of longitude. Relative abundance is intensified in the northern zone, that reaching from 150°W to the region near Baja California, and there is a slight southerly extension in the extent of high abundance near the coast of Mexico. There is also a broader and more intense distribution of swordfish in the equatorial regions.

Swordfish clearly shift southward in both hemispheres during March–April (Fig. 5) as compared to January–February. The southern boundary of the northernmost zone shifts from about 28°N to 24°N at 150°W, and becomes contiguous with the region of high abundance off Baja California during this period. The northern boundary of the southern zone shifts from about 8°S to 12°S. In addition, the southern region of high abundance extends to the coast of South America at about 12°–14°S. There is a coincidental intensification and widening of the distribution of high abundance in the equatorial regions.

By May–June (Fig. 6), swordfish in the southern EPO are concentrated in an area from the coasts of Peru and northern Chile westward to about 90°–95°W. Swordfish are widely dispersed in the northern EPO. The equatorial zone of high concentration has shifts northward and is no longer clearly separated from the northernmost zone in waters west of about 120°W. The southern boundary of the northernmost zone has shifted south-

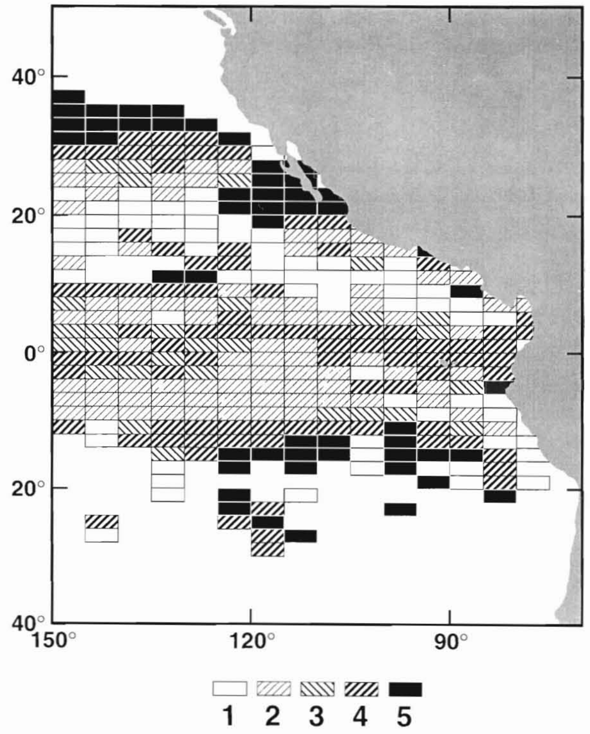

Figure 4

Average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean for January–February, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

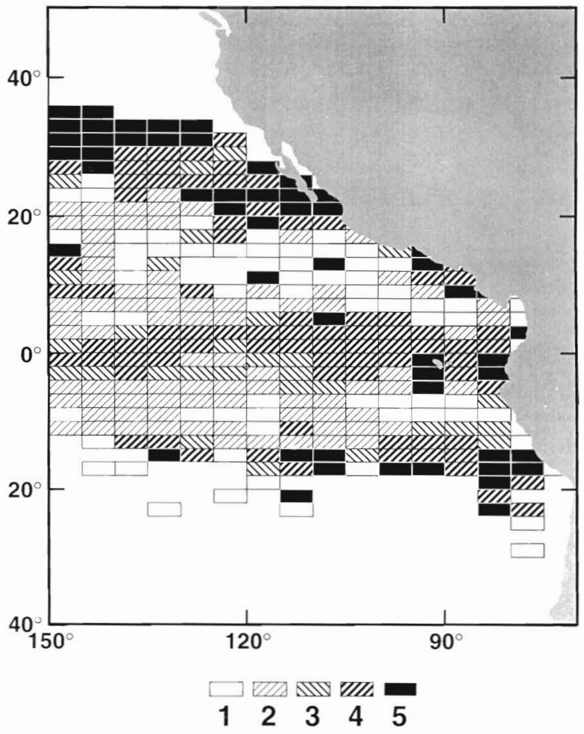

Figure 5

Average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean for March–April, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

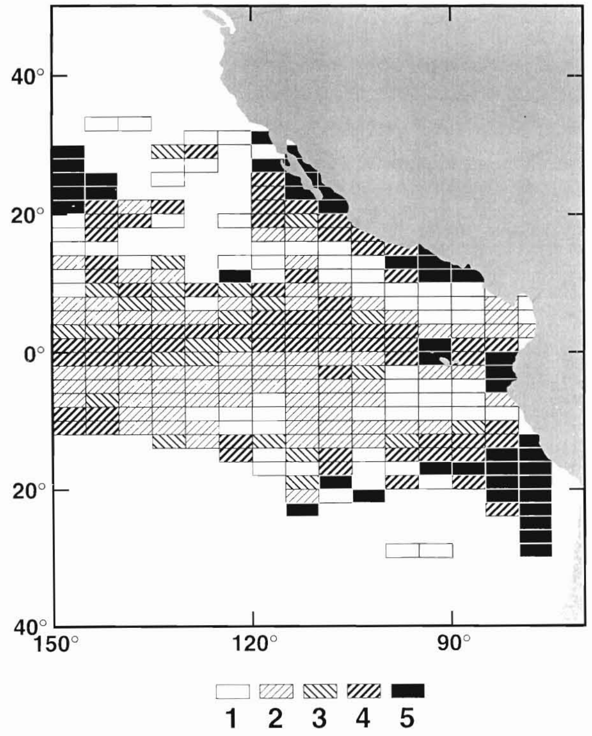

Figure 6
Average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean for May–June, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

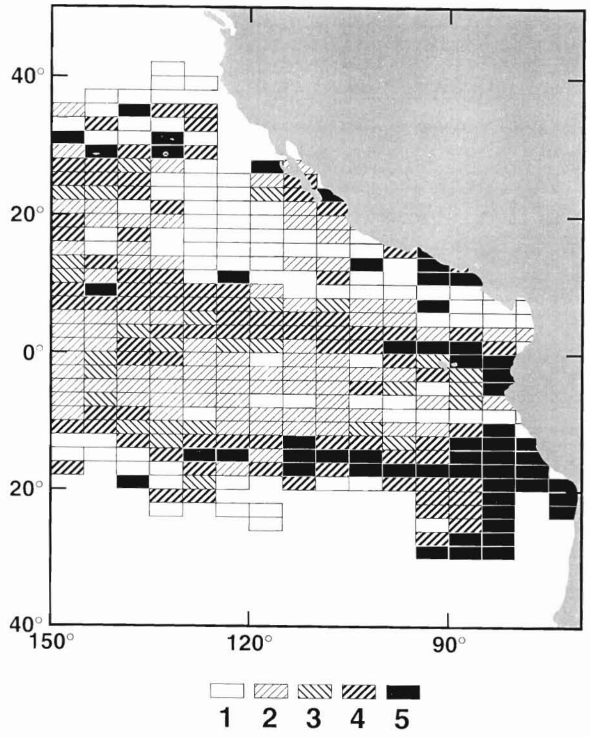

Figure 7
Average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean for July–August, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

ward from about 28°N (in January–February) to about 14°N. The region of high concentration off Baja California now extends southward to Costa Rican waters (about 10°N), and about 10°–15° of longitude westward of the coast of the Americas.

During July–August (Fig. 7), high concentrations of swordfish in the southern EPO extend from the coast to about 110°–115°W, a westward shift of about 10° longitude in comparison to the May–June distribution. This region of high concentration extends south to about 30°S in the region of 80°–95°W. A narrow strip of high abundance is found at about 16° –12°S from the coast to about 145°W. There is also high abundance in the equatorial region in an area bounded by the coast of South America from about 4°S to 4°N and extending westward to 85°–95°W. The contiguous zone of high abundance along the coast of the Americas is again reduced to core regions around Baja California and off the Central American coast from about 10°N (Costa Rica) to 16°N (Guatemala). In the northern EPO the distribution of swordfish is less cohesive than in earlier months, and the southern boundary of the northernmost zone has shifted northward to about 24°–26°N, separating from a zone of high abundance at about 6°–10°N from 130°–150°W.

By September–October (Fig. 8), the zone of high abundance in the northwestern portion of the EPO has fully dissipated. Zones of high abundance in the region about Baja California, extending offshore about 5° of longitude, and in the Guatemala–Costa Rica region persist. There continue to be two zones of relatively high abundance in the equatorial region, one in an area bounded by the coast of South America from about 4°S to 4°N extending westward and northward to 95°–100°W and 6°N, and the other in the central to western EPO, at about 120°–145°W and 6°–16°N. The dominant features in September–October are the northward shift of the southernmost zone of high abundance from south of about 12°S and the development of a contiguous region of high abundance lying south of about 8°–10°S and stretching across the EPO from the coast of South America to 150°W.

During November–December (Fig. 9) there again appears a region of higher abundance in the north-

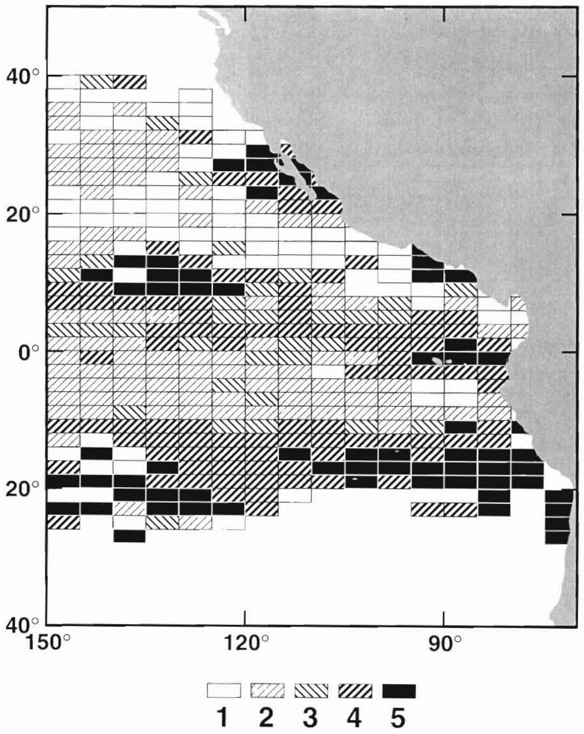

Figure 8

Average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean for September–October, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

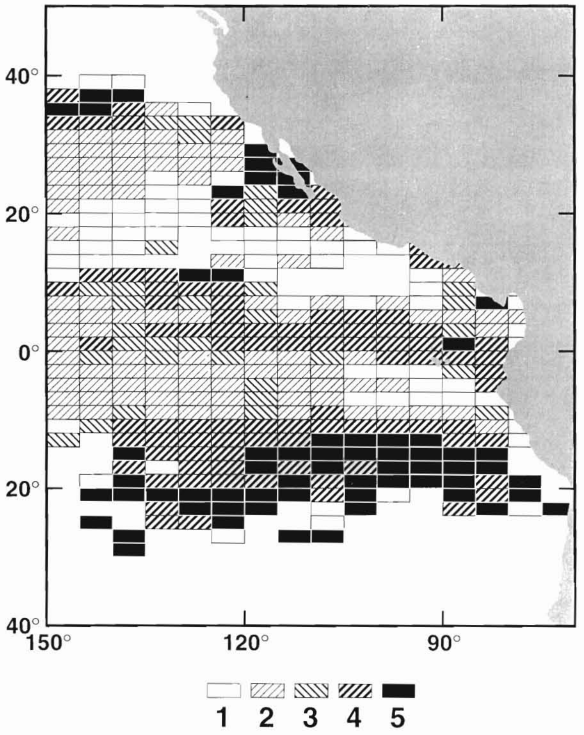

Figure 9

Average swordfish catch per unit of standardized effort (CPUSE) in the eastern Pacific Ocean for November–December, 1971–87. Area rankings are 1: CPUSE = 0 and decile 1; 2: deciles 2–4; 3: decile 5; 4: deciles 6–8; and 5: deciles 9–10.

westernmost portion of the EPO between about 135° and 150°W and 32° and 38°N. This area of high abundance is not contiguous with the region of high abundance about Baja California, as in January–February. There are also southward shifts of about 2°–4° latitude in the northernmost boundary of the high abundance zone in the southern EPO (from about 8°–10°S to about 10°–12°S), and in the southern boundary of the area of high abundance along the coast of Mexico near Baja California.

Stock Status

The results of fitting the DSM model with net immigration/emigration (R) are shown in Fig. 10. A one-to-one relationship between l and R exists, which made it necessary to bound solutions using the range of likely values of natural survival rate, l, i.e. 0.62–0.81 (see prior discussion). Over this range, values of CL ranged from 52.8 to 50.9; however there is no significant difference between these values (χ^2=1, p=0.17), and a null hypothesis would not reject any of the solutions bounded by these l. Within these bounds on l, the estimated values of average maximum sustained yield (AMSY) and associated optimum effort (OE) ranged from 8,400 to 4,000 metric tons (t), and from 156×10^7 to 86×10^7 average hooks, respectively.

At l = 0.62, the fit of the model with R was achieved with significant contributions from both process and measurement error (Fig. 11). This is contrasted by the results at l = 0.81, in which the fit was achieved by attributing almost all error to measurement. However, the difference in the estimated trends in abundance, as given by the series of the natural logarithms of predicted CPUE in these two fittings of the model, were not significantly different (Hollander distribution-free test for parallelism [Hollander, 1970]; n=26, p=0.23)].

In fitting the model without R, i.e. R = 0, CL decreased monotonically from 52.7 to 51.1 over the range of l from 0.62 to 0.81, and as in the model that included R, there was no significant difference between these minimum and maximum values of CL (χ^2=1, p=0.21), which fall within the range of values of CL obtained

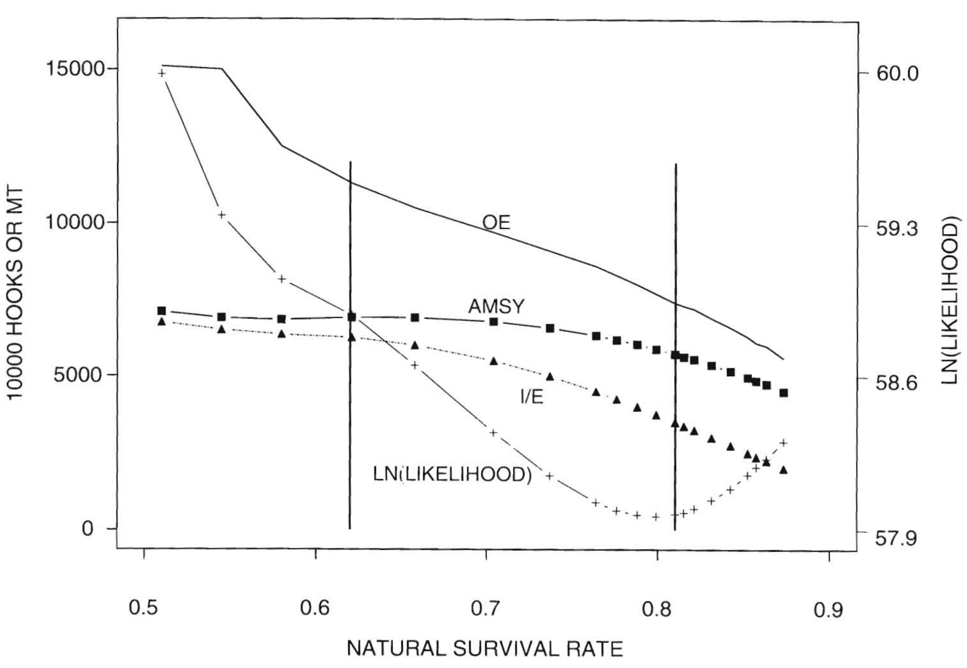

Figure 10
Results of fitting a Deriso-Schnute delay-difference model with Beverton-Holt recruitment and an immigration/emigration term (I/E, in metric tons, t) to catch rates of swordfish from the eastern Pacific Ocean. Vertical lines mark natural survival rates of 0.62 and 0.81. OE = optimum effort (average hooks). AMSY = average maximum sustained yield (t).

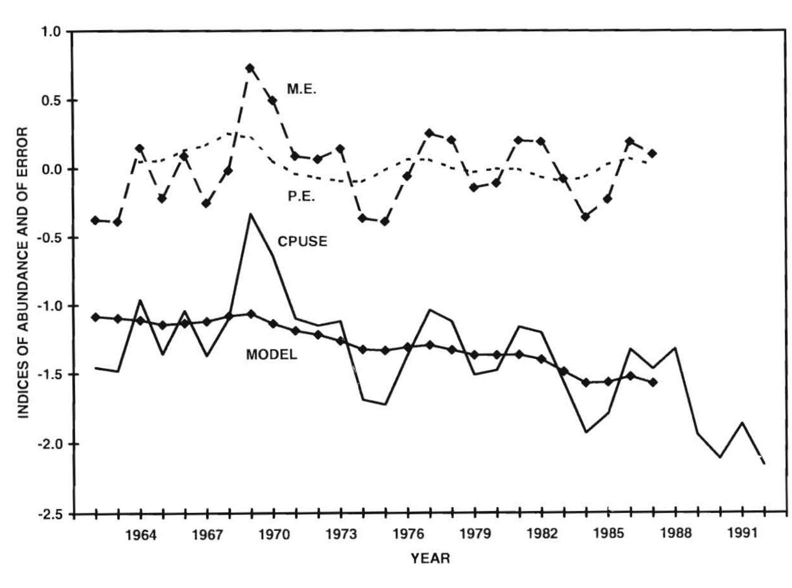

Figure 11
Indices of abundance from the Deriso-Schnute delay-difference model with natural survival rate of 0.62, fitted to 1962–87 abundances from CPUSE for swordfish in the eastern Pacific Ocean, and measurement (M.E.) and process (P.E.) error.

with $R \neq 0$. Thus a null hypothesis would not reject any of the solutions bounded by these l. Within these bounds on l, the estimated values of AMSY and the associated OE for the model without R were 7,200–1,000 t, and 80 × 10^7 to 7 × 10^7 average hooks, respectively.

Model fits obtained using the CPUNE data series for 1962–87 were somewhat similar to those described above. In this case, over the range of l from 0.62 to 0.81, for the model with R the estimated values of AMSY and associated OE ranged from 6,900 to 5,600 t, and from 113 × 10^7 to 86 × 10^7 average hooks, respectively. For the model without R, the estimated values were 1,000–200 t and 6 × 10^7 to 1 × 10^7 average hooks, respectively.

These models and results were tested by generating simulated data using various series of fishing effort, which provided wide ranges of catch and catch rates (e.g. Ludwig and Walters, 1989), and the parameter estimates obtained by fitting the model with the original data. These simulations gave maximum estimates of AMSY and OE of 7,000 t and 107×10^7 average hooks, and 1,000 t and 6×10^7 average hooks for the $R \neq 0$ and the $R = 0$ models, respectively. These values compare well with the results obtained from the initial fitting and parameter-estimation procedures.

Discussion

Distribution and Stock Structure

Information used by fisheries scientists to define the boundaries of stocks of fish include data on relative abundance, size and spawning condition of individual fish, distribution of larval fish, genetics, and movements as determined from tagging. The boundaries determined from this basic research (Brown et al., 1987) may then be employed in studies that estimate the status of a stock with respect to conservation and management objectives. Prior to proceeding, we must address the meaning of the term stock.

The least useful definition of stock, from a management or conservation point of view, is "the part of a fish population which is under consideration from the point of view of actual or potential utilization" (Ricker, 1975). For example, strictly interpreted this definition may exclude portions of a population that contribute to the presence and level of the stock, i.e. a stock may consist only of juveniles whose existence derives from the reproductive success of those surviving utilization, but the survivors are not considered part of the stock. The environment and fishing in any part of the range of a fish population affect the subsequent abundance and distribution of the species throughout its range, giving this narrow definition little value within our current framework of knowledge in oceanography and fisheries science. Application to management or conservation questions requires that a stock be a "self-sustaining component of a particular species" (Sinclair, 1988). So defined, a stock has biological and genetic significance (Sinclair, 1988), which provides a basis for measures (Brown et al., 1987) commonly used to differentiate among stocks. However "in all cases some indications of significant degree of physical separation at spawning is [sic] required to support biological bases for separate stocks" (Brown et al., 1987). To the extent that relative abundance data accurately depict the spatial and temporal distribution of a stock, the stock is a function of nature and not an abstraction (Sinclair, 1988).

Various stock structures have been proposed for swordfish in the Pacific Ocean. Sakagawa and Bell (1980), and more recently Bartoo and Coan (1989) using data through 1980, employed annualized estimates of relative abundance based on CPUNE data to estimate the distribution of swordfish stocks in the Pacific. Each included an EPO stock in their three-stock hypotheses. The ability of such annualized data to accurately reflect the spatial and temporal distribution of stocks that may exhibit migratory behavior is doubtful.

Using CPUNE data with monthly resolution, Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991) hypothesized a more complex stock structure. However at the core of their determination were the independent seasonal trends in the extensions of local relative abundance about centers of high abundance, with the result that their definition of stock was in essence that of Ricker (1975) noted above. Noting the need for increased biological information, Sosa-Nishizaki (1990) concluded

> I think that these four different areas can represent different stocks, not in the complete biological sense, but as fishery management units. In other words, the stocks thus agreed upon were in the sense of defining a manageable resource not to define the borderline of movements of individuals, nor do stocks intend to be referred to [as] isolated genetic units, as was stated for the management of Atlantic swordfish populations (Miyake and Rey, 1989).

Although this four-stock hypothesis may prove of questionable value in defining and achieving management or conservation objectives, such initial hypotheses may provide a sound basis for further research (Brown et al., 1987). This hypothesis includes two stocks centered in the EPO, one centered off Baja California, and another centered off the west coast of South America; we will examine this hypothesis as if these were proposed as self-sustaining stocks.

Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991) reported seasonal variation in the extent of distribution of the swordfish stocks about the centers of distribution, but with one exception, that of contiguous northern and southern EPO distributions of swordfish during the boreal autumn and winter, they noted that the distributions "always seemed to be separated." However, there remained some question concerning these hypotheses, as Sosa-Nishizaki (1990) cautioned that misleading conclusions might be reached as a result of his estimation of relative abundance using the CPUNE statistics, and that catch and effort data analyzed on spatial scales with higher degrees of resolution might lead to alternate hypotheses or conclusions. In their analyses, Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991) used three ranges of average monthly CPUNE measured within 5° latitude by 5° longitude areas. Our use of standardized rather than nominal statistics and a higher degree of spatial resolution (2° latitude by 5° longitude) are responsible for the differences between our results and those of Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991).

The stock of swordfish in the northern EPO was essentially separated through the entire year from the stock in the southern EPO: the zones of relatively low abundance seen in Figure 3 shift latitudinally, but are generally maintained throughout the year. This is in contrast to Sosa-Nishizaki and Shimizu's (1991) observation of a continuous distribution of swordfish from the northern to southern EPO during the boreal fall and winter months (their Figures 4-1 [January] and 4-6 [November–December]).

We found that the Baja California stock of Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991) was not isolated from other stocks in the Pacific, specifically the northwestern-central Pacific stock of these authors, of Sakagawa and Bell (1980), and of Bartoo and Coan (1989). Our results (Fig. 4, 5) suggest that the distribution of the northwestern-central Pacific stock becomes contiguous with Sosa-Nishizaki and Shimizu's (1991) Baja California stock during January–February and March–April each year. As well, the fact that throughout the year the equatorial zone of high abundance (discussed below) extends to the westernmost geographical limits of this study (150°W) indicates that there may be significantly more contact between these two stocks than we have noted here. These results do not confirm that the Baja California and northwestern-central Pacific stocks do not exist as separate reproductive units, only that there exist areas and times during the year in which the stocks may mingle. This is critical because "as long as fish from different breeding areas mingle during a portion of the fishery they have to be managed as a unit" (Brown et al., 1987).

Previous studies of the reproductive condition of swordfish have not indicated the presence of individuals in spawning condition in the Baja California region (Ramon and Castro-Longoria[6]). Shingu et al. (1974) found that high values of gonad indices were found only in high-seas areas, indicating that "spawning is limited to the more offshore waters." Larval surveys (Nishikawa et al., 1985) near Baja California have been limited, with observations recorded for only the January–March period at only two locations in the region from 10° to 20°N and from the coast of Mexico to 120°W, and neither location was in the immediate vicinity of Baja California. Samples collected at these locations did not include larval swordfish. It has been demonstrated (Hinton et al., 1997) that in general the methods that have been used to estimate the reproductive condition of female swordfish are likely not to identify reproductively active individuals. Our analyses, employing the new method of Hinton et al. (1997), indicated that swordfish were reproductively active in the vicinity of Baja California during May–August.

Our results (Fig. 4, 7–9) and, though not described therein, those of Sosa-Nishizaki and Shimizu (1991) indicate an apparently isolated center of relatively high abundance off the coast of Central America from about 10° to 16°N. Our analyses indicate that the distribution centered off Baja California extends southward along the coast of North and Central America during the boreal spring and early summer (Fig. 5, 6), and becomes contiguous with this more southerly region of higher abundance. This connection was not evident in Sosa-Nishizaki and Shimizu (1991).

Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991) found an equatorial zone of high abundance in the EPO from October through January. Their studies indicated that in most other months this distribution consisted of two high-abundance areas, one between South America and about 100°W, and the other between about 115° and 150°W. Sosa-Nishizaki and Shimizu (1991) noted their inability to resolve an equatorial zone of high abundance and more northerly or southerly areas of high abundance. We found a clear and persistent zone of relatively high abundance of swordfish throughout the year in the equatorial region extending to 150°W. The zone showed north–south seasonal movement, and was generally located between about 4°S and 10°N. This equatorial region of high abundance was consistently separated from more southerly centers of high abundance by the previously-noted zone of low abundance. Further, there appears to be clear separation of the high-abundance zone in the southern EPO from waters west of 150°W during much of the year, and therefore from the swordfish stock centered in the southwestern Pacific (Sosa-Nishizaki, 1990; Sosa-Nishizaki and Shimizu, 1991). Thus, our findings provide support for the hypothesis of a separate swordfish stock with distribution centered in the southern EPO.

Integrity of the equatorial zone was not maintained with respect to stocks found in the northern EPO. Sosa-Nishizaki (1990) noted that the Baja California stock appeared to be contiguous with the equatorial region of high abundance between about 120° and 140°W during November–December. Figures 4 and 9 suggest that during November–February the region of high abundance around Baja California is contiguous with the equatorial-centered region of high abundance be-

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[6] Ramon, D., and R. Castro-Longoria. 1994. Sex composition and maturity of swordfish, *Xiphias gladius*, caught in the drift gill net fisheries of the U.S. and Mexico. Paper presented at Symposium on Pacific swordfish, Ensenada, Mexico, December 1994. Available from D. Ramon, NMFS Southwest Fisheries Science Center, 8604 La Jolla Shores Dr., La Jolla, CA 92037-1508.

tween about 115° and 130°W. This connection did not extend into March–April.

In addition to relative abundance data, information from tagging experiments may be used in defining stock boundaries. Previous tag recovery information from the Atlantic has indicated that swordfish may undertake extensive migrations, which may be regular and include migrations between spawning and feeding areas (Carey and Robison, 1981). Billfish tagging efforts in the Pacific have, until recently, been primarily those of recreational fishermen through the National Marine Fisheries Service Cooperative Marine Game Fish Tagging Program. These efforts did not result in significant placement of tags on swordfish, but more recently commercial fishermen operating longline gear in the central Pacific have begun placing tags on small swordfish (Holts[7]).

There have been insufficient tag returns to adequately describe movements of swordfish in the Pacific, but our finding that the northwestern-central Pacific stock and the Baja California stock mingle is supported by the recent recovery of a swordfish tagged on 1 May 1993 northeast of the Hawaiian Islands at 28°20'N, 149°08'W and recovered off San Clemente Island, California, USA, at 32°03'N, 118°29'W on 1 January 1995 (Holts[8]). If one assumes that the location of tagging was central to the travel of this individual, then its ambit could easily have included positions at least as far west as 170°W, and certainly as far north as 40°N and as far south as the equator. Further, this recovery had locations and timing of tag placement and recovery which were consistent with seasonal movement of swordfish from the northwestern Pacific to Baja California, as discussed below.

Length-frequency data (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992) also support our hypothesis of mingling of swordfish stocks in the northern EPO. From October to December about 95% of fish sampled from the EPO region north of 20°N and west of 120°W were less than 145 cm in length. The range of lengths of individuals in this region during January–June was about 80–240 cm, with 30% or more of individuals greater than about 180 cm. Kume and Joseph (1969) estimated the average annual growth in the EPO of swordfish between 62 and 165 cm at about 38 cm per yr, or less than 10 cm per quarter. Thus, growth would not be a reasonable explanation for the observed increase in numbers of larger fish, and individuals must have migrated into the region during the first quarter of the year.

There were four regions from which larger individuals might migrate into this northern and westerly region of the EPO: 1) more westerly regions of the northern Pacific, 2) the Baja California region, 3) the equatorial zone of high abundance, and 4) waters beyond the northern extent of these fisheries. There is insufficient information available to evaluate the presence, abundance, or status of swordfish north of regions in the EPO in which these fisheries occur; however, the lack of significant fisheries for swordfish in those waters suggests that their presence has been found to be minimal. The length data presented by Sosa-Nishizaki (1990) were not summarized in a manner that identified lengths of individuals from waters west of 150°W by area and time so that comparisons to information from the EPO might be made. Thus, of these four regions, samples of lengths of swordfish (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992) were available to us only from regions 2 and 3, and only in region 2 were larger fish present during the period preceding the first quarter of the year, when they appeared in the northwestern EPO.

In the Baja California region, catches of swordfish ranged in length from about 80 to 250 cm during October–December and from about 100 to 200 cm during January–March (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992). The high abundance of fish less than 180 cm in length in the Baja California region during the first quarter suggests that any movement of larger fish from the region was independent of the available food supply. A movement of larger fish westerly or to the south during this period, as previously discussed, would be consistent with movement to a region suitable for spawning (Matsumoto and Kazama, 1974; Nishikawa and Ueyanagi, 1974), as the 23.5°C sea-surface temperature isotherm extends from about 28°N at 150°W to 20°N at 145°W, thence easterly to about 121°W, whence it runs northeasterly to intersect the Baja California peninsula at about 26°N, 113°W during November–December; and during January–February it runs from about 22°N at 150°W to 17°N at 145°W, thence easterly to about 135°W, whence it runs northeasterly to intersect the mainland of Mexico at about 23°N, 108°W (Robinson and Bauer, 1976).

In an effort to determine how far south larger individuals might have gone following emigration from the Baja California region, we re-examined the data on lengths of swordfish summarized by Miyabe and Bayliff (1987) and Nakano and Bayliff (1992) to determine the distribution of the measurements by time and area. These length data were collected by port samplers in Japan and by crew members of training and research vessels, but the positions of capture are known only for data from swordfish sampled by the vessel crews. The data obtained by port samplers can generally be located to 5° (or 10°) latitude

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[7] Holts, D. B. 1994. 1994 billfish newsletter. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SW Fish. Sci. Cent., 9 p. Available from SWFSC, NMFS, P.O. Box 271, La Jolla, CA 92038.

[8] Holts, D. B. 1995. 1995 billfish newsletter. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., SW Fish. Sci. Cent., 12 p. Available from SWFSC, NMFS, P.O. Box 271, La Jolla, CA 92038.

by 10° (or 20°) longitude. We found that the number of samples by area was such that we could not with certainty determine distributions of length frequencies within a zone extending across the EPO from 10° to 20°N on a bimonthly basis. However, data (Kume and Joseph, 1969; Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992) indicate that few, if any, of these larger individuals move south of 10°N during the first quarter. This is not surprising, given the fact that they would encounter regions suitable for spawning well to the north.

Following the January–March period, the range of swordfish lengths in the Baja California region increased from 110–200 cm to include lengths less than 80 cm and up to about 260 cm (Miyabe and Bayliff, 1987); however the relative abundance of larger individuals was significantly less than during October–December. Again, although estimated growth rates are insufficient to explain the renewed presence of large individuals, recruitment from local reproduction or migration would explain the renewed presence of smaller fish in the region. The question is, from whence do these individuals come when they enter the Baja California region?

It seems likely that the larger fish were entering or returning to the Baja California region from more westerly regions of the EPO. The smaller fish, those less than 110 cm, may be progeny of reproductive efforts in the vicinity of Baja California, or they may have entered the EPO as part of the apparent migration of individuals from the more westerly portions of the North Pacific, eventually reaching the waters off Baja California. They also may have moved north from the more southerly equatorial region of high abundance. The equatorial region of the EPO is known to be a region of high productivity throughout the year (Chavez and Barber, 1987), and on the basis of the high frequency of smaller swordfish in length-frequency distributions for the region, Kume and Joseph (1969) identified it as a region of feeding and growth for immature swordfish. Considering that smaller fish leaving this area for waters off Baja California would, in essence, be investing energy to move from one highly-productive region to another, it seems more plausible that the influx of smaller fish to the region of Baja California during the second quarter of the year may be traced either to local reproduction, or to the western North Pacific, as discussed below.

A zone of high abundance lying north of 20°N and west of 120°W first appeared early in the November–April period north of about 32°N at 135°–150°W (Fig. 9). Monthly catch-rate data (Sosa-Nishizaki, 1990) show that a zone of high abundance spreads across the entire North Pacific, from Japan to the EPO, during this period. In the EPO, this zone of high abundance expanded eastward and southward, until in January–February it extended from 150° to 120°W and south to about 26°N. At this point it was nearly contiguous with the zone of high abundance about Baja California, and by the end of March–April a single zone of high abundance extended northward of a line from about 24°N at 150°W to about 18°N at the coast of Mexico (Fig. 5). By May–June the continuity of these two zones was breaking down and the southern boundary of the northwestern center of high abundance had shifted south to about 14° to 18°N between 150° and 135°W, respectively (Fig. 6). During the subsequent July–August period, regions of relatively high swordfish abundance were found widely scattered within the area north of 20°N and west of 120°W (Fig. 7). If the tagged fish previously noted was in fact undertaking an annual migration from the central North Pacific to the EPO, then the information obtained from this individual supports migration as inferred from these data.

Squire and Au (1990) found that the "high-catch-rate areas off Mexico are areas of at least temporary accumulation or aggregation" of striped marlin, *Tetrapturus audax*, into a region of high productivity and food supply (Hanamoto, 1974) and that the "movements of larger fish may be related to maturity and, thus, to spawning seasons and spawning areas." Our findings suggest that the region of high abundance of swordfish in the vicinity of Baja California may be both the center of a stock's distribution and a feeding and growth region, as is the case for striped marlin.

Studies of the distribution of values of swordfish gonad indices in the eastern Pacific have been made by Kume and Joseph (1969), Shingu et al. (1974), Miyabe and Bayliff (1987), Sosa-Nishizaki (1990), Sosa-Nishizaki and Shimizu (1991), and Nakano and Bayliff (1992). Such studies have not indicated a clear separation of areas with high indices in the northern and southern hemispheres (Sosa-Nishizaki and Shimizu, 1991). The results from these studies and our analyses of GI data, when examined with respect to the relative abundance estimates described herein, show that spawning activity is closely associated with high-abundance zones in the four regions of the EPO in which mature females in spawning condition have been found, i.e. the Baja California, northwestern (north of about 20°N and west of about 120°W), equatorial, and southern regions of high abundance we have described.

Kume and Joseph (1969) presented quarterly gonad index data at a resolution of 1° latitude and 1° longitude. The regions of high average values that they identified fall clearly in either the equatorial or southern zones of high abundance. The other earlier studies presented data at a resolution of 5° latitude and 5° longitude, making comparisons difficult and necessitating reanalysis of the GI data. Our re-examination of the data indicated that regions of the EPO with individuals in spawning condition were clearly separated throughout the year. Of the 105 combinations of 2° latitude by

5° longitude area and bimonthly period in which individuals with GI ≥1.375 were found, 6 were within and 1 was adjacent to either the Baja California or the northeastern zone of high abundance, 51 were within the bounds of the equatorial or southern zones of high abundance, and 26 were in areas immediately adjacent to one of these latter two zones. This indication of physical separation at spawning supports the hypothesis (Sosa-Nishizaki, 1990; Sosa-Nishizaki and Shimizu, 1991) of a separate swordfish stock in the southern EPO, and is consonant with our previously-noted finding, founded on CPUSE, that the southern stock is isolated from other stocks of the EPO.

Data on the distribution of genotypes of nuclear or mitochondrial DNA in a population may provide measures of the degree to which, over periods spanning many generations, stocks have been separated during spawning, and therefore may be useful to investigations of stock structure (Ferris and Berg, 1987). For various reasons (see Avise et al., 1987), mitochondrial DNA (mtDNA) is frequently used to investigate the structure of populations (e.g. Graves and McDowell, 1994). Significant differences in the distribution of mtDNA genotypes among stocks would provide positive evidence of previous reproductive isolation and stock structure, but homogeneous distributions of genotypes across hypothesized stocks does not indicate the absence of stock structure. This is because only a few individuals per generation (on the order of tens, regardless of population size) need reproduce with members of other stocks to prevent genetic drift and maintain homogeneity of mtDNA in the population (Allendorf and Phelps, 1981; Slatkin, 1987). These numbers of individuals are trivial in comparison to the large number of individuals with homogeneous vital rate parameters and a high degree of reproductive isolation which underlies the stock structure of a population (Graves[9]). Further, mtDNA inheritance is not linked to inheritance of nuclear DNA, and there may be differences in population structure as inferred using mtDNA and nuclear DNA (Harrison, 1989).

Studies of mtDNA from swordfish in the Atlantic Ocean and the Mediterranean Sea (Magoulas et al., 1993) indicate that distinct stocks exist in these oceans, and the genotypes found in these stocks are different from those found in swordfish in the Pacific Ocean (Chow[10]). Grijalva-Chon et al. (1994) failed to reject the null hypothesis that there was a single stock of swordfish in the North Pacific, and stated that "there is sufficient gene flow across the North Pacific to prevent genetic [mtDNA] differentiation," but it is important to remember that, as discussed above, this does not demonstrate that stocks do not exist in the north Pacific, only that there is mingling among any stocks.

Given the amount of genetic variation reported by Grijalva-Chon et al. (1994), and even greater variation noted in more recent studies (by Alvarado-Bremer and Ely, Rosel and Block, and Chow), samples of swordfish from geographic locations have been far too small to estimate distributions of genotypes with any degree of precision (Graves[11]). Consequently, it would be premature to make a definitive statement regarding the genetic basis of swordfish stock structure in the North Pacific, although it is likely that significant differences in genotypic distribution will be seen among geographically distant locations when adequate samples have been obtained (Graves[11]).

The information and analyses presented to this point support the hypothesis (Sosa-Nishizaki, 1990; Sosa-Nishizaki and Shimizu, 1991) of a swordfish stock with its center of distribution in the southeastern Pacific Ocean, and they do not reject the hypothesis (Sosa-Nishizaki, 1990; Sosa-Nishizaki and Shimizu, 1991) of a swordfish stock centered in the northeastern Pacific Ocean in the vicinity of Baja California. They suggest that the waters near Baja California may be a feeding and growth region for swordfish stocks that spawn elsewhere and are distributed more broadly in the North Pacific Ocean, and that swordfish are reproductively active in the region. The failure of Grijalva-Chon et al. (1994) to identify the presence of stock structure in swordfish in the North Pacific is not surprising in light of the small number of individuals required to maintain genetic homogeneity, and their failure to reject a null hypothesis should not form the basis for restricting or terminating basic research into the stock structure of North Pacific swordfish. In fact, their findings, taken in conjunction with those of Sosa-Nishizaki (1990), Sosa-Nishizaki and Shimizu (1991), and this study indicate that further basic research is required. As part of this research, investigation of the geographical limits of the distributions of swordfish stocks in the EPO should be conducted over a region extending to the west of the 150°W limit of this study.

Stock Status

Sakagawa and Bell (1980) and Bartoo and Coan (1989), among others, have examined the status of swordfish stocks in the Pacific. Sakagawa and Bell (1980) did not estimate AMSY for the stocks of their three-stock hy-

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[9] Graves, J. E. 1995. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA. Personal commun.

[10] Chow, S. 1995. National Research Institute of Far Seas Fisheries, Shimizu, Japan. Personal commun.

[11] Graves, J. 1996. Virginia Institute of Marine Science, The College of William and Mary, Gloucester Point, VA. Personal commun.

pothesis, but using production-model analyses they estimated that under a single-stock hypothesis the annual AMSY for swordfish stocks in the Pacific was about 20,000 t. While cautioning that fisheries should be monitored for changes in technology and fishing practices that might result in catches exceeding AMSY, they concluded that stocks of swordfish were "capable of sustaining increased yields with increased effort." Bartoo and Coan (1989) did not estimate AMSY values, but examining catch-rate trends for swordfish in the entire Pacific (the single-stock hypothesis) and within the three regions identified by relatively high average annual catch rates (the three-stock hypothesis), they concluded that there was no indication "that the stock(s) have been exploited heavily enough to cause a noticeable decline in CPUE through 1980." Sosa-Nishizaki (1990) and Sosa-Nishizaki and Shimizu (1991) did not determine the status of specific stocks because data were unavailable, but referencing the findings of Sakagawa and Bell (1980) and Bartoo and Coan (1989), and following a review of FAO catch statistics, they concluded "that the general situation in the Pacific swordfish resources [is] stable." These analyses of the status of swordfish stocks have at their core either an ill-fitting production model (Squire, 1981) or simple examinations of trends in catches and catch rates.

Analyses of stock status may be designed to provide information not only on the estimates of AMSY and OE commonly sought by fisheries managers, but also to provide some measure of the acceptability of the underlying stock structure hypotheses. The value of such a design has been discussed (see Brown et al., 1987), and studies along these lines were recommended (Sakagawa and Bell, 1980) for swordfish stocks in the Pacific. Our analyses are the first to our knowledge which were specifically structured to differentiate between the likelihoods of various stock-structure hypotheses for swordfish in the EPO.

The results of fitting the Deriso-Schnute delay-difference model with recruitment represented as (Model 1) a function of adult biomass (the Beverton-Holt component) and (Model 2) as a function of both adult biomass and a linear term expressing net migration were not significantly different based on observed values of CL. Model 1 represented a system closed to significant transboundary migration, and Model 2 represented a system open to migration. Thus, these results did not distinguish between the hypotheses that (a) there exists a single stock of swordfish with its distribution centered in the EPO and approximately bounded by the American continents and 150°W (e.g. a geographically-discrete southern or northern stock, or a stock with a distribution spanning the EPO) and (b) there exists a single stock of swordfish as in (a) but the EPO region is also frequented by swordfish stocks with distributions extending well beyond 150°W.

