INTER-AMERICAN TROPICAL TUNA COMMISSION
COMISION INTERAMERICANA DEL ATUN TROPICAL

INTERNAL REPORT--INFORME INTERNO

No. 24

A REVIEW OF INFORMATION ON THE BIOLOGY, FISHERIES, MARKETING AND UTILIZATION, FISHING REGULATIONS, AND STOCK ASSESSMENT OF SWORDFISH, *XIPHIAS GLADIUS*, IN THE PACIFIC OCEAN

by

James Joseph, William H. Bayliff, and Michael G. Hinton

La Jolla, California

1994

PREFACE

The Internal Report series is produced primarily for the convenience of staff members of the Inter-American Tropical Commission (IATTC). It contains reports of various types, some of which will eventually be modified and published in the Bulletin series or in outside journals. Others are methodological reports of limited interest or reports of research which yielded negative or inconclusive results.

These reports are not to be considered as publications. Because they are in some cases preliminary, and because they are subjected to less intensive editorial scrutiny than contributions to the IATTC's Bulletin series, it is requested that they not be cited without permission from the IATTC.

Internal Report 24 is identical to a white paper prepared for the California Seafood Council for use as a source of background information for making plans for rational exploitation of swordfish in the northeastern Pacific Ocean.

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EXECUTIVE SUMMARY

Introduction

Swordfish, *Xiphias gladius*, are widely distributed in tropical, subtropical, and temperate oceans and seas of the world, and they are the object of important commercial fisheries in most areas where they occur. The world demand for swordfish has been increasing in recent years, and this has caused a corresponding increase in their value. This has led to a rapid growth of the U.S. fishery for swordfish in the Pacific Ocean. A number of U.S. vessels which are currently fishing in the Pacific had previously operated in the Atlantic Ocean and the Gulf of Mexico. The owners and operators of those vessels left those areas because of declines in swordfish abundance due to heavy exploitation, and they are concerned that their experience in the Atlantic Ocean and the Gulf of Mexico will be repeated in the Pacific.

There is no indication that swordfish are being overfished in the Pacific Ocean. However, because they are concerned that the problems which have occurred in the Atlantic could also occur in the Pacific, leaders of the fishing industry of the west coast of the United States are formulating a strategy for dealing with the development and management of the swordfish fishery of the Pacific. As a first step, it is necessary to review all available information on the biology, fisheries, and management of swordfish in the Pacific Ocean. Accordingly, the California Seafood Council requested that the Inter-American Tropical Tuna Commission (IATTC) prepare such a review.

The report deals with the biology, fisheries, utilization and marketing, fishing regulations, and stock assessment of swordfish in the Pacific Ocean. When little or no information on Pacific swordfish was available for a particular topic, information on that topic for the Atlantic Ocean was incorporated into the report. The report also reviews current arrangements for management of highly-migratory species in the Pacific Ocean.

Biology

Adult swordfish inhabit the tropical, subtropical, and temperate surface waters of the Pacific, Indian, and Atlantic Oceans and the Mediterranean and Black Seas between about 50°N and 50°S. They are most abundant in areas of convergence of warm and cold currents and of relatively high primary production, which may lead to conditions capable of supporting large pelagic predators, such as swordfish.

It is important to know whether the fish inhabiting a body of water belong to a single stock or to more than one stock, as the various stocks, if they exist, may require individual management. Inferences regarding stock structure are made from analyses of data on distribution of larval, juvenile, and adult fish, tag-and-recapture data, meristic and morphometric data (counts of vertebrae, fin rays, *etc.*, and measurements of various body dimensions), genetic data, data on the chemical composition of the bones of fish caught in different areas, and information on the presence of parasites in fish caught outside the normal ranges of those parasites. Only data on distribution of catches of swordfish have been used for analysis of stock structure of that species in the Pacific Ocean. There are three or four areas of the Pacific Ocean where swordfish are apparently more abundant than in most other areas, and it is possible that these represent separate stocks. Scientists who have studied the population dynamics of swordfish have used two stock-structure hypotheses, the single-stock hypothesis and the multi-stock hypothesis.

No returns have been received from tagged swordfish released in the northwestern Atlantic Ocean and recaptured in the northeastern Atlantic Ocean, nor have any returns been received from tagged swordfish released in the northeastern Atlantic Ocean and recaptured in the northwestern Atlantic Ocean, which may indicate that there are at least two stocks of swordfish in the Atlantic Ocean. Mitochondrial DNA analysis has indicated differences between fish from the Mediterranean Sea and the Gulf of Guinea, so the fish from these two areas may belong to separate stocks. Recent unpublished data on tagging, mitochondrial DNA, length frequencies, and catch-per-unit-of-effort trends, however, suggest that Atlantic swordfish could be considered as a single stock.

Information on maturation and spawning, fecundity, and sex ratio, and on larvae and juveniles, is necessary for studies of stock structure, discussed above, and for assessment of the effects of fishing on a stock of fish, particularly when it is suspected that reduction in the numbers of spawners has reduced the recruitment of young fish to that stock. The gonad index, a ratio of the weight of the gonads to the weight of a fish has been, until recently, the most commonly-used index of maturity of that fish. Data on the gonad indices of swordfish indicate that mature females occur in the eastern Pacific Ocean west of 110°W between 10°N and 30°S, particularly during the first and fourth quarters. In the western Pacific Ocean, mature fish occur between 20°N and 20°S.

Information on age and growth, and on mortality, is necessary for employment of age-structured models for assessment of the effects of fishing on a stock of fish. The age and growth of fish can be estimated by (1) following progressions of modal lengths of fish through time, (2) counting daily or annual rings on hard parts, such as their scales, spines, or otoliths (ear bones), or (3) comparing the lengths of tagged fish at release and recapture.

One-year-old swordfish are 20 to 24 inches long, and they grow at the rate of about 15 inches per year for the next three years or so. After reaching maturity, females grow more rapidly than do males. The life spans of males and females in the Atlantic Ocean may be as long as 14 and 32 years, respectively. Most of the swordfish caught in the Straits of Florida by longline and recreational fishermen are 1 to 6 years old.

Fish experience two types of mortality, natural mortality and fishing mortality. The natural mortality rates are greatest for the youngest fish, and then decrease as the fish become better able to fend for themselves. In most cases, due to lack of data with which to measure size- or age-specific mortality, it is assumed that the natural mortality rate is constant after the fish become large enough to enter the fishery. Estimates of the natural mortality rates of swordfish in the Atlantic Ocean range from 11 to 35 percent per year.

Young swordfish are the prey of tunas, billfishes, and sharks. They presumably compete for food with many other inhabitants of the offshore pelagic environment, and adult swordfish presumably compete for food with tunas, other billfishes, sharks, and dolphins. Young swordfish eat small crustaceans and fish, and older swordfish consume fish and squid. Swordfish are apparently attracted to submarine canyons, where there are concentrations of food organisms which result from the turbulence generated by the rough bottoms. There is evidence that swordfish use their swords to attack and disable their prey before ingesting them and that they frequently descend to the bottom to feed on demersal fish.

Knowledge of the behavior and physiology of swordfish is necessary for determining whether the assumptions necessary for application of various procedures for stock assessment are satisfied. Also, such information is often useful for fishermen in determining when, where, and how to fish.

Information on the daily activity patterns of swordfish has been obtained by monitoring them with acoustic telemetry. The fish tend to remain closer to the surface during the night than during the day, although they occasionally bask at the surface during daylight hours. They may do this to overcome oxygen debts that they accumulate in deeper water or to increase their body temperatures.

Tissue associated with one of the eye muscles of swordfish warms their brains and eyes, enabling them to cope with the drastic changes in ambient temperature they undergo as they rapidly ascend and descend in the water column. Swordfish do not have the countercurrent heat exchangers which enable tunas to regulate their body temperatures, but they are able to accomplish this by increasing the rate of blood flow in warm water and decreasing it in cold water and by changing the amount of blood supplied to the red muscle.

Swordfish occasionally collide with objects of various kinds, and there is evidence that at least some of these collisions are intentional.

Catch records show poleward movement of swordfish off Baja California and California and off Chile in the spring and movement in the opposite direction in the fall.

Swordfish caught with longlines in the eastern Pacific Ocean range from less than 30 to about 110 inches in length, but most of them are less than 94 inches in length. Fish less than 30 inches in length have frequently made up a considerable portion of the catch (in numbers of fish, not weight of fish) within various area-time strata, which is not the case for any other species of billfish. No areal or seasonal trends for these occurrences of small fish are evident. The lengths of fish caught with longlines in the northwestern Pacific Ocean are not much different from those caught with longlines in the eastern Pacific Ocean. The same applies to those caught with drift gillnets off California, except that the incidence of small fish is much less in the gillnet catches.

In 1970 it was discovered that some tunas and billfishes, including swordfish, have total mercury levels exceeding 0.5 part per million (ppm), the interim guideline set by the U.S. Food and Drug Administration as the maximum concentration for fish destined for human consumption. These findings adversely affected the market for swordfish during the early 1970s, but since then it has recovered. In 1979 the upper limit was raised to 1.0 ppm.

Fisheries

Recreational fishermen rarely fish for swordfish, and the catches of this species by recreational fishermen probably average less than 50 fish per year in the eastern Pacific Ocean.

The principal commercial swordfish harvests are made by longline, gillnet and, historically, harpoon fisheries. The catches in the Pacific Ocean have increased from about 18,600 metric tons (mt) in 1982 to an estimated 30,600 mt in 1992. (A metric ton is equal to 1.1 short tons.) At the same time, the world catches of swordfish increased from about 44,000 mt in 1982 to about 73,000 mt during the early 1990s, with a peak catch of 81,000 mt in 1988. Of the 142,200 mt of Pacific swordfish harvested during the 1988-1992 period, Japanese fisheries accounted for the majority of the catch (42 percent), with significant harvests also made by vessels of Chile (20 percent), the Philippines (13 percent), the United States (10 percent), and the Republic of China (9 percent).

The principal U.S. Pacific swordfish fisheries are the drift gillnet fishery and the longline fishery.

Prior to the late 1970s, the only significant U.S. swordfish fishery was the harpoon fishery conducted off Southern California during the late summer and fall. Since the 1978 peak catch of about 1,500 mt, the annual catch in this fishery has dropped to about 100 to 200 mt.

The drift gillnet fishery has dominated the U.S. mainland swordfish catch since 1981. This fishery was originally directed at sharks, but is now directed seasonally at swordfish. During the first few years following this shift in fishing strategy, the annual swordfish catch by drift gillnets increased to a peak of about 1,500 mt in 1984 and 1985. Subsequently the catches decreased to about 700 mt in 1990 and 1991, but then increased to about 1,100 mt per year in 1992 and 1993. Approximately 80 percent of the drift gillnet catch of swordfish is made during September through December.

The most recent significant changes in the U.S. fishery for Pacific swordfish have been in the longline fishery operating from Hawaii and, more recently, Southern California. Prior to 1989, swordfish were an incidental catch of this fishery, which was directed at tunas and took place primarily within the U.S. Exclusive Economic Zone (EEZ) around Hawaii. During the early 1990s, U.S. vessels from the Atlantic coast and Gulf of Mexico, using fishing strategies developed for fishing Atlantic swordfish, including night sets of shallow gear with lighted hooks, entered the Hawaii-based fleet. As the fishing effort has increased with the addition of vessels, there has also been an expansion of the fishery to include significant effort in international waters outside the U.S. EEZ around Hawaii. The catch by the longline fleet based in Hawaii increased ten-fold, from about 200 mt in 1989 to about 1,900 mt in 1990, and then doubled to about 4,500 mt and 4,950 mt in 1991 and 1992, respectively. These catches are made mostly during the January-June period.

In late 1992, longline vessels which had been fishing in the Atlantic Ocean and the Gulf of Mexico began operating in the Pacific Ocean from Southern California ports. Only two or three of these vessels were fishing in 1992, but they have continued to operate, with increasing effort, and by July 1994 the number of vessels had increased to at least 23. Several vessels have fished throughout the year to attempt to determine how best to operate, and other vessels have fished only when good fishing has been reported. As is the case for the Hawaii-based fleet, these vessels also fish for tunas, and direct most of their effort toward swordfish when swordfish are most abundant or easiest to catch.

Marketing and utilization

In 1986, the principal markets for swordfish were western Europe, Japan, and the United States. At that time, the United States was consuming about 22 percent of the world swordfish supply, with about half of this consumption being met by domestic production and half by imports.

The growing U.S. demand for swordfish was met during the late 1980s by increasing domestic production of Atlantic swordfish and increasing imports of swordfish. The domestic production of Atlantic swordfish increased from about 3,000 mt in 1986 and 1987 to a peak of about 6,600 mt in 1990, and the imports exceeded 7,400 mt in 1990. The percentage of the U.S. swordfish consumption which was imported ranged from 38 to 51 percent, and averaged 44 percent, during the 1985-1992 period. Since 1990, the annual U.S. consumption of swordfish has averaged about 16,800 mt.

The principal exporters of Pacific swordfish to the United States since 1985 have been Chile and the Republic of China. In 1986-1987 these two nations provided about 40 percent of the U.S. imports of swordfish, and by 1989-1990 this had risen to about 70 percent. Since 1990, Chile has provided over 90 percent of the imports of swordfish to the United States. The United States has utilized an average of 18 percent of the annual global swordfish production during 1985-1992, and about 42 percent of the Pacific swordfish production during 1990-1992.

Fishing regulations

In California, drift gillnets may not exceed 6,000 feet in length, and the minimum stretched mesh size is 14 inches. Fishing is not permitted within 12 nautical miles (nm) of the mainland south of Point Arguello or east of an imaginary line between Point Reyes and the Farallon Islands at the mouth of San Francisco Bay. In addition, the following seasonal restrictions apply: December 15-January 31, fishing not permitted within 25 nm of the mainland; February 1-April 30, fishing not permitted at all; May 1-August 14, fishing not permitted within 75 nm of the mainland. Also, there are numerous areas off Southern California in which fishing with drift gillnets is not permitted. If a marlin is caught, the operator must not remove it from the boat, and he must immediately notify the California Department of Fish and Game, which will remove it for distribution to public institutions.

The U.S. National Marine Fisheries Service (NMFS) regulations for the Pacific Ocean which affect swordfish, except for the Marine Mammal Protection Act (MMPA) discussed below, apply only to the U.S. EEZ of the western Pacific Ocean (Hawaii, American Samoa, Guam, and other territories under U.S. administration). Longline fishing is prohibited in waters close to the principal Hawaiian Islands. Records of fishing activities must be kept for use by the NMFS, and the vessels must carry NMFS observers when requested to do so. Fishing with drift gillnets is prohibited in the U.S. EEZ of the western Pacific Ocean.

Amendments to the MMPA of 1972 adopted in 1988 require the participants in the drift gill net fishery of California to obtain federal MMPA exemption permits, report marine mammal kills, and allow federal employees to observe fishing operations.