Ideally an estimate of stock status could be made for each hypothesized stock, and results could be compared to aid in determinations of stock structure. In this case that approach was not possible for swordfish stocks in the EPO for several reasons. Historical reporting of total swordfish catch has been on the basis of large statistical reporting areas which are unrelated to boundaries of hypothesized stocks. A positive note is that it was recently agreed among regional fisheries agencies that are responsible for obtaining and maintaining data for high-seas fisheries that catch and effort data should be made available on a stock basis, and at finer resolutions if possible (Anonymous, 1994). Estimates of population parameters may be used to identify stocks (Skillman, 1989); however there are few estimates of rates of growth, recruitment, and mortality of swordfish (Boggs, 1989) and those estimates from the Pacific were obtained without reference to hypothesized stock structure. Thus, these estimates were employed to bound plausible model solutions (natural mortality) or were assumed to be homogeneous (fishing mortality, growth, and recruitment model parameters) within stocks in the EPO.

The estimate of AMSY for swordfish in the EPO from all plausible solutions was less than about 8,400 t, and the optimum effort was 156×10^7 average hooks or less. In comparison, during 1980–85 swordfish catch in the EPO averaged about 6,300 t. In 1987 the catch reached about 9,200 t, exceeding the maximum estimate of AMSY by about 10%, but the effort required to make this catch was only about 41×10^7 average hooks. This indicates that catch rates at that time were higher than they would be once the biomass of the population was reduced to that expected at AMSY. Due to the lack of a direct estimate of the abundance of swordfish in the EPO, as well as the lack of biological data necessary to examine estimates and variability of population parameters such as changes in age-specific reproductive capacity, it was not possible to identify whether swordfish in the EPO have high abundance but low productivity, or whether they are relatively low in abundance and high in productivity.

Since 1987 the catch of swordfish in the EPO has steadily increased, reaching about 18,000 t in 1992 and 1993, the last years for which relatively complete catch data are currently available. Estimates of AMSY and OE obtained by us should be used with caution, because the history of declining catch rates along with increasing fishing effort in the EPO provides us with the most tenuous of data series (Hilborn and Walters, 1992) with which to model the dynamics of the swordfish population. Preliminary examination of more recent catch and effort data from the Japanese longline fishery (Uosaki[12]) indicate that catch rates have continued to

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[12] Uosaki, K. 1995. National Research Laboratory of Far Seas Fisheries, Shimizu, Japan. Personal commun.

decline, though they still exceed those to be expected at AMSY, and that AMSY and OE may be slightly higher than the estimates we obtained herein. As the more recent data are finalized, they should be incorporated into analyses of the status of swordfish stocks in the EPO. Until such analyses are completed, it is not possible to estimate the current level of swordfish stocks in the EPO with respect to the level to be expected at AMSY.

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Standardizing Swordfish, *Xiphias gladius*, Longline Catch per Unit of Effort Using General Additive Models

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ABSTRACT

Catch per unit of effort in the Japanese longline fishery for swordfish in the Pacific Ocean was analyzed using General Additive Models (GAM's). Twenty years of catch and effort data were standardized using various GAM's which incorporated variables of time, proportion of swordfish in the catch, and month of catch. Separate analyses were conducted for various areas.

A modeling exercise was conducted to discover whether it is effective to use the proportion of swordfish in the catch as a proxy for targeting of swordfish by the fishery. Results showed that under some systematic trends in abundance of either swordfish or bycatch species, real catch-per-unit-effort trajectories for swordfish were mis-estimated; without independent external data, this method of analysis applied to this data set has a high risk of misinterpretation.

Introduction

The Japanese longline fishery for swordfish in the Pacific Ocean has the broadest combination of spatial and time coverage of all the fisheries catching swordfish. Swordfish in the Japanese longline catch is and has been both a target species and a valuable incidental catch. The Japanese longline catch-and-effort data series is considered to be the most complete single data set covering the range of tunas and billfish in the Pacific and as such has been used to draw inferences on tuna and swordfish stocks (Bartoo and Coan, 1989).

An important feature of the Japanese longline fleet operations is that the target species varies and with it the fishing strategy, such as time of day, time of year, geographic location, depth of set, type of bait, and use of lightsticks. Such factors are highly likely to affect the power of the gear to attract and capture swordfish. However, not all of these factors are reported in the data set. This paper examines the use of proportion of swordfish and other species in the catch as an indicator of targeting, as an approach to standardizing catch per unit of effort (CPUE).

Data Selection

The data used were catch, in number of fish, and effort, in number of hooks, as reported by the Fisheries Agency of Japan (1963–82) for the fishing years 1960–80. The data were summed by 5° × 5° square by month, yielding approximately 60,000 records. Two spatial stratifications of the data were used: a Pacific-wide examination including all areas of catch, and four regions selected because they had fisheries targeting swordfish and were relatively high-catch areas (Bartoo and Coan, 1989; Fig. 1).

CPUE Standardization

The reason for standardizing CPUE is to remove from the data any variation due to effects other than fish abundance. This is usually accomplished by some sort of multivariate statistical technique with CPUE as a dependent variate explained by a suite of independent variates, including time (e.g. Punsly and Deriso, 1991). To the extent that the independent variates other than time account for all variation in CPUE due to things other than variation in abundance and random noise, the time effect estimates the trajectory of abundance in time.

In our analysis we used a general additive model (GAM) technique (Chambers and Hastie, 1992). This technique allows numerical independent variables to

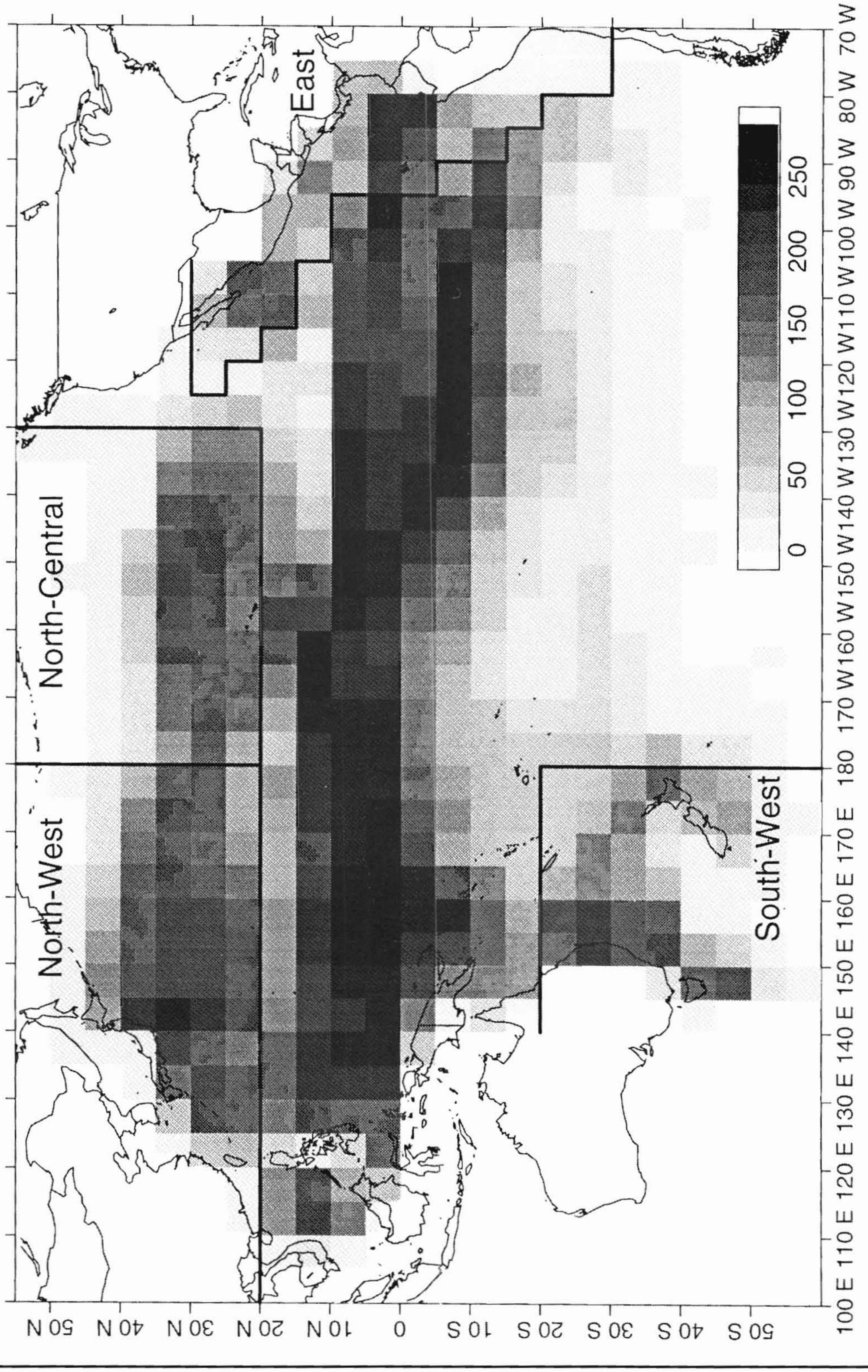

Figure 1
Four regions from which swordfish CPUE data from the Japanese longline fleet were selected for independent GAM analyses. Shading indicates density of longline sets cumulated from 1960 to 1980.

have nonlinear effects on the dependent variable as determined by a smoothing algorithm (Cleveland, 1979). Therefore the effect of an independent variable is not tied to a particular mathematical function but instead is constrained only by the smoothing algorithm.

Our simplest model, in which we entered time as a non-linear variable, is given by

Model 1: $\log(\text{CPUE} + \varepsilon) = a + \text{lo}(t)$

where ε is a small value (0.1) to handle the case where there is zero catch, and lo(t) is a local regression (LOESS; Chambers and Hastie, 1992) smoothing function of time given as the year and decimal fraction thereof (e.g. 85.5 for 1 July 1985). In this and other cases the LOESS functions were of degree 1 and span parameter 0.5.

Because the data do not contain direct information on species targeted, we used a proxy variable consisting of the arcsine transform of the swordfish catch as a proportion of the total catch of tunas and swordfish. The arcsine transform of a variate is the inverse sine of the square root of the variate. It is applied to proportions to spread out the values approaching zero and one, that is, values near the ends of the range of values that a proportion can take (Sokal and Rohlf, 1969). Our second model is given by

Model 2: $\log(\text{CPUE} + \varepsilon) = a + \text{lo}(t) + \text{lo}(P)$

where P is the arcsine transform of the proportion of swordfish in the catch.

To investigate seasonal variability within years, we used a third model given by

Model 3: $\log(\text{CPUE} + \varepsilon) = a + \text{lo}(t) + \text{lo}(P) + \text{factor}(M)$

where factor(M) is the month entered as a categorical (factor) variable. To enter M as a continuous, numerical variable, we would like it to be a circular variable (i.e. with January and December adjacent to each other in the same way as all other pairs of adjacent months). However, we could not find a way to do that with the software we had to work with.

We did not progress to further models with additional independent variables, such as environmental variables, because specific, set-by-set data other than catch were not available. Broader-scale indices could have been used, such as average temperature or the southern oscillation index, but there is a danger that such variables affect swordfish abundance rather than catchability. They would therefore obscure rather than reveal the abundance signal that we wished to elucidate from the CPUE data.

Table 1

Deviance (%) in swordfish CPUE in different areas explained by the models. All tests were significant at $P<0.000001$.

		Deviance explained				
	Test	Northwest	North-central	East	Southwest	Total
Model 1	add lo(t)	2	12	6	4	0.3
Model 2	add lo(P)	66	91	82	84	80
Model 3	add factor(M)	72	93	83	88	81

Standardization Results

We first tried to detect a Pacific-wide abundance trend. Because the whole data set was too large for the software to accommodate in a single analysis, we chose a random subsample of approximately 10% of the records. Using Model 1, which had time as the only independent variate, a gentle, approximately 15-yr cycle was evident (Fig. 2A). The model explained only a small percent of the raw deviance, yet its statistical effect was still significant (Table 1). With Model 2, which added the proxy targeting variable, the temporal effect was smoothed into a steady decline from 1960 to 1980 (Figure 2B). The targeting variable P had a positive effect which leveled off at high values of P (Figure 2C). Thus, as would be expected, CPUE tends to increase with increasing proportion of swordfish in the catch. Repeated subsamplings did not change these results materially.

To allow for the possibility that swordfish abundance in the different regions would vary independently, we conducted separate analyses of 4 regions within the Pacific (Fig. 1). A large number (65%) of the longline records from the tropical regions, where swordfish is not targeted but is retained, were eliminated (Bartoo and Coan, 1989). In this case the software was able to handle all the data in each region. Using Model 1, different patterns of temporal variation were indeed apparent (Fig. 3): an overall declining trend in the northwest and north-central Pacific, a rising trend in the southwest Pacific, and a rise followed by a fall in the northeast Pacific. Under Model 2, the addition of our proxy variable for targeting changed the picture somewhat (Fig. 4). The temporal effect was flattened and the span (maximum – minimum) was reduced, particularly in the north-central and the southwest regions. Model 2 showed a more or less decreasing time trend in all

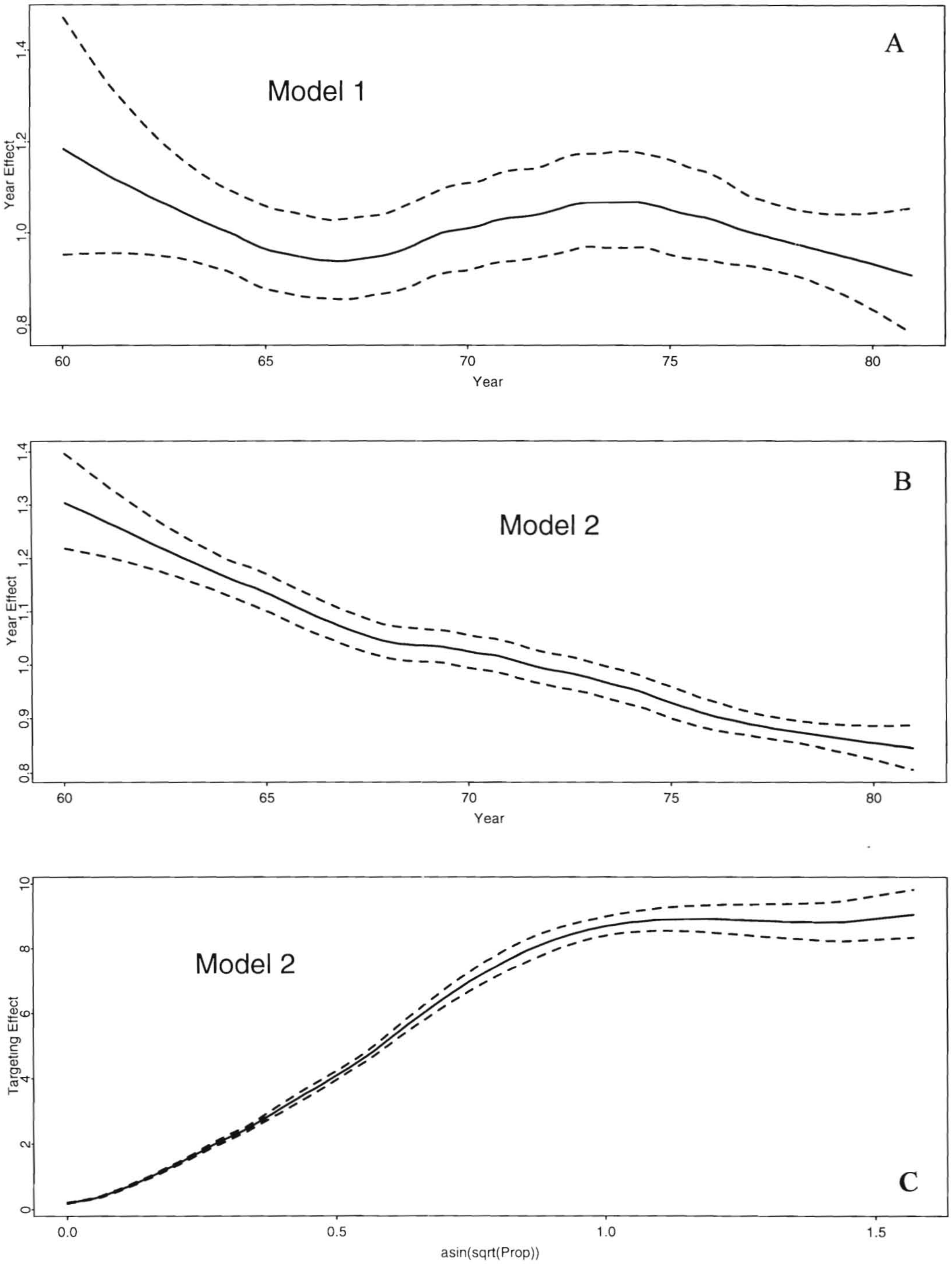

Figure 2

Results from GAM analysis of a random subsample of swordfish CPUE data from the Japanese longline fleet, 1960–80. (A) year effect with Model 1; (B) year effect with Model 2; (C) effect of proxy targeting variable with Model 2. Dashed lines indicate ± 2 standard errors.

regions from 1960 to 1980, the trend in the southwest region being the reverse of that shown in Model 1.

The functional effect of the proxy targeting variable *P* was monotone increasing in all regions except in the

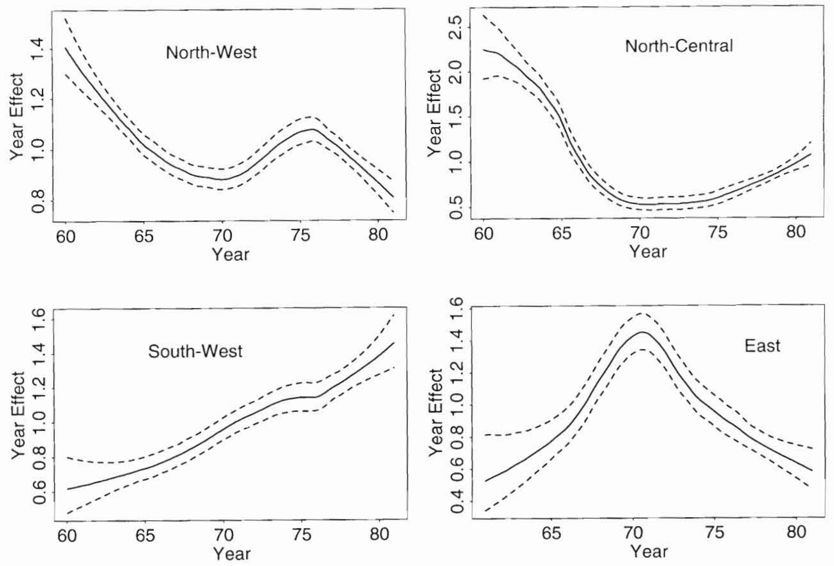

Figure 3
Year effects in four regions analyzed independently under Model 1. Dashed lines indicate ± 2 standard errors.

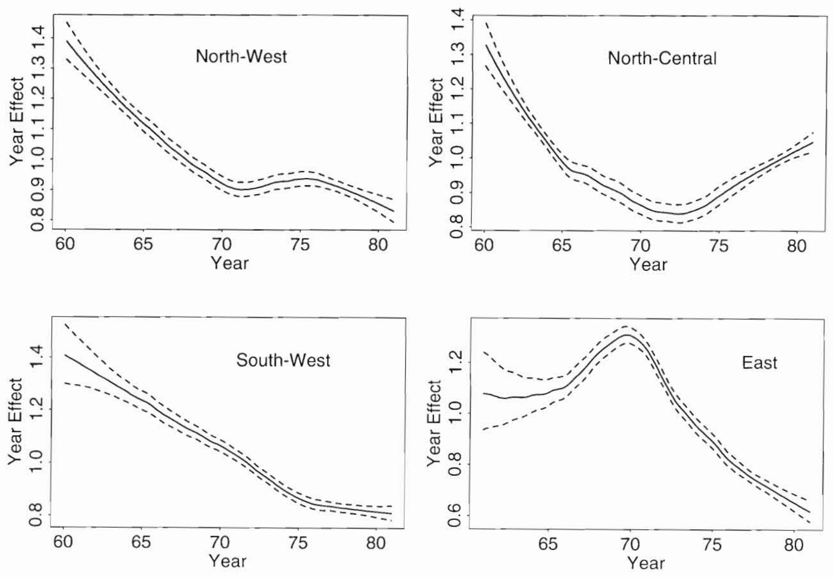

Figure 4
Year effects in four regions analyzed independently under Model 2. Dashed lines indicate ± 2 standard errors.

northwest, which showed a downward trend for high values of P (Fig. 5). In all cases the targeting effect was more pronounced over the range examined than the effect of time over 20 yr.

When residuals were plotted around the time function for Model 1 in the northwest region (Fig. 6), it was obvious that very little of the deviance in the data is explained by the model, as is true for all the regions

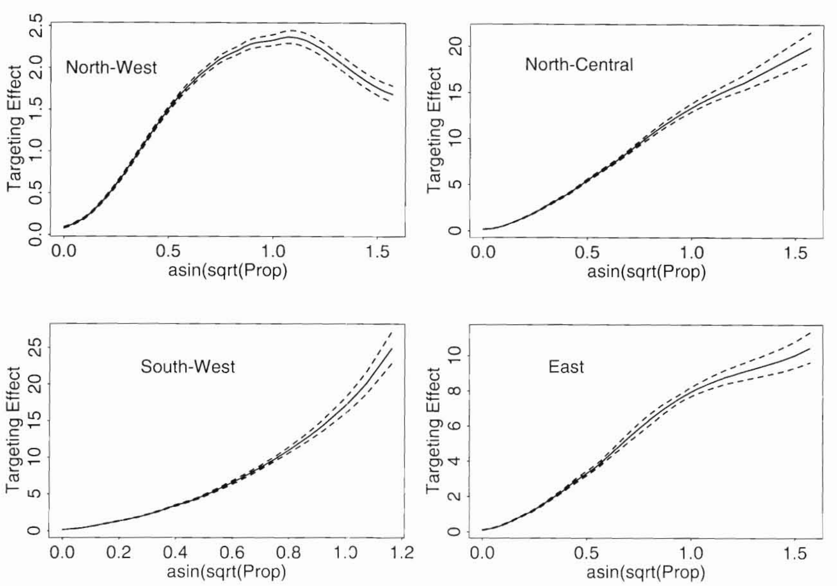

Figure 5

Effects of proxy targeting variable in four regions analyzed independently under Model 2. Dashed lines indicate ± 2 standard errors.

(Table 1). The model fit was still significant statistically, due to the large number of data points, for all regions but the southwest. With addition of the targeting variable (Model 2), much more deviance was explained by the model, between 66% and 91% (Table 1), and the span of the residuals was reduced by 3 orders of magnitude in the northwest (Fig. 6). Seasonality in the residuals was also revealed, which was not picked up by the time-effect function, lo(*t*). We could have attempted to capture this variability by setting the LOESS span parameter to a much smaller value than 0.5. However, we chose to let lo(*t*) focus on interannual variability, and added a month variable (Model 3) which accounted for most of the seasonality and reduced the span of residuals by another order of magnitude (Fig. 6). The month effect showed a minimum in the summer and a maximum in the winter in the northwest region; the basic shapes of the time-effect and targeting-effect functions in Model 3 were not appreciably different from Model 2 (Fig. 7; cf. Fig. 4, 5).

For the north-central and southwest regions, similar results to those in Figures 6 and 7 were observed in the reduction of the span of residuals when progressing from Model 1 to 2 to 3, and in the seasonality revealed by Model 2 residuals and captured by the month effect in Model 3. As would be expected, seasonality in the southwest was 6 mo. out of phase with the two northern regions. As expected for a region that spans the equator, the eastern region revealed no seasonality. Therefore in this case there was no reduction in span of residuals by Model 3 beyond that achieved by Model 2.

Simulation Modeling

An important question about our analyses is whether the proxy targeting function is really doing its job. Ideally this function would be sensitive only to the relative emphasis that fishermen are putting on catching swordfish rather than other target species. While the proportion of swordfish in the catch would seem to reflect the targeting of swordfish relative to other species, it would also be expected to reflect the abundance of swordfish relative to other species.

With a simple simulation model, we investigated this and other possible problems inherent in a proxy targeting variable that uses catch of other species. The model produces synthetic CPUE data for swordfish and for an alternate, non-target species which is a composite of all tuna species caught. In the model, 2,500 fishing sets are distributed throughout 20 yr of simulated time, the date of each set being randomly chosen from a uniform distribution. For each set a random choice is made, according to a probability level, *sprob*, which is the probability that a set targets swordfish. The value of *sprob* can either be held constant or can be varied with the date of the set. The mixture of swordfish and non-swordfish sets, therefore, is either more or less constant (being

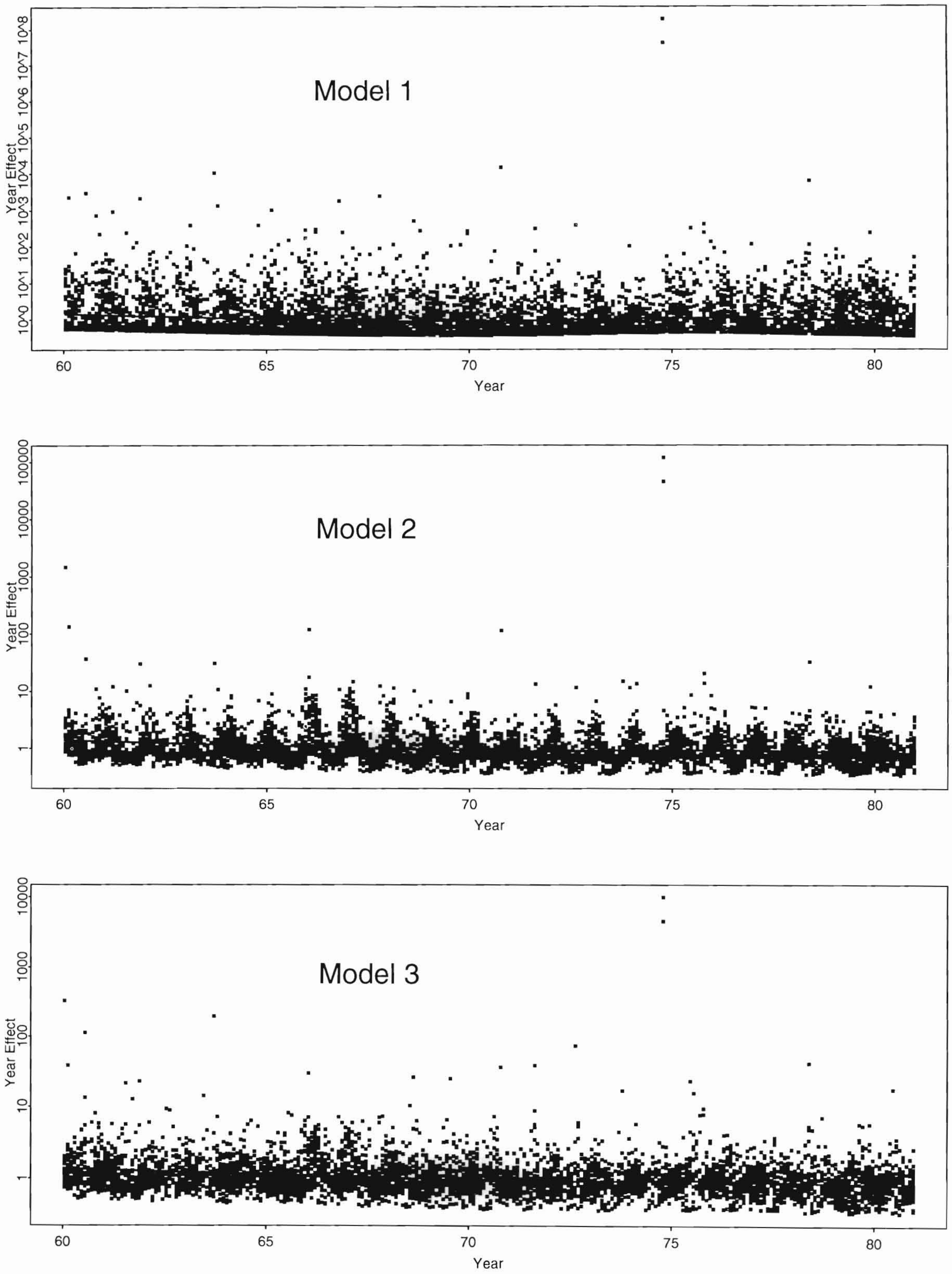

Figure 6

Time effect shown by residuals in northwest region under (from top to bottom) Models 1, 2, and 3.

subject to stochastic variation) or it has additional variation with time governed by the variation in *sprob*. The catchability of swordfish is assumed to be 100 times greater for swordfish sets than for non-swordfish sets, whereas the composite catchability of other species is assumed to be twice as great for non-swordfish sets than

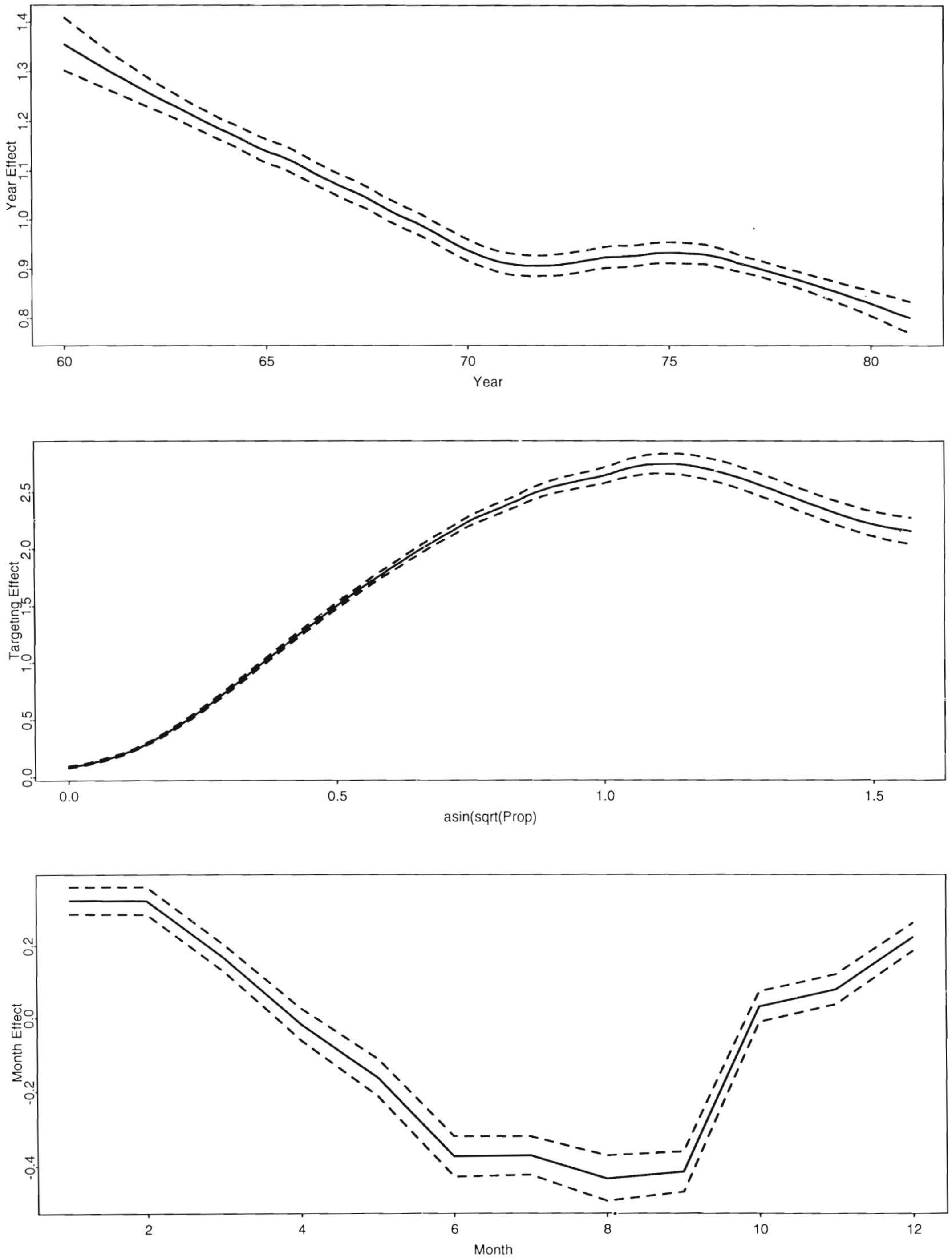

Figure 7

Year, targeting, and month effects in northwest region under Model 3. Dashed lines indicate ± 2 standard errors.

for swordfish sets. The milder response of the composite (other) species catchability to targeting reflects the assumption that some other species are likely to be more vulnerable to swordfish sets and some to non-

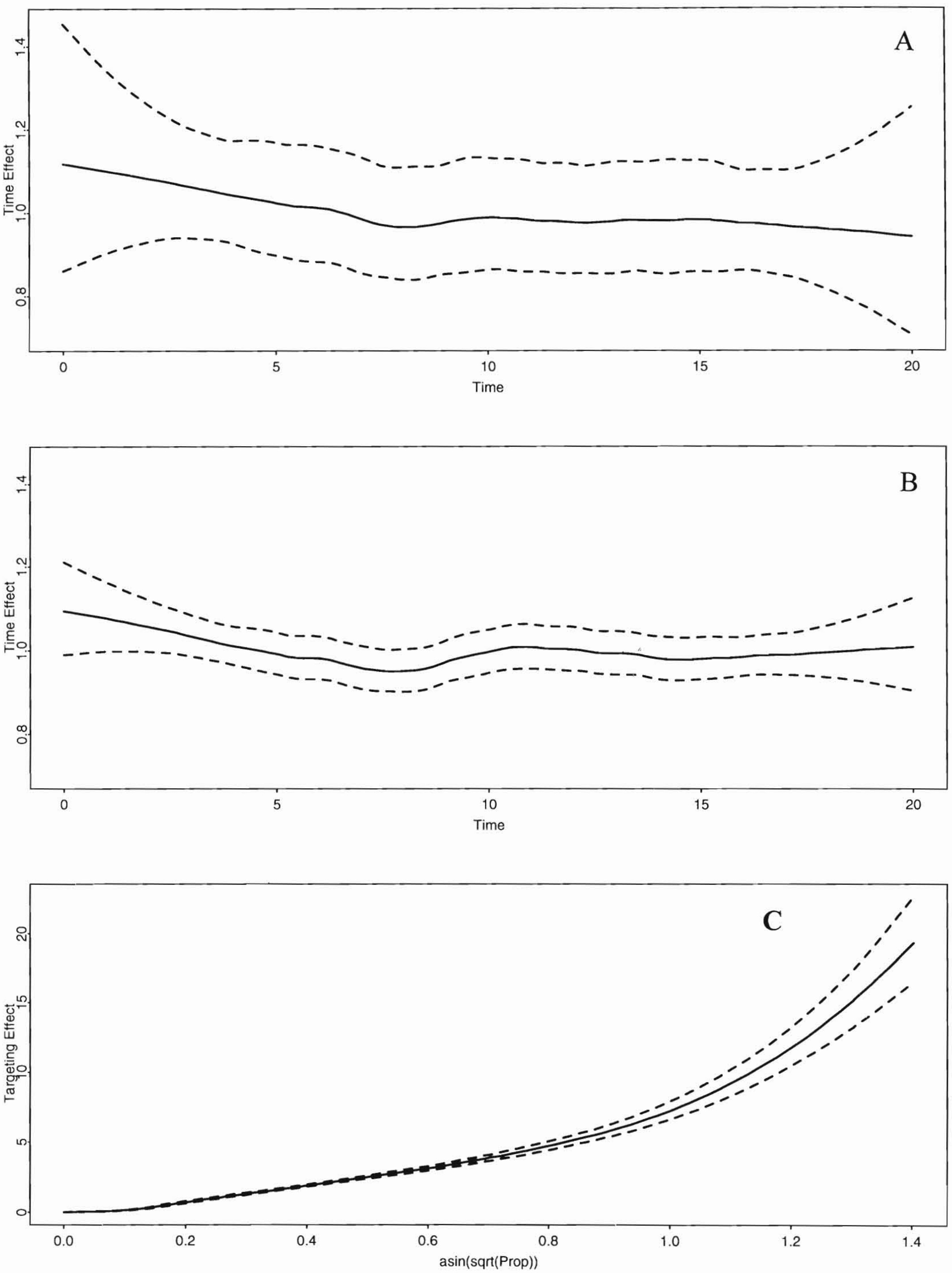

Figure 8

GAM analysis of simulated data with constant abundance of swordfish, constant abundance of other species, and constant targeting probability. (A) Year effect under Model 1; (B) year effect under Model 2; (C) effect of proxy targeting variable under Model 2. Dashed lines indicate ± 2 standard errors.

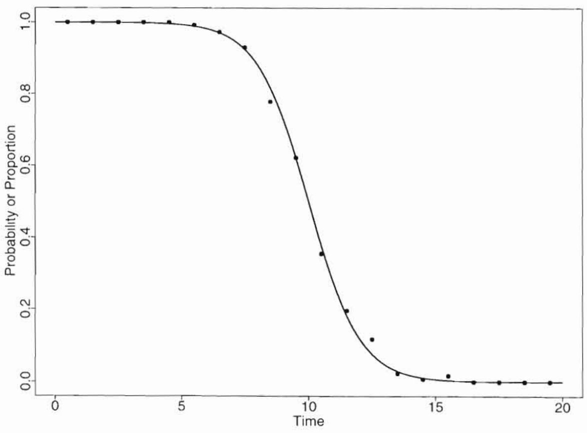

Figure 9

Targeting probability, *sprob*, as a function of time in a GAM analysis of simulated data. Points are actual proportions of sets chosen to target swordfish by 1-yr intervals in one of the simulations.

swordfish sets. Both catchabilities are subjected to lognormal stochastic error. The abundance of either swordfish or the composite (other) species can be held constant or forced to follow any arbitrary trajectory in time. The synthetic data consist of catches (catchability times abundance) of swordfish and other species for each set.

We produced synthetic data sets for a variety of combinations of variability in swordfish abundance, other fish abundance, and swordfish targeting probability, *sprob*. The data sets were then subjected to Model 1 and Model 2 GAM analyses. We did not trouble with Model 3 because we were interested in interannual rather than seasonal variability.

Figure 8 shows GAM results for a situation in which swordfish abundance, other fish abundance, and *sprob* are all held constant. Though the time effects in both Model 1 and Model 2 are not completely flat, attention to the confidence regions shows little indication of a time trend in swordfish abundance in either case. However, the width of the confidence region is reduced in Model 2, reflecting an innate correlation between the dependent variable (swordfish CPUE) and the targeting variable due to the fact that swordfish catch is used in calculating both variables.

To investigate the effect of a change in targeting we forced the targeting probability, *sprob*, to vary with time as in Figure 9. The proportion of sets chosen to target swordfish is also shown for each year. The GAM results for this situation (Fig. 10) show a dramatic drop in apparent swordfish abundance under Model 1, as would be expected. The addition of the targeting variable in Model 2 only partially accounts for the change in targeting. Thus even in this ideal situation, that is, no changes in the abundance of other species, the proxy targeting variable is only partially successful in correcting a false drop in apparent swordfish abundance.

When the abundance of other fish change over time, the problems are even worse. Figure 11 shows GAM results from a scenario in which swordfish abundance is constant, and targeting is constant, but the abundance of other species drops by a factor of 10 over the 20 yr of simulation. The Model 1 results show some variation, but within the confidence region. However, the time effect in Model 2 indicates a dramatic drop in apparent swordfish abundance. In this case the proxy variable creates a false drop in apparent swordfish abundance that did not exist without the proxy variable.

From these results and the results of many other simulations, it is evident that is it possible to simulate almost any scenario of misleading indications of trends in fish abundance from CPUE data, with or without standardization using a proxy targeting variable. Therefore it is clear that there is very limited information about targeting contained in data on the proportion of different species in the catch.

Discussion

In order to standardize swordfish CPUE, we wanted to account for variation in fishing strategy that targets fishing effort either toward swordfish or toward other species. We used the proportion of swordfish in the catch as a proxy variable for targeting, but our modeling results show that it cannot be relied upon to correct for targeting effects in the CPUE time series. Therefore the declining overall swordfish CPUE (Fig. 2) cannot be unequivocally interpreted as indicating a decline in swordfish abundance. Our analyses of separate regions eliminated much of the non-swordfish longline effort in equatorial regions, but the fisheries in those regions remained multi-species fisheries. Some measure of confidence might be taken in results for three of the regions from the fact that the patterns of variation in time are essentially identical with and without the targeting variable (Fig. 3, 4). However, given the simulation results, caution is called for, and the reversal in the time trend for the southeast region depending on the model used must be viewed with extreme caution. The fact that the targeting variable was able to greatly reduce the residual deviances (Fig. 6) could in large part be due to the inherent correlation between swordfish CPUE and the targeting variable.

To adequately analyze catch and effort data from multi-species fisheries such as the Japanese longline fleet, there is a great need for information that is directly relevant to targeting, e.g. depth of set, time of day, and use of light sticks. Provision for such data on

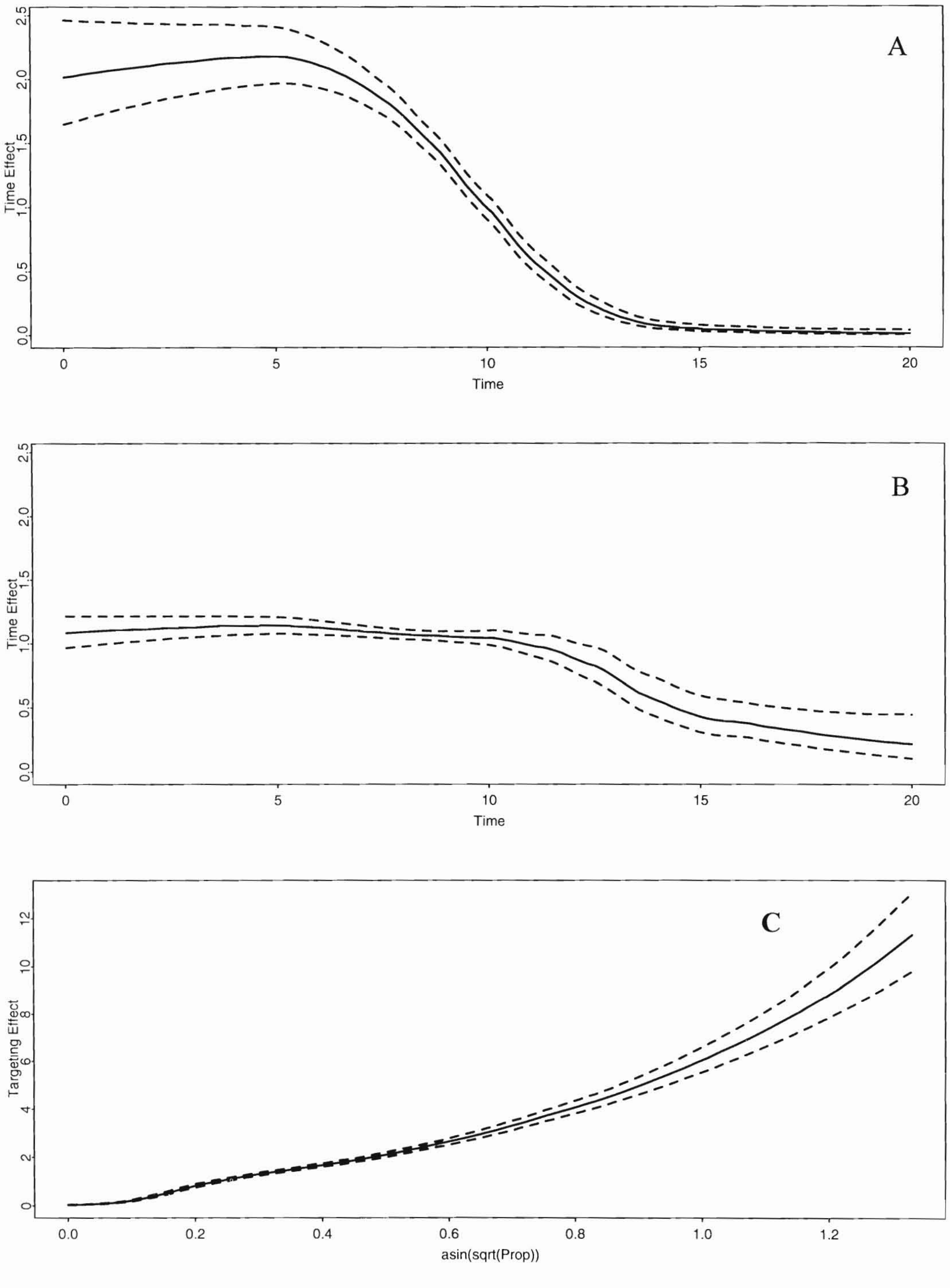

Figure 10

GAM analysis of simulated data with constant abundance of swordfish, constant abundance of other species, and declining targeting probability. (A) Year effect under Model 1; (B) year effect under Model 2; (C) effect of proxy targeting variable under Model 2. Dashed lines indicate ± 2 standard errors.

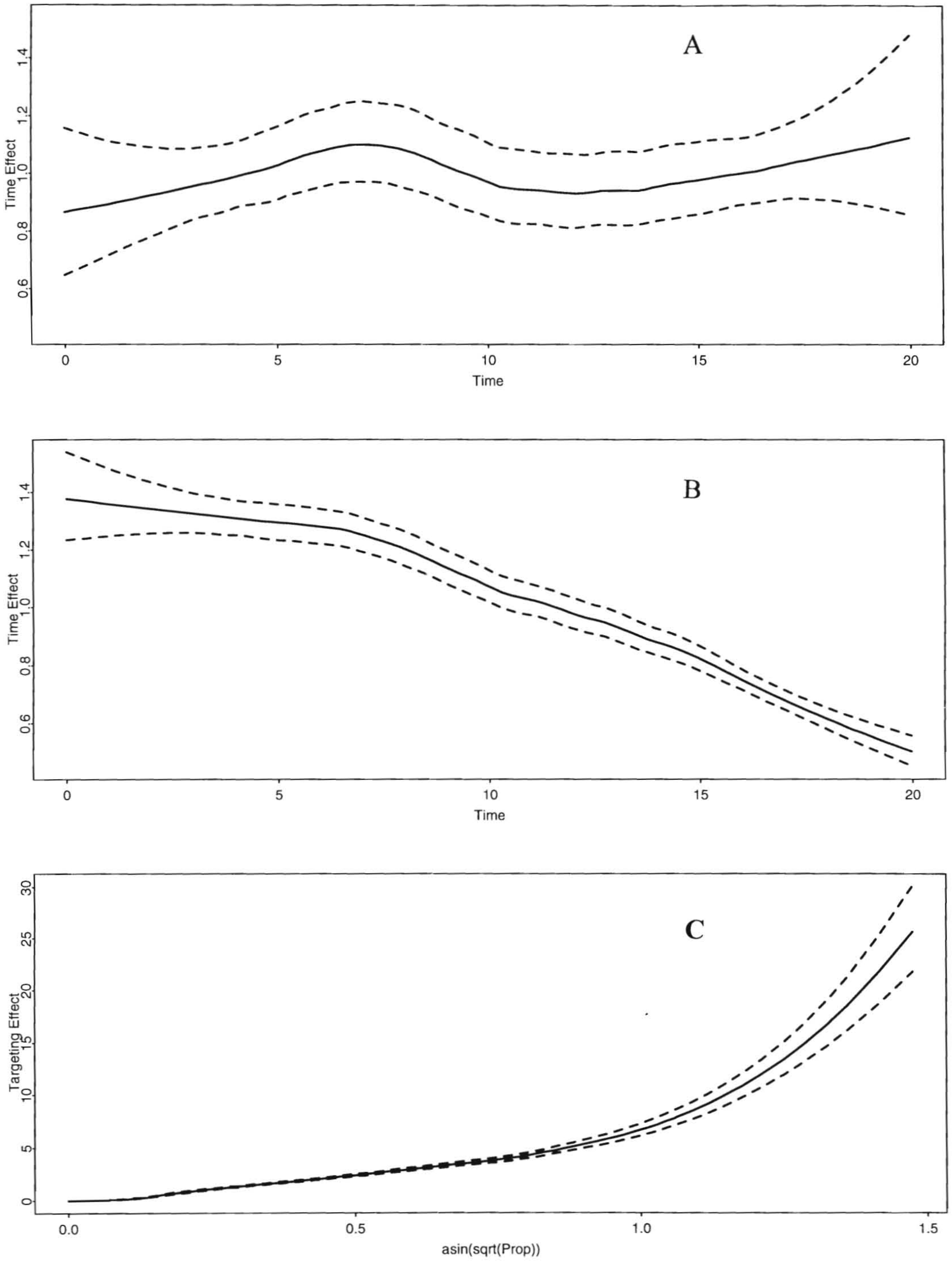

Figure 11

GAM analysis of simulated data with constant abundance of swordfish, declining abundance of other species, and constant targeting probability. (A) Year effect under Model 1; (B) year effect under Model 2; (C) effect of proxy targeting variable under Model 2. Dashed lines indicate ± 2 standard errors.

log sheets will improve the future situation, but will not fix the existing published time series. Because these time series cover extended time periods (20–30 yr) they are potentially of great value, but they would be immensely more valuable if accompanied by targeting data. It may be the case that unpublished (and not computer-encoded) data relevant to targeting is stored away in attics or basements somewhere. Though difficult and time consuming, a data "rescue" effort among fusty shoe boxes and the like might be highly rewarding.

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Stock Status of Pacific Swordfish, *Xiphias gladius*, Inferred from CPUE of the Japanese Longline Fleet Standardized Using General Linear Models

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ABSTRACT

Swordfish catch has increased significantly in recent years in the Pacific Ocean. The Japanese longline fishery is the largest fishery for swordfish in the Pacific in terms of catch, although swordfish is a secondary target species. The historical fishing grounds, seasons, and gear of the Japanese longline boats have changed in response to shifts in target species and fishing strategies of the fishermen. Standardized swordfish catch per unit of effort (CPUE) of the Japanese longline fishery was analyzed for three hypothetical stocks: North Pacific, southwest Pacific, and southeast Pacific, using a Generalized Linear Model. The factors considered in the model were year, season, area, gear configuration, and target species. CPUE decreased over time in the North and southeast Pacific, and increased in the southwest Pacific. In the southeast Pacific, the catch increased from 2,000 to 10,000 metric tons in recent years, while CPUE declined 30%.

Introduction

Swordfish, *Xiphias gladius,* is a large pelagic species found in tropical, subtropical, and temperate waters of the world oceans and adjacent seas (Nakamura, 1985). The world catch of swordfish increased from about 30,000 metric tons (t) in the late 1960's to about 70,000 t in the late 1980's (FAO, 1961–93). In the Pacific Ocean, the swordfish catch increased from about 10,000 t in 1952 to 25,000 t in 1962, then decreased to 10,000 t in 1964 (Fig. 1). Catches have since increased, reaching about 34,000 t in 1993. The recent rapid increase in catch was due to Chile and Mexico (Barbieri et al., 1994; Holts and Sosa-Nishizaki, 1994). The United States catch also increased following a shift of fishing effort from the Atlantic to the Pacific due to fishery restriction in the Atlantic by the International Commission for the Conservation of Atlantic Tunas (Holts and Sosa-Nishizaki, 1994). Thus, concern is appropriate for the status of swordfish stocks in the Pacific, where the relevant information is poor.

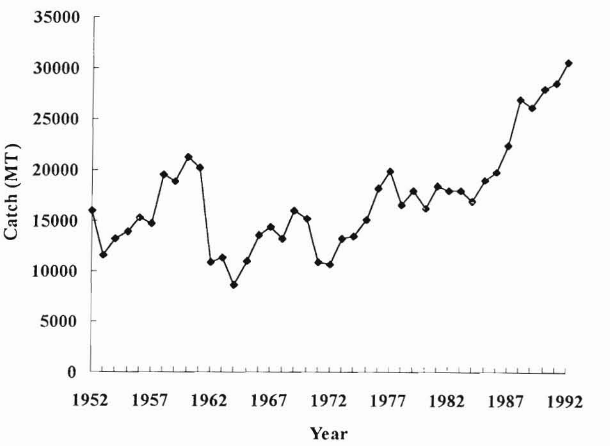

Figure 1
Annual swordfish catch in the Pacific in metric tons, 1952–92.

Since the Japanese catch of swordfish has historically been the largest portion of total swordfish catch in the Pacific Ocean, previous researchers have used Japanese longline catch rates as indices of swordfish abundance (Sakagawa and Bell, 1980; Bartoo and Coan, 1989). Sakagawa and Bell (1980) reported on the condition of swordfish stocks in the Pacific using Japanese longline data and equilibrium-production model analysis for both a single Pacific-wide stock and for a three-stock hypothesis. They concluded that the stock was not overexploited. Bartoo and Coan (1989) revised this stock assessment using updated Japanese longline data and reached the same conclusion, i.e. none of the examined data indicated too-heavy exploitation. This analysis was conducted using updated Japanese catch and effort data, and examines the hypothesis that recent increases in catch have impacted the stocks.

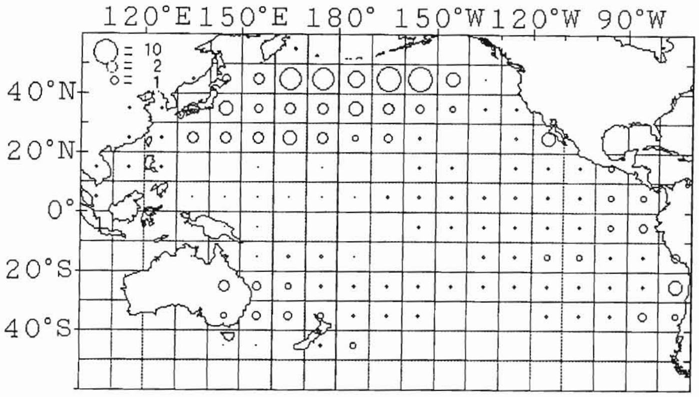

Figure 2
Average swordfish CPUE (number caught per 1,000 hooks) from Japanese longline data, 1952–92.

Materials and Methods

Stock Structure

The stock structure of swordfish in the Pacific Ocean is not well known. Sakagawa and Bell (1980) first suggested two hypotheses based on the distributions of larvae and of the long-term annual mean catch rates of the longline fishery. Those hypotheses were 1) a single, Pacific-wide stock, and 2) three separate stocks with centers of concentration in the northwest, southwest, and east Pacific Ocean. For reference, the average distribution of unstandardized catch per unit of effort (CPUE) of swordfish taken by the Japanese longline fishery is shown in Figure 2. Sosa-Nishizaki and Shimizu (1991) examined the spatial distribution of monthly mean CPUE for swordfish, and proposed four stocks in separate regions of the Pacific: 1) off Japan, in the northwest and central Pacific, 2) off the Baja California Peninsula, 3) off the west coast of South America, and 4) off the east coast of Australia and north of New Zealand. The principal difference from the Sakagawa and Bell (1980) hypothesis is that the four-stock hypothesis divides the eastern Pacific into northern and southern regions. Recent genetic analyses of swordfish indicate that Atlantic and Pacific stocks differ, and also suggest that there is no genetic separation between the northern and other Pacific stocks (Chow[1]). Furthermore, the CPUE for the presumed single stock (Sakagawa and Bell, 1980) was similar to trends in CPUE from the northwestern Pacific, due to overwhelming data from the large Japanese swordfish fishery there. Therefore, three stock units are assumed here: 1) a North Pacific stock in the area north of 10°N, 2) a southwest stock ranging south of 10°N and west of 140°W, and 3) a southeast stock, in the area south of 10°N and east of 140°W. Even if there is only one southern stock, division of the South Pacific into smaller regions will serve to monitor local depletion, which is important in light of the rapidly increasing catches in the southeast Pacific.

Standardization of CPUE

For the Japanese longline fishery operating in the Pacific, the major target species were yellowfin, *Thunnus albacares,* and albacore, *T. alalunga,* tunas in the early period and more recently bigeye, *T. obesus,* and southern bluefin, *T. maccoyii,* tunas. With the exception of a very few vessels which target swordfish (Uozumi and Uosaki, 1998), swordfish is not the target of the longline fishery, but it is an important component of the catch. Nominal swordfish CPUE of the Japanese longline fishery probably has been affected by historical and seasonal changes of fishing grounds, fishing gear, and target species. Therefore, it is difficult to interpret it as an index of stock abundance without standardization for various factors.

The General Linear Model (GLM) (Draper and Smith, 1966) approach to analysis of variance is used to obtain standardized abundance indices. Robson (1966) was the first to use a GLM for standardization of fishing effort. Gavaris (1980) first published this application in a readily-accessible journal; Allen and Punsly (1984) and Punsly (1987) describe the method in detail.

The logbook data of the Japanese longline fishery as compiled by the National Research Institute of Far Seas Fisheries (NRIFSF) were used for the analysis. These data cover more than 90% of the total number of sets, and include information on year, month, day, location, number of hooks, and swordfish catch in number until

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Table 1

Independent variables in General Linear Models used to standardize swordfish CPUE from the Japanese longline fleet. YR = year, QT = quarter, AR = area, SP = species targeted, BET = bigeye tuna, ALB = albacore, YFT = yellowfin.

1952–75					1975–92				
Variable	Mean	Range	Units	Type	Variable	Mean	Range	Units	Type
North Pacific									
YR	63.5	52–75	year	class	YR	79.2	75–92	year	class
QT	2.5	1–4	quarter	class	QT	2.5	1–4	quarter	class
AR	5.5	1–10	5° × 5°	class	AR	4.5	1–8	5° × 5°	class
SP(BET)	2.5	1–4	log (CPUE + 1)	class	GEAR	2.5	1–4	hooks per basket	class
SP(ALB)	2.5	1–4	log (CPUE + 1)	class	SP(BET)	2.5	1–4	log (CPUE + 1)	class
SP(YFT)	2.5	1–4	log (CPUE + 1)	class	SP(ALB)	2.5	1–4	log (CPUE + 1)	class
					SP(YFT)	2.5	1–4	log (CPUE + 1)	class
Southwest Pacific									
YR	63.5	52–75	year	class	YR	79.2	75–92	year	class
QT	2.5	1–4	quarter	class	QT	2.5	1–4	quarter	class
AR	4	1–7	5° × 5°	class	AR	3	1–5	5° × 5°	class
SP(BET)	2.5	1–4	log (CPUE + 1)	class	GEAR	2.5	1–4	hooks per basket	class
SP(ALB)	2.5	1–4	log (CPUE + 1)	class	SP(BET)	2.5	1–4	log (CPUE + 1)	class
SP(YFT)	2.5	1–4	log (CPUE + 1)	class	SP(ALB)	2.5	1–4	log (CPUE + 1)	class
					SP(YFT)	2.5	1–4	log (CPUE + 1)	class
Southeast Pacific									
YR	63.5	52–75	year	class	YR	79.2	75–92	year	class
QT	2.5	1–4	quarter	class	QT	2.5	1–4	quarter	class
AR	2	1–3	5° × 5°	class	AR	2.5	1–4	5° × 5°	class
SP(BET)	2.5	1–4	log (CPUE + 1)	class	GEAR	2.5	1–4	hooks per basket	class
SP(ALB)	2.5	1–4	log (CPUE + 1)	class	SP(BET)	2.5	1–4	log (CPUE + 1)	class
SP(YFT)	2.5	1–4	log (CPUE + 1)	class	SP(ALB)	2.5	1–4	log (CPUE + 1)	class
					SP(YFT)	2.5	1–4	log (CPUE + 1)	class

1975. Additional information on fishing gear was added beginning in 1975, because fishermen began to change their gear configuration, e.g. the number of hooks between floats (Suzuki et al., 1977), to target deep-swimming bigeye tuna. Since then the Japanese fishermen have tended to set their hooks deeper and deeper each year.

Thus two data sets were used for this analysis. One consisted of data aggregated by year, month, and 5° square, extrapolated to 100% coverage for 1952–75 (raised data). The other consisted of data aggregated by month and 5° square, and included the number of hooks between floats, for 1975–92 (unraised data). In general, the greater the number of hooks, the deeper the depth of the hooks. For considering historical trends in CPUE, both data sets were used by adjusting the results of unraised data in 1975 to the results of raised data in the same year. CPUE was calculated as catch in number of fish per 1,000 hooks. Strata with fewer than 20,000 hooks (raised data) and 3,000 hooks (unraised data) were arbitrarily excluded from the analysis to avoid possible problems created by small sample sizes. Japanese longline fisheries usually use 2,000 to 3,000 hooks per set; fewer hooks represent fewer sets.

The model used for this analysis was

$$\mathrm{CPUE}_{ijklm} = \mu \times \mathrm{YR}_i \times \mathrm{QT}_j \times \mathrm{AR}_k \times \\ \mathrm{GEAR}_l \times \mathrm{SP}_m \times \mathrm{INTER} \times \varepsilon$$

where CPUE_{ijklm} is the catch rate obtained in year i, quarter j, area k, and gear class l, for target species m; μ is the overall mean catch rate; YR_i is a year factor; QT_j is a season factor; AR_k is an area factor; GEAR_l is a gear factor; SP_m is a factor of target species; INTER is any combination of 2-way interaction terms between main effects; and ε is a $N(0, \sigma^2)$ error term.

Taking natural logarithms of both sides, we obtain the linear statistical model

$$\ln \mathrm{CPUE}_{ijklm} = \ln \mu + \ln \mathrm{YR}_i + \ln \mathrm{QT}_j + \ln \mathrm{AR}_k + \\ \ln \mathrm{GEAR}_l + \ln \mathrm{SP}_m + \ln \mathrm{INTER} + \ln \varepsilon.$$

In order to include strata in which there was fishing effort but no catch of swordfish, (CPUE + 1) was used instead of observed CPUE. The mean, range, units of measure, and type of variables used in the model are summarized in Table 1. Main effects of the model in-

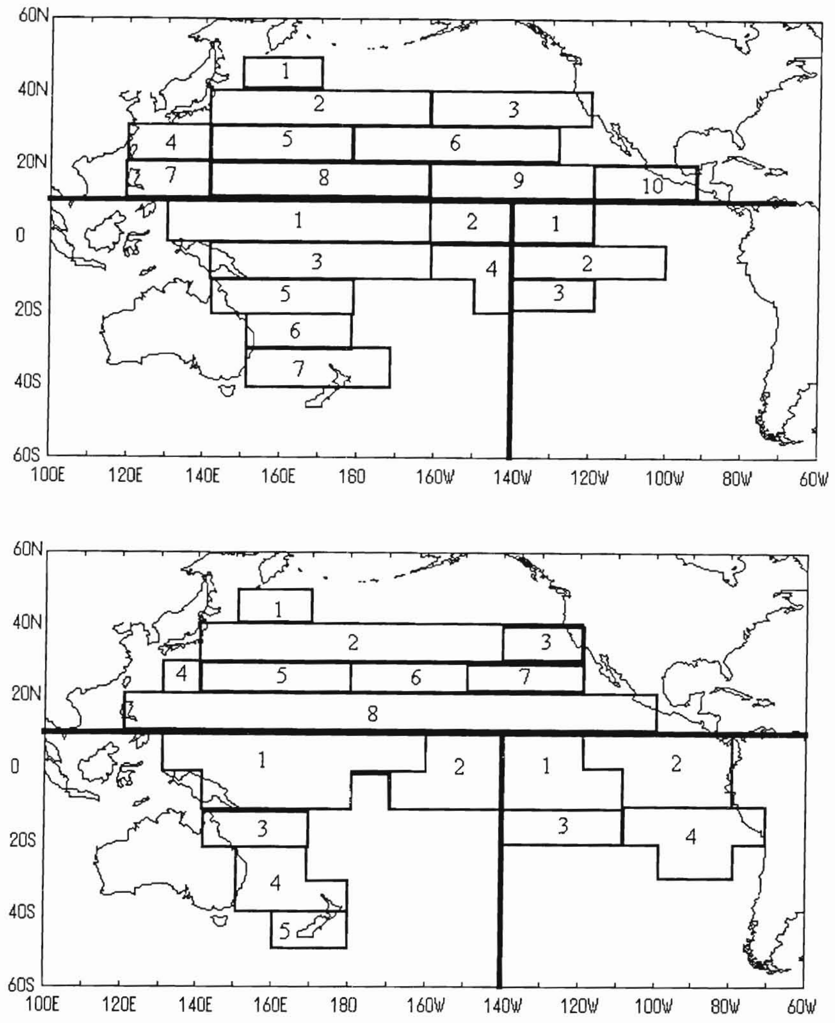

Figure 3

Geographical areas used in this analysis of northern, southwest, and southeast Pacific swordfish stocks during 1952–75 (above) and 1975–92 (below.)

clude year, quarter, area, and log-transformed CPUE of bigeye, albacore, and yellowfin tuna for 1952–75. Log-transformed CPUE was categorized into four levels (CPUE = 0, 0 < CPUE < 1.0, 1.0 ≤ CPUE < 2.0, and CPUE ≥ 2.0)

Hoey et al. (1989) used the proportion of swordfish catch to total catch in U.S. swordfish fishery statistics as a main effect in standardizing North Atlantic swordfish CPUE, since the U.S. swordfish fishery is a mixed species fishery targeted on various species. Miyabe (1994) used log-transformed CPUE of other species as a by-catch effect to obtain standardized CPUE of Atlantic bluefin tuna from Japanese longline fishery statistics. Since swordfish is a sub-target species for the Japanese longline fishery in the Pacific Ocean, log-transformed CPUE's of other species were used in this analysis as a main effect to account for targeting.

Based on mean swordfish CPUE levels, the three stock areas were divided into ten and eight geographical blocks in the North Pacific, seven and five blocks in the southwest Pacific, and three and four blocks in the southeast Pacific for 1952–75 and 1975–92, respectively (Fig. 3). Differences among the blocks are mainly due to the different fishing grounds of the Japanese longline fishery in the two periods. Gear configuration, taken as the number of hooks between floats, was included as an additional main effect for the data of 1975–92. Sets with 4–20 hooks between floats were observed in the data. Following Uozumi and Nakano (1994), these were categorized into 4 levels: 4–7, 8–11, 12–15, and 16–20 hooks between floats, to avoid problems created by lack of information in the data set. All GLM analyses were made using SAS version 6.08 (SAS, 1989).

Results and Discussion

Final Models

Forward stepwise regression and the value of the squared multiple correlation were used to select the best models. After several trials, the final model and combination of factors for north, southwest, and southeast stocks were chosen. For all stocks during 1952–75, the factors included in the final models were

$$\ln(\mathrm{CPUE}+1) = \mathrm{YR} + \mathrm{QT} + \mathrm{AR} + \mathrm{SP(BET)} + \mathrm{SP(ALB)} + \mathrm{SP(YFT)} + \mathrm{QT} \times \mathrm{AREA} + \varepsilon$$

and for 1975–92:

north: $\ln(\mathrm{CPUE}+1) = \mathrm{YR} + \mathrm{QT} + \mathrm{AR} + \mathrm{GEAR} + \mathrm{SP(BET)} + \mathrm{SP(ALB)} + \mathrm{SP(YFT)} + \mathrm{QT} \times \mathrm{AREA} + \varepsilon$

southwest: $\ln(\mathrm{CPUE}+1) = \mathrm{YR} + \mathrm{QT} + \mathrm{AR} + \mathrm{GEAR} + \mathrm{SP(BET)} + \mathrm{SP(ALB)} + \mathrm{SP(YFT)} + \mathrm{QT} \times \mathrm{SP(YFT)} + \varepsilon$

southeast: $\ln(\mathrm{CPUE}+1) = \mathrm{YR} + \mathrm{QT} + \mathrm{AR} + \mathrm{GEAR} + \mathrm{SP(BET)} + \mathrm{SP(ALB)} + \mathrm{SP(YFT)} + \mathrm{QT} \times \mathrm{AREA} + \varepsilon.$

Interactions including year, e.g. YR × AREA or YR × QT, were not examined due to insufficient data. These interactions should be considered in future research if data become available.

The results of the ANOVA indicated that all final models were statistically significant (Table 2–4). The squared multiple correlations in the final models were 0.53 and 0.47 for the north, 0.45 and 0.39 for the southwest, and 0.32 and 0.20 for the southeast for 1952–75 and 1975–92, respectively, which means that the models explain 53%–20% of the variability in the data. It is possible that other factors not included in the model may explain the rest of the variability. Histograms of overall distributions of standardized residuals for the final models are not extremely different from normal distributions (Fig. 4).

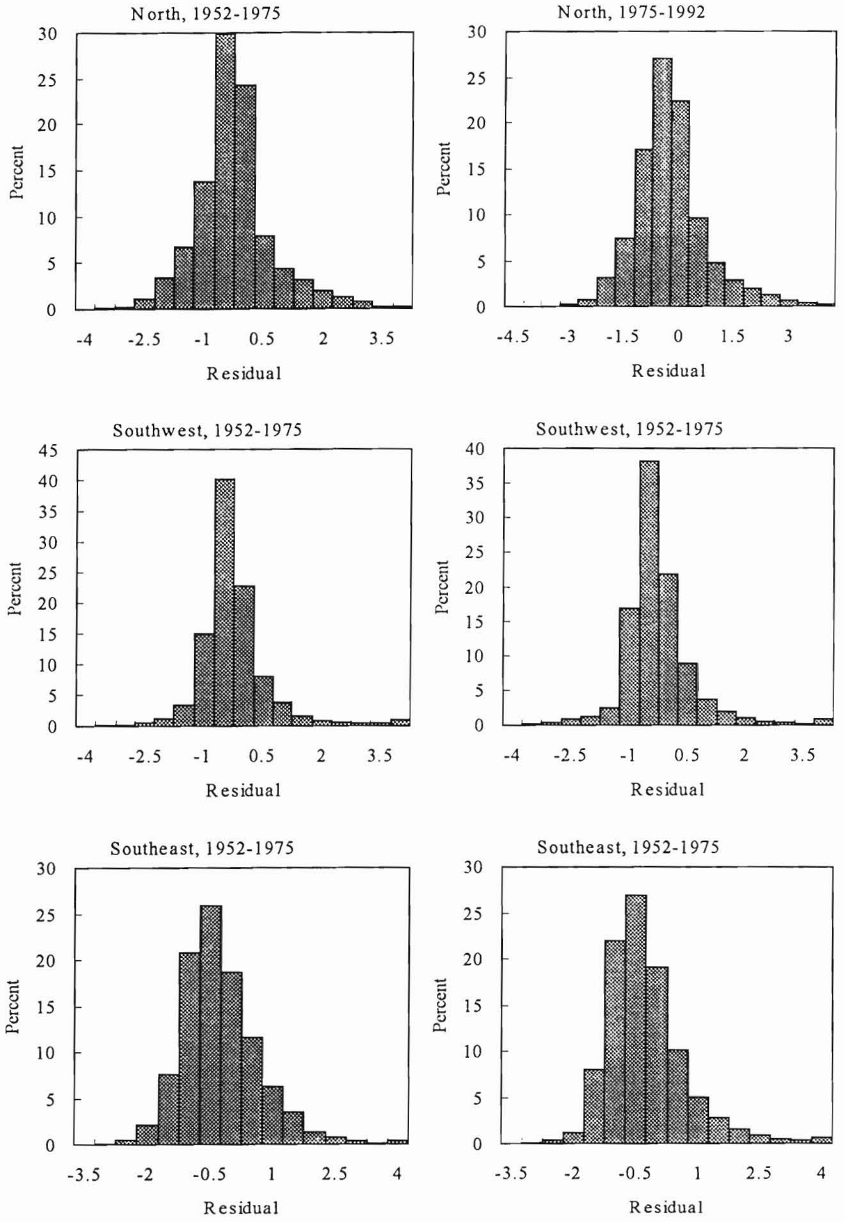

Figure 4

Distribution of standardized residuals from the fitted models for each swordfish stock and time period.

Assessment of Effects

Standardized CPUE at the four levels of each main effect for the North Pacific stock is shown in Figure 5. Main effects and interactions were statistically significant in the final model (Table 2). Seasonal differences were observed in the standardized CPUE for both time periods: the first quarter had the highest CPUE, and the third had the lowest. In areas 1, 2, and 5, east of

Table 2

Results of the ANOVA for the North Pacific swordfish stock.

1952–75

Source	DF	Sum of squares	Mean square	*F*	*P>F*
Model	71	2,253.772	31.74327	184.81	0.0001
Error	11,457	1,967.832	0.17176		
Corrected total	11,528	4,221.605			

Squared multiple correlation= 0.533866 C.V. = 0.80772 Root MSE = 0.41444 Mean = 0.51309

Source	DF	Type III SS	Mean square	*F*	*P>F*
YR	23	79.7177	3.46595	20.18	0.0001
QT	3	27.0770	9.02565	52.55	0.0001
AR	9	353.2747	39.25274	228.54	0.0001
SP(ALB)	3	33.1365	11.04549	64.31	0.0001
SP(BET)	3	86.4296	28.80988	167.74	0.0001
SP(YFT)	3	32.2016	10.73388	62.49	0.0001
QT × AR	27	272.7557	10.10206	58.82	0.0001

1975–92

Source	DF	Sum of squares	Mean square	*F*	*P>F*
Model	60	4,582.521	76.37535	567.32	0.0001
Error	38,314	5,157.981	0.13462		
Corrected total	38,374	9,740.502			

Squared multiple correlation = 0.47046 C.V. = 0.97082 Root MSE = 0.36691 Mean = 0.37794

Source	DF	Type III SS	Mean square	*F*	*P>F*
YR	17	54.4091	3.2005	23.77	0.0001
QT	3	8.3407	2.7802	20.65	0.0001
AR	7	471.9310	67.4187	500.79	0.0001
GEAR	3	380.2856	126.7619	941.60	0.0001
SP(ALB)	3	289.6523	96.5507	717.19	0.0001
SP(BET)	3	278.8754	92.9584	690.50	0.0001
SP(YFT)	3	68.1805	22.7268	168.82	0.0001
QT × AR	21	481.2105	22.9147	170.21	0.0001

Japan, high CPUE's were observed. Gear effects were negatively correlated with swordfish CPUE: CPUE decreased if fishing gear was set deeper. Several types of gear were used in the areas near Japan. For instance, some longline gear had many hooks between floats, and yet it was fished as shallow gear targeting albacore. Thus there were several gear configurations, which could not be accounted for in standard categories of longline gear depth. Therefore it is premature to draw a definitive conclusion as to gear efficiency. Species effects were generally negative for the northern stock, with the exception of a relatively strong effect from bigeye CPUE in 1952–75.

Standardized CPUE at the levels of each main effect during 1952–75 and 1975–92 for the southwest stock is shown in Figure 6. Main effects and interactions were statistically significant in the final model (Table 3). Strong area effects were seen in areas 6 and 7 during 1952–75, and in area 4, which includes the Tasman Sea, during 1975–92. The effects of bigeye CPUE were positively correlated with swordfish CPUE in both time periods.

Figure 7 shows main factor effects for the southeast stock. Main effects and interactions were statistically significant in the final model (Table 4). Strong seasonal changes in CPUE were observed in the southeast

Table 3

Results of the ANOVA for the southwest Pacific swordfish stock.

1952–75

Source	DF	Sum of squares	Mean square	*F*	*P>F*
Model	59	312.4885	5.296414	179.1	0.0001
Error	12,775	377.7889	0.029573		
Corrected total	12,834	690.2773			

Squared multiple correlation = 0.4527 C.V. = 1.03516 Root MSE = 0.17197 Mean = 0.16613

Source	DF	Type III SS	Mean square	*F*	*P>F*
YR	23	10.2493	0.44562	15.07	0.0001
QT	3	5.7028	1.90095	64.28	0.0001
AR	6	108.4591	18.07652	611.26	0.0001
SP(ALB)	3	12.1909	4.06363	137.41	0.0001
SP(BET)	3	4.2749	1.42498	48.19	0.0001
SP(YFT)	3	0.6899	0.22999	7.78	0.0001
QT × AR	18	25.8629	1.43683	48.59	0.0001

1975–92

Source	DF	Sum of squares	Mean square	*F*	*P>F*
Model	44	893.357	20.30358	514.92	0.0001
Error	35,180	1,387.166	0.03943		
Corrected total	35,224	2,280.523			

Squared multiple correlation = 0.391734 C.V. = 1.19072 Root MSE = 0.19857 Mean = 0.16677

Source	DF	Type III SS	Mean square	*F*	*P>F*
YR	17	12.3816	0.72833	18.47	0.0001
QT	3	12.1535	4.05119	102.74	0.0001
AR	4	312.8623	78.21556	1,983.63	0.0001
GEAR	2	2.6686	1.33432	33.84	0.0001
SP(ALB)	3	3.4264	1.14216	28.97	0.0001
SP(BET)	3	4.2153	1.40512	35.64	0.0001
SP(YFT)	3	5.2359	1.74531	44.26	0.0001
QT × SP (YFT)	9	12.4345	1.38162	35.04	0.0001

stock. Of the area effects, those in area 1, the equatorial eastern Pacific, during 1954–75, and in area 4, off Peru, during 1975–92, were the strongest observed. The effects of bigeye CPUE were positively correlated with swordfish CPUE. There was a difference in bigeye effect between the North and South Pacific: it was negative in the north, but positive in the south. More detailed study of the cause of this inconsistency is needed in the future.

Various attempts have been made to standardize CPUE for longline fisheries with mixed target species (Hoey et al., 1989; Miyabe, 1994). Here and in Miyabe (1994) the log-transformed CPUE of other species was used as a main effect. However, there may be problems with this practice. Although excluding the target species effect showed similar trends in annual standardized CPUE, there is the possibility that the factor may be related to abundance rather than to targeting, i.e. it may simply reflect changes in relative abundance or in relative temporal and spatial distributions of species. A reasonable approach should be developed in the future to account for fishing strategy in standardizing the CPUE of non-target species.

Some interactions, e.g. that between quarter and yellowfin (QT × SP(YFT)) for the southwest Pacific, and various quarter–area interactions (QT × AR) were signifi-

Table 4
Results of the ANOVA for the southeast Pacific swordfish stock.

1952–75

Source	DF	Sum of squares	Mean square	*F*	*P>F*
Model	41	34.732	0.847134	33.71	0.0001
Error	3,003	75.476	0.025134		
Corrected total	3,044	110.209			

Squared multiple correlation = 0.315151 C.V. = 0.59706 Root MSE = 0.15854 Mean = 0.26553

Source	DF	Type III SS	Mean square	*F*	*P>F*
YR	21	3.23000	0.153810	6.12	0.0001
QT	3	5.81158	1.937194	77.08	0.0001
AR	2	16.74744	8.373722	333.17	0.0001
SP(ALB)	3	0.17807	0.059357	2.36	0.0695
SP(BET)	3	0.88302	0.294343	11.71	0.0001
SP(YFT)	3	0.62972	0.209908	8.35	0.0001
QT × AR	6	2.76630	0.461050	18.34	0.0001

1975–92

Source	DF	Sum of squares	Mean square	*F*	*P>F*
Model	44	368.406	8.37287	183.4	0.0001
Error	32,509	1,484.143	0.045653		
Corrected total	32,553	1,852.549			

Squared multiple correlation = 0.198865 C.V. = 0.87135 Root MSE = 0.21367 Mean = 0.24521

Source	DF	Type III SS	Mean square	*F*	*P>F*
YR	17	61.2459	3.6027	78.91	0.0001
QT	3	127.4766	42.4922	930.76	0.0001
AR	3	98.6999	32.8999	720.65	0.0001
GEAR	3	0.9401	0.3133	6.86	0.0001
SP(ALB)	3	4.8031	1.6010	35.07	0.0001
SP(BET)	3	14.9572	4.9857	109.21	0.0001
SP(YFT)	3	1.0361	0.3453	7.57	0.0001
QT × AR	9	91.5053	10.1672	222.71	0.0001

cant. Other interaction terms could not be examined due to insufficient data. In the case of the QT × AR interaction, area effects probably differ by quarter due to the migration of fish, which might be seen in the quarter–species interaction. For example, a significant QT × SP(YFT) interaction would mean that the CPUE of yellowfin tuna changes over time, which could be caused by migration.

Trends in Standardized CPUE

Standardized CPUE and 95% confidence intervals for the three swordfish stocks are shown in Figure 8. CPUE in the North Pacific peaked in 1958, then decreased until 1968, and has increased since. CPUE in the southwest Pacific showed an increasing trend until 1987, followed by a moderate decrease. CPUE in the southeast Pacific showed an increasing trend until 1977, decreased until 1984, then increased until 1987, and has decreased since then. These trends may indicate changes in abundance of swordfish in each region. However, Punsly and Nakano (1992) pointed out that even these standardized hook rates may be unrelated to abundance. For example, annual variation in swordfish vulnerability to longlines due to variability in the depth of the fish, resulting from variations in vertical thermal

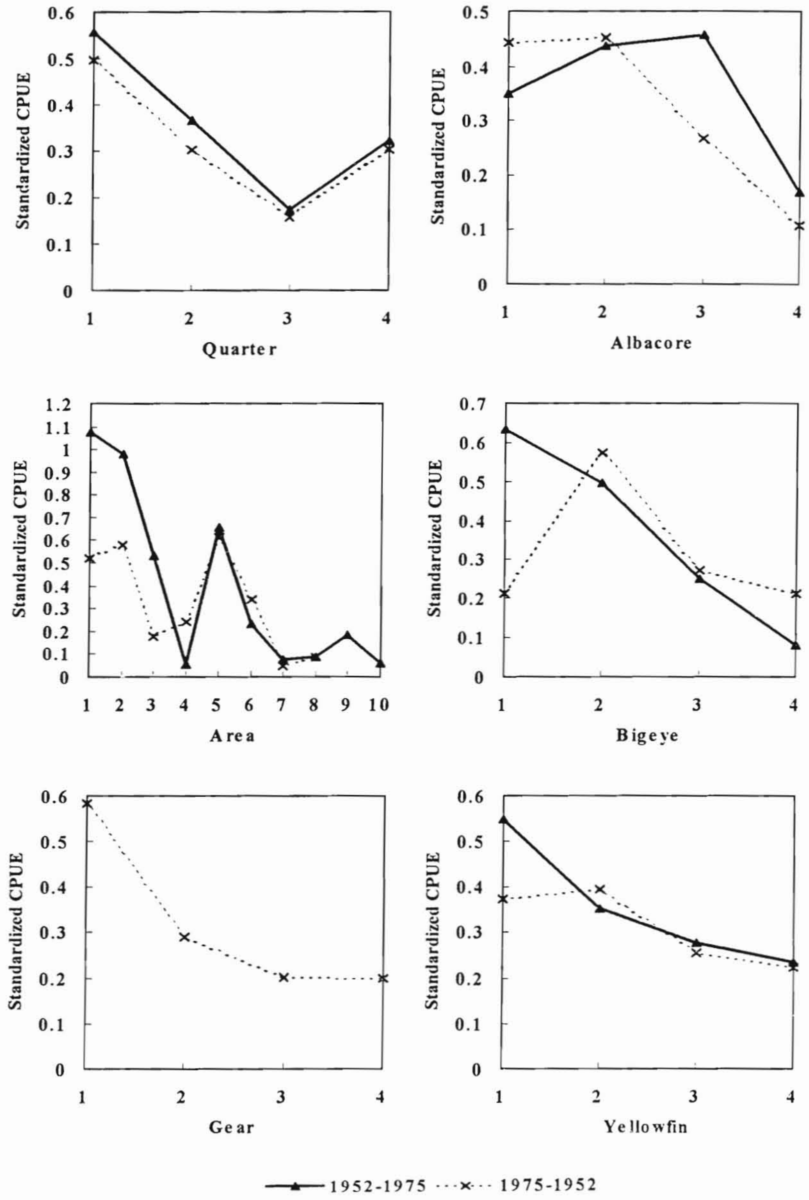

Figure 5
Standardized CPUE at each level of the main effects for the North Pacific swordfish stock, 1952–75 and 1975–92.

structure, oxygen level, or food availability, could have a greater effect on hook rates than does abundance.

Swordfish Catch in the Pacific

Annual catches of swordfish from each region are shown in Figure 9. The catches of all nations except Japan were taken from FAO fishery statistics yearbooks (FAO, 1961–92). Japanese swordfish catches were calculated from catch and effort statistics compiled by NRIFSF by multiplying the average weight (calculated from length-frequency data) for various time and area strata by number of fish caught in these strata. These estimates were summed to obtain catches by Japanese fisheries in the north, southwest, and southeast areas.

The catch of swordfish in the north increased from 14,000 t in 1952 to 20,000 t in 1960, decreased to 7,000

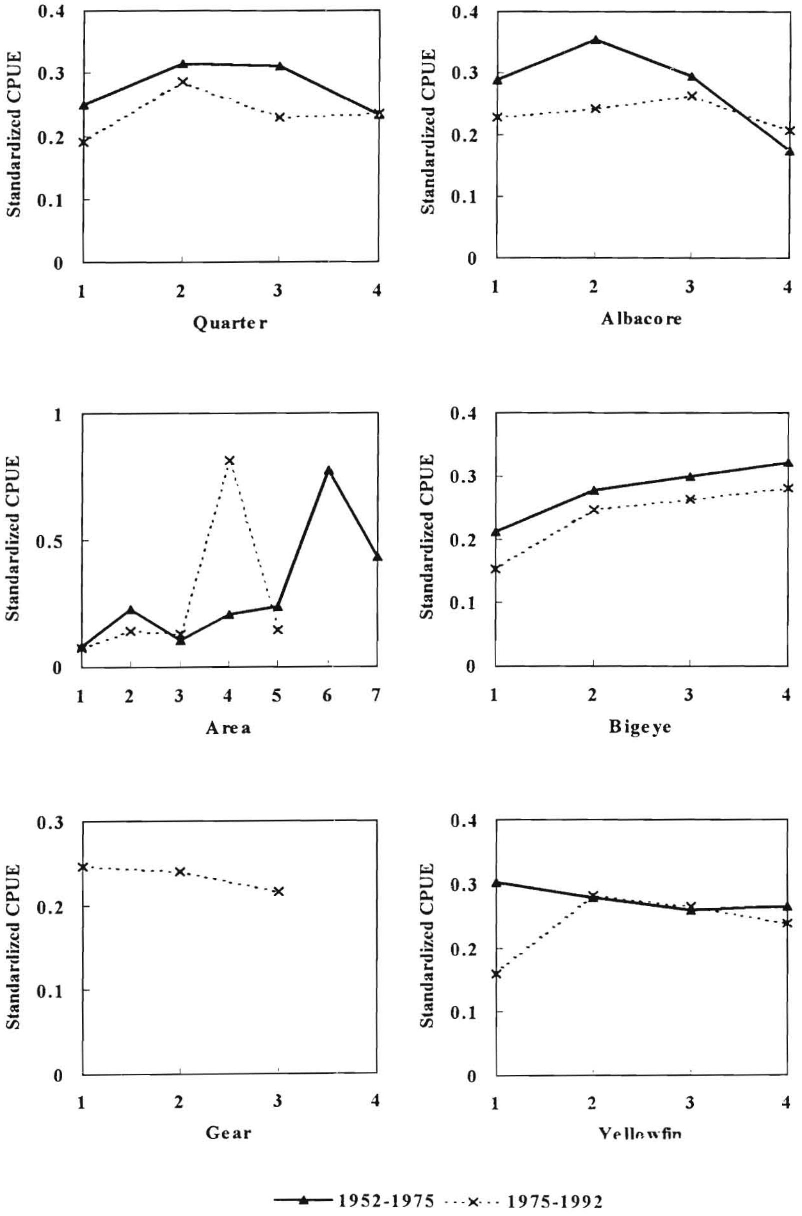

Figure 6
Standardized CPUE at each level of the main effects for the southwest Pacific swordfish stock, 1952–75 and 1975–92.

t in 1964, then gradually increased to 18,000 t in 1990. Changes in standardized CPUE for the North Pacific were almost parallel to changes in catch, although the Japanese longline effort was stable at about 120 million hooks during this time.