The U.S. NMFS regulations for the Atlantic Ocean are the result of recommendations based on the research described in the section of this report entitled STOCK ASSESSMENT. The following quotas for swordfish applied to U.S. fishermen operating in the Atlantic Ocean during 1994:

- directed fishery - 7,000,000 pounds (dressed weight)
  - drift gillnet fishery - 69,286 pounds during the January 1-June 30 period and the same amount during the July 1-December 31 period
  - longline and harpoon fisheries - 3,430,714 pounds during the January 1-June 30 period and the same amount during the July 1-December 31 period
- incidental catch - 560,000 pounds (dressed weight)

When a quota is reached a closure goes into effect for the gear in question, and additional catches of swordfish by that gear are counted as incidental catches. During a closure, the limit on incidental catches of swordfish is two fish per vessel per trip. It is unlawful to fish for swordfish with a drift gillnet more than 2.5 kilometers (8,200 feet) in length. The minimum legal size for swordfish is 31 inches, measured from the cleithrum (collarbone) to the anterior portion of the caudal keel (the bony structures on the sides of the fish just anterior to the tail). However, up to 15 percent, by number, of the swordfish landed from a trip may be smaller than the legal limit. Records of fishing activities must be kept for use by the NMFS, and the vessels must carry NMFS observers when requested to do so. Vessels fishing with gear other than drift gillnet, longline, or harpoon gear may not direct their efforts toward catching swordfish. The limit for possession of swordfish by such vessels is five fish for squid trawlers and two fish for all other vessels.

In Mexico, commercial fishing for billfishes is not permitted within 50 nm of the Pacific coast of that nation nor within two areas which are more than 50 nm offshore. A fishery directed at marlins and sailfish may be conducted with longlines. Longline fishing may be conducted with a maximum of 2,000 hooks per boat, and the maximum annual effort permitted for the entire fleet is 6,250,000 hooks. A fishery directed at swordfish may be conducted only with gillnets.

In Chile, vessels more than 92 feet in length may not fish within 120 nm of the coast. The maximum length permitted for drift gillnets is 8,100 feet. The maximum numbers of hooks which may be deployed by vessels up to 92 feet in length and vessels more than 92 feet in length are 1,200 and 2,000, respectively.

Stock assessment

Three general types of models, production models, age-structured models, and spawner-recruit models, are used to assess the condition of stocks of fish.

Production models, which make use of data for the stock as a whole, rather than for individual fish, are fairly simple to use, as they require only data on catch and fishing effort. Because the assumptions which are required when using production models are not always fully satisfied, they often provide less precise estimates of the effects of fishing than do more sophisticated models.

Age-structured models require data on recruitment and on the growth and mortality rates of individual fish, which are often difficult to obtain, but they often produce better results than do production models. Estimates of these parameters are obtained from analyses of size and age data from fish in the catch and from tag-and-recapture experiments. The differences in growth and longevity of males and females can be incorporated into age-structured models.

Spawner-recruit models are based upon comparisons of the relationships between abundance of spawners and subsequent abundance of eggs, larvae, juveniles, or recruits to the fishery. The differences in growth and longevity of males and females must be incorporated into spawner-recruit models.

Production and age-structured models have been used extensively to study the population dynamics of swordfish. Most of this work, however, has been done with Atlantic swordfish.

Only production models, using data from the Japanese longline fishery for 1963 through 1980, have been applied to swordfish in the Pacific Ocean. It was concluded that the swordfish were capable of supporting greater catches than those which were taken during that period. The fisheries have changed since then, however. By 1992, the swordfish catch in the Pacific Ocean had reached nearly 31,000 mt, a 50-percent increase since 1986. The Japanese share of this catch declined from about 75 percent to about 35 percent, so the Japanese fishery may no longer provide coverage adequate to monitor the entire fishery. Data for the coastal fisheries of Chile, Costa Rica, Ecuador, Mexico, the Philippines, the United States, and other nations should be included in future analyses. Because the fisheries are expanding, it is important to initiate such analyses as soon as possible.

It is important to review the studies which have been conducted in the Atlantic Ocean, as the fishery of the Pacific Ocean is developing similarly to the way that the fishery of the Atlantic developed during the 1970s and 1980s. Stock assessment and management of the Atlantic fisheries are carried out internationally under the auspices of the International Commission for the Conservation of Atlantic Tunas (ICCAT). Although fisheries for swordfish have taken place in the Atlantic Ocean since the 1800s, and even before that in the Mediterranean Sea, it was not until the late 1970s and early 1980s that fishing effort began to increase to the present levels. At first the catches increased with increasing effort, but then they began to decline. The catch in the Atlantic reached an historic high of about 33,500 mt in 1989, but by 1992 it had declined by 30 percent to 23,500 mt. This decline was a matter of growing concern for the governments of the nations whose vessels participated in the fishery. These concerns resulted in intensive scientific investigations, under the auspices of ICCAT, of the status of swordfish in the Atlantic Ocean and Mediterranean Sea. The stock assessment carried out for the north Atlantic is the most comprehensive to date for any swordfish stock in the world. The scientists conducting these analyses reached a number of conclusions regarding the fishery of the north Atlantic, the most important of which were:

1. The age-structured analyses showed that the fishing mortality rate on 1- to 4-year-old swordfish generally increased through 1988, and then declined during 1989-1991. The pattern for the older fish was similar.

2. The age-structured analyses showed some increases in abundance of adults during the early 1990s as the apparent result of increased recruitment during the late 1980s and reduced catches since 1987.

3. Production modeling produced estimates of maximum sustainable yield (MSY) of 13,100 to 14,300 mt, with a "base-case" estimate of 14,200 mt. The 1991 catch of 13,200 mt was less than the MSY, but about equal to the "equilibrium catch," *i.e.* the catch that could be harvested on a sustained basis at the current population size. The current abundance of swordfish was estimated to be approximately 15 percent less than that which would produce the MSY, indicating overfishing.

Based on these analyses, ICCAT recommended a number of management measures for swordfish designed to halt the apparent decline in abundance and to restore the stocks to levels of abundance which would support greater catches. These recommendations, which took effect in mid-1991, were as follows:

1. For the fleets of nations with major catches of swordfish fishing for swordfish as a target species in the north Atlantic: a reduction in fishing effort sufficient to reduce the fishing mortality on fish larger than 25 kg (55 pounds) by 15 percent.

2. For the fleets of all nations fishing anywhere in the Atlantic Ocean: a prohibition against capturing and landing swordfish less than 25 kg, with a maximum 15-percent incidental allowance in numbers of fish.

3. For the fleets of nations with minor catches of swordfish fishing for swordfish as a target species anywhere in the Atlantic Ocean: a limit on the catches to the levels of 1988.

4. For the fleets of all nations which are members of ICCAT fishing anywhere in the Atlantic Ocean for species other than swordfish: a limit on the incidental catches of swordfish to no more than 10 percent of the entire catch by weight.

Discussion and conclusions

After a decline in the catches of swordfish in the Pacific Ocean during the early 1960s, when the Japanese longline fleet in the northwestern Pacific began to direct its effort toward species other than swordfish, the Pacific-wide catch began to increase. Based on the growing world demand for swordfish and the steady increase in catches in the Atlantic and Mediterranean, it is expected that the catches in the Pacific will continue to increase as long as the abundance of the fish will support that increase. If the catches continue to increase, it is likely that, based on the Atlantic experience, the abundance of swordfish will be reduced to the point that the catches will eventually decline. The question arises as to how overfishing might be avoided, that is how exploitation can be kept in balance with the ability of the swordfish population to support the catches. The answer, of course, is that we must gain sufficient understanding of the population dynamics of swordfish and possess the political will and administrative ability to utilize this understanding for purposes of management.

There are a number of technical requirements that must be met to ensure adequate stock assessment. One of the most important prerequisites for management is an understanding of the population structure of the stocks of swordfish that are the object of exploitation. It must be known whether the fish which are the object of a particular fishery mingle with fish which are the objects of other fisheries and whether they interbreed with those fish, as attempts to manage one fishery would not be effective if fish moved from that fishery into other fisheries where there were no similar or complimentary management measures. It is therefore necessary to understand the stock structure of the species in question before production and age-structured models can be applied with confidence.