The swordfish catch in the southwest Pacific gradually increased to 2,000 t in 1972, and has fluctuated about this point since that time. Both catch and CPUE in this area show comparable trends after the mid-1960's. The fishing ground was expanding to the south before 1980. Since then, catch and CPUE have tended to stabilize in this area.

In the southeast Pacific, swordfish catch increased from about 100 t in the 1950's to 1,000–2,000 t in the 1960's. Catches then fluctuated between about 1,000 and 4,000 t, until they began increasing again in about 1987, increasing to about 10,000 t in 1991. This rapid increase was due to the Chilean catch, which increased

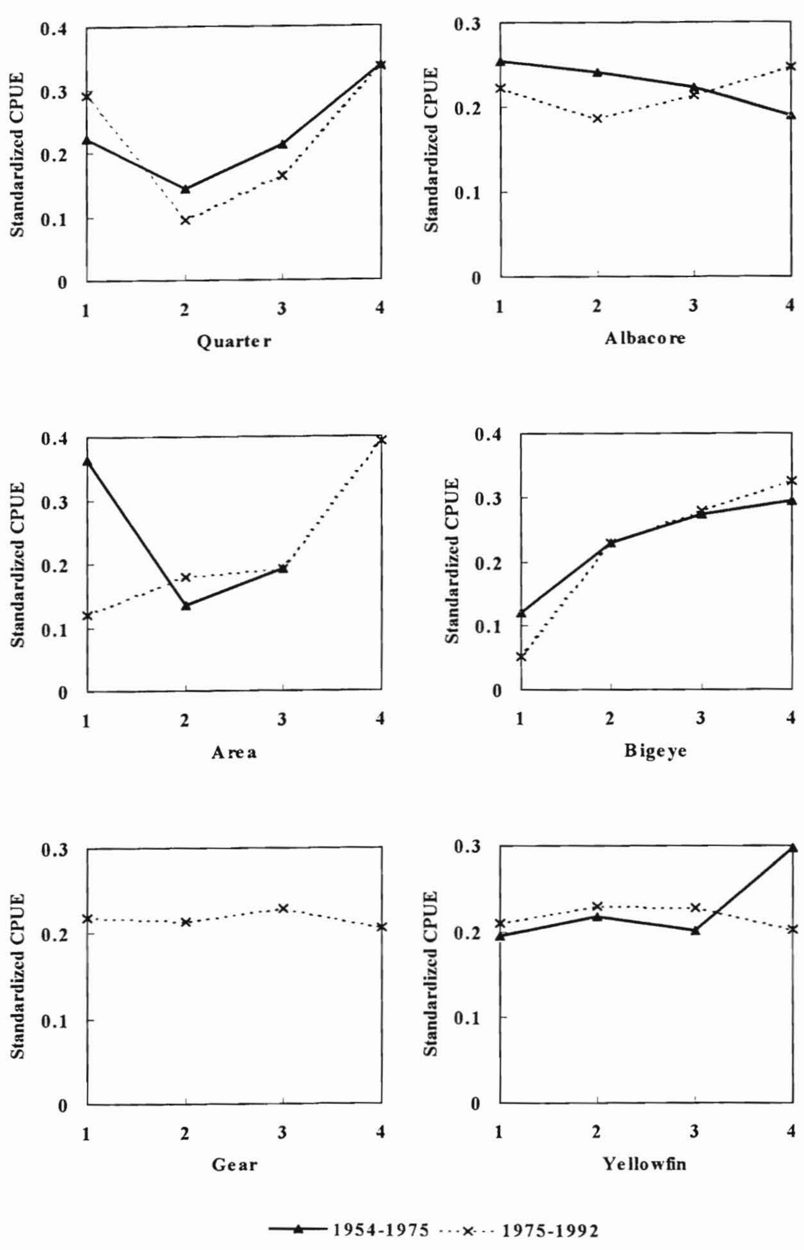

Figure 7
Standardized CPUE at each level of the main effects for the southeast Pacific swordfish stock, 1952–75 and 1975–92.

from 342 t in 1985 to 7,255 t in 1991. Such rapid increases in catch, concomitant with decreasing CPUE, should be carefully monitored.

Standardized Effective Effort and Catch

The relation between standardized effective effort and catch in each region is shown in Figure 10. Estimates of effective effort were obtained by dividing total catch by standardized CPUE. Effective effort does not appear to correlate with catch in the North Pacific, whereas the relation exhibits a linear trend in the southwest Pacific. It seems that the abundance of the southwest stock is under the MSY level; it is the most stable of the three stocks hypothesized here. Judging from the trend in CPUE and the low level of catch, the fishery for sword-

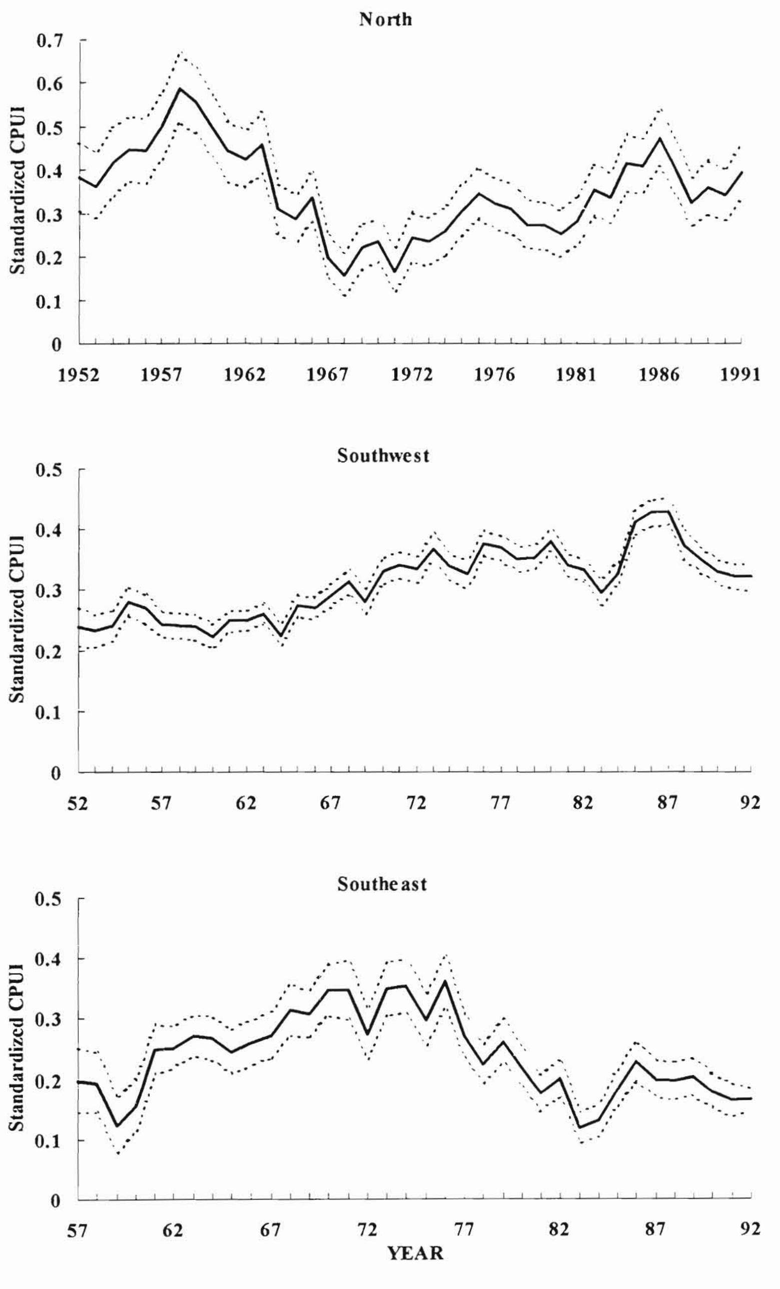

Figure 8

Annual standardized CPUE from Japanese longline fisheries data, and 95% confidence intervals, for each Pacific swordfish stock. Note differing *x* scales.

fish appears to be in a developing stage in the southwest Pacific. In the southeast Pacific, the relation between effective effort and catch was different before and after 1980. Standardized CPUE has decreased in the southeast Pacific since about 1977, while catch has drastically increased since about 1986. However, there is a possibility that CPUE trends in this region indicate changes in local abundance and are not representative of overall stock status in the region. The swordfish fishing grounds of South American fleets are very small and concentrated nearshore. Even for a high-seas fishing country like Japan, swordfish fishing grounds in the South Pacific are much smaller than those in the North Pacific, being concentrated in the Tasman Sea and off

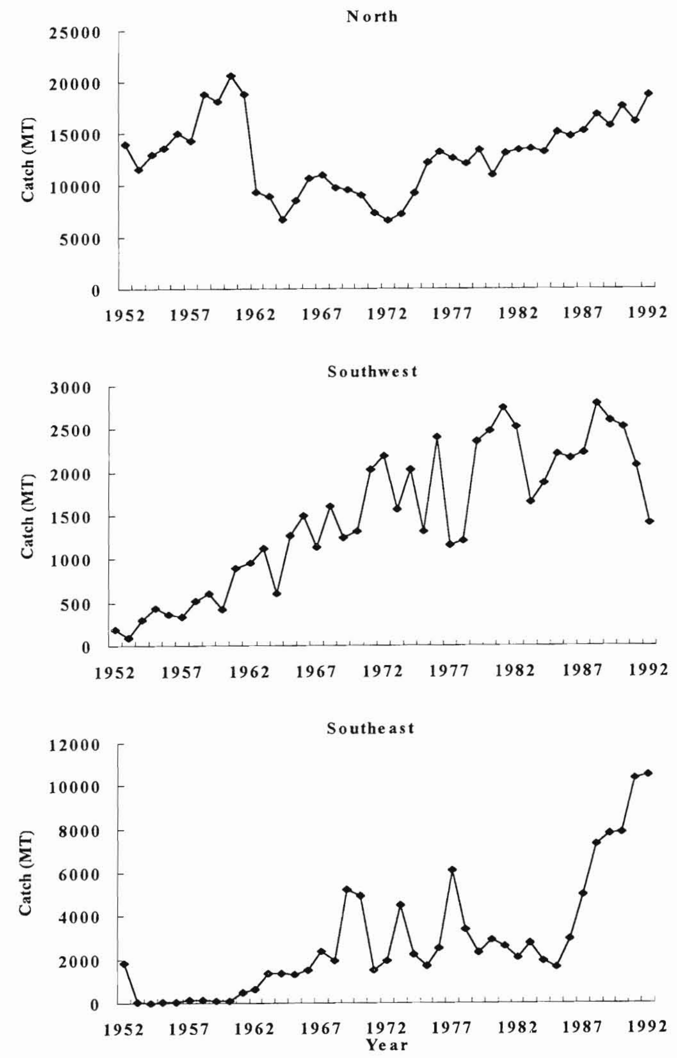

Figure 9

Annual swordfish catch (metric tons) in three regions of the Pacific Ocean, 1952–92. Note differing *y* scales.

Peru. Therefore, the CPUE of the Japanese longline fishery may represent local stock reductions or increases in the South Pacific. Different approaches, such as nonequilibrium production or delay difference models (e.g. Hinton and Deriso, 1994), should be applied in future assessments of the status of swordfish stocks.

Conclusion

Average standardized CPUE from recent years, 1983–92, was compared with that of earlier periods, 1952–61 for the north and southwest stocks, and 1961–67 for the southeast stock. CPUE decreased from 0.46 to 0.38 in the North Pacific and from 0.26 to 0.18 in the southeast Pacific, and it increased from 0.26 to 0.36 in the southwest. In the southeast Pacific, the catch increased rapidly from about 3,000 t to about 10,000 t in recent years. This stock should be carefully monitored because of the observed declining CPUE coupled with an increasing catch, which may be indicative of a decrease in abundance. In addition, since swordfish catches have increased in the North and southeast Pacific Ocean in recent years, fishery activities and abundance indices of stocks on both a wide and a local area basis should be carefully monitored.

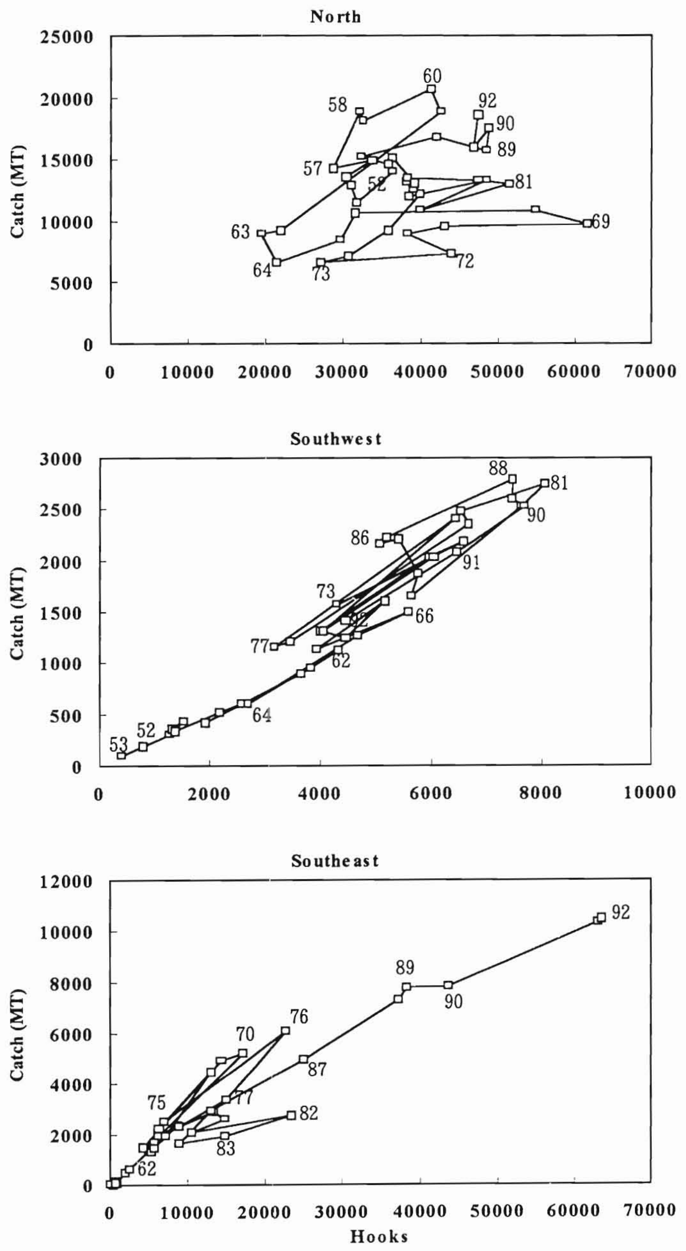

Figure 10

Relation between standardized effective effort for swordfish and swordfish catch in each region of the Pacific Ocean. Numerals indicate years. Note differing x and y scales.

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Mitochondrial and Nuclear DNA Analyses in the Study of Swordfish, *Xiphias gladius*, Population Structure

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ABSTRACT

We review two complementary approaches to the genetic differentiation of swordfish populations. The first involves direct sequencing of PCR-amplified fragments of the mitochondrial genome. A 300-base-pair (bp) fragment of the ATPase 6 gene yielded relatively low values of nucleotide sequence divergence and haplotypic diversity. In contrast, analysis of a 330-bp nucleotide sequence, corresponding to the hypervariable left domain of the mitochondrial control region, confirmed that mtDNA harbors a large amount of variation. Very high values of haplotypic diversity were obtained for samples from the North Pacific, Atlantic, and Mediterranean, with at least 68 mtDNA types among 109 individuals. The phylogenetic relationship of haplotypes revealed the presence of two highly divergent clades. Monte Carlo simulations suggested heterogeneous frequency distributions of mitochondrial types in North Pacific (n=25), Atlantic (n=39), and Mediterranean (n=45) samples. Phylogeographic analysis revealed that certain mtDNA lineages are found almost exclusively in the Atlantic, while others are ubiquitous in all oceans.

The study of mtDNA gives only a partial view of genetic population structure because it reflects primarily the history of maternal lineages. Therefore, to study nuclear DNA we developed a genomic library of several anonymous loci. To facilitate screening large samples, we employed PCR-based assays combined with restriction analysis. In addition we report the development of PCR primers that target the growth hormone gene and may have a wide range of application.

Introduction

Current management practices for most large pelagic species of fish are subject to both national and international controversies, primarily because of the dramatic decline in the catches of many species, including swordfish. The international commissions in charge of regulating fisheries, of which most major fishing nations are signatories, have been criticized for making erroneous assumptions regarding the state of fish stocks.

Among the most controversial issues is the structure of stocks. Hypotheses about stock structure have often been established without sufficient knowledge about the biology of the species in question. This issue is further complicated by differences in the interpretations of the term *stock*. Ideally, a stock is an intraspecific group of randomly-mating individuals with temporal or spatial integrity (Ihssen et al., 1981). Unfortunately, to what extent management units fulfill the conditions of random mating and temporal and spatial genetic integrity is extremely difficult to assess in most cases.

Recently, genetic studies have been used to test hypotheses on stock structure of several scombroid fishes. These studies include some based on allozyme electrophoresis (Ward et al., 1995) and several focused on mitochondrial DNA polymorphisms. Mitochondrial studies include restriction fragment length polymorphism studies (RFLP) (e.g. Graves et al., 1984; Graves and Dizon, 1989; Scoles and Graves, 1993; Graves and McDowell, 1994, 1995) and direct sequencing of PCR-amplified portions of mtDNA (Finnerty and Block, 1992). The advantages of using the mitochondrial genome in the study of population structure have been summarized by Avise et al. (1987) and Moritz et al. (1987). RFLP analyses have been conducted on swordfish populations in the Atlantic Ocean (Alvarado

Bremer, 1992), the Mediterranean Sea (Magoulas et al., 1993), and the North Pacific (Grijalva-Chon et al., 1994). Both the North Atlantic and the global population structures of the swordfish have been examined using direct sequencing of the mitochondrial genome (Alvarado Bremer, 1994; Alvarado Bremer et al., 1995a, b). In the first portion of this paper, we review the major findings on swordfish stock structure reported in these papers. We emphasize the advantages and limitations of using sequence data of the mitochondrial control region to study the population structure of swordfish.

The second portion of this paper focuses on the analysis of nuclear DNA variation. Because mtDNA is almost exclusively maternally inherited, it provides evidence primarily for female population structure. If patterns of distribution and migration are similar between sexes, mtDNA data may provide an accurate description of the geographic structure of the species. However, when the rates of dispersal of males and females differ significantly, the conclusions derived from mtDNA data apply only to maternal lineages. Because there is ample evidence of significant differences in distribution and behavior between male and female swordfish (Palko et al., 1981), we decided to also assess the variation contained in the nuclear genome to offer a more complete scenario of the population structure of swordfish.

Mitochondrial DNA Sequence Data

The development of the polymerase chain reaction (PCR) (Saiki et al., 1985, 1988) has made it possible to amplify and directly sequence relatively large stretches of DNA from a variety of organisms. The protocols and primers employed to amplify and sequence portions of the swordfish mitochondrial genome (Alvarado Bremer, 1994) are given in Appendix 1. These control region primers appear to be universal for fishes, and are routinely used in our laboratory to amplify and sequence the hypervariable portion of the genomes of a wide variety of fish species (Alvarado Bremer and Ely, unpublished results).

There are appreciable differences in the mutation rate of different portions of the swordfish mitochondrial genome (Alvarado Bremer, 1994). Only five variable positions, which define four distinct types, were found in an approximately 300-base-pair (bp) nucleotide sequence of the ATPase 6 gene from a sample which included six Atlantic and four Pacific individuals (Table 1). In contrast, in a 630-bp control region sequence from the same sample we identified nine distinct genotypes defined by 47 variable positions. More than 70% of the variable positions in the control region were found in a nucleotide sequence roughly 280 bp long and adjacent to the tRNA proline gene (Alvarado Bremer, 1994). The analysis of 330 bp including this hypervariable segment from 109 individuals collected in the Pacific (*n*=25), Atlantic (*n*=39), and Mediterranean (*n*=45) (Alvarado Bremer et al., 1995b) confirmed the presence of two highly divergent lineages. These two lineages, referred to henceforth as clade I and clade II, are separated by a total of ten fixed differences: 1 transversion, 2 insertions or deletions (indels), and 7 transitions.

Table 1

Bases found at polymorphic sites in a 300-bp sequence of the ATPase 6 gene surveyed among 6 Atlantic and 4 Pacific swordfish (from Alvarado Bremer, 1994). CAN = Georges Bank, Nova Scotia; PAC = Pacific Ocean. T = thymine, C = cytosine, G = guanine, A = adenine.

	Position				
Specimens	54	102	138	240	255
21 (CAN)	T	G	G	T	C
19 (CAN)	C	A	A	C	C
10, 11, 15, 22 (CAN); 6S, 16S, 20 (PAC)	C	G	G	T	C
JLC5S (PAC)	C	G	G	T	A

None of the 68 characterized genotypes was present at a high frequency. A test of geographic heterogeneity in haplotype frequency distribution using Monte Carlo simulations (Roff and Bentzen, 1989) revealed that the Pacific, Atlantic, and Mediterranean samples were significantly different ($P<0.05$; Fig. 1). However, within oceans there is evidence that extensive mixing has occurred.

While statistical analysis of frequency distribution, such as Monte Carlo simulations of chi-square values (Roff and Bentzen, 1989) and *G*-tests of independence (Sokal and Rohlf, 1981), give valuable information about the heterogeneity of populations, additional insight into the present distribution of genotypes can be obtained through the analysis of their phylogenetic relationship (Fig. 2). For instance, the phylogeographic information shows that certain lineages have an uneven distribution. The largest observed difference results from the absence of members of clade II in the Pacific Ocean and the high proportion of members of this clade in the Mediterranean Sea and the eastern North Atlantic. Less obvious, but equally important, is the uneven distribution of certain clade I lineages in the Pacific and Atlantic samples. A total of 22 genotypes, which include 37 individuals, derive from the branch emerging from a single node (labeled A in Fig. 2) and represent almost exclusively Atlantic and Mediterranean samples. Only one of these individuals was collected in the Pacific Ocean (genotype 43). The branch emerging from this

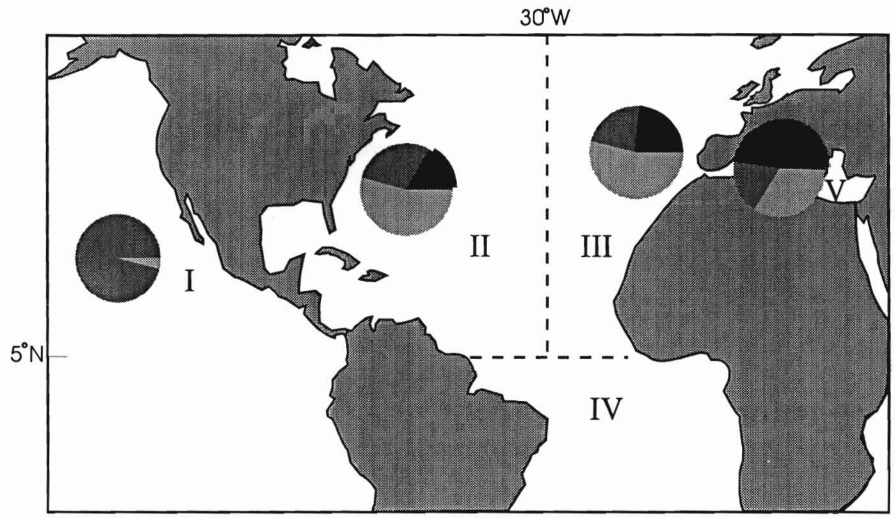

Figure 1
Frequency distribution of swordfish genotypes in sampling regions used in this study. Sampling areas were: I, Pacific Ocean (PAC); II, northwest Atlantic (NWA); III, northeast Atlantic (NEA); IV, South Atlantic (SAT); and V, Mediterranean (MED). The frequency of three major families of mtDNA lineages are represented in the pie charts as follows: alpha, light grey; beta, dark grey; and theta (clade II), black.

node is short and it is supported by only one fixed difference, a transition from adenine to guanine at nucleotide position 127. Some of the lineages in this group share an additional transition from cytosine to thymine at nucleotide position 133, whereas others share a transversion change from cytosine to guanine at nucleotide position 180.

Most Pacific genotypes (97%) emerged from the basal branches of clade I. However, some Mediterranean and Atlantic lineages emerged from these basal branches as well. Thus clade I appears to consist of two families of haplotypes: one which is ubiquitous and another which consists primarily of Atlantic and Mediterranean samples. The presence of two differentially distributed groups of lineages is consistent with the phylogeographic patterns described for the highly divergent mtDNA lineages of both blue marlin and sailfish in the Atlantic and Indo-Pacific Oceans (Graves and McDowell, 1995). The present asymmetric distribution of mtDNA types for these two species represents the differential migration of females from the Indo-Pacific into the Atlantic. A similar uni-directional migration of lineages may have taken place in swordfish. There is evidence that substantial east–west gene flow has taken place in the North Pacific (Grijalva-Chon et al., 1994; but see Grijalva-Chon et al., 1996). In the absence of barriers, movement from the Indian Ocean to the South Atlantic may be occurring at the present time.

Identification of Nuclear DNA Markers

Nuclear DNA markers can provide information that cannot be obtained from the analysis of mtDNA. For population studies, assays of nuclear markers must be easy to perform and adaptable for use with large numbers of samples. To meet these criteria, we developed assays based on PCR amplification of sample DNA, followed by an RFLP analysis. We used two approaches in the development of these assays, the analysis of DNA regions containing microsatellites, and the development of PCR primers based on the DNA sequences of known genes. Both approaches allowed us to identify intraspecific variation that can be easily surveyed in large samples.

Microsatellite regions generally vary in size due to differences in the number of repeat units in the microsatellite sequence (Beckman and Weber, 1992). These differences can be observed by analyzing the products of PCR amplification on a DNA sequencing gel. However, these gels are cumbersome and require the use of radioactivity or a fluorescent marker to detect the variable DNA bands. To provide a simpler assay, we screened PCR products for the presence of restriction-site polymorphisms. We reasoned that stretches of DNA containing microsatellite sequences were likely to contain other variation as well. For striped bass, *Morone saxatilis*, we found that in two of three cases

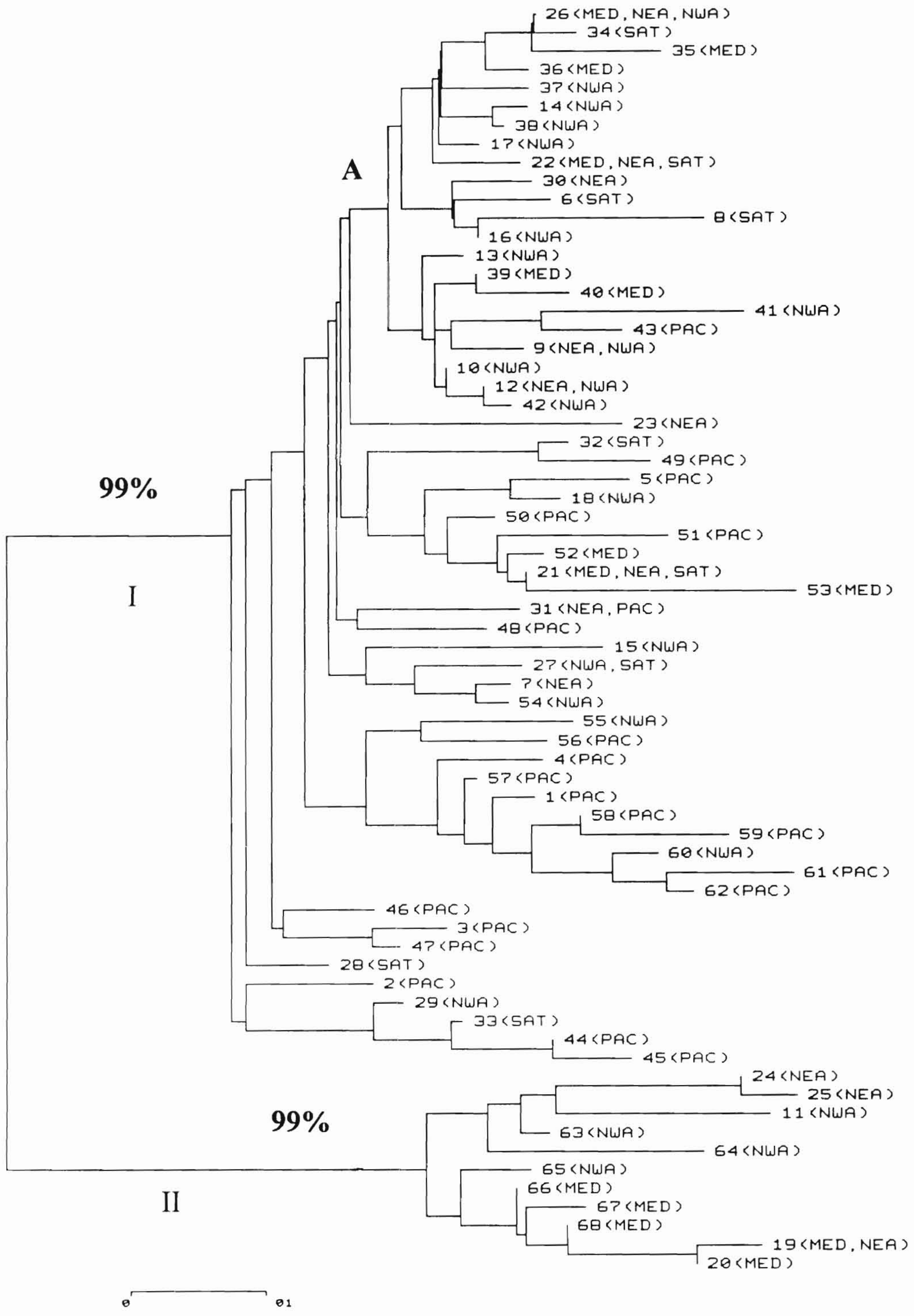

Figure 2

Neighbor joining tree calculated from Tamura-Nei distances (modified from Alvarado Bremer et al., 1995b) using the computer program MEGA (Kumar et al., 1993). Numbers on the tips of the branches correspond to the swordfish mtDNA haplotypes defined by Alvarado Bremer et al. (1995b). They are followed by a list of areas where this genotype was found (PAC = Pacific Ocean; NEA = northeast Atlantic; NWA = northwest Atlantic; SAT = South Atlantic; MED = Mediterranean). Branch lengths are proportional to genetic distances. The branches separating clades I and II are supported by confidence probability (CP) values >99%. The length of branch A was supported by CP values of 97% using Kimura 2-parameter distances (Kimura, 1980).

examined, a polymorphic restriction site was located within the amplified region. We therefore assayed population samples by digesting PCR products with the appropriate restriction enzyme and examining the resulting bands by ethidium bromide staining after agarose gel electrophoresis. Preliminary results with striped bass from South Carolina rivers indicate that allele frequencies at one of these loci differ in samples from different rivers. This approach is currently being applied to clones containing swordfish nuclear DNA.

Table 2

Growth hormone cDNA sequence sources. Consensus primers: GH-U24 5'ACCARCGNCTSTTCWMCATCGCNGT3' (forward); GH-U25 5'ACCTTGTGCATGTCCTTCTTGAAGCA3' (reverse).

Accession number (GenBank/EMBL)	Fish species	Sequence length (base pairs)
K03050	*Oncorhynchus keta*	1,120
M19999	*Oncorhynchus kisutch*	1,201
M22731	*Oncorhynchus mykiss* GH1	1,171
M22732	*Oncorhynchus mykiss* GH2	1,212
S54890	*Sparus aurata*	958
S78253	*Morone saxatilis*	928
X06735	*Thunnus thynnus*	911
X06962	*Pagrus major*	906
X13670	*Cyprinus carpio*	1,158
X14305	*Salmo salar*	1,169
X15055	*Paralichthys olivaceus*	831
X60475	*Hypophthalmichthys molitrix*	1,170

Fish Growth Hormone Primers

A second successful strategy for developing nuclear DNA markers is to design primers for PCR amplification based on the DNA sequences of known genes. We designed primers based on published sequences of the growth hormone (GH) genes of several fish species (Table 2). The growth hormone gene was chosen because the coding portions of the gene (exons) are highly conserved through a wide range of fish species. However, interspecific comparisons reveal that exons are flanked by introns of variable length and number. It is in these non-coding portions of the gene that intraspecific variation is most likely to be found. We compared the nucleotide sequences of GH genes from 11 fish species (Table 2) to determine a consensus sequence, which was then used to design primers capable of amplifying fish GH genes. We used these primers successfully to amplify the GH gene from both striped bass and swordfish nuclear DNA. Subsequent analyses have revealed a restriction-site polymorphism which can be used to discriminate striped bass from other species of *Morone*. Experiments are underway to determine whether a restriction-site polymorphism can be identified for swordfish.

Summary

We have shown that nucleotide sequence analysis of the D-loop region of mtDNA can be used to characterize genetic variation in swordfish. A phylogenetic analysis of the resulting haplotypes demonstrated that the distribution of mtDNA lineages differs among swordfish populations from the Pacific Ocean, Atlantic Ocean, and Mediterranean Sea. We also developed PCR-based RFLP assays that can be used to examine the distribution of alleles of nuclear genes among fish populations.

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Appendix: Procedures

Universal Mitochondrial Primers

The universal primer set for the ATPase 6 gene that we used for amplification and sequencing was designed by Oliver Haddrath of the Royal Ontario Museum, using as reference the salmonid ATPase 6 sequence in Thomas and Beckenbach (1989) and the published mitochondrial sequences of chicken and frog. The set consists of the light-strand primer A1 (5'ATG AAC CTA AGC TTC TTC GAC CAA TT-3') and a heavy-strand primer A2 (5'ATA AAA AGG CTA ATT GTT TCG AT-3'), beginning at positions 9240 and 9673, respectively, of the chicken mitochondrial genome.

Double-stranded amplification reactions were carried out in 25-μl volumes containing 67 mM Tris-HCl (pH 8.8), 50 mM KCl, 1.5–2.0 mM $MgCl_2$, 10 mM β-mercaptoethanol, 0.1% Triton[1] X-100, 1 unit of Taq polymerase, 200 μM of each dNTP, and 8 picomoles of each primer. The template was 1 μl of purified mtDNA

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

or total DNA extractions. The reactions were subject to 38 cycles of the following temperature profile: 93°C for 45 sec, 50°C for 45 sec, and 72°C for 90 sec, in a thermal cycler (Perkin-Elmer/Cetus). The amplified product was visualized with a UV transilluminator; approximately 1 μl of a gel region containing amplified DNA was collected and dissolved in 1 ml of sterile deionized water heated at 55°C for 5 min. Exactly 1 μl of this solution was used as a template for single-strand amplification in a 100 μl volume containing the same reactants as double-strand amplification, but reducing the concentration of one primer by 100 times. The cycling profile was the same as in the double-stranded amplification, with the exception that the annealing temperature was increased to 52°C. Single-stranded amplified product was purified by selective isopropanol precipitation (Sambrook et al., 1989). Sequencing of single-stranded DNA was done using a Sequenase kit (United States Biochemical).

Control Region Primers[2]

Two swordfish-specific primers were designed: L15998-PRO (5'-TAC CCC AAA CTC CCA AAG CTA-3') and H00585-PHE (5'-CAG TGT TAA GCT TTA ACT AAG CT-3'), placed in the tRNA^{pro} and tRNA^{phe}, respectively. PCR amplifications using this primer set were carried out in 25-μl reactions subjected to 35–38 cycles of 93°C for 1 min, 52°C for 1 min, 72° for 90 sec, and a final extension at 72°C for 5 min. The primer H235 (5'-CGT GTG CAC TCT GAA ATG TCA-3') was used with L15998 to amplify a fragment approximately 545 bp long which included the left domain and most of the central domain. Similarly, the primer L318 (5'-GTC ATT GAA GGT GAG GGA CA-3') was used with the oligonucleotide H00585 to amplify a 510-bp fragment corresponding to the central and right domains. Because the amplified products overlapped, the complete sequence of the central domain was obtained in both directions for five specimens that had extremely divergent profiles for the left and right domains. A fifth (heavy) primer, CSBDH (5'-TGA ATT AGG AAC CAG ATG CCA G-3'), located in the conserved block D of the central domain of the control region, was used in combination with primer L15998-PRO. This primer combination is universal and has been used successfully to amplify a wide variety of species of fish genetic material. The cycling profile began with an initial denaturing step of 5 min at 94°C, followed by 34–36 cycles of denaturing at 94°C for 45 sec, annealing at 55–59°C for 45 sec, and extension at 72°C for 1 min. The final extension was at 72°C for 5 min.

Amplification of Growth Hormone Genes

PCR conditions were optimized with a PCR-Optimizer kit (Invitrogen, Inc.). About 20 ng of uncut genomic DNA was added to a 1× PCR mixture consisting of 60 mM Tris-HCl, pH 9.0; 2 mM $MgCl_2$; 0.5 μM of each primer; 200 μM of each dNTP; and 1.25 units of AmpliTaq DNA polymerase (Perkin Elmer). PCR amplification was carried out on a 50-μl aliquot, and consisted of initial denaturation for 6 min at 94°C followed by 36 cycles in a thermal cycler (denaturation: 1 min at 94°C; annealing: 1 min at 57°C; extension: 3 min at 72°C), and a final incubation for 10 min at 72°C to ensure maximum full-length product formation.

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[2] Alvarado Bremer (1994).

Protecting the Reproductive Value of Swordfish, *Xiphias gladius*, and Other Billfishes

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ABSTRACT

The intrinsic rate of population growth (r) and the reproductive value of females at given age (v_x) are estimated for swordfish, *Xiphias gladius,* and other billfishes to determine how protecting reproductive value affects population sustainability. The procedure used involves the standard demographic equations and standard assumptions regarding density-dependent changes in vital rates from basic deterministic population dynamics. It appears that to ensure population sustainability of swordfish and blue marlin, age at first capture should be high enough to protect the first 1–2 mature age classes, but need not protect the most reproductively valuable, older females. For striped marlin and sailfish, however, the most valuable females may need protection.

Introduction

An argument frequently raised regarding the management of billfishes is that large, mature individuals, especially females, should be protected for their valuable reproductive capability. That very large and fecund females are valuable to their populations is intuitively obvious, and especially so if they are scarce or solitary, as adult billfishes usually are. In addition, female billfishes grow rapidly to sizes that are larger than males of the same age (see Boggs, 1989) and tend to be outnumbered by males on the spawning grounds (Hopper, 1990); this suggests they constitute a particularly valuable reproductive resource. Some protection of these females would obviously be beneficial—but to what extent?

The purpose of this paper is to estimate the reproductive value of billfish females to their populations, using the demographic formulae of Lotka (1907) and Fisher (1958). How a population's potential for increase is affected by protecting females below the most reproductively valuable age will be examined. This involves first estimating the population's intrinsic rate of increase when it is near the size that produces maximum sustainable yield, and then using that estimate to determine reproductive value and the effects of protection. The focus will be on the commercially important swordfish, *Xiphias gladius*, but the cases for blue marlin, *Makaira mazara*, striped marlin, *Tetrapturus audax*, and sailfish, *Istiophorus platypterus*, will also be evaluated for perspective.

Classical demographic analyses are not much used in studying the dynamics of fishes other than sharks (e.g. Cailliet, 1992; Cailliet et al., 1992; Cortes, 1995), because most teleosts have extremely low larval and juvenile survival rates which are very difficult to measure. Proposed survival schedules are therefore not very convincing for these fishes. However, the demographic relationships allow this difficulty to be circumvented, as will be shown.

Methods

Estimating Life History Parameters

Estimates of age at maturity (α), maximum age of reproduction (w), and instantaneous natural mortality (M) are basic for a demographic analysis. These parameters were estimated from the biological characteristics of billfishes taken in the eastern Pacific. Age at 50% maturity (α) was estimated as the age at which a species' gonad index increased rapidly to values greater than 3 (see Eldridge and Wares, 1974; Miyabe and

Bayliff, 1987; Nakano and Bayliff, 1992). Maximum reproductive age (w) was obtained from converting maximum sizes observed historically in the longline fisheries (Shingu et al., 1974; Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992) to age (von Bertanlanffy growth parameters as listed by Boggs,1989; Table 1). Maximum age w is difficult to estimate from growth relationships without underestimation, and very old fish are expected to be rare, especially in an exploited population; therefore the calculated maximum ages were arbitrarily increased by 10% to estimate unexploited w for this analysis. Natural mortality was obtained from this age, w, using Hoenig's (1983) relationship for fishes ($\ln M = 1.46 - 1.01 \ln w$).

To estimate fecundity (m_x), size at age was converted to weight at age using length–weight relationships as given by Kume and Joseph (1969) for swordfish and by Wares and Sakagawa (1974) for the other billfishes. Fecundity–weight relationships are best known for swordfish (10^6 advanced mode ova = 2.725 + 0.015 * adult weight in kg; Uchiyama and Shomura, 1974); that relationship, which is nearly identical to one reported for sailfish (Eldridge and Wares, 1974), was used for all species considered here. There is no quantitative information on batch frequency of spawning among the billfishes. The final fecundities calculated were divided by 2 to obtain age-specific estimates of female newborn per adult female, i.e. m_x.