Comprehensive catch and effort data are necessary for application of production models. For each fishery, data are needed on the catches for small areas and short time intervals, along with measures of fishing effort, such as numbers of vessels operating, numbers of hooks set per day, hours of deployment for drift gillnets, including corresponding information for recreational fisheries if and when the catches by those fisheries became important. A practical way to collect such information for commercial fisheries and recreational charter boats is through the establishment of a logbook system to be maintained by vessel captains or crew members, complemented by an observer program. Other systems, such as monitoring of important landing locations, could be developed for smaller vessels. With this sort of data, analyses utilizing production models could be carried out. Although limited in scope, these models could provide initial estimates of potential catches and early warnings of overfishing.

Measurements of the lengths and/or weights of fish in the catch, plus catch data, are necessary for application of age-structured models. These data can be used to estimate the rates of growth and of natural and fishing mortality. In addition, information on reproductive characteristics, such as sex ratio, fecundity, frequency of spawning, and location of spawning areas, should be collected. A program to collect such data would have to include sampling at most of the major landing sites of the commercial fisheries, and perhaps the recreational fisheries as well. Samples would have to be collected on a regular basis for an extended period of time.

Assuming that an adequate understanding of the population dynamics of swordfish is available, there are, nevertheless, several non-scientific issues that may complicate the implementation of management. These have to do with an ever-increasing awareness of and concern over "bycatch" (capture of species other than the "target" species), conflicts among commercial fishermen using different types of gear, conflicts between commercial and recreational fishermen, and the eventual problems of allocation of catches among nations. (In this report bycatch is defined as the total catch of non-target species, including fish and other animals which are retained, released alive, or discarded dead. The principal target species are tunas and billfishes for the longline fisheries and swordfish and sharks for the drift gillnet fisheries.)

Longlines and drift gillnets take the greatest amounts of swordfish in the Pacific Ocean. The probability of capturing swordfish can be increased by altering the locations in which the gear is deployed, the configuration of the gear, *etc.*, but in no case can catches of only swordfish be assured. Longlines and drift gillnets normally capture a variety of large pelagic fishes, such as tunas, marlins, and sharks, along with swordfish. Marlins are less common in the catches of gillnet vessels than in those of longline vessels. In addition, a few marine mammals and turtles are occasionally taken by both longline and gillnet vessels.

The actual and perceived capture of marine mammals, turtles, and birds by longlines and and marine mammals and turtles by drift gillnets has resulted in action on the part of some environmental organizations to limit the use of these types of gear. It is imperative, if this perceived problem is to be resolved, that information be collected on the numbers and kinds of animals taken as bycatches. (It should be noted that information on the bycatches of drift gillnet vessels operating off California has been published by the California Department of Fish and Game and the U.S. National Marine Fisheries Service.) Hand and hand with these efforts to collect data should be a major effort to design, develop, and implement modifications to fishing gear, if it is shown that the longline or drift gillnet fisheries have significant impacts on the species making up the bycatches.

The other major issue that must be dealt with is allocation--who gets what? This is the crux of most fisheries problems, and in an international fishery in which vessels of a number of nations participate it is the most difficult to solve.

A proper institutional format for managing the swordfish resources of the Pacific must be responsive to the unique characteristics of swordfish and the fisheries for them. Swordfish are distributed widely throughout the tropical, subtropical, and temperate waters of the Pacific Ocean, and they frequently move from the EEZs of various nations to the high seas and *vice versa* and across national boundaries from one coastal state to another. At least half of the total Pacific catch of swordfish is probably taken on the high seas beyond the EEZs of any nation. The fleets that fish for swordfish are at least as mobile as the fish, and probably more so. The market for swordfish is international; swordfish from Chile, for example, may end up in Japanese, European, or U.S. markets, depending on supply, demand, and price. Research on swordfish is conducted by several national research institutions on stocks or portions of stocks of concern to the respective nations. International research is conducted in the eastern Pacific Ocean by the National Research Institute of Far Seas Fisheries of Japan and the IATTC.

Considering the characteristics of swordfish and the fisheries for them in the Pacific Ocean, it is clear that cooperation among the interested nations is required for proper management of these resources. This is not a new concept. In fact, Article 64 of the United Nations Convention on the Law of the Sea calls for such cooperation in the management of highly-migratory species. Most of the nations whose fleets harvest swordfish in the Pacific Ocean are signatories to the treaty or are members of international fisheries organizations that have responsibility for the scientific study and management of highly-migratory species.

The IATTC is the only Article-64 type organization concerned with tunas and billfishes in the Pacific Ocean. This organization, which was created in 1949, has responsibility for the scientific study of tunas and other fishes taken by vessels fishing for tunas in the eastern Pacific Ocean and for making recommendations for management of the fisheries for these species. The

Convention establishing the IATTC does not define the limits of the eastern Pacific Ocean, but it conducts most of its studies of tunas, billfishes, and marine mammals in the area between the mainland of the Americas and 150°W.

There are a number of options for institutional arrangements for swordfish in the Pacific Ocean. Some of these which could be used in combination with Pacific-wide management of swordfish are:

1. Creation of a Pacific-wide Article-64 type organization. However, because of the position of the Forum Fisheries Agency (FFA), which represents the coastal states of the South Pacific region, regarding distant-water fishing nations and non-coastal states, it is not likely that this approach would be successful over the near term.

2. Creation of two independent organizations in the western Pacific, one including the member nations of the FFA and the other including the rest of the interested nations. The boundaries for the two organizations might bear no resemblance to the natural boundaries of the swordfish stocks, however.

3. Creation of a new organization in the eastern Pacific which would deal only with swordfish. This would be redundant, as the IATTC, an Article-64 type organization with responsibility for tunas and other fishes caught by vessels fishing for tunas, is already in existence and is currently working on swordfish.

These are only a few of the options that might be considered for swordfish. Regardless of which option is chosen, there are certain criteria that must be met if effective research and management are to become realities. The most important of these criteria is that the studies and management, as already noted, must apply over the entire range of the stock being exploited. Coordination must be exercised to ensure that adequate statistical and biological data are collected by the various research programs of the nations involved. All nations which participate in the fisheries must be party to any agreement for management.

It is only through such international cooperation, as called for in the United Nations Convention on the Law of the Sea, that the swordfish stocks of the Pacific Ocean can be maintained in a healthy condition, which would be beneficial to everyone concerned.

INTRODUCTION

Swordfish, *Xiphias gladius*, are widely distributed in tropical, subtropical, and temperate oceans and seas of the world, and they are the object of important commercial fisheries in most areas where they occur. Swordfish have been the object of commercial exploitation in the Pacific Ocean since the early 1900s. Although the commercial fishery of California dates back only to about 1916, swordfish formed an important component of the diet of native Californians before recorded history. Archeological digs and cave paintings in California reflect the importance of swordfish to these people. Swordfish had special meaning to the Chumash Indians of California, and swordfish skulls were buried with Chumash leaders (Davenport *et al.*, 1993).

The world demand for swordfish has increased in recent years, causing a corresponding increase in their value. This has led to rapid growth of the U.S. fishery for swordfish in the Pacific Ocean. A number of U.S. vessels which are currently fishing in the Pacific had previously operated in the Atlantic Ocean and the Gulf of Mexico. The owners and operators of those vessels left those areas because of declines in swordfish abundance due to heavy exploitation, and they are concerned that their experience in the Atlantic Ocean and the Gulf of Mexico will be repeated in the Pacific.

There is no indication that swordfish are being overfished in the Pacific Ocean. However, because they are concerned that the problems which have occurred in the Atlantic could also occur in the Pacific, leaders of the fishing industry of the west coast of the United States are formulating a strategy for dealing with the development and management of the swordfish fishery of the Pacific. As a first step, it is necessary to review all available information on the biology, fisheries, and management of swordfish in the Pacific Ocean. Accordingly, the California Seafood Council requested that the Inter-American Tropical Tuna Commission (IATTC) prepare such a review. It selected the IATTC for this task because that organization has responsibility for the scientific study of tunas and other species, including billfishes and marine mammals, taken by tuna fishing vessels in the eastern Pacific Ocean, and has carried out studies of the longline fishery which harvests swordfish in that area.

This report deals with the biology, fisheries, utilization and marketing, fishing regulations, and stock assessment of swordfish in the Pacific Ocean. When little or no information on Pacific swordfish was available for a particular topic, information on that topic for the Atlantic Ocean was incorporated into the report. The report also reviews current arrangements for management of highly-migratory species in the Pacific Ocean.

BIOLOGY

Preface

Frequent references are made in this section to lengths and weights of swordfish. Swordfish and other billfishes are measured and weighed in different ways, and reports with length and/or weight data in them do not always state clearly how the fish were measured and/or weighed. Information about the various ways swordfish have been measured and weighed is given in the Appendix.

Classification

Swordfish, *Xiphias gladius*, constitutes a single species which occurs in the Pacific, Atlantic, and Indian Oceans (Nakamura, 1985).

Distribution

Adult swordfish inhabit the tropical, subtropical, and temperate surface waters of the Pacific, Indian, and Atlantic Oceans and the Mediterranean and Black Seas between about 50°N and 50°S (Figure 1) from the surface to depths of about 50 m (27 fathoms) off Southern California (Holts *et al.*, 1994), about 100 m (55 fathoms) off Baja California, and about 600 meters (328 fathoms) near Cape Hatteras in the western Atlantic (Carey and Robison, 1981). The larvae occur in tropical and subtropical waters of the three oceans and contiguous seas between about 30°N and 30°S (Figure 2).

Stock structure

It is important to know whether the fish inhabiting a body of water belong to a single stock or to more than one stock, as the various stocks, if they exist, may require individual management. "A unit fish stock is one consisting of randomly interbreeding members whose genetic integrity persists whether they remain spatially and temporally isolated as a group, or whether they alternately segregate for breeding and otherwise mix freely with members of the other unit stocks of the same species" (Kutkuhn, 1981). Inferences regarding stock structure are made from analyses of data on distribution of larval, juvenile, and adult fish, tag-and-recapture data, meristic and morphometric data (counts of vertebrae, fin rays, *etc.*, and measurements of various body dimensions), genetic data, data on the chemical composition of the bones of fish caught in different areas, and information on the presence of parasites in fish caught outside the normal ranges of those parasites.

Sakagawa and Bell (1980), after examining data on the distribution of swordfish larvae and on longline catch rates, selected two stock-structure hypotheses, the single-stock hypothesis and the three-stock hypothesis, for assessment of the Pacific swordfish resource. The areas occupied by the three stocks correspond to Areas 1, 2, and 3 in Figure 1.

Bartoo and Coan (1989) also employed single- and three-stock hypotheses, but the areas occupied by their three stocks (Figure 3) are slightly different from those occupied by Sakagawa and Bell's (1980) three stocks. Bartoo and Coan's (1989) single-stock hypothesis is based on the "rationale that the resource appears to be contiguous, with zones of local high catches due to high abundance or high vulnerability, and the assumption that the population is sufficiently mobile to make the concept of local depletion on an annual basis a non-issue." Their three-stock hypothesis is based on the fact that they observed three "general areas of apparent high abundance in the northwest, southwest and east Pacific, made contiguous by a broad region of lower catches."

Skillman (1989) compared catch-per-unit-of-effort data for four index areas (Figure 4), and concluded that "swordfish consist of a single Pacific-wide stock."

Sosa Nishikawa and Shimizu (1991), on the basis of locations of areas with high catches per unit of effort, designated four stocks, one "off Japan, in the northwestern and central Pacific," one "off Baja California peninsula," one "off the western coast of South America," and one "off the eastern Australian coast and north of New Zealand." They emphasized, however, that "in order to make a complete discrimination of the stocks, more biological information is needed."

No returns have been received from tagged swordfish released in the northwestern Atlantic Ocean and recaptured in the northeastern Atlantic Ocean, nor have any returns been received from tagged swordfish released in the northeastern Atlantic Ocean and recaptured in the northwestern Atlantic Ocean (Farber, 1988; Miyake and Rey, 1989), which may indicate that there are at least two stocks of swordfish in the Atlantic Ocean.

Alvarado Bremmer (1992), Finnerty and Block (1992), and Magoulas *et al.* (1993) have used mitochondrial DNA analysis to study the stock structure of swordfish in the Atlantic Ocean. Alvarado Bremmer (1992) found considerable genetic divergence among six fish sampled on Georges Bank, suggesting "that the sample consists of individuals belonging to separate breeding stocks." Finnerty and Block (1992) found two genotypes in two swordfish collected off Italy and a third in two swordfish caught off North Carolina and Massachusetts. Magoulas *et al.* (1993) analyzed 377 fish, 242 from the Mediterranean Sea (Greece, Italy, and Spain), 40 from Tarifa, Spain, in the Strait of Gibralter, and 95 from the Gulf of Guinea. The fish from the Mediterranean Sea and Tarifa were similar to one another, but those from the Gulf of Guinea were considerably different from the others, indicating "drastic reduction in gene flow between these two ... areas." They noted that "swordfish with bite marks of *Isistius brasilienses*, a dwarf shark found only the tropical and subtropical Atlantic, were observed in the Mediterranean Sea." They mentioned the possibility that fish from the Mediterranean Sea travel to the area where the dwarf shark resides for feeding, and then return to the Mediterranean Sea to spawn.

Recent unpublished data on tagging, mitochondrial DNA, length frequencies, and catch-per-unit-of-effort trends (Hoey, 1994) suggest that Atlantic swordfish could be considered as a single stock.

Maturation and spawning, fecundity, and sex ratio

Information on maturation and spawning, fecundity, and sex ratio, and on larvae and juveniles (next section), is necessary for studies of stock structure, discussed above, and for assessment of the effects of fishing on a stock of fish, particularly when it is suspected that reduction in the numbers of spawners has reduced the recruitment of young fish to that stock.

Yabe *et al.* (1959), Kume and Joseph (1969b), Shingu *et al.* (1974), Weber and Goldberg (1986), Miyabe and Bayliff (1987), and Nakano and Bayliff (1992) have studied the maturation of swordfish in the eastern Pacific Ocean. The gonad index, a ratio of the weight of the gonads to the weight of a fish or to the cube of its length, has been, until recently, the most commonly-used index of maturity of that fish. The indices for swordfish in the eastern Pacific Ocean have been calculated by $GI = (W/L^3) \times 10^4$, where GI = gonad index, W = weight of gonads in grams, and L = length of fish (from the posterior margin of the orbit to the fork of the tail) in centimeters, by Kume and Joseph (1969b), Shingu *et al.* (1974), Miyabe and Bayliff (1987), and Nakano and Bayliff (1992). In recent years, histological examination of the gonads of both males and females has produced more accurate indices of maturity of various species of fish, and these techniques were applied by Weber and Goldberg (1986) to female swordfish caught off California.

Kume and Joseph (1969b) and Shingu *et al.* (1974) considered female swordfish with gonad indices of 3.0 or greater to be mature. Kume and Joseph (1969b) reported occurrences of females with gonad indices of 3.0 or greater west of 98°W between 12°N and 31°S, and stated that it appeared that mature fish were most abundant in northern latitudes from March through July and in southern latitudes around January. Shingu *et al.* (1974) noted the incidence of average gonad indices of 3.0 or greater west of 95°W between 10°N and 30°S throughout the year. They stated that their data "may indicate that spawning is limited to ... offshore waters," but remarked on the lack of samples from coastal waters off Mexico, where commercial fishing takes place. Weber and Goldberg (1986) examined the gonads of 23 males and 67 females caught off Southern California during the August 25-November 20, 1978, period. They stated that, "ovaries from our sample contained no mature oocytes and, in addition, did not contain abundant atretic oocytes indicative of the resorption process. Instead the ovaries were in the regressed stage and contained primary oocytes lining the tissue septa. These results indicate that the swordfish were reproductively inactive during the sampling period and for at least a month or two before capture." None of these had a gonad index greater than 1.8. Miyabe and Bayliff (1987) and Nakano and Bayliff (1992) considered only females with gonad indices of 7.0 or greater to be mature. Miyabe and Bayliff (1987) reported that mature fish occurred west of 110°W between 10°N and 30°S (Figure 5). The incidence of mature fish was greatest during the first and fourth quarters, but mature fish were encountered between 145°W and 150°W during the second and third quarters. Nakano and Bayliff (1992) found fish with average gonad indices of 7.0 or greater west of 135°W between 25°N and 15°S. These occurred north of the equator during the second quarter and south of the equator during the fourth quarter. The relationship between gonad index and length is shown in Figure 6. Of the 138 females over 150 cm long shown in the figure, 61, or 44.2 percent, had gonad indices of 7.0 or greater. The greatest gonad index which has been reported (Nakano and Bayliff, 1992) is 31.11, for a 208-cm (82-inch) fish with gonads weighing 28,000 g (62 pounds).