Estimating Intrinsic Rate of Increase

The intrinsic rate of population increase (r) is estimated here by incorporating the standard concept that density-dependent compensation occurs in a population as a response to reduction by fishing. Lotka's equation (more correctly, the Euler-Lotka equation) expresses the fundamental relation between survival from birth to age x (i.e. l_x), m_x, α, and w, and rate of population growth, r, of a stable-aged population. The term stable-aged means that all population segments (e.g. age classes) are growing at the same rate, the abundance ratio of any one segment relative to another remaining the same. Lotka's equation may be written (e.g. Stearns, 1992, Chapter 2, p. 20–38)

$$\sum_{x=\alpha}^{w} l_x e^{-rx} m_x = 1.0. \qquad (1)$$

It states that recruitment into a population must come from offspring, with contributions from older females discounted at rate r relative to those from younger females because they have less time to contribute to population growth. In terms of survival to maturity (l_α), l_x equals $l_\alpha(l_x/l_\alpha) = l_\alpha e^{-M(x-\alpha)}$ for $x \geq \alpha$. Thus Equation (1) becomes

$$l_\alpha \sum_{x=\alpha}^{w} e^{-M(x-\alpha)} e^{-rx} m_x = 1.0 \qquad (2)$$

which can be solved for r if m_x, M, and l_α are known.

Our interest is finding r when the population is most productive, i.e. at the size that produces maximum sustainable yield (MSY). Theory and experience (e.g. Shepherd, 1982; Kimura, 1988; Clark, 1991) suggest

Table 1

Growth and life history parameters of billfishes.

		Von Bertanlanffy growth parameters[1]			Life history parameters		
Species	Sex[2]	L_∞ (cm)	K (yr^{-1})	t_0 (yr)	α[5] (yr)	w[6] (yr)	M[7] (yr^{-1})
Swordfish	U	309	0.124	−1.169	5	20	0.21
Blue marlin	F	487[3,4]	0.116	−0.161	4	11	0.38
Striped marlin	U	275	0.264		4	9	0.47
Sailfish	U	232	0.472		3	8	0.53

[1] From Boggs (1989).

[2] U = Unidentified/unreported sex; F = female. U growth rate used for striped marlin because F growth rate did not accommodate the largest size observed.

[3] Corrected from value listed by Boggs (1989).

[4] After age 8, size at age was based on a freehand-drawn curve rather than predictions from growth parameters, because the largest blue marlin in the E. Pacific longline catch (332 cm) was much smaller than the reported maximum size (about 389 cm).

[5] Age at 50% maturity.

[6] Maximum reproductive age.

[7] Natural mortality derived from $\ln M = 1.46 - 1.01 \ln w$ (Hoenig, 1983).

that MSY usually occurs in teleosts at population sizes between 1/2 and 1/5 of initial biomass, usually closer to the smaller fraction. A fishing mortality (F) with values between M and $2M$ (total mortality $Z = (F + M) = 2M$ to $3M$) would reduce an exploited population to approximately between 1/2 and 1/3 of its initial numerical size. In terms of biomass the reduction would be greater (Beverton and Holt, 1957), though it may not be if growth is density-dependent (Beverton[1]). Therefore, this range of F should conservatively bracket the MSY population size and will be used here for that purpose.

With this fishing mortality emplaced, total reproductive output would be reduced and the population would decline. If, however, the decline ends at a level that is sustainable, there must be density-dependent compensation such that Equation (2) describing the smaller, now stationary ($r = 0$) population is satisfied. Under total mortality Z (= $2M$ or $3M$) this compensation is assumed here to result from an increase in the survival of immature fish, to (say) survival $l_{\alpha,Z}$.

Equation (2) then becomes, with $r = 0$,

$$l_{\alpha,Z}\sum_{x=\alpha}^{w} e^{-Z(x-\alpha)}m_x = 1.0 \tag{3}$$

from which $l_{\alpha,Z}$ can be estimated as the reciprocal of the summation term, given that the other parameters are specified. Estimation of $l_{\alpha,Z}$ enables specification of the particular adult survival schedule of a population at its Z-reduced size. The actual, age-specific survival rates of pre-adult fish need not be of concern.

If fishing mortality is removed ($F = 0$) and if $l_{\alpha,Z}$ holds, this stationary population will begin growing, eventually at a rate here designated r_Z. This is the r-potential at the MSY population size, and it is found by iteratively solving for r_Z from Equation (2), now written

$$l_{\alpha,Z}\sum_{x=\alpha}^{w} e^{-M(x-\alpha)}e^{-r_Z x}m_x = 1.0. \tag{4}$$

Estimating Reproductive Value

The reproductive value (v_x) of a female at age x from a stable-aged cohort can be written (Fisher, 1958)

$$v_x \sum_{t=x}^{w} e^{-r(t-x)}(l_t \,/\, l_x)m_t. \tag{5}$$

It measures that female's relative contribution to future population growth, again discounting for the lesser effect that contributions made at older ages will have.

Equation (5) is more meaningfully expressed in terms of the standing population, which is the abundance at hand and the focus of fishermen's interest. Then v_x would be a measure of the reproductive output of ages x and older in the population, normalized by the relative abundance at age x. The standing relative abundance of fish at each age x (designated S_x) in such a population is

$$S_x = l_x e^{-rx} \tag{6}$$

and similarly for S_t (e.g. Caughley, 1977). Gathering those terms and substituting S_x gives

$$v_x = 1/S_x \sum_{t=x}^{w} S_t m_t$$

or

$$v_x = 1/(S_x/S_\alpha)\sum_{t=x}^{w}(S_t/S_\alpha)m_t \tag{7}$$

i.e. reproductive value in terms of the standing abundance of age-α fish (S_α). Values of v_x can be readily calculated for any age $x \geq \alpha$ in a population with fishing mortality removed, using the abundance ratio $S_x/S_\alpha = (l_x/l_\alpha)(e^{-rx}/e^{-r\alpha}) = e^{-(M+r)(x-\alpha)}$ (and similarly for (S_t/S_α). At the MSY population size, r is the r_Z estimated previously.

Evaluating Effects of Protection

Reproductive value in a population capable of increasing at rate r, and therefore with survival l_α (designated $l_{\alpha,r}$) and relative abundance $S_{\alpha,r}$ at age α ($S_{\alpha,r} = l_{\alpha,r}e^{-r\alpha}$), can be protected to ensure that the population's rate of increase remains at least equal to r', where $r' \leq r$. This protection can be obtained by raising the age at first capture to compensate for reduced r'. Lotka's equation would still remain satisfied, but now by the reproductive output from the protected ages alone. Operationally, a certain r' is assumed, and then the age to which protection needs to be extended ($x_{r'}$) for obtaining that r' is found.

To determine this age ($x_{r'}$) for an r' less than or equal to a given r, survival $l_{\alpha,r}$ must first be determined. From Equation (5), reproductive value at age 0 (v_0) equals 1.0, because its expression is then equivalent to Lotka's equation (since $l_0 = 1.0$). Also $S_0 = 1.0$, from Equation (6). Thus, using Equation (7), v_0 becomes

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[1] Beverton, R. J. H. 1994. Montana, Old Roman Rd., Langstone, Gwent, NP6 2JU, U.K. Personal commun.

Table 2

Fecundity (m_x) schedules, in 10^6 female newborn per adult female at each age x, for four species of billfish. From age–length relationships calculated by von Bertanlanffy equations (see Boggs, 1989). Length–Weight relationship for swordfish is log W = –4.675 + 2.961 log L (Kume and Joseph,1969). L–W for other billfishes as described by Wares and Sakagawa (1974). Fecundity–weight relationship as per Uchiyama and Shomura (1974): 10^6 advanced-mode ova = 2.725 + 0.015 kg adult weight; m_x is the final fecundity divided by 2.

Age	Swordfish	Blue marlin	Striped marlin	Sailfish
0				
1				
2				
3				1.67
4		2.07	1.89	1.74
5	2.04	2.49	2.07	1.80
6	2.24	2.99	2.24	1.82
7	2.45	3.50	2.38	1.85
8	2.65	4.01	2.50	1.87
9	2.89	4.54	2.60	
10	3.05	5.01		
11	3.24	5.42		
12	3.41			
13	3.58			
14	3.72.			
15	3.86			
16	3.99			
17	4.11			
18	4.22			
19	4.31			
20	4.40			

$$\begin{aligned} v_0 &= S_{\alpha,r} \sum_{t=\alpha}^{w} (S_t/S_\alpha) m_t \\ &= S_{\alpha,r} \sum_{t=\alpha}^{w} e^{-(M+r)(t-\alpha)} m_t = 1.0 \end{aligned} \tag{8}$$

and $S_{\alpha,r}$ can now be found as the reciprocal of the above summation term. Finally, $l_{\alpha,r}$ is found from $S_{\alpha,r}$ using Equation (6).

With $l_{\alpha,r}$ determined, and additionally assuming that r' is to be ensured, v_0 or Lotka's equation (Equation 8) is written

$$S_{\alpha,r'} \sum_{t=\alpha}^{x_{r'}} e^{-(M+r')(t-\alpha)} m_t = 1.0 \tag{9}$$

where $S_{\alpha,r'} = l_{\alpha,r} e^{-r'\alpha}$ and $x_{r'}$ is the upper summation age to be found that satisfies the equation. The condition described is thus that of a population capable of increasing at rate r but now increasing at rate r'.

Table 3

Estimates of intrinsic rate of increase (r_Z) for several species of billfishes. $l_{\alpha,Z}$ is survival to maturity at age α, where $Z = 2M$ or $3M$ (to bracket the mortality level at which MSY likely occurs); r_{2M} and r_{3M} are the corresponding r estimates.

Species	α (yr)	w (yr)	M (yr^{-1})	$l_{\alpha,2M}$ ($\times 10^{-6}$)	$l_{\alpha,3M}$ ($\times 10^{-6}$)	r_{2M} (yr^{-1})	r_{3M} (yr^{-1})
Swordfish	5	20	0.21	0.142	0.201	0.076	0.118
Blue marlin	4	11	0.38	0.216	0.298	0.104	0.159
Striped marlin	4	9	0.47	0.306	0.388	0.090	0.135
Sailfish	3	8	0.53	0.385	0.472	0.107	0.158

If all fish are taken above age $x_{r'}$, the population would still increase at rate r' since Lotka's equation is still satisfied for rate r'; if no fish are taken (all ages are protected) the population would increase at its native rate r, which is here estimated by r_Z. In the analysis to follow, r' is set to zero to investigate the protection needed to ensure that the population is at least stationary at the MSY level.

Results

Life History Parameters

Age at maturity α was estimated as 5, 4, 4, and 3 yr and maximum reproductive age w as 20, 11, 9, and 8 yr for swordfish, blue marlin, striped marlin, and sailfish respectively (Table 1). The natural mortality M estimates were 0.21, 0.38, 0.47, and 0.53 respectively for these same billfishes. Fecundity m_x estimates are as listed in Table 2.

Intrinsic Rate of Increase (r)

Values for survival to maturity which bracket the likely range for the MSY condition, i.e. $l_{\alpha,Z}$ with $Z = 2M$ or $3M$ from Equation (3), are listed in Table 3 along with the resulting r estimates. The latter, which are the r_Z from Equation (4) using the $l_{\alpha,Z}$ survival values, are 0.08–0.12, 0.10–0.16, 0.09–0.14, and 0.11–0.16 per yr for swordfish, blue marlin, striped marlin, and sailfish respectively. These ranges correspond to the $Z = 2M$ and $Z = 3M$ estimates. An example of this computation for r, as well as for reproductive value and age to protect (described next), is given in Table 4.

Reproductive Value (v_x)

The above estimates of r suggest that it would be useful to examine reproductive value for populations at the

MSY size that are assumed to have native rates of r in the range of the values estimated. Accordingly, v_x was calculated from Equation (7) with $r = 0.07–0.13$ for swordfish, and with $r = 0.08–0.16$ for the other billfishes.

The resulting reproductive value curves for billfishes peak at the age of maturity α or later, as v_x curves always do. But the age of maximum v_x is much larger than α if fecundity increases greatly with further age, as with the long-lived swordfish, and also blue marlin. The v_x curves begin with a value of 1.0 at age 0 ($v_0 = 1.0$ as previously explained) and end at zero after age w. They are shown only after age α in Figure 1. Among the billfish species, the high-fecundity swordfish has the highest levels of v_x, and sailfish the lowest. Within any species, v_x is seen to be reduced and to peak later as r increases. This is because increased r means higher survival to maturity, and this depreciates v_x and slows its rise with age. The correct v_x curve for a species may be considered as lying approximately midway between the curves depicted.

Protection Age

The ages ($x_{r'}$) up to which protection would ensure an r' rate of increase (from Eq. 9) are shown in Figure 1 by the ages at which dashed x_0 lines cross appropriate v_x curves (here, $r' = 0$, so $x_{r'} = x_0$ for ensuring a just-sustainable population). Thus the protection age or age at first capture is 7–8 yr for swordfish, considerably short of the peak v_x age at 13–14 yr. But for the shorter-lived, apparently higher-r sailfish, x_0 is between 4 and 5 yr, approximately the same age that gives peak v_x.

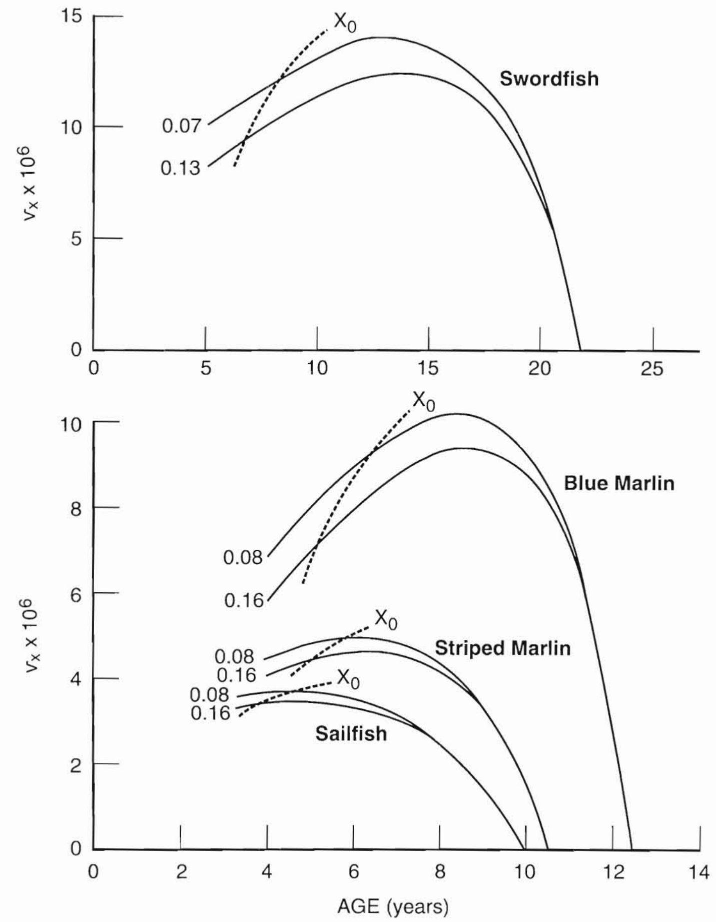

Figure 1

Intersection of protection age (x_0) curves (dashed) with reproductive value (v_x) curves (solid). Each v_x curve is for the specified assumed level of population, r. The x_0 curves specify the age at first capture that would ensure the $r = 0$ condition (population at least stationary). Note the change of scales in comparing swordfish with the other billfishes.

Discussion

Strictly speaking, the demographic analyses presented here pertain to populations that have become stable-aged, although any real population probably never achieves that state. Even so, the demographic approach is useful, because Lotka's equation captures robust features of demography and thus predicts long-term, underlying effects that are at least qualitatively correct (Stearns, 1992, chapter 2, p. 20–38). Vandermeer (1968), who also derived Equation (7) through a more involved argument, concluded the same. In defense of the demographic approach in fisheries work, it is worth noting that Murphy's (1967) sardine study is one of the better known demographic analyses in the ecological literature.

Reproductive value (v_x) and its protection is naturally of interest in conservation considerations. Fisher (1958) first noted in 1930 that natural selection acts through v_x, and reproductive value has since been the subject of numerous discussions of long-term evolutionary dynamics, e.g. Goodman's (1982) explanation of how optimal life histories maximize v_x. In terms of reproductive value, an optimal predator or fishery should avoid or protect the most valuable v_x ages and harvest mainly juveniles (MacArthur 1960), notwithstanding the loss from taking individuals before they

Table 4

Example of a computation to determine r, v_x, and age to protect, $x_{r'}$, for swordfish when total mortality Z equals $2M$. Swordfish population parameters are $\alpha = 5$ yr, $w = 20$ yr, $M = 0.21$/yr, and $Z = 2M = 0.42$/yr.

	Determining r			Determining v_x when $r = 0.07$				Determining $x_{r'}$ for $r' = 0$ when $r = 0.07$[10]		
x (yr) (1)	l_x/l_α (2)	l_x ($\times 10^{-6}$) (3)	m_x ($\times 10^{6}$) (4)	S_x/S_α (5)	$(S_x/S_\alpha)\,m_x$ ($\times 10^{6}$)	$\Sigma(S_x/S_\alpha)\,m_x$	v_x ($\times 10^{6}$) (6)	S_x/S_α (7)	$l_\alpha(S_x/S_\alpha)\,m_x$ (8)	Cumul (9)
5	1.0000	0.1420	2.04	1.0000	2.0400	10.5500	10.5500	1.0000	0.2744	0.2744
6	0.6570	0.1151	2.24	0.7558	1.6930	8.5100	11.2596	0.8106	0.2442	0.5186
7	0.4320	0.0933	2.45	0.5712	1.3994	6.8170	11.9345	0.6570	0.2165	0.7351
8	0.2840	0.0756	2.65	0.4317	1.1440	5.4176	12.5495	0.5326	0.1898	0.9249
9	0.1860	0.0613	2.86	0.3263	0.9332	4.2736	13.0971	0.4317	0.1661	1.0900
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
19	0.0028	0.0061	4.31	0.0198	0.0853	0.1513	7.6414	0.0529	0.0207	
20	0.0018	0.0000	4.40	0.0150	0.0660	0.0660	4.4000	0.0429	0.0254	

[1] Age in years.

[2] Relative survival is $l_x/l_\alpha = e^{-Z(x-\alpha)}$.

[3] Survival to age x is $l_x = l_\alpha(l_x/l_\alpha)$, where (from Equation 3) $l_\alpha = 1/\Sigma(l_x/l_\alpha)\,m_x = 1/7.0425 = 0.1420 \times 10^{-6}$.

[4] Fecundity at age x.

[5] Relative standing abundance at age $x = S_x/S_\alpha = e^{-(M+r)(x-\alpha)}$, where $r = 0.07$ (from the estimate of $r = 0.0763$ in note 10).

[6] Reproductive value at age x. $v_x = 1/(S_x/S_\alpha)\,\Sigma(S_t/S_\alpha)\,m_t$ = previous column/column 5 = $\Sigma_x^{20}(S_x/S_\alpha)\,m_x\,/\,(S_x/S_\alpha)$ (see Equation 7).

[7] Relative standing abundance at age x when $r' = 0$ is $S_x/S_\alpha = e^{-(M+r')(x-\alpha)} = e^{-M(x-\alpha)}$.

[8] These are the terms of Equation 9 when $r = 0.07$ and $r' = 0$, for then (from Equation 6) $S_{\alpha,r'} = l_{\alpha,r} = S_\alpha/e^{-r\alpha}$ where $S_\alpha = 1/10.550$ (from Equation 8) and $e^{-r\alpha} = e^{-0.7(5)}$. Thus $l_{\alpha,r}$ (here designated l_α) $= 0.1345 \times 10^{-6}$.

[9] Cumulative sum of previous column from age 5 to age x, according to Equation 9.

[10] Summing from $x = 5$ to 20 yr, $\Sigma l_x m_x = 1.9884$; $\Sigma x l_x m_x = 18.9736$; $\Sigma(l_x/l_\alpha)\,m_x = 7.0425$; $\Sigma(S_x/S_\alpha)\,m_x = 10.5550$.
Generation length $T = \Sigma x l_x m_x / \Sigma l_x m_x = 18.9736/1.9884 = 9.5420$ yr. Thus $r \approx (\ln \Sigma l_x m_x)/T = (\ln 1.9884)/9.5420 = 0.0720$/yr. Or, $r = 0.0763$/yr by iterative solution of Lotka's equation (Eq. 1).
The age $x_{r'}$ to which protection must be extended to ensure $r' = 0$ is given in the last column ("Cumul") where the cumulative sum becomes 1.0 (see Equation 9). This occurs at an interpolated age of 8.4 yr (or 8.9 yr if column values are considered to occur at midpoints of age).

have realized most of their growth. For a given population r, reproductive value at any age is proportional to fecundity and inversely proportional to survival. Thus the few surviving large adult billfishes acquire high v_x.

The approach used here is simple and essentially requires solution of Lotka's equation, which is equivalent to finding the dominant eigenvalue of a population's Leslie matrix. The assumptions employed are from ordinary, deterministic population dynamics. Even the assumption that all compensation effects are through increases in l_α and that m_x is unchanged is not unusual, for any actual m_x changes can be considered as manifested through changes in l_α. Such l_α-compensation has been demonstrated in groundfish populations (Myers and Cadigan, 1993) and is implicit in constant-recruitment fishery models.

Accuracy of the v_x estimates presented here depends strongly upon the accuracy of the r and m_x estimates. The former is most sensitive to the estimates of age α, which, as here, must at least appear reasonable in terms of other life history parameters. More problematical are the m_x schedules, which are derived from rather sketchy information. There can be little doubt, however, that fecundity increases rapidly with age in the fast-growing swordfish and blue marlin, thus setting those two species apart.

This analysis shows that the age to which protection should be extended to ensure a population is at least stationary ($r' = 0$) is much lower than the age of maximum v_x in the reproductively more valuable, longer-lived swordfish, more so than in the other species, especially striped marlin and sailfish. Protecting swordfish up to age $x_{r'} = x_0$ would therefore exclude protection for the most valuable v_x ages (valuable for enabling an r rate of increase), but without endangering the population. On the other hand, the protection ages for striped marlin and sailfish do include the peak v_x ages, so those ages are needed to ensure that their populations remain sustainable. Of course if the objective were to ensure a condition of $r' > 0$, e.g. to allow stock rebuilding, then the $x_{r'}$ lines would cross the v_x curves to the right of the lines shown in Figure 1, i.e. the protection ages (ages at first capture) would have to increase.

The demographic analysis here is more fundamental than the similar spawning-stock biomass per recruit (SSB/R) analysis (see Gabriel et al., 1989). Both derive from the same population theory. SSB/R can be used to determine whether present recruitment or survival to recruitment is adequate for stock rebuilding, although the findings can only be as definite as the stock-recruitment (S-R) relationship employed. That S-R relationship can be provided by demographic analysis by using an estimate of the rate of increase at the population size that produces MSY (i.e. r_Z with $Z = 2M$ or $3M$), as in this study. Noting that any such population that is stable-aged, as well as any of its segments, has potential to grow at annual rate $e^{r_Z} - 1$, it is in principle only necessary to find an S-R curve that describes an MSY exploitation rate equal to that annual rate. If recruitment (R) is defined as recruits to age at maturity α, (i.e. R_α), then this S-R_α relationship will determine the stock size produced by any mortality Z (and the converse), as established by the point on that S-R_α curve where the R_α:S survival diagonal with slope equal to $l_{\alpha,Z}$ (from Eq. 3) crosses that curve.

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Report Generation and Data Display from the NMT Archival Tag

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ABSTRACT

The Northwest Marine Technology[1] (NMT) Archival Tag promises to provide researchers with fisheries data never before obtainable. Implanted in a large pelagic fish such as a tuna or swordfish, the tag records depth, internal and external temperature, and light intensity every two minutes for up to 10–12 yr.

The tag employs three separate logs: a time series log, which stores measurements every 128 sec., a day log containing daily summaries, and a histogram log which records a tally of the number of times each possible value was measured in each data channel. While the time series log may overflow on a long mission, resulting in lost data, the day log and histogram logs cannot overflow, and will preserve information from the time the tag was initialized.

Software supplied with the kit runs under MS-DOS on an IBM-compatible personal computer, and allows the user to communicate with the tag and read its data. Software currently under development allows the user to browse a graphical representation of the Archival Tag data, zooming in and out on the details, and print, save to disk, and export the graphs to other Window™ applications.

Introduction

Tag Description

The Northwest Marine Technology[1] (NMT) Archival Tag is designed to be attached to or implanted in a large pelagic fish such as a tuna or swordfish to determine and record its position and key environmental variables every day for a period of years. When recovered and interrogated it will yield position data along with statistical summaries of all data measured and a detailed time series record of a portion of the mission.

The tag is housed in a stainless steel cylinder 16 mm in diameter and 100 mm long (Fig. 1). A thin, flexible measurement stalk 2 mm in diameter (stalk length can be customized but is nominally 200 mm) is attached to one end; when the tag is implanted the stalk extends through the skin of the animal to trail in the water. The end of the stalk houses a light sensor and a sensor for external temperature. A pressure sensor and a sensor for internal temperature are in the body of the tag.

The tag makes direct measurements of temperature internal and external to the fish, pressure, and narrow-band blue-green light intensity. As first proposed by NMT in 1987, the tag perfoms onboard data processing to reduce memory requirements. Depth is inferred from pressure. Temperatures at standard depths are interpolated. A measure of water clarity is computed from depth, light intensity, and time of day; the tag utilizes water clarity and depth data to extrapolate to noontime light intensity at the surface. Times of sunrise and sunset are inferred from light intensity as corrected for depth, and used to determine longitude; latitude is determined from sea temperature at standard depths (Smith and Goodman, 1986).

Temperature measurements, light intensity, and depth are recorded in a "time series log" every 128 sec. The tag extracts from each day's data, and records in a

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

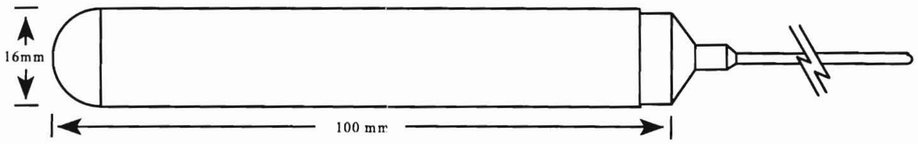

Figure 1
The NMT archival tag.

"day log," the comparatively small amount of information required to fix position, plus some additional diagnostic information. The day log is compact enough so that it can log every day of a multi-year mission and never lose data for lack of memory space.

Either NMT or the user can handle the tasks of initially setting parameters and of reading data from a recovered tag. Host software running on an IBM-compatible personal computer communicates with the tag through an adapter to do either task. The data file from a recovered tag is initially in compact binary form, maximum size 257 Kbytes, which is easy to handle and store. A second program translates the compact data record into a set of printable reports. A third program (under development) provides graphical display of the data for easy browsing, and generates various kinds of graphical output.

Data Logs

Day Log

The day log is the primary position record, and holds a 12-byte entry for each day of a mission. Primary quantities recorded are the times of sunrise and sunset, and the temperatures at the surface and at 61 m (200 ft) and 122 m (400 ft) depth. These standard depths can be changed as a user option. The record also contains some engineering information and a cross-reference to the day's data in the time series log. Seven years' worth of storage space is allocated to the primary day log. Even after this initial log space fills up, no day log entries are lost. Instead the log is expanded into space otherwise used for time series records, converting time series log into day log. This overwrites 1.6 days (1,100 records) of the oldest time series for every additional year of mission beyond 7 yr.

Histogram Log

The most compact data summary is a set of histograms which tally the number of occurrences of every possible data value in each measurement channel. These tallies include all measurements taken since the tag was initialized. For example, the histograms can provide information on the extreme values of depth and temperature ever measured and on the fraction of time the animal spent, say, below 250 m depth.

Time Series Log

The remaining memory, 215 Kbytes, is devoted to a time series log containing 4-byte records of raw data. The user may specify the rate at which data are recorded by setting the time series log interval (N). Measurements are always taken every 128 seconds, 675 times per day; the user can choose to *record* one out of every N of these measurements. For example, if he chooses to record every seventh measurement ($N=7$), a new record will be added about every 15 minutes.

The time series log has two parts. Section A fills up with the first data measured and does not change thereafter. Next section B fills up, but when it is full, new data begin to overwrite the oldest data in that section. Thus the time series log preserves the very first data measured, and the last data measured. The user may choose how much of the available space to devote to each section.

Tag Communication Kit

Tags arrive with the clock and all parameters set as requested, and are ready to use. There is no way to turn them off, so it is not possible to release an inactive tag. NMT's Archival Tag Communication Kit contains the necessary hardware and software to communicate with the tag and read its data. The two software applications supplied with the kit, HOST.EXE and READABLE.EXE, run under MS-DOS on an IBM-compatible personal computer. This communication kit has been successfully tested on a wide variety of computers, including very old and slow machines.

Using HOST.EXE, the user may adjust the tag's parameters to customize its operation for the mission at hand and to clear the logs just before the tag is released. When the tag is recovered at the end of a mission, HOST.EXE is used to download the stored data from the tag into a compact data file.

The data download yields a compact binary file, size 257 Kbytes or less, intended for easy storage on the floppy disk of the minimal portable computer which is likely to be available in the field. READABLE.EXE is used to translate the compact binary data into a set of formatted text files which are easily printed or imported into any word processing program. The reports contain control codes which allow the user to easily write a custom program to read the reports from disk and perform further processing of the data.

Graphical Display

A program called DATAPLOT, presently under development, displays the log contents graphically. This program runs under Windows™ and allows the user to browse through the three logs, zooming in on areas of interest. Individual graphs can be printed directly or saved as Windows metafiles for import into other Windows applications.

Summary

The NMT archival tag is more than a simple data logger. It has sensors carefully adapted to solve the real problems of fixing the position of pelagic fish. It performs data processing and keeps a day log which is compact enough so that it never loses position information due to data overflow. Finally, it is part of a complete system of hardware and software which presents data to the user in a convenient and ready-to-use form.

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Age Determination of Swordfish, *Xiphias gladius* L., from Waters off Baja California, Mexico, Using Anal Fin Rays and Otoliths

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ABSTRACT

Age was estimated based on otolith (sagittae) microstructure and on cross sections of the second ray from the first anal fin from 255 swordfish collected on board commercial drift gillnet vessels operating off Baja California during 1992 and 1993. We were able to successfully analyze 47% of otoliths examined. Annular counts ranged from 204 to 1,329 assumed daily rings (0.55–3.64 yr). Ninety-two percent of the anal-fin second rays were readable; estimated ages ranged from 0+ to 9+ for females and 0+ to 7+ for males. Based on the ray sections, 2- and 3-yr-old fish of both sexes were most frequent. Otolith age and age from second ray sections from the same fish (n=56) were highly similar for the first 2 yr (86% and 77% respectively); in older fish, similarity was <60%. Based on our results, as well as studies of swordfish in other oceans, we highly recommend the use of cross sections of the second ray from the first anal fin to determine ages of swordfish in the Pacific Ocean.

Introduction

The determination of age in fishes is crucial to understanding their population dynamics and the impact of exploitation. Age-composition data provide fundamental insight into fish biology and stock productivity, and allow the estimation of basic parameters for describing growth, mortality rates, and recruitment.

Attempts at aging swordfish, *Xiphias gladius*, have been made using several methods, including modal analysis of length frequencies and examination of hard parts such as vertebrae, otoliths, and dorsal and anal-fin ray[1] sections (Yabe et al., 1959; Berkeley and Houde, 1983; Radtke and Hurley, 1983; Wilson and Dean, 1983; Prince et al., 1987; Megalofonou and De Metrio, 1989; Tsimenides and Tserpes, 1989; Cavallaro et al., 1990; Megalofonou et al., 1990a, b; Ehrhardt, 1992; Tserpes and Tsimenides, 1995; Ehrhardt et al.[2]). However, discrepancies exist among the different methods used to study growth and age (Ehrhardt, 1992).

Most swordfish age determination studies have dealt with Atlantic populations. Berkeley and Houde (1983) analyzed the age of swordfish using anal-fin ray sections and proposed that the observed annuli could be annual marks. Radtke and Hurley (1983) analyzed the external features of otoliths and proposed that superficial ridges represented annual marks. Wilson and Dean (1983) analyzed otolith (sagittae) microstructures that they thought were daily rings and external features assumed to be annual increments. They also analyzed anal-fin ray sections from the same fishes, and found a good agreement (91%) between ages based on presumed annual growth increments in sagittae and ages based on annular bands on the fin ray sections. Prince et al. (1987) intended to validate the accuracy of the fin ray method for estimating swordfish age and growth, using marginal increment analysis, but their results did not provide sufficient evidence to validate the method. Ehrhardt (1992) used previously-reported data and ap-

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[1] Several authors have used the term "fin spines." However, swordfish fins lack spines, going by the diagnostic features reported by Nakamura (1983, 1985).

[2] Ehrhardt, N. M., R. Robins, and F. Arocha. 1995. On the age and growth of the swordfish in the northwest Atlantic. Int. Comm. Cons. Atl. Tunas Working Document SCRS/95/99, 23 p. ICCAT, Estebanez Calderon 3, E-28020, Madrid, Spain.

plied statistically more robust protocols to test the seasonal formation of marginal increments in anal fin ray sections. He found a significant difference in growth of marginal increments between seasons, with the maximum during summer, and concluded that rings in anal fin rays indicate annual events. Ehrhardt et al.[2] validated the use of these annual marks in anal fin rays of northwest Atlantic swordfish, using the same statistical algorithm as Ehrhardt (1992) and newly-collected data.

Tserpes and Tsimenides (1995) analyzed swordfish age and growth in the eastern Mediterranean using anal-fin ray sections. Their marginal increment analysis demonstrated that growth bands are deposited annually in fish 2–5 yr of age. However, they stated that these results constituted only partial validation of the method, which can not be considered successful until all reported ages of each population have been validated (Beamish and McFarlane, 1983).

In the Pacific, only a few swordfish aging studies have been done. Yabe et al. (1959) described the age composition and growth of swordfish caught in the western Pacific, based on modal analysis of length frequencies. Uchiyama et al. (1998) used hard parts, including rays of the first dorsal and first anal fins, vertebrae, and sagittae, for aging swordfish in the central north Pacific. They stated the necessity of validating the use of annuli on rays, vertebrae, and sagittae, and daily growth increments on sagittae.

In 1986, a swordfish drift gill net fishery commenced in waters off Baja California, Mexico. Between 1988 and 1993 the landings averaged 535 metric tons (t) (Holts and Sosa-Nishizaki, 1998). Due to the recent development of this fishery, it lacks a science-based management scheme. In order to produce the necessary information, a cooperative program was established in 1992 between the commercial drift gillnet fishermen and scientists at CICESE. This study is part of that effort.

The objectives of this research were to use the internal morphology of sagittal otoliths to age swordfish caught off Baja California, and to compare the results with those from the analysis of growth bands in first anal fin rays from the same fishes. Using these methods, we describe the age composition of the commercial fishery catch in the area.

Materials and Methods

Swordfish (n=366) were sampled on board commercial drift gillnet vessels operating in waters off Baja California, Mexico (between 22°N, 109°W and 32°N, 118°W), during 1992 (January–December) and 1993 (October–December). Postorbital eye–fork length (EFL) to the nearest centimeter was measured on board. Samples of heads for otolith extraction (n=166), first anal fins for excision of the second ray (n=255), and gonads for sex discrimination (n=255) were brought to the laboratory for analysis.

Semicircular canals were removed from the cranial cavity and preserved in 95% ethanol. Complete otoliths (right or left sagittae) were later removed from the tissue, cleaned in 5.23% sodium hypochlorite (Wilson and Dean, 1983), rinsed in distilled water, and dried in an oven at 40°C for 24 hr. In 34 cases the heads did not contain the inner ear organs, and the otoliths from 14 fish were lost due to handling, hence 118 sagittae were recovered from the 166 fishes.

Weights of the sagittae were measured to the nearest microgram using an electronic Mettler UM3[3] ultramicrobalance. Right and left sagittae mean weights were compared. The relationship between otolith weight and EFL was described by a power function. All comparisons of data were performed with the Student's t test, analysis of covariance, or analysis of variance, using a significance level of $\alpha = 0.05$ for statistical inferences.

External morphology of a subsample of 10 sagittae was examined with a scanning electron microscope (SEM) using the method of Radtke and Hurley (1983). Because the external surface of the rostrum of these otoliths lacked the ridge formation reported in the literature (Radtke, 1983; Radtke and Hurley, 1983), we did not use this method of age determination.

The internal microstructure of the sagittae was examined by two methods. First, a subsample of three sagittae were embedded in epoxy resin and sectioned in the transverse plane on a Buehler Isomet saw (Wilson and Dean, 1983). This method was also discarded because of the difficulty in obtaining good otolith sections.

A second method was used following Laurs et al. (1985). After cleaning and without further preparation, the otoliths were placed on a culture microslide filled with immersion oil to improve transparency and resolution and viewed through a compound microscope at magnifications of 100, 400 and 1000×, using transmitted light. This treatment revealed marks similar to daily increments described in other species (Fig. 1). Counts of increments were made on either right or left sagittae along the major axis of the rostrum, where the definition of increments was best (ordinarily at 1000×). The counting path was usually not linear, due to otolith topography, and frequent refocusing was necessary.

One experienced reader counted increments twice in a random subsample of otoliths (n=54) to assess counting precision. The precision of age estimates was calculated using the Index of Average Percent Error (IAEP) (Beamish and Fournier, 1981).

To verify ages estimated from sagittal otoliths, assuming that the marks we counted represented daily incre-

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

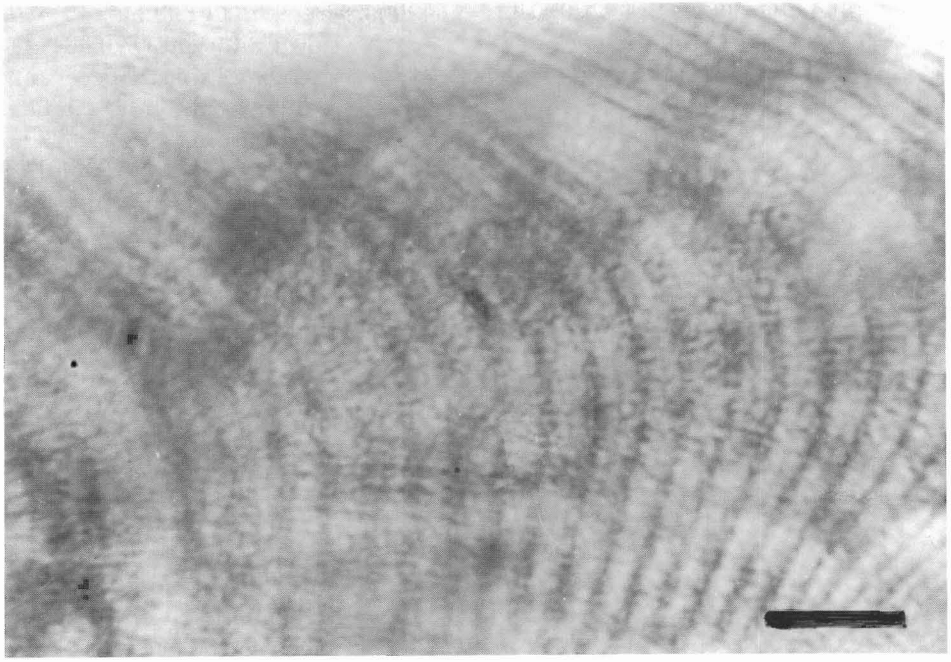

Figure 1
Light micrograph of daily increments along the rostrum of an otolith (sagitta) of swordfish, *Xiphias gladius*, from Baja California, Mexico. Scale bar = 8 µm.

ments, we compared them with ages estimated from sections of the second ray of the first anal fin from the same fish. The second ray was separated from the fin, cleaned in hot water, and air dried. All cross sections (about 1 mm thick) were cut with a Buehler Isomet saw at a point which was 10% of the total ray length from the condyle base to the tip of the ray, where growth patterns were observed more clearly. Sections were read by the two authors three times under a stereomicroscope at either 6 or 12× magnification, depending on ray size, using transmitted light. A series of opaque and hyaline annuli were observed (Fig. 2), as described by Jolley (1977) and Berkeley and Houde (1983). The light annulus (hyaline zone) was counted as an annual mark (Jolley, 1977). Here also the IAPE was calculated to assess precision.

During the aging process, the readers did not have any information about the length of the fish. All readings for both hard parts were done randomly and reading repetitions were spaced by one month.

The increments counted on each otolith were divided by 365 to obtain age in years. Ages from fin rays were expressed as the number of complete annuli, and the marginal increment was not considered.

For comparisons between readings of otoliths and fin ray sections, an index of similarity, *S*, was applied:

$$S = \frac{2C_i}{A_i + B_i}(100),$$

where C_i = number of fish assigned the same age class i by both otolith and fin ray readings,

A_i = number of fish of age class i according to the otolith reading, and

B_i = number of fish of age class i according to the fin ray reading.

Results

Swordfish females ranged from 85 to 245 cm in EFL, while males were from 79 to 239 cm (Fig. 3). Females caught in the Baja California swordfish fishery were significantly larger than males (F=16.6, P<0.001).

The otoliths from females weighed 0.50–2.75 mg (n=87), while those from males weighed 0.25–1.75 mg (n=27). No difference between the mean weights of left and right otoliths was observed (t=0.95, P=0.34). The relationship between fish EFL and otolith weight (OW) is represented by the following equations (Fig. 4):

$$\text{Females: OW} = 0.1196 \exp^{(0.0133 \times \text{EFL})},\ R^2 = 0.792\ (n=88)$$
$$\text{Males: OW} = 0.1831 \exp^{(0.0108 \times \text{EFL})},\ R^2 = 0.76\ (n=27).$$

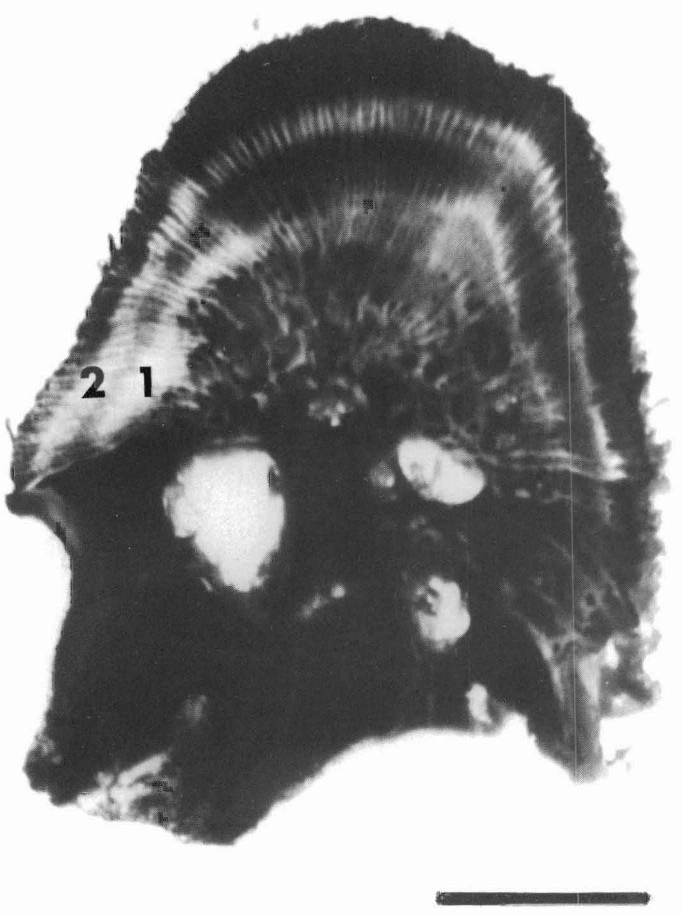

Figure 2

Transverse section of a first anal-fin ray viewed under transmitted light, showing two annual increments (1, 2). The sample was from a swordfish, *Xiphias gladius*, male of 138 cm EFL. Scale bar = 1.5 mm.

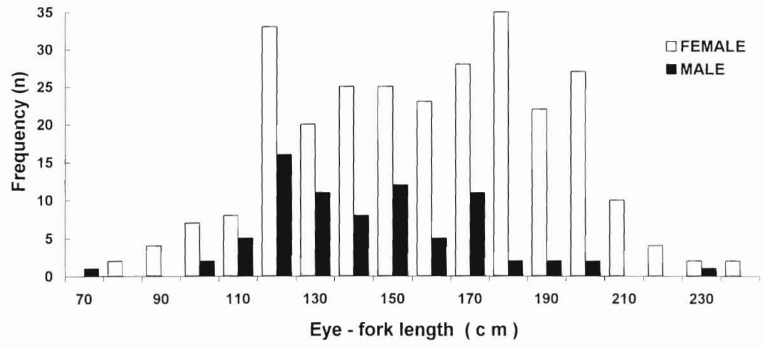

Figure 3

Length frequency distribution of swordfish, *Xiphias gladius*, males (n=84) and females (n=282) from Baja California, Mexico.

The slopes of the log-transformed EFL–OW regressions for females and males were significantly different (P<0.001).

We were able to successfully analyze 56 (47%) of the 118 otoliths sampled. Annular counts ranged from 204 to 1,329 apparent daily rings (0.55–3.64 yr). No significant difference was found between mean values of two increment counts (t=0.40, P=0.68), and the precision of age estimates (IAEP) was 6%.

The rest of the otoliths (n=62) were hard to read, either because only a portion of the rostrum could be discerned, or because the space between increments decreased toward the edge of the otolith in older fish, where our highest magnification (1000×) was insufficient to observe them.

Ray sections were easier to handle, prepare, and read than otoliths. Two hundred and thirty-four (92%) second rays from the 255 first anal fins sampled were analyzed successfully (61 males and 173 females). Samples were considered unreadable (n=21) if there was no agreement between readers due to the presence of multiple bands (as described by Berkeley and Houde, 1983) or because growth bands were unclear, especially for the first several growth marks which were sometimes obscured by vascularization in the central matrix. We found 12% IAEP when the age determinations of the two readers were compared.

Estimated ages from ray sections ranged from 0+ to 9+ for females and from 0+ to 7+ for males. The highest age frequencies were observed for fishes of 2 and 3 yr old for both sexes (Fig. 5).

Ages estimated from otoliths and second ray sections from the same fish (n=56) were highly similar for 1-yr-old and 2-yr-old fish (86% and 77%, respectively), but similarity for older fish was less than 60% (Fig. 6). The age frequency distributions based on the two structures are shown in Figure 6, where the otolith age distribution appears to be more right-skewed (predominately younger) than that from fin rays. Otoliths showed a tendency to underestimate age compared to fin ray sections in fishes 2 yr or older (Fig. 7), assuming fin ray counts to be more accurate.

Discussion

Our results demonstrate that otoliths grow proportionally in weight with body size, following a exponential function with different trends by sex. As was reported by other authors (Radtke and Hurley, 1983; Wilson and Dean, 1983; Uchiyama et al., 1998), our results show that otolith internal microstructures can be treated as daily increments to estimate swordfish age. Our data show consistent microstructure increments along the rostrum plane in otoliths from 1- and 2-yr-old swordfish; precision was unsatisfactory for older fish. Other studies have reported the use of otoliths to estimate the age of fish up to 9 yr old (e.g. Radtke and Hurley, 1983). Our inability to age older fishes may have been due to our difficulty in discerning the growth path along the rostrum of the otolith or to inadequate sample preparation.

Counting external ridges along the rostrum of sagittae was proposed as a method of age estimation for swordfish by Radtke and Hurley (1983) and for Istiophorids by Radtke (1983). Radtke and Hurley (1983) used an SEM to study otoliths of Atlantic swordfish and found a maximum age of 14 yr for males and 32 yr for females. According to our study, the applicability of that method may be questionable due to the lack of consistent external ridge formation. This problem was also reported by Wilson and Dean (1983). Furthermore, Hill and Calliet (1990) found high variability in Pacific blue marlin age estimates, using an SEM to study otolith external morphology. They compared otolith age estimates with ages determined by dorsal and anal fin techniques, and concluded that the high variability of sagittal otolith age estimates may reflect problems in interpretation of ridges in regions of acute calcium overburdening, overlapping ridges, or multiple ridges within a large ridge. Their results show how difficult the application of this technique can be. Thus, at least for swordfish, we do not recommend using otolith external morphology for age estimation.

Growth patterns observed in anal-fin ray sections were similar to those previously described for Atlantic (Berkeley and Houde, 1983), Aegean (Tsimenides and Tserpes, 1989), and eastern Mediterranean swordfish (Tserpes and Tsimenides, 1995). The use of anal-fin ray sections as a source of age information for commercial fishery catches of swordfish has the advantages that growth patterns can be clearly seen and samples can be easily obtained without altering the commercial value of fish. Nevertheless, the core of the fin rays in older fish can undergo resorption and become vascularized, obscuring and even eliminating the first growth zone in some specimens. The presence of multiple bands may also be a problem, but can be easily overcome with experience (for an extensive discussion see Tserpes and Tsimenides, 1995).

Three conditions are necessary for accurate age estimation: the existence of a periodic mark in some body part; the ability to identify these marks reliably (which includes distinguishing them from false marks); and the ability to convert accurately a count of marks to an absolute age, the demonstration of which is considered validation of an aging method (Francis et al., 1992). The confirmation of agreement in results between two aging methods, i.e. verification (Wilson et al., 1983), offers a good estimation of ages that have not been validated, providing confidence in a given interpretation (Casselman, 1983). The term verification has also been defined as "a term usually used in reference to the precision of estimated age" (Hill and Calliet, 1990).

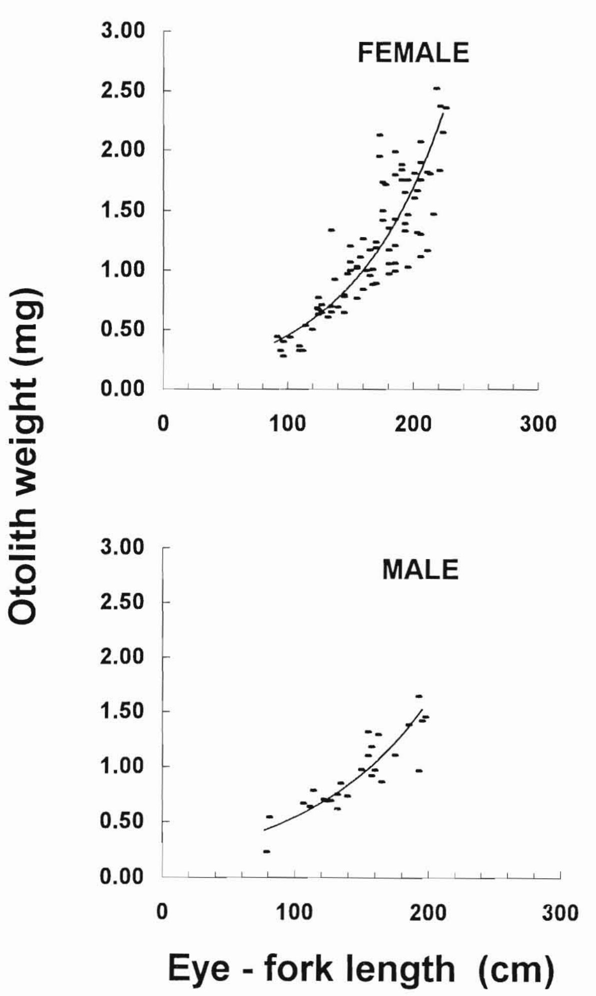

Figure 4

Relationship between otolith weight and eye–fork length (EFL) by sex for swordfish, *Xiphias gladius*, from Baja California, Mexico.

The agreement in this study between presumed annuli in fin rays and daily rings in otoliths enables us to verify the anal-fin-ray method of determining age in northeast Pacific swordfish, at least for fishes younger than 3 yr old. The use of anal-fin ray sections for aging

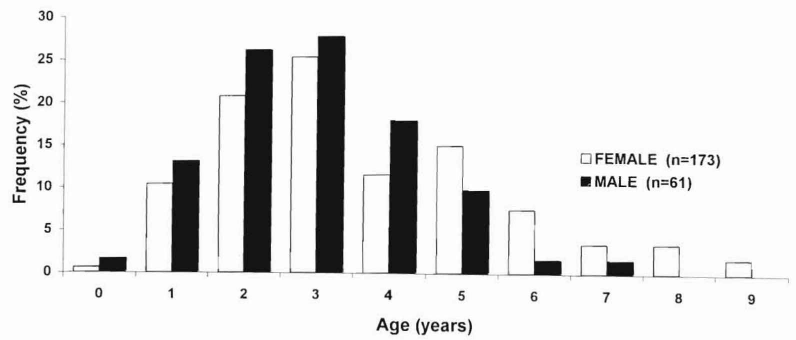

Figure 5
Age frequency distributions estimated by anal-fin ray sections of swordfish, *Xiphias gladius*, from Baja California, Mexico.

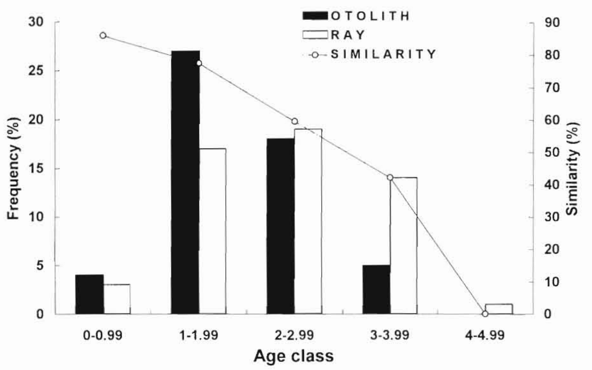

Figure 6
Age frequency distribution of swordfish, *Xiphias gladius*, estimated by otoliths and anal-fin ray sections from the same fish. Values of the index of similarity (S) between ages estimated from the two structures are also shown.

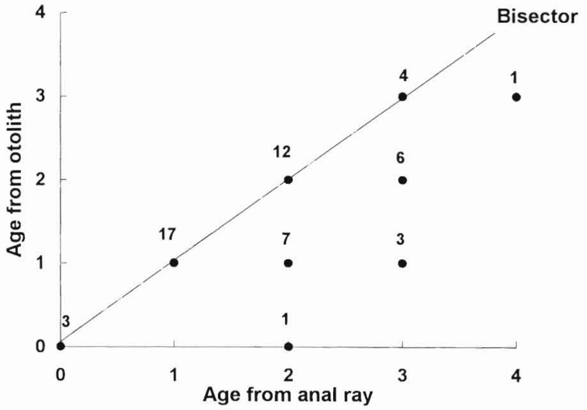

Figure 7
Comparison between ages assigned on the basis of otoliths and anal fin ray sections for swordfish, *Xiphias gladius*. The number of fish at each point is indicated. The bisector line represents 100% agreement.

swordfish has previously been partially validated (for the case of one to five growth bands) by means of marginal increment analysis for swordfish from the northwest Atlantic and Mediterranean (Ehrhardt, 1992; Ehrhardt et al., 1995; Tserpes and Tsimenides, 1995). Taking into consideration the verification of the fin ray section method, and the partial validation of this method in other papers, we highly recommend the use of anal-fin ray sections as a reliable method for aging Pacific fish.

The age frequency histogram (Fig. 5) shows that the commercial catch in Baja California was dominated by young male and female fishes (2–3 yr). This could be an indication that fishes under 2 yr old are not fully recruited to the fishery. This result is similar to the catch composition reported by Berkeley and Houde (1983) and Wilson and Dean (1983) for the northwest Atlantic more than 10 yr ago. The difference seen in the sample between maximum age of females (9+ yr) and of males (7+ yr) (Fig. 5) could be a result of temporal-spatial difference in catchability or of a difference in lifespan. Further studies should be carried out in order to understand the population dynamics of the swordfish resource in this region.

Acknowledgments

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Genetic Comparison of Pacific and Mediterranean Swordfish, *Xiphias gladius*, by RFLP Analysis of the Mitochondrial D-loop Region

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ABSTRACT

The mitochondrial DNA D-loop region of swordfish, *Xiphias gladius*, was amplified by the polymerase chain reaction (PCR), and the amplified DNA fragments (1,950 base pairs) were subjected to restriction fragment length polymorphism (RFLP) analysis to investigate genetic differentiation among geographically distant samples. Four endonucleases (*Alu* I, *Dde* I, *Hha* I, and *Rsa* I) detected high levels of RFLP's in western (n=45) and eastern (n=35) North Pacific samples. Estimated diversity (h) was 59.9% and 56.1% (*Alu* I), 44.0% and 39.2% (*Dde* I), 42.1% and 21.4% (*Hha* I), and 60.4% and 64.0% (*Rsa* I) for western and eastern samples, respectively. In contrast, no RFLP was detected with *Hha* I and *Rsa* I in the Mediterranean sample (n=34). Frequency distributions of the restriction patterns in all endonuclease digestions were significantly different between the Mediterranean and Pacific samples, while no significant differences were observed between western and eastern Pacific samples. Much higher haplotypic diversity was observed in the Pacific (92.0%–94.4%) than in the Mediterranean (70.2%) samples, indicating that little genetic exchange has occurred between the two populations.

Introduction

Restriction fragment length polymorphism (RFLP) analysis of the whole mitochondrial DNA (mtDNA) molecule has been used to investigate genetic diversity within and between local samples of swordfish, *Xiphias gladius* (Grijalva-Chon et al. 1994; Katoulas et al., 1995). Katoulas et al. (1995) showed that genotype frequencies were significantly different in samples of swordfish from the Gulf of Guinea and from the eastern Atlantic (off Gibraltar) and Mediterranean (Greece, Italy, and Spain), suggesting the existence of genetically different stocks in the Atlantic. In contrast, no genetic heterogeneity was observed between swordfish samples from the eastern, central, and western North Pacific (Grijalva-Chon et al., 1994).

Recently, a direct nucleotide sequencing method based on the polymerase chain reaction (PCR) has been introduced and applied to further investigate genetic differentiation within and between swordfish populations (Finnerty and Block, 1992; Alvarado Bremer et al., 1996; Rosel and Block, 1996). In particular, Alvarado Bremer et al. (1996) and Rosel and Block (1996) reported that the left domain of the mtDNA D-loop region of the swordfish is hypervariable. They compared swordfish samples from the Atlantic, Mediterranean, and Pacific on the basis of sequence variation, and reported that mtDNA haplotype frequencies were significantly different.

This study reports on intraspecific RFLP in the D-loop region of swordfish mtDNA amplified by PCR. Genetic comparisons were made among two Pacific samples and one Mediterranean sample of swordfish.

Materials and Methods

All swordfish samples included both adults and juveniles. The western North Pacific sample (n=45) was caught by the Japanese commercial longline fleet and was collected at the landing site in Yaizu City, Japan, during November 1991–February 1992. Muscle dissected from the fresh fish was transferred on ice to the laboratory of the National Research Institute of Far Seas Fisheries (NRIFSF), where DNA extraction was carried out.

The eastern North Pacific swordfish sample (n=35) was caught by the Mexican commercial fleet using drift gillnets from November 1991 to February 1992. Crude DNA extracted from these fish was kindly provided by

O. Sosa-Nishizaki and J. M. Grijalva-Chon, Centro de Investigación Cientifica y de Educatión Superior de Ensenada (CICESE), Mexico.

The Mediterranean sample (n=34) was collected by A. Di Natale of Aquastudio, in Italy, in 1994. A small piece of tissue dissected from frozen muscle was preserved in ethanol and transferred to the laboratory.

DNA extraction and PCR amplification procedures are described elsewhere (Chow and Inoue, 1993; Chow et al., 1993; Grijalva-Chon et al., 1994). Primer sequences for amplifying the mitochondrial D-loop region were from Palumbi et al.[1]; the nucleotide sequences were CB3R-L: 5'-CATATTAAACCCGAATGATATTT-3' and 12SAR-H: 5'-ATAGTGGGGTATCTAATCCCAGTT-3'. The PCR products were electrophoresed in 1% agarose gel to confirm amplification, whereafter the amplified samples were directly digested by the restriction endonucleases and electrophoresed through 2%–2.5% agarose gel (Biogel, Bio 101, La Jolla, CA[2]) followed by ethidium bromide staining and photography. Diversity (h) was calculated using the frequencies of restriction patterns and haplotypes (Nei, 1987). The G test of independence (Sokal and Rohlf, 1981) was employed to compare frequencies of restriction patterns and haplotypes between samples.

Table 1

Polymorphisms and genetic diversity, h, in mtDNA from western Pacific swordfish (n=45).

Endonuclease	Sequence at site	Variation[1]	No. individuals	h^2(%)
Alu I	AGˇCT	P	45	59.9
Bsa JI	CˇCNNGG	M	14	0.0
Bsl I	CCN$_5$ˇN$_2$GG	M	22	0.0
Bst UI	CGˇCG	M	14	0.0
Dde I	CˇTNAG	P	45	44.0
Hae III	GGˇCC	M	22	0.0
Hha I	GCGˇC	P	45	42.1
Hinf I	GˇANTC	M	22	0.0
Mbo I	ˇGATC	M	14	0.0
Mse I	TˇTAA	P	18	9.1
Nla III	CATGˇ	P	45	38.0
Rsa I	GTˇAC	P	45	60.4
Sau 96I	GˇGNCC	M	22	0.0
Scr FI	CCˇNGG	M	10	0.0
Taq I	TˇCGA	P	18	24.7

[1] P = polymorphic; M = monomorphic.

[2] After Nei (1987).

Results

RFLP Analysis

The western North Pacific sample was tried with 15 endonucleases, of which 7 detected polymorphisms (Table 1). Since 4 of the 7 (*Alu* I, *Dde* I, *Hha* I, and *Rsa* I) detected relatively high polymorphisms in this sample, these 4 endonucleases were used to analyze the other 2 samples. The electrophoretic profiles of all detected restriction patterns (alphabetically labeled) are shown in Figure 1. The observed number of restriction patterns was 4 in *Alu* I and *Dde* I, 3 in *Hha* I, and 6 in *Rsa* I digestions.

Comparisons between the Samples

Frequencies of the restriction patterns in each endonuclease digestion of swordfish mtDNA are shown in Table 2. In the *Alu* I digestions, pattern *A* was common and occurred at a similar frequency in all samples. Frequencies of patterns *B* and *C* were similar in western and eastern North Pacific samples, but the Mediterranean sample had a much lower frequency of *B* and a higher frequency of *C* than the Pacific samples. In the *Dde* I digestion, *C* was common in all samples; *A* was not observed in the Mediterranean sample; and *D* was much more frequent in the Mediterranean than in the Pacific sample. Similarly, for *Hha* I digestion the Mediterranean sample was monomorphic (h = 0), while a moderate level of variation was observed in the Pacific samples (h = 42.1% for the western and 21.4% for the eastern sample). The largest difference between the Pacific and Mediterranean samples was observed in the *Rsa* I digestion. The Mediterranean sample was monomorphic for this endonuclease digestion, as all individuals examined possessed pattern *C*. In contrast, the Pacific samples were highly polymorphic (h = 60.4% and 64.0% for the western and eastern samples, respectively).

A G test of independence indicated that the frequency distributions of the restriction patterns were significantly different between the Pacific and Mediterranean samples for all digestions (P<<0.05). In contrast, no significant difference was observed between the western and eastern North Pacific samples.

An analysis of the composite haplotypes derived from the restriction patterns of all 4 endonuclease digestions also demonstrated differences between the samples. All in all, 24 haplotypes were observed among 113 individuals (Table 3). Twenty and thirteen haplotypes were found in the western and eastern Pacific samples, respectively, while only five were observed in the Mediterranean sample.

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[1] Palumbi, S., et. al. 1991. The simple fool's guide to PCR, version 2.0. Dep. of Zoology, Univ. Hawaii, Honolulu.

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

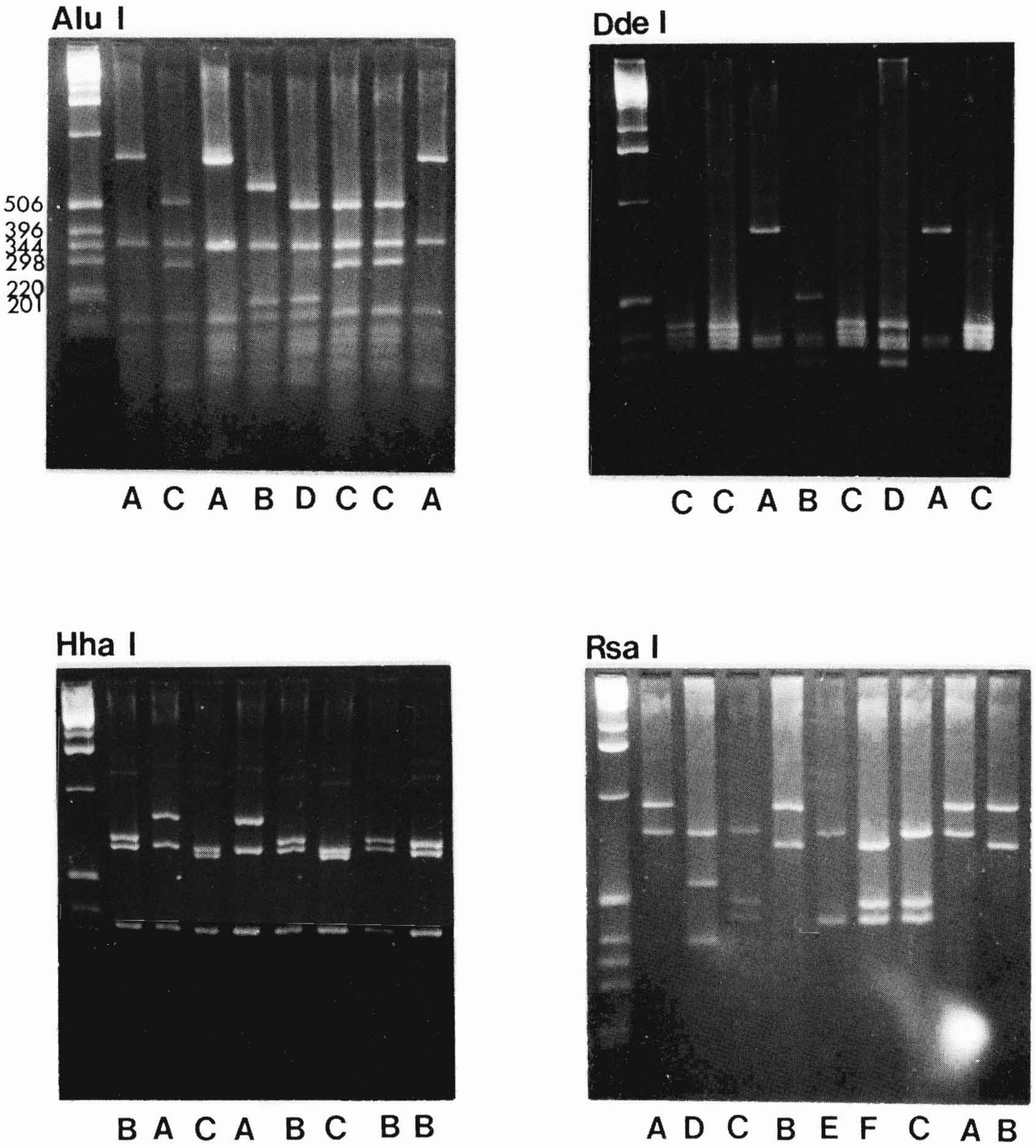

Figure 1
Restriction patterns of the swordfish mitochondrial D-loop fragment digested by four endonucleases. Restriction patterns were alphabetically labeled. The leftmost lane in each electrophenogram is 1-kb DNA ladder (Gibco, BRL).

Haplotypic diversity estimates (*H*; Nei, 1987) reflected the skewed number of haplotypes in the Mediterranean sample. Thus, the eastern and western Pacific samples had much higher diversity (94.4% and 92.0%, respectively) than the Mediterranean sample (70.2%).

This difference was amplified when only *Hha* I and *Rsa* I restriction fragment patterns were considered (Table 4). Eight and five haplotypes were found in the western and eastern Pacific samples, respectively, and only one (*BC*) was observed in the Mediterranean sample. The haplotypic diversities were 77.6% and 71.5% for the western and eastern Pacific samples, respectively, while that of the Mediterranean was 0. The difference in haplotype distribution between the Pacific and Mediterranean samples was highly significant ($P \ll 0.001$). These results indicate that there is little gene flow between the swordfish populations of the Pacific Ocean and the Mediterranean Sea.

Table 2

Number (% frequency) of restriction patterns in each of four restriction endonuclease digestions of mtDNA from three swordfish samples, and calculated genetic diversity, *h* (after Nei, 1987).

		North Pacific		
Endonuclease	Patterns	Western	Eastern	Mediterranean
Alu I	*A*	29 (57.8)	21 (60.0)	18 (53.0)
	B	9 (20.0)	10 (28.6)	1 (2.9)
	C	9 (20.0)	4 (11.4)	14 (41.2)
	D	1 (2.2)	0 (0.0)	1 (2.9)
	n[1]	45	35	34
	h	59.9	56.1	56.4
Dde I	*A*	7 (15.6)	6 (17.6)	0 (0.0)
	B	1 (2.2)	0 (0.0)	0 (0.0)
	C	33 (73.3)	26 (76.5)	27 (79.4)
	D	4 (8.9)	2 (5.9)	7 (20.6)
	n[1]	45	34	34
	h	44.0	39.2	33.7
Hha I	*A*	10 (22.2)	4 (11.8)	0 (0.0)
	B	33 (73.3)	30 (88.2)	34 (100.0)
	C	2 (4.5)	0 (0.0)	0 (0.0)
	n[1]	45	34	34
	h	42.1	21.4	0.0
Rsa I	*A*	17 (37.8)	15 (42.9)	0 (0.0)
	B	3 (6.7)	3 (8.5)	0 (0.0)
	C	23 (51.1)	15 (42.9)	34 (100.0)
	D	0 (0.0)	2 (5.7)	0 (0.0)
	E	1 (2.2)	0 (0.0)	0 (0.0)
	F	1 (2.2)	0 (0.0)	0 (0.0)
	n[1]	45	35	34
	h	60.4	64.0	0.0

[1] *n* = number of individuals examined.

Discussion

Evaluation of intraspecific haplotypic diversity via RFLP analysis is very sensitive to the numbers of endonucleases used and individuals sampled (Nei, 1987), and RFLP analyses appear to miss many nucleotide substitutions (Beckenbach, 1991). Therefore, comparisons of haplotypic diversity between species via RFLP analysis are much less meaningful than spatio-temporal comparison of values within species. Especially for genetic stock analysis, it is much more important to find a way to detect diagnostic variation.

PCR-RFLP analysis is well suited for analyzing large numbers of specimens because it is quite simple and less costly than conventional restriction analysis of mtDNA via Southern blotting or with direct nucleotide sequencing. This technique has been used to detect genetic polymorphisms in the mitochondrial ATPase gene of albacore, *Thunnus alalunga*, using a large number of individuals (*n*=620; Chow and Ushiama, 1995). Examination and selection of a target gene region and the length of the amplified fragments are critical for PCR-RFLP analysis (Chow and Inoue, 1993; Chow et al., 1993). Alvarado Bremer et al. (1995, 1996) demonstrated that the D-loop region of swordfish mtDNA is extremely polymorphic, using nucleotide sequence analysis. In the present study, RFLP analysis of the amplified swordfish D-loop region was able to detect a considerable amount of genetic variation. In addition, the haplotypic diversity obtained by using a limited number of endonucleases was higher than that obtained by restriction analysis of the entire mtDNA molecule (see Grijalva-Chon et al., 1994; Katoulas et al., 1995).

The present results coincide with those of previous studies. Samples from the Pacific were found to be genetically homogeneous (Grijalva-Chon et al., 1994) using RFLP analysis on the entire mtDNA molecule, whereas large differences in haplotypic distributions

Table 3

Number of composite haplotypes (% frequency) in mtDNA from three swordfish samples. Four columns of the haplotype represent four endonucleases: *Alu* I, *Dde* I, *Hha* I, and *Rsa* I, from left to right.

		North Pacific		
Clone	Haplotype	Western	Eastern	Mediterranean
1	*AAAA*	3 (6.7)	3 (8.8)	0 (0.0)
2	*AAAC*	2 (4.5)	0 (0.0)	0 (0.0)
3	*AABC*	0 (0.0)	3 (8.8)	0 (0.0)
4	*AABE*	1 (2.2)	0 (0.0)	0 (0.0)
5	*ABBA*	1 (2.2)	0 (0.0)	0 (0.0)
6	*ACAA*	2 (4.5)	1 (2.9)	0 (0.0)
7	*ACAC*	3 (6.7)	0 (0.0)	0 (0.0)
8	*ACAF*	1 (2.2)	0 (0.0)	0 (0.0)
9	*ACBA*	1 (2.2)	3 (8.8)	0 (0.0)
10	*ACBB*	2 (4.5)	2 (5.9)	0 (0.0)
11	*ACBC*	6 (13.3)	7 (20.6)	11 (32.4)
12	*ADBA*	3 (6.7)	1 (2.9)	0 (0.0)
13	*ADBC*	1 (2.2)	0 (0.00)	7 (20.6)
14	*BCBA*	3 (6.7)	4 (11.8)	0 (0.0)
15	*BCBB*	1 (2.2)	0 (0.0)	0 (0.0)
16	*BCBC*	5 (11.1)	4 (11.8)	1 (2.9)
17	*BCBD*	0 (0.0)	2 (5.9)	0 (0.0)
18	*CACA*	1 (2.2)	0 (0.0)	0 (0.0)
19	*CCBA*	1 (2.2)	2 (5.9)	0 (0.0)
20	*CCBC*	6 (13.3)	1 (2.9)	14 (41.2)
21	*CCCA*	1 (2.2)	0 (0.0)	0 (0.0)
22	*CDBB*	0 (0.0)	1 (2.9)	0 (0.0)
23	*DCBA*	1 (2.2)	0 (0.0)	0 (0.0)
24	*DCBC*	0 (0.0)	0 (0.0)	1 (2.9)
Total		45	34	34
H^1(%)		94.4	92.0	70.2

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[1] Haplotypic diversity (Nei, 1987).

Table 4

Comparison of composite haplotype frequencies between three swordfish samples on the basis of restriction patterns in digestions by *Hha* I and *Rsa* I endonucleases.

		North Pacific		
Clone	Haplotype	Western	Eastern	Mediterranean
1	*AA*	5 (11.1)	4 (11.8)	0 (0.0)
2	*AC*	5 (11.1)	0 (0.0)	0 (0.0)
3	*BC*	18 (40.0)	15 (44.1)	34 (100)
4	*BE*	1 (2.2)	0 (0.0)	0 (0.0)
5	*BA*	10 (22.2)	10 (29.4)	0 (0.0)
6	*AF*	1 (2.2)	0 (0.0)	0 (0.0)
7	*BB*	3 (6.7)	3 (8.8)	0 (0.0)
8	*BD*	0 (0.0)	2 (5.9)	0 (0.0)
9	*CA*	2 (4.4)	0 (0.0)	0 (0.0)
Total		45	34	34
H^1(%)		77.6	71.5	0

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[1] Haplotypic diversity (Nei, 1987).

were observed between Pacific and Mediterranean samples using nucleotide sequence analysis, as reported by Alvarado Bremer et al. (1996) and Rosel and Block (1996). Thus, regardless of the methods employed, mtDNA analysis may be quite powerful for the detection of genetic differentiation among geographically distinct populations. Further PCR-RFLP analysis is underway on swordfish samples from other locations in the Pacific as well as the North and South Atlantic and Indian Oceans. The results may be useful in clarifying the global population structure of this highly migratory and cosmopolitan fish.

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Food and Feeding Habits of Swordfish, *Xiphias gladius* L., off Western Baja California

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ABSTRACT

Stomach contents of 173 swordfish caught off the west coast of Baja California in eight commercial fishing trips during 1992 and January 1993 were analyzed. Cephalopods dominated the stomach contents over the first four trips, off southern Baja California: 85% by number, 90% by weight, and 96% by frequency of occurrence. The species composition in the diet was constant during the four trips; ommastrephid squid, *Sthenoteuthis oualaniensis*, was the most important prey. Fishes dominated the diet in the last four trips, off northern Baja California: 62% by number, 84% by weight, and 65% by frequency of occurrence. The fish species composition varied during the four trips, mesopelagic species being the most important. Significant differences were found in the numerical composition of prey species between the eight trips.

Values of a fullness weight index indicated that swordfish eat equal quantities off northern and southern Baja California. However, differential digestion could be masking a greater quantity of feeding off the southern area, where swordfish reach sexual maturity during migration. Swordfish feed mostly alone on schooling prey, and appear to be efficient and opportunistic predators whose diet indicates prey abundances in the environment. This may allow swordfish to be used as an efficient biosampler. Swordfish trophic level off western Baja California varies between 4 and 4.5.

Introduction

The swordfish, *Xiphias gladius* Linnaeus, is a large, pelagic, predatory fish distributed worldwide in tropical and temperate waters, and between 50°N and 35°S in the Pacific Ocean (Nakamura, 1974). Almost half the total catches of this species occurs in the Pacific (Holts and Sosa-Nishizaki, 1998), and the western Baja California coast is a major fishing zone (Sakagawa, 1989).

Studies of swordfish food habits have been made mainly in the North Atlantic and Mediterranean Sea, where some authors reported cephalopods (mainly ommastrephids) as the most important prey (see historical summary by Toll and Hess, 1981; Stillwell and Kohler, 1985; Bello, 1991; Guerra et al., 1993). However, other studies found fishes to be the principal component of stomach contents (Tibbo et al., 1961; Scott and Tibbo, 1968, 1974; Moreira, 1990; Clarke et al., 1995). Few authors have focused on seasonal and geographical changes in swordfish diet (Maksimov, 1969; Stillwell and Kohler, 1985; Hernández-García, 1995).

The trophic ecology of the swordfish in the Pacific Ocean is poorly known; observations on its food habits have been made as part of more extensive studies. LaMonte and Marcy (1941) and LaMonte (Hubbs and Wisner, 1953, p. 130) found only squid in the stomach contents of swordfish caught off Chile. Nakamura (1949) reported cod, rockfish, and myctophids as swordfish prey in a study of tuna and billfish biology and fisheries. Yabe et al. (1959), studying swordfish biology in the western Pacific, found mostly zooplankton and pelagic fish larvae in the guts of ten larval swordfish; squids,

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fishes, and amphipods in twenty young swordfish; and mainly squid, fishes, and crustaceans in six adult swordfish. De Sylva (1962) identified 24 jumbo squids, *Dosidicus gigas*, in five of seven female swordfish stomachs examined during a study of dinoflagellate bloom off northern Chile, and concluded that feeding occurs near the surface. He also reported that Pacific bonito, *Sarda chiliensis*, are eaten by swordfish. Wisner (de Sylva, 1962, p. 276) reported that the stomach contents of swordfish off southern California indicated feeding on rather deepwater fishes.

Fitch and Lavenberg (1971), in a study of California marine fishes, found that most swordfish off California had fed on anchovies and cephalopods (squid) and other fishes such as hake, jack mackerel, and shortbelly rockcod. A few stomachs contained deep-sea fishes such as lanternfish, barracudinas, pencilsmelt, and other oddities. Frey (1971) enumerated northern anchovies, squid, hake, jack mackerel, rockfish, barracudinas, black smelt, ribbonfish, and shrimp as swordfish prey off California, and considered whether swordfish may undergo ontogenic change in feeding habits, foraging at greater depths with age.

Mearns et al. (1981) analyzed the stomach contents of 17 swordfish caught near the Channel Islands, California, as part of a study of the trophic structure of marine ecosystems. In 15 individuals that contained food, northern anchovy and Pacific hake each accounted for over 40% of the index of relative importance, the remainder being almost entirely fish tissue. Seki (1993) studied the stomachs of 22 swordfish caught north of the Hawaiian Archipelago to examine predator–prey relationships with a squid, *Ommastrephes bartramii*. The cephalopod fauna was composed of *O. bartramii* (40.9%), *Sthenoteuthis oualaniensis* (18.3%), *Thysanoteuthis rhombus* (31.8%), and unidentified ommastrephid (13.6%).

Yatsu (1995), in a paper on the ecology of slender tuna in the South Pacific Ocean, reported mainly unidentified fishes and cephalopods from the stomachs of 19 swordfish. Barbieri et al. (1998) found that longtailed hake, *Macruronus magellanicus*, and jack mackerel, *Trachurus murphyi*, were the most important prey (60% each) in 55 swordfish stomachs caught off Chile. Squids, *Dosidicus gigas* and *Loligo gahi* (15%), fish remains (15%), and shrimp, *Heterocarpus reedi* (10%) occurred less frequently.

The purpose of this paper is to increase knowledge of the food and feeding habits of swordfish caught off the western Baja California coast.

Materials and Methods

The stomachs of 173 swordfish were obtained by swordfish drift gillnet vessels based in El Sauzal harbor, Ensenada, during eight commercial trips along the western coast of Baja California. A description of this fishery is given by Holts and Sosa-Nishizaki (1998). The first four trips were made off southern Baja California between 23°58' and 29°38'N from February to August 1992, and the last four off northern Baja California between 29°10' and 32°21'N from October 1992 to January 1993 (Fig. 1, Table 1). Stomachs were preserved by an observer on board the vessels in 10% buffered formalin, and their contents transferred to 70% ethanol in the laboratory. The eye–fork length of each swordfish was measured to the nearest centimeter and its sex was determined. Weights were estimated using allometric relationships calculated by Castro-Longoria (1995).

Identification of pelagic fishes in the stomach contents was based on external anatomy or vertebral char-

Table 1

Dates of collection and number, size, sex, and stomach condition of swordfish sample caught during 1992 and January 1993 off Baja California.

			Eye–fork length (cm)			Sex			Number of stomachs		
Trip	Date	*N*	Range	Mean	SD	Female	Male	Unid.	Contents	Empty	Everted
1	29 February–21 March 1992	28	88.9–233.7	156.0	38.1	21	7		23	2	3
2	5–22 April 1992	18	99–200.6	160.7	35.9	16	2		17	1	
3	29 June–16 July 1992	22	93.9–220.9	166.4	34.4	22			22		
4	28 July–7 August 1992	26	88.9–223.5	164.5	32.2	22	4		22	4	
5	17–27 October 1992	33	111.7–218.4	162.3	33.4	23	9	1	32	1	
6	10–13 November 1992	8	116.8–210.8	157.1	35.7	7	1		8		
7	10–22 December 1992	26	76.5–208.2	166.1	31.3	19	5	2	24	1	1
8	14–20 January 1993	12	116.4–203.2	156.8	27.1	9	3		11		1
Pooled		173	76.5–233.7	161.9	33.4	139	31	3	159	9	5

acteristics (Clothier, 1950). Well-preserved mesopelagic fishes were identified by R. H. Rosenblatt, C. Klepadlo, and H. J. Walker, Jr.,[1] and the vertebrae from these specimens were used to identify the bony remains of other specimens. Cephalopods were identified mainly from beaks, using available keys (Pinkas et al., 1971; Wolff, 1984; Clarke, 1986) and a reference collection, under the supervision of F. G. Hochberg.[2] Fish otoliths were not used to quantify diet in this study, as only those belonging to Pacific hake remained complete, even though buffered formalin was used to fix samples. This is not surprising, since otoliths of a related family, Gadidae, are among the most durable (Jobling and Breiby, 1986; Pierce et al., 1993; Hernández-García, 1995).

Percent number (%N), weight (%W), and frequency of occurrence (%FO) (Cailliet, 1976) were quantified for each prey species or group of species in the diet, including trace amounts, not including everted stomachs. Counts of fish remains were based on the maximum number of vertebrae possible per species, or by counting heads or tails. The larger of the two counts of upper and lower beaks was taken as the minimum number of cephalopods represented (Perrin et al., 1973). Prey remains were weighed to the nearest 0.1 g. Although weight and volume measures give the same information (Cailliet, 1976), weight was preferred because it is more accurate and less time consuming. Number and weight of prey were calculated pooling the contents of all stomachs from the same trip.

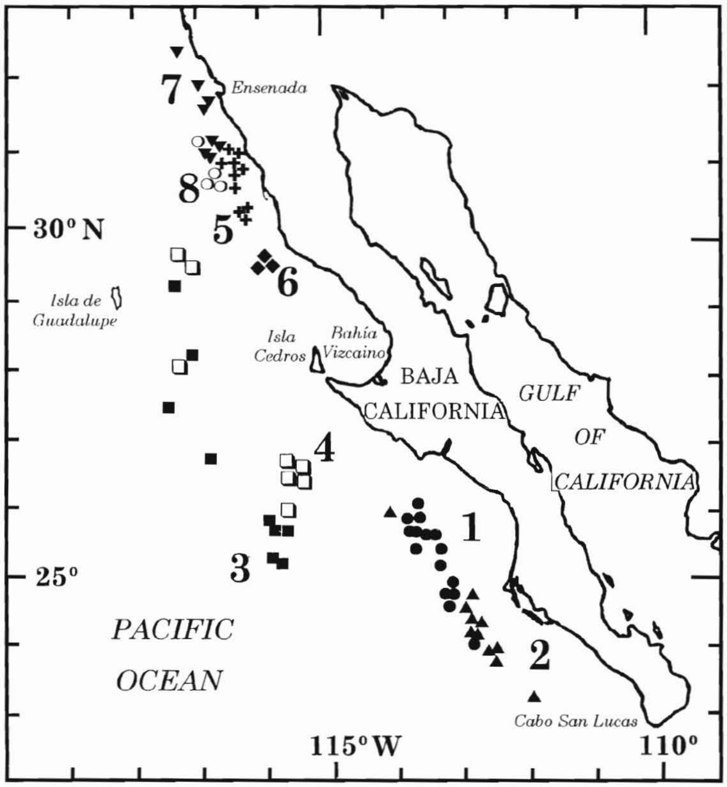

Figure 1

Swordfish fishing area off western Baja California. Numbers indicate locations where 173 swordfishes analyzed for this study were caught during eight fishing trips (see Table 1 for collection dates and numbers).