In the vicinity of Hawaii, swordfish with the greatest gonad indices were caught in April through July (Uchiyama and Shomura, 1974).

In the western Pacific Ocean, mature fish were found between 20°N and 20°S by Yabe *et al.* (1959). In the northern region, spawning was presumed to occur from February to August, with a peak from March to June. In the equatorial region, "spawning might be effected the year round."

According to Yabe *et al.* (1959), swordfish first reach maturity at 5 to 6 years of age, when they are 150 to 170 cm (59 to 67 inches) in length. The smallest mature fish encountered by Kume and Joseph (1969b) was 139 cm (55 inches) long. Nakano and Bayliff (1992), however, observed one swordfish in the 101- to 110-cm (40- to 43-inch) length class which had reached maturity.

An ovary of a swordfish contains hundreds of millions of ova, portions of which mature throughout the life of the fish after it reaches maturity. Uchiyama and Struhsaker (1974) obtained estimates of 2.24 to 9.38 million ova of the most advanced group from fish weighing 83 to 204 kg (183 to 450 pounds). Swordfish probably spawn at frequent intervals, in which case their annual fecundities would be much greater.

According to Sakagawa (1989), female swordfish tend to inhabit higher latitudes than male swordfish, in which case unequal sex ratios should occur frequently. Kume and Joseph (1969b) found the sex ratio to be about equal for fish between 130 and 170 cm (51 and 67 inches) in length in all areas of the eastern Pacific Ocean except that bounded by 10°N, 100°W, 5°S, and the coastline of the Americas. In this area females were more abundant than males, especially during the first quarter. For fish greater than 170 cm in length, the proportion of females to males increased with increasing length. Weber and Goldberg (1986) found that 26 percent of 90 swordfish collected off Southern California were males and the rest were females.

Larvae and juveniles

Illustrations of larval and juvenile swordfish are included in papers by Nakamura *et al.* (1951), Yabe (1951), Arata (1954), Yabe *et al.* (1959), and Markle (1974). Yabe *et al.* (1959), Matsumoto and Kazama (1974), Nishikawa and Ueyanagi (1974), and Nishikawa *et al.* (1978 and 1985) have studied the distribution of swordfish larvae and juveniles. Yabe *et al.* (1959) found larvae in the Pacific Ocean west of 160°W between 25°N and 25°S. Matsumoto and Kazama (1974) recorded 20 larvae and/or juveniles caught between about 23°N and 17°S and between about 145°W and 173°W. Nishikawa and Ueyanagi (1974) and Nishikawa *et al.* (1978 and 1985) recorded many more larvae in the Pacific Ocean, most of them west of 120°W. All of these were found in waters in which the surface temperature exceeded 24°C (75°F). Not surprisingly, larvae and juveniles were captured more frequently north of the equator during the second and third quarters of the year and more frequently south of the equator during the fourth and first quarters of the year. The larvae and juveniles grow and develop rapidly (Dewees, 1992), which reduces the likelihood of mortality due to predation.

Age, growth, and longevity

Information on age and growth, and on mortality (next section), is necessary for employment of age-structured models for assessment of the effects of fishing on a stock of fish.

The age and growth of fish can be estimated by (1) following progressions of modal lengths of fish through time, (2) counting daily or annual rings on hard parts, such as their scales, spines, or otoliths (ear bones), or (3) comparing the lengths of tagged fish at release and recapture. If the first or second methods are used, it is best to verify the estimates by comparing them with those obtained from tag-and-recapture experiments.

There are problems with all of these methods for estimating age and growth. The first method is usable only with younger fish, or it may not be usable at all if reproduction takes place during most or all of the year. The second method is useful for some species, but not so for others, and in many cases it is useful only for younger fish. Large amounts of data are required for the third method, and the lengths of the fish must be accurately measured or estimated at both release and recapture.

According to Dewees (1992), 1-year-old swordfish are 20 to 24 inches (51 to 61 cm) long. Yabe *et al.* (1959) estimated the age and growth of swordfish in the western Pacific Ocean by following progressions of modes of longline-caught fish (Figure 7). Kume and Joseph (1969b), using length-frequency data, estimated the growth rate to be about 38 cm (15 inches) per year for 62- to

165-cm (24- to 65-inch) fish. They observed that females grow more rapidly than do males. Boggs (1989) summarized Yabe *et al.*'s (1959) data and estimates of the age and growth of swordfish of the western Atlantic Ocean obtained from progressions of modes, examination of sections of anal fin spines and of otoliths, and release and recapture data for tagged fish. These results are summarized in Figure 8 and Table 1.

Radtke and Hurley (1983) estimated the ages of the oldest male and female swordfish from the western Atlantic examined by them to be 14 and 32 years, respectively. The corresponding estimates of Wilson and Dean (1983) were 9 years for males and 15 years for females. It is somewhat surprising that females grow more rapidly and live longer and than do males, as the opposite is the case for yellowfin tuna, which Wild (1986) has attributed to the physiological demands that spawning imposes on females.

Mortality

Fish experience two types of mortality, natural mortality and fishing mortality. The natural mortality rates are greatest for the youngest fish, and then decrease as the fish become better able to fend for themselves. In most cases, due to lack of data with which to measure size- or age-specific mortality, it is assumed that the natural mortality rate is constant after the fish become large enough to enter the fishery. The total (natural plus fishing) mortality for a population of fish is estimated from data on the age composition of that population. If the population is unexploited, the natural mortality is the same as the total mortality. If the population is exploited, and age composition data are available for a series of years during which the fishing effort has varied, the total mortality can be separated into its natural and fishing components. If the population is exploited, but adequate data on age composition and fishing effort are not available or the fishing effort has not varied much from year to year, the only recourse is to make a crude estimate of the natural mortality from K, a parameter of the von Bertalanffy growth equation (Table 1), using the equation of Pauly (1980). This is how Boggs (1989) obtained the estimates of natural mortality which are reproduced in Table 1. The estimates are expressed as natural logarithms of their survival rates multiplied by -1, so a coefficient of natural mortality of 0.22 is equivalent to a survival rate of 0.80 and a mortality rate of 0.20, or 20 percent per year. Since the estimate of natural mortality for the Pacific Ocean is based upon an unverified estimate of K obtained from data for younger fish only, not much reliance can be placed on stock assessments which incorporate this estimate.

Predators, competitors, and food

Young swordfish are the prey of larger fishes. Yabe *et al.* (1959) found young swordfish in the stomachs of yellowfin tuna (*Thunnus albacares*), bigeye tuna (*T. obesus*), albacore (*T. alalunga*), black marlin (*Makaira indica*), blue marlin (*M. nigricans*), striped marlin (*Tetrapturus audax*), shortbill spearfish (*T. angustirostris*), sailfish (*Istiophorus platypterus*), dolphinfish (*Coryphaena* spp.), and blue shark (*Prionace glauca*).