In order to assess whether collected stomachs were sufficient to describe adequately the diet of swordfish, the minimum sample size for each trip was estimated by plotting a general form of Bernouilli's diversity index against number of pooled stomachs, as described by Hoffman (1979):

$$H_k = (1/N_k) \log (N_k!/\prod N_{ki}!)$$

where H_k is the diversity in k pooled stomachs, N_k the number of individuals in those stomachs, and N_{ki} is the number of individuals of the ith species in k pooled stomachs. The point where the cumulative diversity of the pooled stomachs stabilizes represents the minimum sample size needed to describe the diet.

A fullness weight index was calculated for each swordfish as the relationship between the weight (g) of the stomach contents and the total body weight (g) of the swordfish multiplied by 10,000. This index removes bias caused by the effect of predator size; it is frequently used to determine feeding behaviour (Hyslop, 1980). The mean fullness weight indices for the eight trips were compared using ANOVA after testing for normality and homogeneity of variance of the data. Empty stomachs were taken into account in sample size estimation and fullness weight index calculations.

The index of relative importance, IRI = (%N + %W) × %FO (Pinkas et al., 1971) was represented graphically for only those taxa that accounted for more than 1% of IRI on a trip.

A G-statistic contingency table analysis (Crow, 1982) was used to test for differences in diet composition between trips, employing the number of individuals in each prey taxon. Prey species were pooled in ecologically similar groups to increase the number of observed frequencies in each cell of the contingency table. In the R × C contin-

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[1] Rosenblatt, R. H., C. Klepadlo, and H. J. Walker Jr. 1994. Scripps Marine Vertebrates Collection, Scripps Institution of Oceanography, 8604 La Jolla Shores Drive, La Jolla, CA 92037-1508. Personal commun.

[2] Hochberg, F. G. September 1994. Dep. of Invertebrate Zoology, Santa Barbara Museum of Natural History, 2559 Puesta del Sol Road, Santa Barbara, CA 92105-2936.

gency table, R was the number of pooled prey categories and C the number of trips. The test was performed repeatedly, removing less likely variables, as prey category or trip, from the contingency table when a significant difference was obtained, and testing again with the remaining variables until no significant difference was obtained.

Results

Swordfish sizes ranged from 76 to 233 cm eye–fork length (Fig. 2). No differences in size between trips were found (one-way ANOVA; $F_{7,162}$=0.317, P=0.94) after tests for normality (Kolmogorov-Smirnov; n=170, d_{max}=0.07583, P>0.20) and homogeneity of variance (Levene; $F_{7,162}$=0.692, P=0.677) were made. The sample included 139 females, 31 males, and 3 undetermined. Frequencies of females were not significantly different between trips (χ^2=1.690, df=7, P>0.95). Nine stomachs were empty, 5 everted, and 159 contained food remains. Information about the samples is summarized in Table 1.

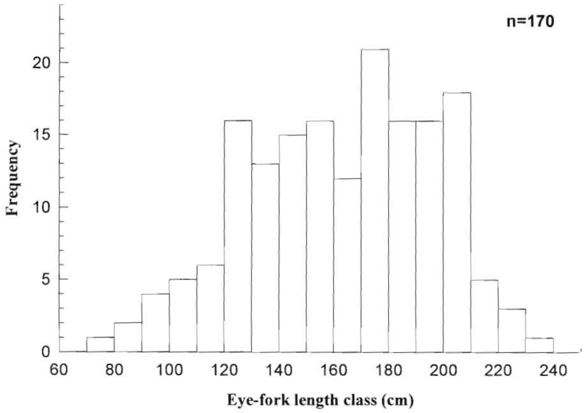

Figure 2
Eye–fork length distribution of 170 swordfish analyzed in this study.

Hoffman's (1979) graphic method suggested an ideal sample size of about 20 stomachs, or 25 in the case of the first trip (Fig. 3). Diversity of trips 6 and 8 didn't reach the stability point, because few samples were taken during these trips. We concluded that samples were of sufficient size to describe the food habits of swordfish except for trips 6 and 8. The second trip showed a drop in diversity due to the thirteenth stomach, which had 23 flying purple squid, the dominant species.

The fullness weight index was not calculated for eight swordfish because three were not measured for length and five had everted stomachs. The log-transformed mean and standard deviation of the index for each trip are shown in Figure 4. There were no significant differences between trips (one-way ANOVA; $F_{7,157}$=0.768, P=0.61), after transformed data were tested for normality (Kolmogorov-Smirnov; n=165, d_{max}=0.7039, P>0.20) and homogeneity of variance (Levene; $F_{7,157}$=1.355, P=0.227).

The remains of 1,108 cephalopods belonging to 3 orders and at least 19 species, and 709 teleosts belong-

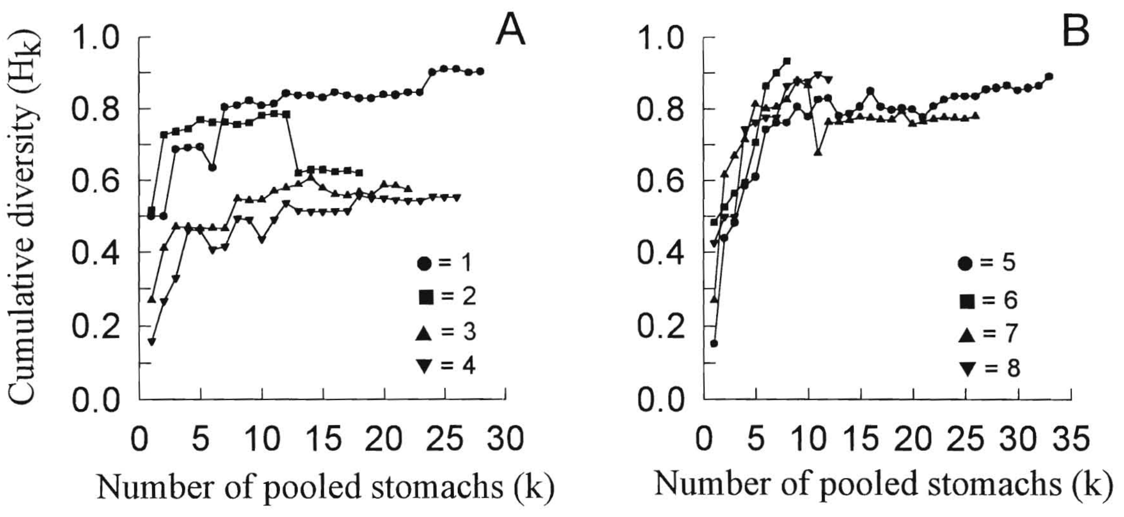

Figure 3
Bernouilli's diversity index plotted against the number of pooled stomachs from each trip in A. southern Baja California and B. northern Baja California.

ing to more than 8 orders and 16 species were found in the stomach contents (Table 2). An unidentified ray was the only elasmobranch found.

Off southern Baja California, cephalopods accounted for the major part of the swordfish diet composition (85%N, 90%W, 89%FO) (Fig. 5, Table 3). Ommastrephid squids dominated the diet by all counts, and flying purple squid, *Sthenoteuthis oualaniensis*, was the major prey species (44%N, 40%W, 64%FO). Jumbo squid, *Dosidicus gigas*, was the second most important ommastrephid species (15%N, 6%W, 48%FO). Gonatids were the second most important family, represented by *Gonatus berryi* and *G. californiensis*. *Ancistrocheirus lesueurii* and *Thysanoteuthis rhombus* followed in frequency of occurrence. *Argonauta* spp. were the only octopods with some importance in the swordfish diet. Unidentified cephalopod remains accounted for a large proportion of weight in the diet and were mainly composed of squid mantles without beaks. However, it is likely that most of this belonged to the Ommastrephidae family. Pacific hake, *Merluccius productus*, was the most important fish prey in %N and %W; it occurred only in February–March. An unidentified Stromateoidei had some importance in %FO during June–July.

Fish was the most important component in swordfish diet off northern Baja California (62%N, 83%W, 64%FO) (Fig. 6, Table 4). Unlike squids, important fish species varied by trip. Pacific hake, the fish that occurred in the greatest percentage of the samples (11%N, 15%W, 48%FO) was relatively important only in October and December (trips 5 and 7). Duckbill barracudina, *Paralepis atlanticus*; pearleye, Scopelarchidae; king-of-the-salmon, *Trachipterus altivelis*; and jack mackerel, *Scomber japonicus*, varied greatly in importance in different months. Pacific sardine, *Sardinops sagax caeruleus*, occurred only in January 1993 (trip 8). Larger prey, such as king-of-the-salmon and cutlassfish, *Lepidopus fitchi*, were important by weight but not by number. Sixteen individual cutlassfish were found in a stomach during November (trip 6), accounting for almost all the stomach-content weight for that month. Northern anchovy, *Engraulis mordax*; frigate and bullet tuna, *Auxis* spp.; Panama lightfish, *Vinciguerria lucetia*; and unidentified Species A each appeared in only one month. California needlefish, *Strongylura exilis*, and dusky pencilsmelt, *Microstoma microstoma*, also each appeared in only one month, in northern Baja California, but their IRI's were always less than 1%.

Contingency table analysis showed highly significant differences between trips in numerical diet composition when the following prey groups were tested: Pacific hake, pelagic fishes, mesopelagic fishes, and cephalopods (G=1682, d.f.=21, P<0.01). In general, fish and cephalopod proportions were significantly different between all trips (G=616, d.f.=7, P<0.01). No significant differences were obtained in the proportion of ommastrephids (flying purple squid and jumbo squid) between the four trips off southern Baja California (G=4.54, d.f.=3, P>0.05).

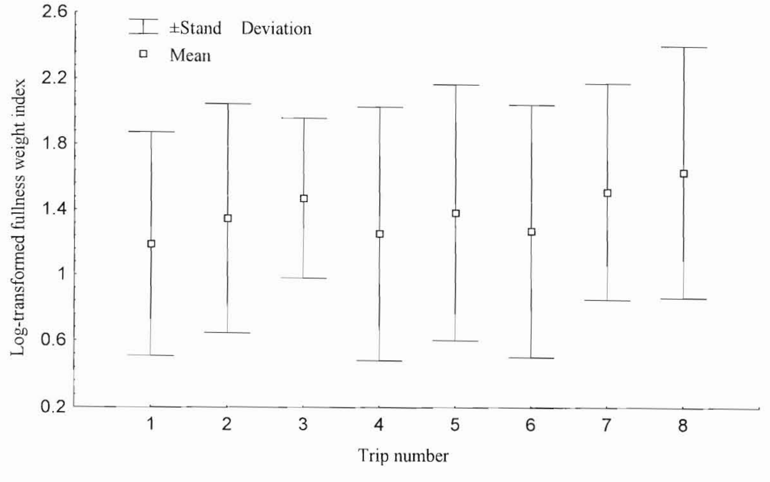

Figure 4

Log-transformed mean and standard deviation of the fullness weight index for each trip that collected swordfish stomachs off Baja California, 1992–93.

Discussion

Methodology in marine predator diet studies has improved notably in recent years due to studies on marine mammals (Pierce and Boyle, 1991; Pierce et al., 1993) and advances in the identification of cephalopod beaks (Clarke, 1986).

Secondary prey, those ingested by primary prey, may be mistaken for food items of the predator (Perrin et al., 1973). Remains of the pelagic red crab, *Pleuroncodes planipes*, were determined to be secondary prey originating from Pacific hake and king-of-the-salmon. Three species of euphausiids were found in stomachs of duckbill barracudina. These crustaceans were also considered to be secondary prey of swordfish, and they were not taken into account in the analysis of stomach contents. One swordfish stomach contained a whole *Octopoteuthis deletron* in the open stomach of a king-of-the-salmon, and also a pair of beaks of another squid; it was impossible to discern whose prey the beaks represented.

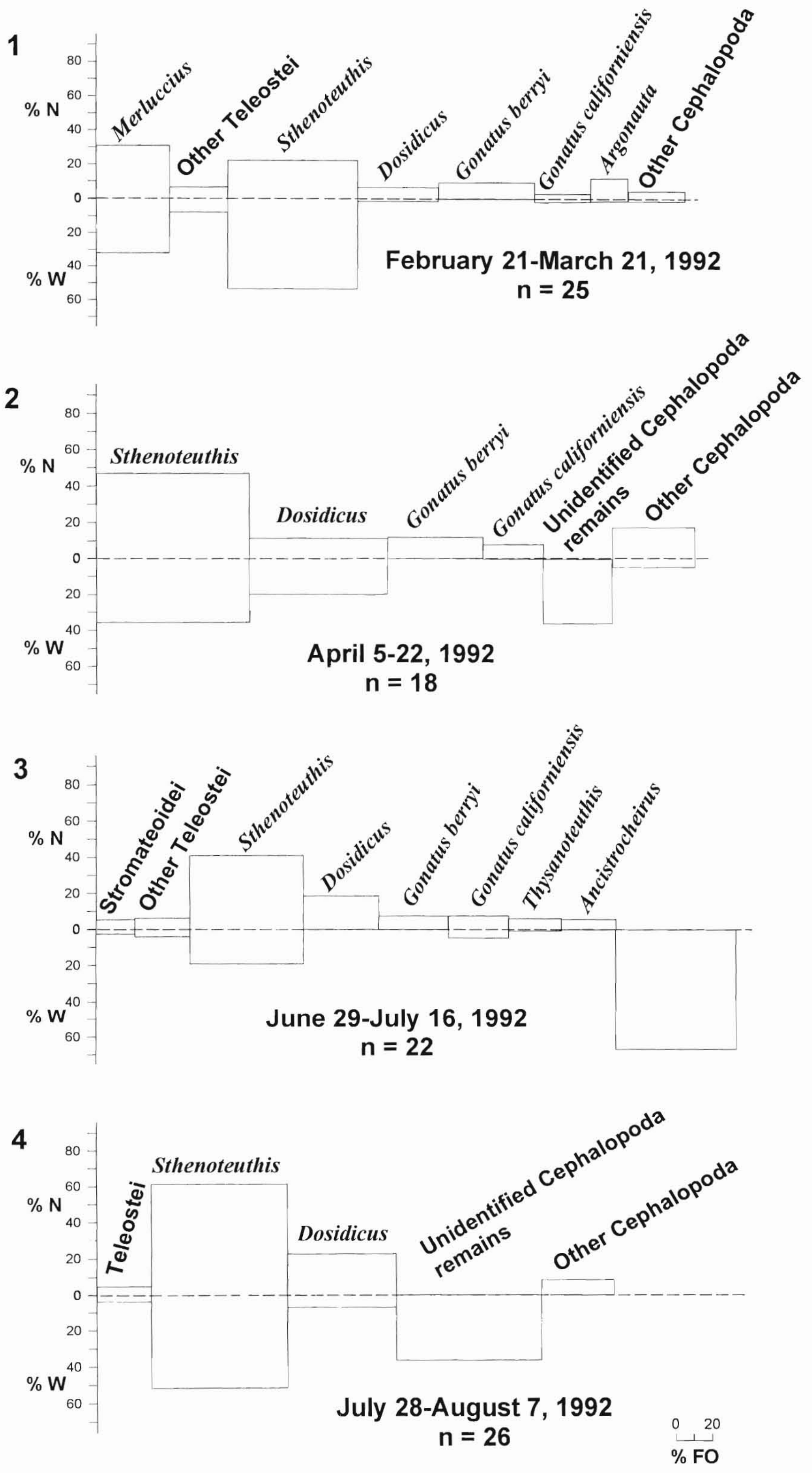

Figure 5

Percent composition of swordfish stomach contents collected off southern Baja California during 1992: number (%N), weight (%W), and frequency of occurrence (%FO) of prey groups that accounted for more than 1% of index of relative importance. n = number of stomachs with food remains.

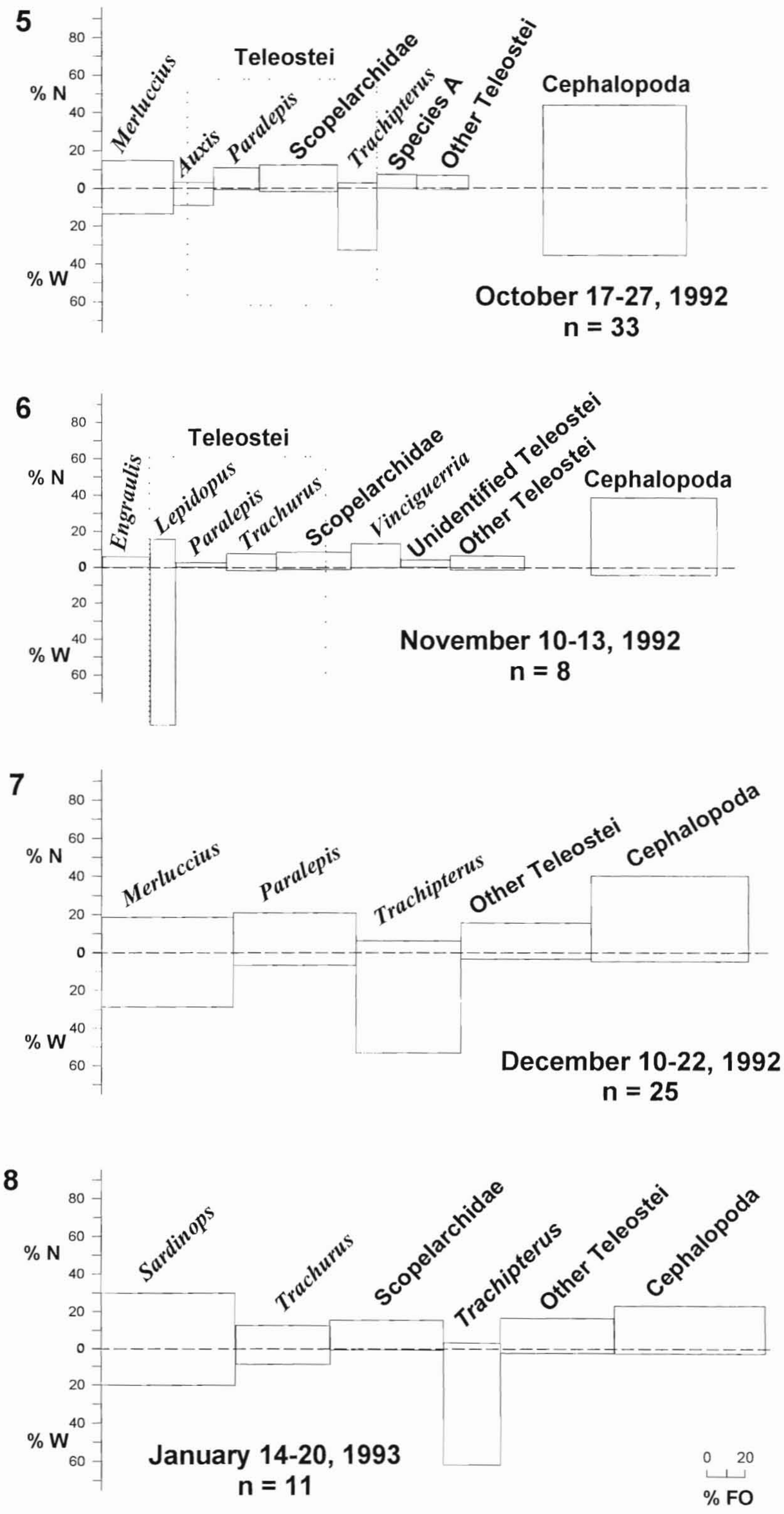

Figure 6

Percent composition of swordfish stomach contents collected off northern Baja California during 1992 and January 1993: number (%N), weight (%W), and frequency of occurrence (%FO) of those prey groups that accounted for more than 1% of index of relative importance. n = number of stomachs with food remains.

Probably some of the smaller prey were, in fact, secondary prey of the swordfish. However, smaller prey were of low importance in the swordfish diet, and we feel that this problem caused little bias.

Back-calculation of cephalopod weights using the lower rostral lengths of beaks was not conducted in this study because it is well known that beaks can remain undigested in stomachs for much longer periods of time than fish otoliths and bones (Bigg and Fawcett, 1985; Hernández-García, 1995).

Table 2

Prey species or taxa (*=new record for swordfish diet) identified in the stomach contents of swordfish caught off Baja California during 1992 and January 1993.

- CEPHALOPODA
  - TEUTHOIDEA
    - Ommastrephidae
      - _Dosidicus gigas_
      - _Sthenoteuthis oualaniensis_
    - Gonatidae
      - _Gonatopsis borealis_*
      - _Gonatus berryi_*
      - _Gonatus californiensis_*
    - Thysanoteuthidae
      - _Thysanoteuthis rhombus_
    - Ancistrocheiridae
      - _Ancistrocheirus lesueurii_
    - Onychoteuthidae
      - _Onychoteuthis banksii_
      - _Onychoteuthis_ spp.
    - Histioteuthidae
      - _Histioteuthis heteropsis_*
      - _Histioteuthis hoylei_ (=_H. dofleini_)
    - Mastigoteuthidae
      - _Mastigoteuthis dentata_*
      - _Mastigoteuthis_ spp.
    - Grimalditeuthidae
      - _Grimalditeuthis bonplandi_
    - Octopoteuthidae
      - _Octopoteuthis deletron_*
    - Pholidoteuthidae
      - _Pholidoteuthis boschmai_*
  - OCTOPODA
    - Argonautidae
      - _Argonauta argo?_
      - _Argonauta_ spp.
    - Bolitaenidae
      - _Japetella diaphana_*
    - Alloposidae
      - _Haliphron atlanticus_
    - Octopodidae
      - _Octopus rubescens_*
  - VAMPYROMORPHA
    - Vampyroteuthidae
      - _Vampyroteuthis infernalis_*

- ELASMOBRANCHII
  - RAJIFORMES*

- TELEOSTEI
  - CLUPEIFORMES
    - Clupeidae
      - _Etrumeus teres_*
      - _Sardinops sagax caeruleus_*
    - Engraulididae
      - _Engraulis mordax_
  - OSMERIFORMES
    - Microstomatidae
      - _Microstoma microstoma_*
    - Bathylagidae
      - _Bathylagus_ sp.*
  - STOMIIFORMES
    - Photichthydae
      - _Vinciguerria lucetia_*
    - Stomiidae
      - _Idiacanthus antrostomus_*
  - AULOPIFORMES
    - Scopelarchidae*
    - Synodontidae
      - _Synodus lucioceps_*
    - Paralepididae
      - _Paralepis atlanticus_
    - Alepisauridae
      - _Alepisaurus ferox_
  - LAMPRIDIFORMES
    - Trachipteridae
      - _Trachipterus altivelis_*
  - GADIFORMES
    - Merluciidae
      - _Merluccius productus_
  - BELONIFORMES
    - Belonidae
      - _Strongylura exilis_*
    - Scomberesocidae
      - _Cololabis saira_*
  - PERCIFORMES
    - Carangidae
      - _Trachurus symmetricus_*
    - Trichiuridae
      - _Lepidopus fitchi_*
    - Scombridae
      - _Auxis_ spp.
      - _Scomber japonicus_*
    - Stromateoidei

Interpretation of the fullness weight index should consider the differential digestion of different prey; it has been reported that cephalopods are digested faster than fishes (Bigg and Fawcett, 1985; Olson and Boggs, 1986). Therefore, the fullness weight index for swordfish caught off southern Baja California could be underestimated, as they contained a greater weight of cephalopods than those caught off the northern coast (Fig. 5, 6). Due to the lack of information on differential rates of gastric evacuation in swordfish, we are not able at this point to discern whether differential digestion may be hiding significant differences between the fullness weight indices for northern and southern Baja California swordfish. It is probable that swordfish females eat more as they mature during their migration to the south; Kume and Joseph (1969) and Bedford and Hagerman (1983) suggested that swordfish migrate along California and Baja California coasts, and Castro-Longoria (1995) found initial stages of mature gonads in female swordfish off southern Baja California. Frontal zones of high productivity where swordfish tend to concentrate (Sakagawa, 1989), such as the western Baja California coast, provide swordfish with rich food resources for sexual maturation while they migrate toward the tropics.

Previous studies have noted that the diet of swordfish varies by geographic area (Maksimov, 1969; Hernández-García, 1995) depending upon the prey species present in the area (Tibbo et al., 1961; Scott and Tibbo, 1968). This would explain the great differences observed in the diet of swordfish off western Baja California. The variability in food habits found in our study could not be explained by sex or size.

The fact that merluciids, gadids, paralepidids, and scombrids have been described as the most important fish prey species of swordfish (Tibbo et al., 1961; Scott and Tibbo, 1968, 1974; Mearns et al., 1981; Stillwell and Kohler, 1985; Moreira, 1990; Hernández-García, 1995; this study) indicates the great abundance of these groups in the coastal pelagic ecosystems where swordfish are usually caught. The fish species composition in the diet of swordfish caught in oceanic waters seems to be different (Yabe et al., 1959; Maksimov, 1969; Hernández-García, 1995; Clarke et al., 1995), although more studies of the oceanic ecosystem are needed. Ommastrephids have been described as the most important cephalopod prey in other regions

Table 3

Prey species by number, weight, and frequency of occurrence in 84 stomachs of swordfish caught off southern Baja California.

Taxon	Number	%	Weight (g)	%	Frequency	%
TELEOSTEI	136	15.16	3,034.2	10.00	27	29.67
Merluccius productus (Pacific hake)	81	9.03	1,658.4	5.51	11	12.08
Unidentified Stromateoidei	17	1.89	285.2	0.94	8	8.79
Scomber japonicus (Pacific mackerel)	4	0.44	259.2	0.86	3	3.29
Trachipterus altivelis (king-of-the-salmon)	4	0.33	169.1	0.56	4	4.39
Alepisaurus ferox (longnose lancetfish)	2	0.22	128.9	0.42	2	2.19
Lepidopus fitchi (cutlassfish)	2	0.22	50.9	0.16	2	2.19
Engraulis mordax (northern anchovy)	5	0.55	5.0	0.01	1	1.09
Synodus lucioceps (California lizardfish)	2	0.22	320.0	1.06	1	1.09
Paralepis atlanticus (duckbill barracudina)	1	0.11	21.0	0.06	1	1.09
Auxis spp. (frigate or bullet tuna)	1	0.11	18.5	0.06	1	1.09
Trachurus symmetricus (jack mackerel)	1	0.11	13.8	0.04	1	1.09
Scopelarchidae (pearleye)	1	0.11	0.7	0.00	1	1.09
Microstoma microstoma (dusky pencilsmelt)	1	0.11	0.1	0.00	1	1.09
Unidentified Teleostei	14	1.56	103.4	0.34	8	8.79
CEPHALOPODA	761	84.83	26,971.9	89.69	81	89.01
Sthenoteuthis oualaniensis (flying purple squid)	396	44.14	11,982.7	39.84	59	64.83
Dosidicus gigas (jumbo squid)	137	15.27	1,977.9	6.57	44	48.35
Unidentified Ommastrephidae	5	0.55	0.8	0.00	5	5.49
Gonatus berryi	67	7.46	11.7	0.03	34	37.36
Gonatus californiensis	42	4.68	568.4	1.89	24	26.37
Ancistrocheirus lesueurii	18	2.00	3.5	0.01	14	15.38
Thysanoteuthis rhombus	22	2.45	452.8	1.50	14	15.38
Mastigoteuthis dentata	7	0.78	0.3	0.00	2	2.19
Mastigoteuthis spp.	2	0.22	0.2	0.00	2	2.19
Histioteuthis heteropsis	6	0.66	0.7	0.00	2	2.19
Histioteuthis hoylei (=*H. dofleini*)	1	0.11	0.2	0.00	1	1.09
Grimalditeuthis bonplandi	2	0.22	0.6	0.00	2	2.19
Pholidoteuthis boschmai	1	0.11	0.2	0.00	1	1.09
Unidentified Teuthoidea	4	0.44	0.4	0.00	3	3.29
Argonauta spp.	43	4.79	49.2	0.16	12	13.18
Haliphron atlanticus	3	0.33	0.2	0.00	2	2.19
Octopus rubescens	3	0.22	0.1	0.00	2	2.19
Unidentified Octopoda	1	0.11	0.1	0.00	1	1.09
Vampyroteuthis infernalis	1	0.11	0.1	0.00	1	1.09
Cephalopoda remains			11,920.9	39.64	40	43.95
UNIDENTIFIED REMAINS			64.9	0.21	2	2.19
TOTAL	897		30,071.0		91	

of the world (Tibbo et al., 1961; Scott and Tibbo, 1968, 1974; Maksimov, 1969; Toll and Hess, 1981; Stillwell and Kohler, 1985; Moreira, 1990; Bello, 1991; Guerra et al., 1993; Seki, 1993; Hernández-García, 1995) in both coastal and oceanic pelagic ecosystems.

The use of the "sword" for disabling or killing prey has been recorded by previous workers (Bigelow and Schroeder, 1953; Tibbo et al., 1961; Scott and Tibbo, 1968; Stillwell and Kohler, 1985). In this study, most prey showed evidence of being slashed or cut. Whole king-of-the-salmon (as large as 160 cm) were folded in the stomach due to cuts. Small prey such as *Argonauta* spp. showed no damage and probably had been ingested whole.

Predation upon schools of fish (Scott and Tibbo, 1968; Stillwell and Kohler, 1985; Bello, 1991) and cephalopods (Toll and Hess, 1981; Guerra et al., 1993; Seki, 1993) has been previously noted. As many as ten individuals of the same species, namely, Pacific hake, Pacific sardine, and jack mackerel, occurred in some stomachs. As many as 44 lower beaks from flying purple squid were found in another stomach. A Bray-Curtis index of similarity (Ludwig and Reynolds, 1988) was calculated for the number of prey species shared by all possible swordfish pairs caught during the same night. It did not show any congruence, suggesting that swordfish feed alone upon prey schools that are patchily distributed.

Table 4

Prey species by number, weight, and frequency of occurrence in 75 stomachs of swordfish caught off northern Baja California.

Taxon	Number	%	Weight (g)	%	Frequency	%
TELEOSTEI	573	62.21	41,200.5	83.16	49	63.63
Merluccius productus (Pacific hake)	103	11.18	7,378.7	14.89	37	48.05
Paralepis atlanticus (duckbill barracudina)	109	11.83	1,643.1	3.31	27	35.06
Scopelarchidae (pearleye)	91	9.88	736.4	1.48	25	32.46
Trachipterus altivelis (king-of-the-salmon)	33	3.58	21,458.1	43.31	21	27.27
Sardinops sagax caeruleus (Pacific sardine)	55	5.97	2,125.7	4.29	7	9.09
Trachurus symmetricus (jack mackerel)	24	2.60	991.6	2.00	7	9.09
Unidentified Species A	23	2.49	99.4	0.20	7	9.09
Auxis spp. (frigate or bullet tuna)	12	1.30	1,552.9	3.13	7	9.09
Strongylura exilis (California needlefish)	8	0.86	216.5	0.43	7	9.09
Microstoma microstoma (dusky pencilsmelt)	38	4.12	156.3	0.31	6	7.79
Scomber japonicus (Pacific mackerel)	4	0.43	181.8	0.36	3	3.89
Lepidopus fitchi (cutlassfish)	17	1.84	4,298.1	8.67	2	2.59
Vinciguerria lucetia (Panama lightfish)	13	1.41	3.1	0.00	2	2.59
Engraulis mordax (northern anchovy)	6	0.65	3.8	0.00	2	2.59
Etrumeus teres (round herring)	2	0.21	156.2	0.31	2	2.59
Bathylagus sp. (blacksmelt)	3	0.32	16.5	0.03	2	2.59
Alepisaurus ferox (longnose lancetfish)	1	0.10	73.6	0.14	1	1.29
Cololabis saira (Pacific sauri)	1	0.10	61.2	0.12	1	1.29
Idiacanthus antrostomus (Pacific blackdragon)	1	0.10	12.0	0.02	1	1.29
Unidentified Stromateoidei	1	0.10	0.5	0.00	1	1.29
Unidentified Teleostei	28	3.04	35.0	0.07	15	19.48
ELASMOBRANCHII						
Rajiformes	1	0.10	128.5	0.25	1	1.29
CEPHALOPODA	347	37.67	7,804.3	15.75	57	74.02
UNIDENTIFIED REMAINS			406.9	0.82	12	15.58
TOTAL	921		49,540.2		77	

Swordfish can feed at great depth during diurnal vertical migrations (Carey and Robison, 1981), and has demonstrated great ability to catch powerful prey (Toll and Hess, 1981). As an opportunistic predator whose diet reflects the presence and abundance of its prey, swordfish could be used as a biosampler which would aid us in obtaining information about other potential commercial resources off western Baja California, for example, jumbo squid and Pacific hake.

Mearns et al. (1981) assigned a trophic level of 3.97 to swordfish in the Southern California Bight, based on stomach content analysis in which northern anchovy accounted for almost half of the diet. Planktivorous fishes were not found to be important components of the swordfish diet in other studies. On the contrary, squids and mesopelagic carnivorous fishes seem to be more commonly reported, resulting in a somewhat higher trophic level. Assuming that the trophic levels of more important prey (Fig. 5, 6) fluctuate between 3 and 3.5 (Mearns et al., 1981; Yang, 1982; Brodeur and Pearcy, 1992), swordfish's trophic level off the western Baja California coast would vary between 4.0 and 4.5. The prey of swordfish are shared by numerous other predators in the eastern Pacific Ocean, as shown in Appendix Table 1 and 2. A comprehensive study of the marine predator assemblages that populate these waters is lacking.

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Appendix Table 1

Predators in the Eastern Pacific of teleost fishes found in the diet of swordfish caught off Baja California. Where a source identifies a predator as having a prey similar to that in column 1, this prey is shown in parentheses.

Prey	Predator (Similar prey) [Source[1, 2]]
Merluccius productus	*Alepisaurus richardsoni*; *Anoplopoma fimbria*; *Ophiodon elongatus*; *Galeorhinus zyopterus*; white shark, *Carcharodon carcharias*; Pacific electric ray, *Torpedo californicus* [5]. Common thresher, *Alopias vulpinus* [21]. Blue shark, *Prionace glauca* [13, 22, 31]. Bluefin tuna, *Thunnus thynnus*; albacore, *Thunnus alalunga*; Pacific bonito, *Sarda chilensis* [26]. Striped marlin, *Tetrapturus audax* [1]. Sea birds [22]. Pinnipeds, odontocetes [7, 9, 10, 19, 21, 22].
Trachipterus altivelis	*Alepisaurus ferox* [28]. Pacific white-sided dolphin, *Lagenorhynchus obliquidens* [30]. Northern fur seal, *Callorhinus ursinus* [23, 29]. Spinner dolphin, *Stenella longirostris* (*Trachipterus fukuzakii*) [25]. Albacore (*Trachipterus* sp.) [20]. Bigeye tuna, *Thunnus obesus* [6]. Yellowfin tuna, *Thunnus albacares* [3].
Paralepis atlantica	Bigeye tuna; albacore [17, 26]. Albacore (Paralepididae) [15, 20]. Yellowfin tuna [3]. Spotted dolphin, *Stenella attenuata*; spinner dolphin [11, 25].
Sardinops sagax	Striped marlin, *Tetrapturus andax* [1, 8, 14, 27]. Blue marlin, *Makaira nigricans* [1]. Dolphinfish, *Coryphaena hippurus* [2].
Trachurus symmetricus	Albacore; bluefin tuna; Pacific bonito [20, 26]. Yellowfin tuna [3]. Striped marlin [8, 14]. Blue shark [31]. Mako shark, *Isurus oxyrinchus* [21]. Northern fur seal; Steller sea lion, *Eumatopias jubatus* [24, 29]. California sea lion, *Zalophias californicus* [19].
Auxis spp.	Yellowfin tuna [3, 6, 16, 21]. Skipjack, *Katsuwonus pelamis* [3, 21]. Bigeye tuna [6]. Albacore; spotted dolphin [25]. Dolphinfish [2]. Striped marlin; blue marlin [1]. Striped marlin (*A. thazard*) [8]. Silky shark, *Carcharhinus falciformis* [21].
Engraulis mordax	Albacore; bluefin tuna; Pacific bonito [4, 20, 21, 26]. Yellowfin tuna; skipjack [3]. Striped marlin [8, 14]. Other teleosts [22]. Pacific mackerel, *Scomber japonicus*; California barracuda, *Sphyraena argentea*; common thresher [21]. Blue shark [13, 21, 22, 31]. Sea birds [22]. Northern fur seal; Pacific white-sided dolphin; Dall's porpoise, *Phocoenoides dalli*; common dolphin, *Delphinus delphis* [9, 22, 24, 29, 30]. California sea lion [10, 19, 21, 22].
Lepidopus fitchi	Bluefin tuna; skipjack [3]. Albacore (Trichiuridae) [15]. Yellowfin tuna; skipjack [3]. Striped marlin [8].
Vinciguerria lucetia	Yellowfin tuna; skipjack [3]. Albacore [20, 26]. Tunas; dolphins, *Stenella* spp. [11, 18]. Sailfish, *Istiophorus platypterus* [8].
Scopelarchidae	Spinner dolphin [11]. *Alepisaurus*; opah, *Lampris regius*; albacore; salmon, *Oncorhynchus* sp. (*Benthalbella liguidens*) [12].
Stromateoidei	Albacore (Stromateidae) [15]. Yellowfin tuna [3]. Pacific bonito [26]. Striped marlin; sailfish [8]. Spinner dolphin; spotted dolphin [25].

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[1] [1] Abitia-Cardenas et al., 1997, [2] Aguilar-Palomino et al., 1998, [3] Alverson, 1963, [4] Bernard et al., 1985, [5] Best, 1963, [6] Blunt, 1960, [7] Condit and Le Boeuf, 1984, [8] Evans and Wares, 1972, [9] Fiscus, 1979, [10] Fiscus and Baines, 1966, [11] Fitch and Brownell, 1968, [12] Fitch and Lavenberg, 1968, [13] Harvey, 1989, [14] Hubbs and Wisner, 1953, [15] Iversen, 1962, [16] Juhl, 1955, [17] Kajimura, 1969, [18] Lavenberg and Fitch, 1966, [19] Lowry et al., 1990, [20] McHugh, 1952, [21] Mearns et al., 1981, [22] Morejohn et al., 1978, [23] Perez and Bigg,[2] [24] Perez and Bigg, 1986, [25] Perrin et al., 1973, [26] Pinkas et al., 1971, [27] Ramírez-González, 1979, [28] Roedel, 1938, [29] Spalding, 1964, [30] Stroud et al., 1981, [31] Trikas, 1979.

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Appendix Table 2

Predators in the eastern Pacific Ocean of cephalopods found in the diet of swordfish caught off Baja California. Where a source identifies a predator as having a prey similar to that in column 1, this prey is shown in parentheses. Prob. = prey identified as probable for this predator.

Prey	Predator (Similar prey) [Source[1]]
Sthenoteuthis oualaniensis	Yellowfin tuna [3, 14, prob. 28]. Striped marlin [1]. Tunas [27]. Galapagos fur seal, *Arctocephalus galapagoensis* [prob. 8]. Spinner dolphin; spotted dolphin [prob. 28]. Sperm whale, *Physeter macrocephalus* [prob. 9]. Pigmy sperm whale, *Kogia breviceps*; Dall's porpoise (Ommastrephidae) [26].
Dosidicus gigas	Albacore; bluefin tuna [29]. Yellowfin tuna [3, 14, prob. 27]. Bigeye tuna [5, 21]. Dolphinfish [2]. Striped marlin; blue marlin [1]. Blue shark [18, 32]. Northern fulmar, *Fulmarus glacialis* [26]. Northern elephant seal, *Mirounga angustirostris* [4]. Spinner dolphin; spotted dolphin [prob. 28]. Sperm whale [9, 13].
Gonatus berryi	Albacore [29 *in* 19]. Northern elephant seal [4]. Sperm whale [13]. Yellowfin (*Gonatus* sp.) [14]. Blue shark; sea birds; northern elephant seal; California sea lion; northern fur seal; pigmy sperm whale; Dall's porpoise; Pacific white-sided dolphin [12, 18, 22, 26, 31]. Northern fur seal (Gonatidae) [12].
Gonatus californiensis	Hubb's beaked whale, *Mesoplodon carlhubbsi* [24 *in* 6].
Gonatopsis borealis	Albacore; bluefin tuna [prob. 29]. Northern elephant seal [4, prob. 10, prob. 17]. Northern fur seal [12]. Pacific white-sided dolphin [31]. Short-finned pilot whale, *Globicephala macrorhynchus* [prob. 16]. Sperm whale [13, prob. 7 *in* 13].
Thysanoteuthis rhombus	Bigeye tuna [5]. Yellowfin tuna [3, 14]. Tunas [27]. Blue shark (Thysanoteuthidae) [32]. Pigmy sperm whale [26].
Onychoteuthis borealijaponicus	Yellowfin [14]. Albacore; bluefin tuna; Pacific bonito [29]. Blue shark [18, 32]. Sea birds [26]. California sea lion [22, 26]. Northern elephant seal [4, 10, 17]. Pacific white-sided dolphin; Dall's porpoise; northern fur seal [12, 25, 30]. Hubb's beaked whale [24]. Short-finned pilot whale [16]. Pigmy sperm whale [26]. Sperm whale [13].
Onychoteuthis banksii	Yellowfin tuna [3]. Albacore [23]. Tunas [27]. Smooth hammerhead, *Sphyrna zygaena* [15]. Galapagos fur seal [8].
Histioteuthis heteropsis	Albacore [29]. Blue shark [26, 32]. Hammerheads, *Sphyrna* spp. [15]. Northern elephant seal [17]. Short-finned pilot whale [16]. Sperm whale [13]. Blue shark (*Histioteuthis* sp.) [18, 31]. Yellowfin tuna; spinner dolphin; spotted dolphin [28]. Northern elephant seal [4]. Sperm whale [9, 13].
Histioteuthis hoylei (=*H. dofleini*)	Northern elephant seal [4]. Short-finned pilot whale [17]. Sperm whale [13].
Argonauta spp.	Yellowfin tuna (*A. pacifica*) [3]. Blue shark [18]. Albacore; bluefin tuna (*A. nouryi*) [29]. Yellowfin tuna (*A. cornuta*) [3]. Bigeye tuna; yellowfin tuna; skipjack (*Argonauta* spp.) [3, 5, 14, 25]. Albacore [20]. Dolphinfish [2, 30]. Striped marlin; blue marlin; sailfish [1, 11, 30]. Pigmy sperm whale [26].

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[1] [1] Abitia-Cardenas et al., 1997, [2] Aguilar-Palomino et al., 1998, [3] Alverson, 1963, [4] Antonelis et al., 1994, [5] Blunt, 1960, [6] Clarke, 1986, [7] Clarke and MacLeod, 1980, [8] Clarke and Trillmich, 1980, [9] Clarke et al., 1976, [10] Condit and LeBoeuf, 1984, [11] Evans and Wares, 1972, [12] Fiscus, 1982, [13] Fiscus et al., 1989, [14] Galván-Magaña et al., 1985, [15] Galván-Magaña et al., 1989, [16] Hacker, 1992, [17] Hacker, 1994, [18] Harvey, 1989, [19] Imber, 1978, [20] Iversen, 1962, [21] Juhl, 1955, [22] Lowry et al., 1990, [23] McHugh, 1952, [24] Mead et al., 1982, [25] Mearns et al., 1981 [26] Morejohn et al., 1978, [27] Okutani and Tsukada, 1988, [28] Perrin et al., 1973, [29] Pinkas et al., 1971, [30] Ramírez-González, 1979, [31] Stroud et al., 1981, [32] Trikas, 1979.