Young swordfish presumably compete for food with many other inhabitants of the offshore pelagic environment, and adult swordfish presumably compete for food with tunas, other billfishes, sharks, and dolphins.

Arata (1954) found copepods (small crustaceans) in the stomachs of 7.8- to 9.0-mm swordfish and fish remains in the stomachs of 12.1- to 192.1-mm larval and juvenile swordfish caught in the western Atlantic Ocean. Yabe *et al.* (1959) found small crustaceans (copepods, mysids, phyllopods, and amphipods) in the stomachs of larval swordfish up to 14 mm in length and marlin larvae in the stomachs of early juveniles 45 to 48 mm in length caught in the western Pacific Ocean.

According to Dewees (1992), "swordfish tend to concentrate along food-rich temperature fronts between cold upwelled waters and warmer oceanic water masses." Yabe *et al.* (1959) found that young swordfish about 100 to 250 mm in length found in the stomachs of "tunas and their relatives" and young swordfish about 300 to 500 mm in length caught on longlines had consumed mostly fish and squid. De Sylva (1962) reported that adult swordfish were eating squid (*Dosidicus gigas*) and bonito (*Sarda chiliensis*) off northern Chile. Carey and Robison (1981) stated that swordfish may feed on demersal fish during the daytime and on "squid and other vertically-migrating fauna ... at night" off Baja California, and Holts *et al.* (1994) also mentioned the possibility that swordfish feed on bottom fish.

Scott and Tibbo (1968) found that adult swordfish sampled during March off Virginia and during July-October off New England and Nova Scotia were feeding mainly on mackerel (*Scomber scombrus*), barracudinas (Paralepididae), silver hake (*Merluccius bilinearis*), redfish (*Sebastes marinus*), herring (*Clupea harengus*), and squid (*Illex illecebrosus*). They said that "there is evidence that the swordfish frequently uses its sword to attack and disable even small individual food items before ingesting them." According to Nakamura (1985), "large adults often make feeding trips to the bottom where the temperatures may be 5° to 10°C [41° to 50°F] and feed on demersal fishes (hakes, Bramidae, trichiurids, gempylids, redfish, lanternfishes (Myctophidae), Gonostomatidae, Sternoptychidae, etc.)." Carey (1990) reported on the stomach contents of a swordfish which he had tracked over Georges Bank, off New England. It had eaten butterfish (*Peprilus triacanthus*) and ruffs (*Centrolophus medusophagus*), both midwater species.

<u>Movements</u>

Carey and Robison (1981) reported on the daily activity patterns of swordfish monitored with acoustic telemetry. Two fish tagged near the tip of the Baja California peninsula occupied an inshore bank during the daytime, and moved offshore at night. During the daytime they remained near the bottom at a depth of 91 m (50 fathoms), where they may have been feeding on demersal fish, and at night they stayed close to the surface, where they are believed to have been feeding on squid and other fauna which concentrate near the surface at night. Two others tagged in the same general area, which were in water 400 to 800 m (219 to 437 fathoms) deep when they were tagged, moved westward until they were over a submarine canyon, at which time they changed course and moved southward along the length of the canyon. Fishermen suggested that the first two fish were part of a resident population, while the other two were transients. A swordfish tagged near Cape Hatteras, North Carolina, swam eastward, crossing the Gulf Stream, and entered the Sargasso Sea. This fish also descended to deeper water at sunrise and rose to the surface at sunset. The fish tagged off Baja California reached maximum depths of only about 250 meters (137 fathoms) and spent most of the daylight hours at depths of about 100 meters (55 fathoms), whereas the one tagged off Cape Hatteras spent its second and third days at depths of 400 to 600 meters (219 to 328 fathoms). Carey and Robison believed that the difference was due to the fact that there is an oxygen-minimum layer at about 100 m in the area where the Pacific Ocean experiments took place. They noted that swordfish frequently bask at the surface off Baja California during the daytime, and postulated that they do this to overcome oxygen debts that they accumulate in deeper water.

Holts *et al.* (1994) reported on the daily activities of a swordfish monitored by acoustic telemetry off Southern California. Its horizontal speed ranged from 0.7 to 2.5 knots. The fish spent virtually all of its time below 10 m (5 fathoms) and about 75 percent of its time between 10 and 50 m (5 and 27 fathoms) in or just below the upper mixed layer, where the temperature was about 14°C (57°F). It made two dives to about 300 m (165 fathoms), where the temperature was about 8°C (46°F). Both dives were made during daylight, but during other periods the depths during daylight were only slightly greater than those during darkness. During the second dive the fish was over 14-mile Bank (33°24'N-118°00'W), where "it may have been foraging at or very close to the bottom."

According to Kume and Joseph (1969b), "catch records tend to show a movement of fish from off the tip of Baja California during the spring towards the north during the summer and fall." Bedford and Hagerman report that "a coastwide movement of fish between Baja California and California is evidenced by limited tagging data and Japanese longline hooks in fish taken off southern California. This hypothesis is further supported by the ... [fact that] ... the Japanese longline fishery peaks off Baja California in December and January, followed by the southern California season, running from summer through fall." The fish "move offshore for spawning" (Dewees, 1992). De Sylva (1962) reported an apparent northward migration of swordfish off northern Chile in April and May. Tagging of billfishes with conventional (non-acoustic) tags in the Pacific Ocean has been accomplished principally by recreational fishermen who have used tags furnished by the U.S. National Marine Fisheries Service and equivalent organizations in other countries. The numbers of black marlin and striped marlin released and recaptured have been adequate to permit analyses of the movements of these species (Squire and Nielson, 1983; Squire, 1987), but such has not been the case for swordfish.

In the northwestern Atlantic Ocean at least 2,253 swordfish have been tagged with conventional tags by U.S. observers aboard Japanese longline vessels, U.S. longline fishermen, U.S. NMFS scientists on research cruises, and recreational fishermen, and 109 of these have been returned, all from fish recaptured in the northwestern Atlantic (Farber, 1988). Returns have been received for only 2 of 190 tagged fish released in the northeastern Atlantic; both of these fish were recaptured in the northeastern Atlantic (Miyabe and Rey, 1989).

Size and age distributions of fish caught by the fishery

Data on the length frequencies of longline-caught swordfish in the eastern Pacific Ocean have been published by Shiohama (1969), Kume and Joseph (1969b), Shingu *et al.* (1974), Miyabe and Bayliff (1987), and Nakano and Bayliff (1992). The 1,816 fish of Nakano and Bayliff's study (Figures 9, 11, and 12) ranged from less than 80 to about 280 cm (31 to 110 inches) in length, but most of them were less than 240 cm (94 inches) in length. It would obviously be desirable to show the length frequencies of fish less than 80 cm in length, but this is not possible because the lengths were obtained by converting weights to lengths, and the fish were weighed only to the next-highest 5 kg (11 pounds). Fish less than 80 cm in length frequently have made up a considerable portion of the catch (in numbers of fish, not weight of fish) within various area-time strata, which is not the case for any other species of billfish. No areal or seasonal trends for these occurrences of small fish are evident.

There was considerable variation among areas in the length frequencies (Figure 9). Fish less than 120 cm (47 inches) in length were most important in Areas 1, 4, and 9, and fish greater than 200 cm (79 inches) were most important in Areas 1, 5, and 9. The ranges of length frequencies were least in Areas 2 and 3.

Considerable variation in the occurrence of modes of lengths in different quarters is evident in the data for Areas 3, 4, and 7 (Figure 11). Smaller fish (less than about 100 cm (39 inches) occurred in many area-quarter strata, but temporal progressions of modes within years or among years (Figure 12) cannot be followed. This makes it appear that recruitment to the longline fishery takes place over wide geographic and temporal ranges and over a wide range of sizes of fish.

Data on the length-frequency distributions of swordfish caught off California by drift gillnets (Hanan *et al.*, 1993) are shown in Figures 13 and 14. These lengths are not much different from those shown in Figures 9, 11, and 12, but the incidence of small fish is much less in the gillnet catches.