A Preliminary Assessment of the Use of Hard Parts to Age Central Pacific Swordfish, *Xiphias gladius*

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ABSTRACT

We describe the results of preliminary work that contributes to ongoing studies of the age and growth of swordfish, *Xiphias gladius*, in the central Pacific. Multiple hard parts (first dorsal and first anal fin rays, caudal vertebrae, and otolith sagittae) were evaluated for their suitability as ageing structures. Proportional relations were observed between counting-path dimensions of various hard parts (width of fin rays, depth of vertebral cones, and length of sagittae) and eye–fork length of swordfish. Age estimates (counts of presumed annuli) were evaluated within and among tissues and between pairs of readers.

A provisional growth model is presented for swordfish in the Hawaii longline fishery, based on presumed annuli observed in cross sections of the second ray of first anal fins. The validations of annuli on fin rays and sagittae, and of daily growth increments on sagittae, are indicated as key topics for continuing studies. Validation of annuli should include analysis of marginal growth increments on both fin rays and sagittae collected at expanded spatial and temporal scales. Complementary research needs are identified, emphasizing an expanded mark–recapture program to provide specimens needed for conclusive age validation.

Introduction

The age and growth of swordfish, *Xiphias gladius*, stocks in the Atlantic Ocean have received much attention (Ovchinnikov, 1970; Beckett, 1974; Berkeley and Houde, 1983; Radtke and Hurley, 1983; Wilson and Dean, 1983; Prince et al., 1988; Ehrhardt, 1992; Turner[1]), because the status of these stocks has been assessed primarily with age-structured stock assessment models (Megrey, 1989; Miyake and Rey, 1990). Age-structured rather than surplus production models have been used, at least until recently (Cosner et al., 1992; Prager, 1992), because high-quality effort statistics were unavailable for all segments of the fleet. In addition, the size and sex composition of landings varied considerably among different national fleets because of differential targeting.

In the Pacific Ocean, swordfish is not as heavily exploited as in the North Atlantic (Sakagawa, 1990), and Pacific swordfish stocks are presently believed to be under-exploited (Bartoo and Coan, 1990; Skillman, 1990; NOAA, 1993). Yet concern has been raised during recent deliberations of the Western Pacific Fisheries Management Council (WPFMC) that management restrictions in the Atlantic and continued market demand could result in considerable expansion of the Pacific fishery and a rapid decline in Pacific stock (WPFMC[2]).

Dependency on age-structured stock assessment modeling may be expected also in the Pacific because of similar problems with the availability of comprehensive fishing-effort statistics, and differences in fishing strat-

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[1] Turner, S. 1986. Further examination of the marginal increments observed by Berkeley and Houde in cross sections of anal spines from swordfish. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southeast Fisheries Center Swordfish Workshop Working Paper 86/4, 5 p. SEFC, 75 Virginia Beach Dr., Miami, FL 33149.

[2] Western Pacific Fishery Management Council. 1994. Amendment to the fishery management plan for the pelagic fisheries of the Western Pacific Region. Western Pac. Fish. Manage. Counc., 1164 Bishop St., Rm. 1405, Honolulu, HI 96813.

egy between geographically-separated fisheries. The adequacy of age-structured models is of course dependent on accurate and precise estimates of age and growth rates.

Data are generally lacking on growth of Pacific swordfish. Yabe et al. (1959) analyzed the length frequency distribution of swordfish landed in the western North Pacific during 1948–56; and Sakagawa and Bell (1980) estimated the von Bertalanffy growth function (VBGF) *K* from these data. Kume and Joseph (1969) examined length frequency distributions of swordfish from the eastern Pacific. The ages of swordfish from the Mexican fishery have recently been estimated by counting presumed annuli on cross sections of anal fin rays and presumed daily growth increments (DGI's) on otoliths (Castro-Longoria and Sosa-Nishizaki, 1998).

The validation of annuli and DGI's is crucial for any ageing study. To date, only Ehrhardt (1992) and Tserpes and Tsimenides (1995) have been able to provide partial validation of swordfish ages using anal fin rays. Wilson and Dean (1983) verified, but did not validate, counts of DGI's and annuli on cross sections of sagittae from the same swordfish, as did Radtke and Hurley (1983) for counts of DGI's and of external ridges on sagittae. All these comparisons were limited to Atlantic and Mediterranean swordfish. Since neither annuli nor DGI's have been validated for Pacific swordfish, validation of these methods is of the utmost importance in the Pacific, as elsewhere.

Because current knowledge of swordfish growth is insufficient to support age-structured stock assessment, the Honolulu Laboratory of the Southwest Fishery Science Center initiated a program to describe size-at-age relations for swordfish in the central Pacific. In this paper, we report our progress to date in estimating the age of swordfish caught by the Hawaii longline fishery. We first evaluate the basic suitability of various hard parts as ageing structures based on proportionate growth of counting paths on tissues and of fish length, and we evaluate the related issue of variation in tissue preparations among individual fish. We then compare age estimates by the same reader and between age readers, and among different tissues from the same fish. A provisional growth model is next presented, and work in support of age validation is described. Lastly, key topics for future research are identified.

Methods and Materials

Specimen Collection

Hard parts were obtained from swordfish caught north and west of the Hawaiian Islands (Fig. 1) by monofilament longline gear fished from the NOAA research vessel *Townsend Cromwell* on cruises TC-9101 (10 January–15 February 1991), TC-9203 (13 April–7 May 1992), and TC-9303, Leg I (12 March–8 April 1993). We hereafter refer to these three series of collections as 1991, 1992, and 1993, respectively. The longline gear was set around 2000 and retrieved the following morning at 0700. Retrieval of the longline was usually completed by noon. Dead swordfish and some live fish needed for very fresh tissue samples were brought aboard ship. Most viable swordfish were injected with oxytetracycline (~600 mg/fish), marked externally with a stainless steel dart tag (Squire, 1974), and released for use in future age validation studies based on time-marked recaptures.

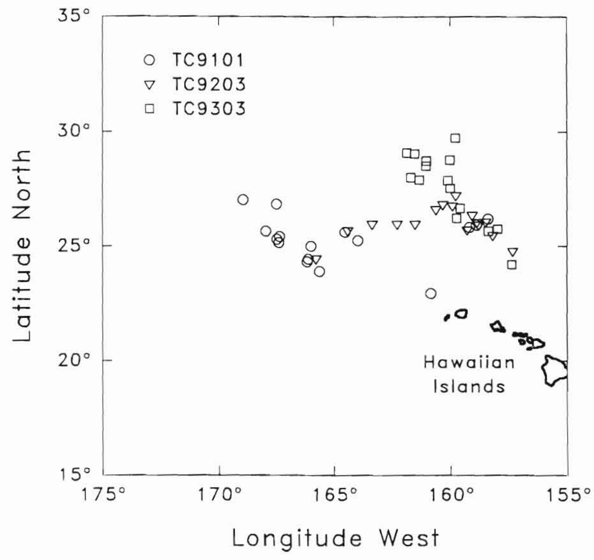

Figure 1
Location of longline sets on *Townsend Cromwell* cruises TC-9101, TC-9203, and TC-9303.

For fish brought aboard ship, eye–fork length (EFL, the distance from posterior edge of orbit to fork of tail) was measured to the nearest 0.1 cm. Sex was assessed macroscopically while dressing the fish, and gonad samples were collected and fixed in 10% formalin (seawater-buffered). Sex was later re-evaluated by microscopic examination of standard histological preparations (Harris' hematoxylin stain, eosin counterstain). Several tissues were collected and frozen for processing and subsequent estimation of age at the Honolulu Laboratory. Fin rays and otoliths were taken in part because prior studies (Berkeley and Houde, 1983; Radtke and Hurley, 1983; Wilson and Dean, 1983) suggested their potential usefulness in ageing swordfish. Future availability was also a criterion in the selection of tissues. The caudal peduncle containing terminal vertebrae, for example, can be easily collected from landed car-

Table 1

Number of counts made by each of three readers on various tissues (one specimen of each) used to age swordfish, for each of the three (1991, 1992, and 1993) series of collections. D1, D2, D3 = dorsal fin rays 1–3; A1, A2, A3 = anal fin rays 1–3.

	Counts by reader and year								
	Reader A			Reader B			Reader C		
	1991	1992	1993	1991	1992	1993	1991	1992	1993
Rays									
D1	1	3	1	1	4	3	1	1	1
D2	1	3	1	1	4	3	1	1	1
D3	1	3	1	1	4	3	1	1	1
A1	1	3	1	1	4	3	1	1	1
A2	1	3	1	1	4	3	1	1	1
A3	1	3	1	1	4	3	1	1	1
Vertebrae		1	1		1	1			1
Sagittae									
Rostral ridges		3	1		4	3			
Postrostral bands		3	1						
Daily growth increments	10			10	10	10			

casses. The skull, with otoliths, and the anterior portions of the first dorsal and first anal fins can be collected by observers or by fishers during onboard processing.

Preparation and Examination of Specimens

The counting of presumed annual marks (hereafter referred to as annuli) was done by three readers with different types and levels of experience. Reader A had the most experience at reading material from different species and tissues. Reader B read greater numbers of specimens for this study, except for vertebrae and band counts on the postrostrum of otolith sagittae (described below). Reader C, experienced in using a computerized optical image analyzer to age hard parts, used an image analyzer to count annuli. The number of counts made on each tissue type by each of the three readers is summarized in Table 1. All repeat counts of presumed annuli on fin rays, and of ridges and bands on sagittae, were made a month apart without knowledge of fish size or of previous counts on that part, to assure independence among readings.

Rays—Because the terminology of swordfish fin morphology is obscure, we first define our usage. The first dorsal (hereafter called dorsal) and first anal (anal) fins of swordfish have both unbranched and branched rays. The first two or three rays in these fins are unbranched, have right and left sides joined by a medial suture, and have an opened gap in their bases (Fig. 2). These structures thus match Summerfelt and Hall's (1987) definition of soft rays, even though the unbranched rays of swordfish have been variously called spines, spiny rays, or spinous rays. None of the dorsal or anal fin rays of swordfish appear to be segmented.

The rays of dorsal and anal fins were separated from their fins, cleaned of tissue, and dried in a dehydrator at about 52°C for 24–48 h. For each fin ray collected in 1993, length was measured to the nearest mm along its convex cephalad surface from a proximal point on its base to its distal tip (Fig. 2) using a fabric measuring tape. After cross sections were cut from the ray (described below), the distance between base of the ray and the point at which the ray was cut was also measured. For 1992 and 1993 specimens, ray widths were measured to the nearest 0.1 mm with a dial caliper on the proximal side of the point at which the ray was first cut.

Using an Isomet[3] low-speed saw, a first cut was made across the ray proximal to the point at which its left and right sides converged posteriorly (Fig. 2). Then 3–5 sections about 1 mm thick were cut successively toward the ray tip (distal end) so that the first section included the point at which the left and right sides converged. Sections were mounted on a glass microscope slide using a synthetic mounting medium (Flo-texx) and examined without further preparation. Counts of annuli were made using a dissecting microscope at 12× magnification with reflected light against a black background.

Annuli were defined as alternating pairs of opaque and translucent bands. These concentric bands ran continuously and in parallel along the lateral circumference of the sectioned ray from the anterior to poste-

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

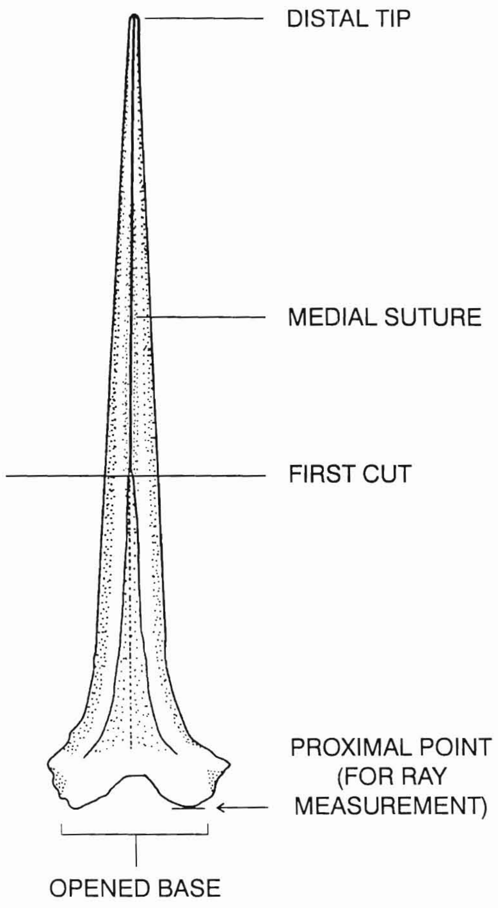

Figure 2
Truncated caudad view of a curved swordfish fin ray, illustrating position at which ray was first cut for cross sections used in ageing. Also indicated are the proximal and distal points between which the length of ray was measured along its cephalad surface.

rior side of the medial suture, but were absent along the relatively flat-sided medial suture (Berkeley and Houde, 1983; Tsimenides and Tserpes, 1989, Fig. 1). It was assumed that one pair of bands had formed each year. Multiple bands sometimes occurred, but could be distinguished from true annuli, in that the opaque bands of neighboring annuli remained distinct from one another around the entire lateral circumference of the section, including the region of the medial suture. Conversely, multiple bands converged on one another near the suture; they were counted as a single annulus. Another type of opaque band ("false check") sometimes occurred, but was not counted. False checks did not extend to the region of the medial suture and usually varied greatly in band width. An opaque band at the edge was scored as a "plus" growth and not a year mark.

Vertebrae—Flesh around the 23rd and 24th (caudal) vertebrae was removed, and vertebrae were separated with a knife. Vertebral annuli were defined as concentric alternating pairs of opaque and translucent bands within cartilaginous tissue on the anterior and posterior cones of vertebral centra. Annuli were counted once by unaided eye before vertebrae were processed further. The vertebrae were then boiled, all remaining soft tissue was removed, and they were dried in a dehydrator at 52°C for 24–48 h. Both anterior and posterior depths of cones (perpendicular distance from the open end of the cone to the apex) were measured to the nearest 0.1 mm using a dial caliper.

Otoliths—The semicircular canals, located lateral to the spinal cord's foramen in the skull, were extracted using watchmaker's forceps. Using a dissecting microscope at 6×, the sagitta (largest of the three otoliths) was teased out of the sacculus with size 00 insect pins. The sagitta was then cleaned of tissue under 25× magnification using pins and a fine-tip brush, and stored in 75% EtOH.

Length of sagittae was measured by placing complete sagittae, antirostrum side down, in the well of a culture slide. The ventral profile was viewed through a video camera mounted on a dissecting microscope and its length measured with an image processor. End-to-end line segments were measured along the middle of the profile, from the tip of the rostrum to tip of the postrostrum (Fig. 3).

Sagittae were further prepared in one of two ways. A sagitta for which DGI's were to be enumerated (Radtke and Hurley, 1983; Wilson and Dean, 1983) was glued onto a microscope slide, sulcus (medial) side down. The exposed surface of the rostrum was sanded lightly with 600-grit silicon carbide paper with frequent inspections until DGI's became visible in the sagittal plane from the core to the distal tip of the rostrum. The sagitta was then mounted in Euparal under a cover slide. All apparent DGI's were enumerated from the core to the tip of the rostrum using a compound microscope at 600× with transmitted light. In a preliminary comparison of counts of DGI's on the rostrum, antirostrum, and postrostrum of sagittae, DGI counts on the rostrum were always highest. We assumed that these highest counts were most representative and thereafter counted DGI's on the rostrum only. After a number of practice counts, we decided on using the average of ten consecutive counts to estimate specimen age. DGI counts were divided by 365 to convert to years.

External ridges have been observed on the proximal surface of sagittae rostrums for northwest Atlantic (Radtke and Hurley, 1983), but not southwest Atlantic (Wilson and Dean, 1983) swordfish. We additionally observed alternating pairs of opaque and translucent

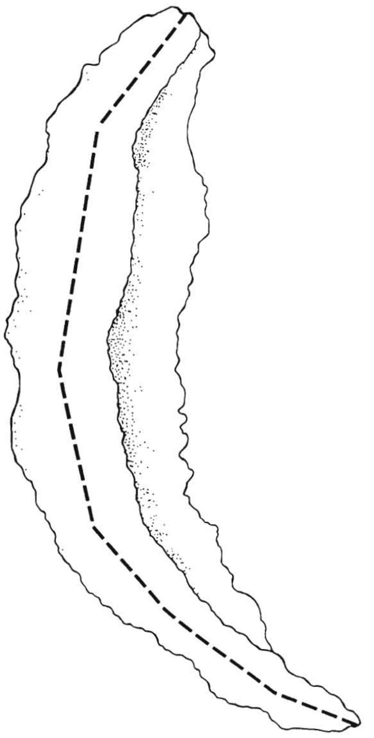

Figure 3
Diagrammatic curved ventral profile of a swordfish sagitta. Dashed line represents a series of end-to-end straight line segments drawn by an image processor and used to estimate total length of the sagitta.

bands on the postrostrums of sagittae (heretofore unreported for swordfish); these also may represent annual marks. A sagitta for which rostral ridges and postrostral bands were to be enumerated was mounted on a microscope slide, sulcus side up, in Euparal without any processing. Ridges and bands were counted using a dissecting microscope at 25× with reflected light.

Data Analysis

Tissue–EFL Relations—Proportionality between EFL and the growth axis of hard parts used for ageing was evaluated by product-moment correlation. The relation between width of fin rays and EFL was examined-for males and females separately. Depth of vertebral cones was related to EFL for the sexes combined because sex is indeterminable for fish in the landed catch. The relation between sagitta length and EFL also was examined for the sexes combined because the number of intact otoliths available for measurement was small.

Position of Sections—Preliminary observations suggested much variability among fin rays and individual fish in the location at which the left and right sides of rays joined at their medial suture. Hence, unavoidable variation existed in the position at which fin ray sections were cut. To evaluate the extent of this variation, we expressed the distance between the base of the ray and its first cut as a percentage of the total length of the ray, and compared coefficients of variation (CV = SD/mean × 100%) among the six different rays.

Precision of Readers—The precision of ages estimated by each of two readers (A and B) was evaluated as average percent error (APE, Beamish and Fournier, 1981). APE values were calculated for repeat counts of annuli on fin ray cross sections, for bands on postrostrums of sagittae, and for rostral ridges on sagittae of all 1992 specimens. Although Reader B made four readings of the hard parts, only B's last three readings were used so that B's APE's would be comparable to Reader A's APE's which were based on three readings.

Comparisons among Readers—To compare counts of annuli among readers, the count of one reader was regressed on a second reader's count for the same tissue using ordinary least squares. Data included all six different rays from the three collection series. The significance of each pairwise comparison was evaluated by Student's *t* test of whether the regression slope equaled zero (i.e. whether reader counts were related). The equivalence of counts between readers was similarly tested by hypothesizing slope = 1. Only the last of the repeat counts by Readers A and B, and Reader C's single count, were used. Comparisons were made for all three pairwise reader combinations. Analogous comparisons among readers were made for counts on vertebrae.

Comparisons among Tissues—To evaluate whether the counts made on the six different rays equivalently estimated age, we used Friedman's two-way ANOVA by ranks (Daniel, 1978). This test analyzed the difference in counts (responses) among rays (treatments) for each swordfish (block). The null hypothesis tested was that counts were equal among rays, within fish. These data consisted of the last series of repeat counts by Reader A for 1992 and 1993 specimens.

Age–Length Relation—Reader A's last series of counts for second anal rays of 1992 specimens, and A's single count of second anal rays from 1993, were used to calculate VBGF parameters. Nonlinear regression using Marquardt's algorithm and Statgraphics version 5.0 (Statistical Graphics Corp., 1991) was used to obtain least squares estimates of parameters. Parameters were estimated by sex and for all fish pooled.

Results

Proportionality of Tissues and EFL

In general, all tissues that we examined satisfied the minimum requirement of proportionality between counting path of hard part and body size of fish. Correlations between width of ray at point of cut and EFL were significant for all six different rays (Table 2). Relation between depth of vertebral centrum and EFL were also significant (Table 3), as was that between EFL and length of sagitta (r=0.69, N=25, P<0.001).

Location of Sections on Rays

The distance from the base at which the left and right sides of the ray converged (relative to length of the ray) decreased from the first to the third ray for dorsal and anal fins (Table 4). The third rays of dorsal and anal fins were the least variable (Table 4).

Precision of Readers

The APE's of repeat counts of annuli for the six different fin rays, for external ridges on the rostrums of sagittae, and for bands on the postrostrums of sagittae were calculated for Readers A and B (Table 5). Values were consistently less for Reader A than for Reader B. Counts of ridges on the rostrum and of bands on the postrostrum were less precise than counts of annuli on rays. Values for the second ray of dorsal and anal fins were less than for other rays (Table 5).

Comparisons between Readers

When we employed Student's t test to compare counts of annuli by different readers for the 6 different fin rays pooled, all regressions were significant, indicating that readings by different readers were related (Table 6). However, each of the regressions had a slope significantly different from 1, indicating a significant difference within each pair of readers (Table 6). Reader counts on specific rays were therefore examined to identify where disagreements occurred. Differences were significant for the first ray of both dorsal and anal fins, but never significant for the second ray of either fin for any pairwise reader comparison (Table 7).

Results of reader comparisons were variably conclusive for the other hard parts examined. All regressions of counts on vertebrae by different readers were significant, but all differences in counts between readers also were significant (Table 8). Only five sagittae were read by both Readers A and B, and the mean difference in counts between readers did not significantly differ from zero (t=1.413, d.f.=4, P=0.23).

Table 2
Correlation (r) between swordfish eye–fork length (EFL) and cross section width of the first, second, and third rays of the first dorsal (D1, D2, D3) and first anal (A1, A2, A3) fins.

	Dorsal fin rays			Anal fin rays		
	D1	D2	D3	A1	A2	A3
Males						
r	0.614	0.694	0.740	0.891	0.665	0.725
N	26	29	29	19	27	26
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Females						
r	0.866	0.942	0.967	0.843	0.891	0.940
N	30	34	33	21	30	31
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 3
Correlation (r) between swordfish eye–fork length (EFL) and the depth of vertebral cones for anterior and posterior faces of the 23rd (V23) and 24th (V24) vertebrae.

	V23		V24	
	Anterior	Posterior	Anterior	Posterior
r	0.959	0.920	0.965	0.894
N	48	48	69	70
P	<0.0001	<0.0001	<0.0001	<0.0001

Comparisons of Tissues

Reader A's last counts of annuli clearly differed among the 6 different rays (Friedman's two-way ANOVA, χ^2=34.8, d.f.=5, P<0.001). Counts ranked lowest for the first ray of dorsal and anal fins (average rank = 3.11) and highest for the second ray of the anal fin (average rank = 3.88), but this apparent maximal contrast was not significant (Friedman's a posteriori multiple comparison test; $P \approx 0.10$; Daniel, 1978, p. 231). Mean counts ranged from a minimum of 2.62 for the first ray of the dorsal fin to a maximum of 3.26 for the second ray of the anal fin.

Reader B's average DGI counts on sagittae of 1992 and 1993 specimens were converted to years for comparison with annuli in rays and vertebrae from the same fish (Table 9). Estimated ages based on DGI's and on

Table 4

Summary statistics for relative position of the first cross section of fin rays for swordfish specimens collected in 1993. Coefficient of variation, CV = (SD/mean) × 100%.

	Dorsal fin rays			Anal fin rays		
	D1	D2	D3	A1	A2	A3
Relative position (%)						
CV	16.7	22.4	18.2	23.7	29.4	19.2
Mean	35.4	25.9	17.6	33.3	22.1	18.2
SD	5.9	5.8	3.2	7.9	6.5	3.5
Maximum	48.0	38.5	25.0	59.5	42.3	26.6
Minimum	22.0	15.3	10.7	15.4	11.9	11.0
Ray length (cm)						
Maximum	16.0	39.0	54.5	10.7	36.0	36.5
Minimum	3.3	6.9	19.5	2.8	8.5	13.0
No. rays measured	41	42	42	41	42	40

Table 5

Precision of repeat counts (APE = average percent error) for individual specimens of swordfish collected in 1992. N = number of specimens.

	Reader A		Reader B	
	N	APE	N	APE
Dorsal fin rays				
D1	29	12.18	29	22.20
D2	28	5.97	28	16.98
D3	29	10.39	29	27.01
Anal fin rays				
A1	29	9.76	29	21.22
A2	30	9.06	30	17.58
A3	26	7.25	26	15.28
Sagittae				
Ridges	29	20.62	7	77.36
Postrostral bands	28	14.45		

annuli generally agreed among the 12 relatively small and young fish for which comparison was possible (r=0.89, P<0.001), although DGI's appeared somewhat under-counted (Table 9).

Provisional Growth Model

A provisional estimate of the VBGF equation for central North Pacific swordfish with sexes combined was

$$L_t = 321[1 - e^{-0.14(t+1.3)}]$$

Growth curves fit to EFL-at-age for males and females broadly overlapped, at least for ages 4 or less; seven of nine fish aged 6 and older were females (Fig. 4).

Table 6

Comparisons between readers of counts of presumed annuli on all six different swordfish rays.

				Test of H_0: slope = 1	
Readers	N	Regression coefficient	SE	t	P
A vs B	502	0.913	0.0162	5.34	<0.001
A vs C	353	0.891	0.0129	8.43	<0.001
B vs C	345	0.890	0.0179	6.14	<0.001

Validation

A total of only 28 apparently viable swordfish were caught on the 1991 (10 fish), 1992 (9), and 1993 (9) cruises; each was injected with oxytetracycline, tagged, and released. None of these marked fish has been recaptured as of October 1995.[4]

Discussion

Tissue–EFL Proportionality and Variability

All hard parts that we evaluated for ageing swordfish grow proportionally with body size. Berkeley and Houde (1983) and Tsimenides and Tserpes (1989) similarly observed proportionality between the width of second anal fin rays and body length of swordfish. Our findings of proportionality between sagitta length and body length, though, seem to be the first to date for any billfish. This should not be surprising, as our study is

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[4] Nor as of September 1998.

Table 7

Comparisons between readers of counts of presumed annuli on each of six different swordfish fin rays. D = dorsal, A = anal.

Readers	Ray	N	Regression coefficient	SE	Test for H_0: slope = 1	
					t	P
A vs B	D1	74	0.753	0.0472	5.25	<0.001
	D2	88	1.011	0.0356	−0.32	>0.5
	D3	87	1.059	0.0348	−1.68	>0.1
	A1	76	0.740	0.0492	5.28	<0.001
	A2	95	1.033	0.0371	−0.88	>0.2
	A3	82	1.000	0.0307	<0.001	>0.9
A vs C	D1	50	1.128	0.0268	−4.78	<0.001
	D2	65	1.042	0.0366	−1.16	>0.2
	D3	56	1.115	0.0299	−3.85	<0.001
	A1	43	1.106	0.0310	−3.42	<0.001
	A2	77	0.927	0.0402	1.82	>0.05
	A3	62	1.045	0.0344	−1.30	>0.2
B vs C	D1	50	0.653	0.0533	6.50	<0.001
	D2	65	0.962	0.0281	1.37	>0.1
	D3	54	0.950	0.0356	1.41	>0.1
	A1	42	0.713	0.0522	5.49	<0.001
	A2	73	1.052	0.0407	−1.28	>0.2
	A3	61	0.877	0.0383	3.21	<0.001

apparently the first to use a series of short straight-line segments to approximate distance along the major axis of a billfish sagitta. The sagitta becomes progressively more curved in large billfish (Radtke and Hurley, 1983), and describing its length by a single straight-line measurement disproportionately underestimates the length of larger sagittae in older fish.

Some potentially useful ageing tissues can be prepared and measured with less variability than others. Among the fin rays that we examined, for example, cuts for cross sections can be most precisely located on the second and third rays of dorsal and anal fins.

Table 8

Comparisons between readers of counts of presumed annuli on swordfish vertebrae.

Readers	N	Regression coefficient	SE	Test H_0: slope = 1	
				t	P
A vs B	47	0.963	0.0279	1.33	>0.1
A vs C	33	0.937	0.0418	1.50	>0.2
B vs C	14	0.927	0.0564	1.30	>0.2

Table 9

Matched estimates of the number of presumed daily growth increments (DGI's, converted to years) on sagittae and the number of presumed annuli on cross sections of rays and vertebrae of the same swordfish. Counts of annuli agreed across all hard parts examined for these 12 fish.

EFL (cm)	Sex[1]	DGI (yr)	Presumed annuli
76.8	I	0.85	1
80.7	I	0.78	1
82.5	M	0.75	1
88.6	M	0.95	1
95.3	F	0.85	1
105.8	M	1.37	2
107.4	F	1.36	2
107.5	F	1.47	2
116.0	M	1.31	2
140.9	F	1.55	3
141.3	F	1.69	3
165.6	U	2.52	3

[1] F = female, M = male, U = unrecorded, I = immature.

Tissue Suitability for Ageing

Additional factors such as reader precision, agreement among readers, and preparation efficiency are also important criteria when choosing tissues to use for ageing. The APE of repeat counts of annuli was consistently lowest for the second ray of both the dorsal and anal fin. Counts made using the second ray of dorsal and anal fins also did not differ between readers, whereas counts clearly differed between readers for other fin rays. On average, counts of annuli did not differ between the second and third rays of either dorsal or anal fins. Second rays typically are the widest and usually have the clearest bands. In general, the preparation of fin ray cross sections and the counting of annuli on ray sections are relatively easy, and fins can be obtained in large quantities because they are discarded as swordfish are dressed at sea. Lastly, the second ray of the first anal fin has precedence in studies of Atlantic and Mediterranean swordfish (Berkeley and Houde, 1983; Prince et al., 1988; Tsimenides and Tserpes, 1989; Ehrhardt, 1992; Tserpes and Tsimenides, 1995; Turner[1]). The second ray of the first anal fin is the most logical choice if fin rays are used to age swordfish, even though there are inevitable complications in using fin ray sections, as there are with other hard parts, for ageing studies. Difficulties in interpreting annuli on swordfish fin rays and other hard parts are discussed in the sections that follow.

Dorsal and Anal Fin Rays—Counts of annuli sometimes varied greatly among the different fin rays of individual fish, especially for large specimens (>165 cm EFL).

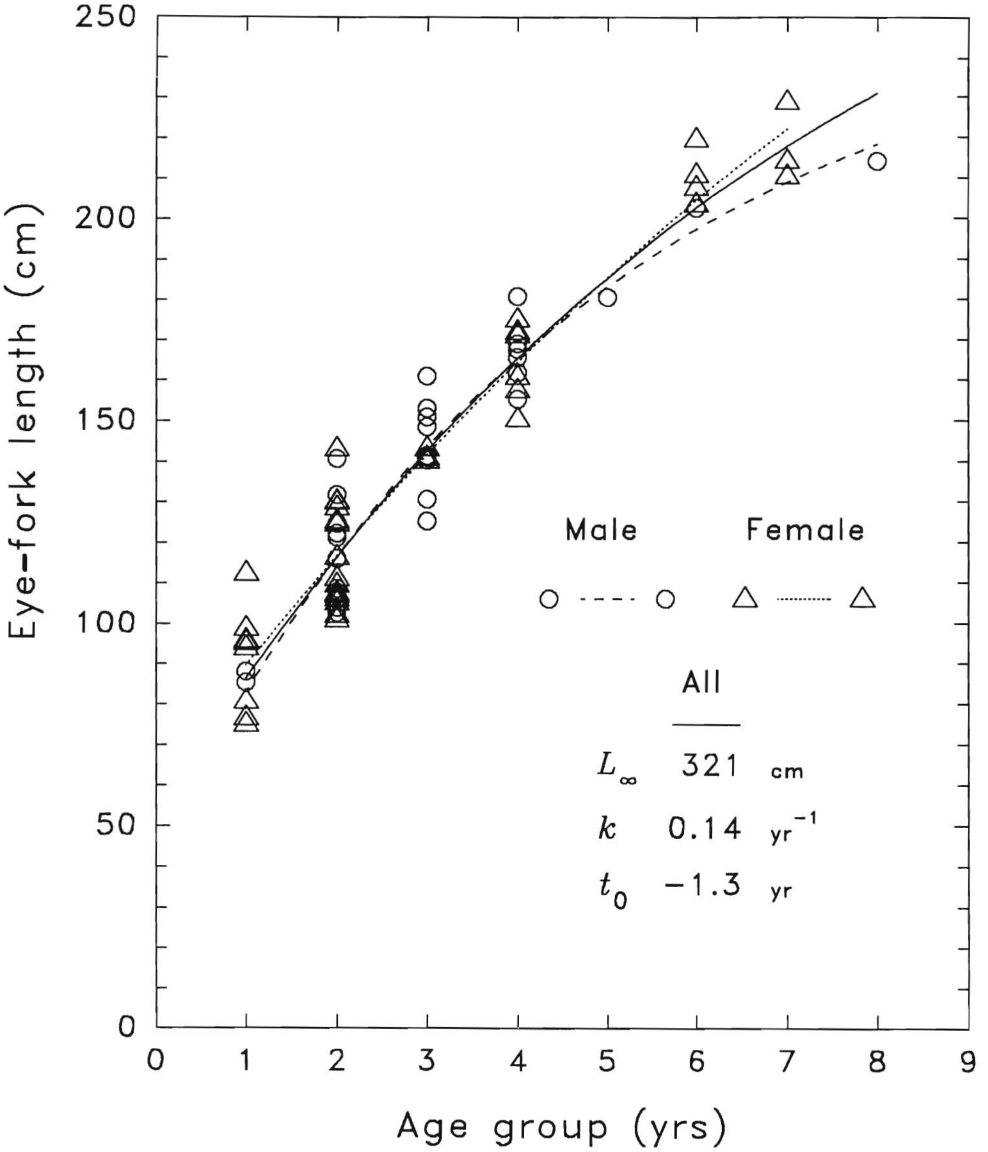

Figure 4
Von Bertalanffy growth curves (VBGF's) for adult male (n=33) and female (n=40) swordfish collected in 1992 and 1993. Provisional estimates of VBGF parameters (L_∞, K, and t_0) are noted for all (n=77) fish, including three immatures and one of undetermined sex. Age estimates were based on presumed annuli counts on cross sections of the second anal ray.

Second rays of dorsal and anal fins sometimes appeared to have more bands than adjacent rays. Higher counts may represent mistaken inclusion of multiple bands or false checks. Berkeley and Houde (1983) and Tsimenides and Tserpes (1989) both observed multiple bands on swordfish fin rays, but (like ourselves) only counted the more prominent bands as annuli.

Loss of early annuli is theoretically a problem whenever living tissues such as fin rays are used to estimate age. Neither Berkeley and Houde (1983) nor Tsimenides and Tserpes (1989) rigorously adjusted their fin ray counts for potential loss of annuli due to internal resorption. Tsimenides and Tserpes (1989) in part elected to use the second anal ray because external wear (erosion) did not seem to be a problem and because the vascularized matrix (core) of the second ray is small. Under-counting can be an important problem if early-formed annuli are missing due to resorption in the core of fin rays; back-calculating the location of resorbed first annuli has been modestly successful for other billfishes (Hill et al., 1989). Loss of the first and second annuli may not be a problem when fin rays are cut (as we have done, Fig. 2) at a moderate distance above the base, thereby potentially minimizing the effects of internal resorption and external wear. The general agreement that we found between DGI's and annuli counts for the same fish (Table 9) suggests that first annuli were present in our ray preparations, although these comparative data were limited to young fish for which resorption and wear may be less or not a problem. Further studies are needed that compare counts of annuli between sections of fin rays cut at various distances above the base and cut at the more conventional location (base) of the same fin ray, particularly for old fish.

Vertebrae—It is possible to obtain a large number of age estimates requiring no tissue preparation by counting bands on vertebral centra of landed swordfish. However, the use of vertebrae for ageing poses several problems. When counts of annuli on centra were compared to counts on rays, higher counts sometimes occurred on vertebrae, suggesting the presence of multiple bands or false checks. Since pairing of adjacent bands does not occur on centra, we had no objective basis for adjusting counts. Counts also sometimes differed between the anterior and posterior cones of the same vertebra. The last pair of bands to form on the cartilaginous faces of centra can easily be damaged or lost when vertebrae are separated with a knife or scalpel. Bands on swordfish vertebrae have previously been investigated by Beckett (1974), with similarly inconclusive results.

Otoliths—The potential of using DGI's on sagittae to estimate swordfish ages has been demonstrated by Radtke and Hurley (1983) and Wilson and Dean (1983). However, several unresolved problems exist. A major difficulty in using otoliths is the care needed to extract and prepare the tiny (1–5 mm long), delicate sagitta. To obtain age estimates, the long fragile rostrum must be extracted and prepared intact. Also, more time is required to count DGI's than to count annuli. Furthermore, increment widths near the tip of the rostrum may be too narrow to be resolved by light microscopy (Campana and Neilson, 1985), requiring scanning electron microscopy. Light microscopic counts of the relatively broad DGI's that form during rapid early growth may be the best way to age larval and young-of-year juvenile swordfish (Megalafonou et al., 1995), however.

The ridges reported by Radtke and Hurley (1983) on the rostrums of sagittae of northwest Atlantic swordfish have now also been observed on sagittae of central Pacific swordfish. Since rostral ridges are surface structures, the angle at which rostrums are viewed affects their counts. Identifying the first and last ridges can be subjective because these ridges are sometimes less developed than others, and an obvious potential bias exists for underestimating ages. Conversely, we observed some specimens for which ridge counts were higher than counts of annuli on other tissues from the same fish. Ridges did not appear to form pairs or groupings on these latter specimens, so there was no obvious basis for objectively adjusting counts. The use of rostral ridges on sagittae for estimating ages of swordfish merits further study.

We also observed bands on the postrostrums of sagittae that possibly could be used to estimate age. However, counts of these bands were usually higher than counts on other tissues of the same fish. As with vertebral bands and otolith ridges, these postrostral bands did not appear to form pairs or groupings whose numbers could be objectively adjusted downwards. Postrostral bands on swordfish sagittae appear to be among the least reliable time markers and we discourage their use.

Age Validation

Ehrhardt's (1992) and Tserpes and Tsimenides's (1995) edge analyses of annuli on anal fin rays of Atlantic and Mediterranean swordfish, respectively, remain the only partially successful attempts to date at validating swordfish ages based on a hard part. Wilson and Dean (1983) and Radtke and Hurley (1983) only verified their results when they found agreement between counts from different preparations or tissues. We have similar verification based on a general agreement between estimates from second and third rays from dorsal and anal fins, caudal vertebrae, and otolith ridges and DGI's. To date we have been unable to validate our results, however, because no oxytetracycline-marked fish have been recaptured. Thus far we also lack a comprehensive time series of specimens necessary for an analysis of the seasonal progression of marginal growth increments on ageing structures. Insufficient seasonal samples seriously limited Ehrhardt's (1992) study.

Provisional Growth Model

We are reasonably confident that our estimates of age in whole years for swordfish collected in 1992 and 1993 neither over- nor under-estimate ages by significant fractions of a year. Even though the fin rays used for this analysis were collected during a limited period of the year (March–May), a translucent zone was always present on the edges of ray cross sections of the young-of-year and age-1 fish, indicating completion or near-completion of the last annulus. Some edges of ray cross sections of older fish (≥2 yr) were translucent, but most were partly translucent and opaque or still fully opaque (Uchiyama, unpublished observation). Our current study of fin rays emphasizes the timing and duration of opaque and translucent band formation for most early age groups of central North Pacific swordfish.

Yabe et al. (1959) consistently identified four length modes (73, 102, 128, and 148 cm EFL) for swordfish caught during 1948–56 in the western North Pacific. Our provisional growth curve for swordfish of both sexes in the central North Pacific generally agrees with these length modes, if the second, third and fourth length modes of Yabe et al. (1959) correspond to fish ages 1+ (18 mo), 2+ (30 mo), and 3+ (42 mo). Our curve estimates a length of 74 cm in about 7 mo, 104 cm in 18 mo, 132 cm in 30 mo, and 157 cm in 42 mo (Fig. 4). Our estimate of the VBGF parameter, $K = 0.14$, for the sexes pooled is similar to the $K = 0.124$ estimated by Sakagawa and Bell (1980) using Yabe et al.'s (1959) progression of length modes and $L_\infty = 309$ cm, graphically estimated using Walford's (1946) method. Our growth curve describes an average growth increment of about 28 cm/yr for swordfish between 74 and 157 cm EFL, compared to Yabe et al.'s (1959) estimate of about 25 cm/yr for swordfish of 73–148 cm EFL from the western North Pacific. Using length frequency data for swordfish caught in the eastern Pacific, Kume and Joseph (1969) estimated growth rates of 38 cm/yr for fish of 62–165 cm EFL.

These general agreements between length modes and estimates of the VBGF parameter, K, are limited to only the first several apparent age classes entering their respective fisheries. Clearly, additional data for both small (young-of-year and yearling) and very large (>200 cm EFL) fish are needed to adequately describe the shape of the VBGF growth curve. The von Bertalanffy parameters K and L_∞ are inversely related, and L_∞ is greatly influenced by data that lie near and on the asymptote of the curve (Southward and Chapman, 1965).

Kume and Joseph (1969) further concluded that females grow faster and larger than males among eastern Pacific swordfish. Also, based on size frequency distributions, female swordfish in the eastern Atlantic appear to grow faster and larger than males (Beckett, 1974). The hard-part ageing studies of Berkeley and Houde (1983), Radtke and Hurley (1983), and Wilson and Dean (1983) all suggest or indicate faster growth rates for female swordfish in the western Atlantic, as did analogous studies by Tsimenides and Tserpes (1989) and Megalofonou et al. (1991) of swordfish of the Mediterranean and Aegean Seas. Our data likewise suggest that male growth starts decelerating earlier, perhaps because males mature at smaller sizes or younger ages in the Pacific as well as the Atlantic (Taylor and Murphy, 1992; Arocha et al., 1994). Greater numbers of large (>165 cm EFL) specimens of both sexes are needed before we can adequately evaluate possible sexual dimorphism in the growth and mortality rates of Pacific swordfish.

Research Needs

Since the end of summer 1993, observers have been placed aboard commercial longline vessels operating from Honolulu, and these observers have collected anal fins and otoliths for our ageing studies. These samples will enable us to expand our studies over a broader geographical area and obtain greater numbers of large fish. In addition, better seasonal coverage should result than can be accomplished with our single research vessel.

A larger-scale tagging program with a more efficient system for tagging and recovering tagged fish is necessary for validation. Greater involvement of the fishing industry, other U.S. agencies, and foreign investigators would vastly improve the chances of recapturing time-marked fish. On research cruises, we have learned how to select and handle swordfish during the tag application process to maximize apparent viability, and these findings need to be implemented on observer and cooperating fishermen cruises. A more accurate method for estimating size of fish at the time of tag release also still needs to be developed.

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