Data on weight-frequency distributions of swordfish landed at the Honolulu market are given by Royce (1957), and Strasburg (1970) gives data on weight frequencies of swordfish caught in the central Pacific Ocean by commercial and recreational gear. The weight range of Royce's fish was from about 75 to 863 pounds (34 to 391 kg), whereas most of Strasburg's fish weighed less than 60 pounds (27 kg) and none weighed more than 100 pounds (45 kg).

Length-frequency data for swordfish caught by longlines in the north Pacific Ocean (mostly the northwestern Pacific Ocean) are shown in Figure 15. These lengths are not much different from those shown in Figures 9, 11, and 12. The modes were displaced downward during the 1948-1956 period.

Date on the age composition of swordfish caught with longline and recreational gear in the Straits of Florida (Berkeley and Houde, 1983) are shown in Figure 16.

Weight-length relationships

Procedures for assessment of the effects of fishing on a stock of fish usually require estimates of the distributions of the weights of the fish caught by the fishery. It is usually more convenient to measure fish than to weigh them, so scientists calculate weight-length relationships which they then use to estimate the distributions of the weights of the fish caught.

The weight-length relationship of a fish is usually expressed by the equation $W = aL^b$ or $\log W = \log a + b \log L$, where W = weight, L = length, and a and b are constants. Data on the weight-length relationships of swordfish in the Pacific Ocean are given in Table 2.

Behavior

Information on behavior, and on physiology and relationships with the environment (next two sections), is necessary for determining whether the assumptions necessary for application of various procedures for stock assessment are satisfied. Also, such information is often useful for fishermen in determining when, where, and how to fish.

Carey and Robison (1981), as described in the section entitled Movements, reported that swordfish ascend to the surface at sunset and descend to greater depths at sunrise. They noted that swordfish frequently bask at the surface off Baja California during the daytime, and postulated that they do this to overcome oxygen debts that they accumulate in deeper water. The depths inhabited by a swordfish tracked by Holts *et al.* (1994) were only slightly greater during daylight than during darkness, however, except during two dives to about 300 m (165 fathoms) which the fish made during daylight.

Carey and Robison (1981) described the movements of two swordfish which were tagged with acoustic tags in water 400 to 800 m (219 to 437 fathoms) deep. They moved westward until they were over a submarine canyon, at which time they changed course and moved southward along the length of the canyon. They said that "commercial fishermen feel that the submarine canyons and hummocky areas along the continental shelf are good places to find swordfish... Currents flowing over rough bottom produce eddies and flow separation features which may extend to the surface... The concentration of organisms as a result of turbulence generated by the rough bottom may be the feature that attracts swordfish to the waters over submarine canyons."

As described in the section entitled Predators, competitors, and food, Scott and Tibbo (1968) reported that "there is evidence that the swordfish frequently uses its sword to attack and disable even small individual food items before ingesting them."

According to Palko *et al.* (1981), "swordfish have a reputation for being a pugnacious fish. There are records of attacks on boats ..., whales ..., and even submersibles." Davenport *et al.* (1993) reported that "swordfish (and marlins) attack objects of various kinds, dead or alive, swimming, drifting or power-driven," and stated that there is "evidence that such 'attacks' can be, and often are, direct and intentional."

Physiology

Swordfish are "stalkers and sprinters," and "do not maintain the high level of continuous activity that we associate with warm fishes with elevated body temperatures such as the tunas" (Carey 1982).

Swordfish are exposed to drastic changes in ambient temperature as they rapidly ascend or descend in the water column. Carey (1982) reported that there is tissue associated with one of the eye muscles which warms the brain and eyes. This is necessary, as "the large and abrupt temperature changes that swordfish experience daily would chill the brain and affect central nervous system processes."

Swordfish do not have the countercurrent heat exchangers which enable tunas to regulate their body temperatures, but Carey (1990) reported that they are able to accomplish this by other means. He described the muscle temperatures of three swordfish tagged with acoustic tags in the western Atlantic Ocean. He said the "the muscle cooled slowly when they went into cold water, but re-warmed rapidly when they returned to warm surface water. In the best example, there was a 12-fold difference between the rates of warming and cooling." This is achieved by increasing the rate of blood flow in warm water and decreasing it in cold water and by changing the amount of blood supplied to the red muscle.

In 1970 it was discovered that some tunas and billfishes, including swordfish, have total mercury levels exceeding 0.5 part per million (ppm), the interim guideline set by the U.S. Food and Drug Administration (FDA) as the maximum concentration for fish destined for human consumption (Shomura and Craig, 1974). "In 1971, the U.S. strictly enforced a regulation on the permissible level (0.5 ppm) of mercury in imported fish" (Sakagawa, 1989). The 1970 findings adversely affected the market for swordfish during the early 1970s, but since then it has recovered (Lipton, 1986). "In 1979 the mercury regulation was revised to allow a higher level of 1.0 ppm" (Sakagawa, 1989).

"When the FDA introduced the safety guidelines, which eventually were instrumental in removing nearly all swordfish and substantial quantities of canned tuna from the market, it acted essentially under the assumption that the fish product was 'adulterated' by an 'added substance.'" However, "there is no evidence that the mercury in tunas, swordfish, marlins, and some other of the high-seas pelagic fishes can be attributed to contamination resulting from human activities" Peterson *et al.*, 1973).

<u>Relationships with the environment</u>

Swordfish are most abundant in "zones of high production of food organisms and where major ocean currents meet" (Sakagawa, 1989).

"In the Pacific Ocean, there are five frontal zones ... where swordfish are found in fishable concentrations ...: (1) in the northwestern Pacific ..., where the warm Kuroshio Current meets the coastal waters of Taiwan and Japan, and where the Kuroshio Extension Current meets the Oyashio Current to the north; (2) off southeastern Australia ..., where the warm East Australian Current meets intrusions of the cold Southern West Wind Drift Current; (3) off northern New Zealand ..., where the warm South Equatorial Current intersects with intrusions of the cold Southern West Wind Drift Current; (4) in the eastern tropical Pacific ..., where the warm Equatorial Counter Current intersects with the colder Peru Current; and (5) along Baja California, Mexico, and California, U.S.A. ..., where the cool offshore California Current intersects with intrusions along the coast of warmer water from the south" (Sakagawa, 1989). These are shown in Figure 17.

Nakamura (1985) stated that adult swordfish tolerate temperatures of 5° to 27°C (41° to 81°F), and that their optimum temperature range in the northwestern Pacific Ocean is 18° to 22°C (64° to 72°F). As mentioned in the section entitled <u>Movements</u>, they avoid water with low concentrations of dissolved oxygen. As mentioned in the section entitled <u>Larvae and juveniles</u>, swordfish larvae have been found only at temperatures exceeding 24°C (75°F).

The attraction of swordfish to waters over submarine canyons is discussed in the section entitled <u>Behavior</u>.

De Sylva (1962) reported that during April and May of 1956, in the vicinity of Iquique, Chile, there was "an influx of a thin warm-water layer from the north containing dinoflagellate populations; an admixture of nutrients, derived at least in part from upwelled coastal water from the south, caused growth of the dinoflagellate population, which resulted in a concentration of the zooplankton crop. Subsequently, anchovies concentrated and fed in these plankton patches and they in turn attracted squid and bonito. Swordfish and striped marlin moved into this region apparently attracted by the concentrations of squids as well as of anchovies. However, they were also probably affected by decreasing water temperatures, as this concentration seemed to be part of a northerly migration toward the onset of winter, following the northward-retreating warm front. It was reported that by late May, most swordfish were being taken well north of the Iquique area toward Arica. This exodus may have been further prompted by the growth in area (to 60 miles offshore) of reported red-water conditions unfavorable to swordfish."

FISHERIES

Recreational

Recreational fisheries for swordfish are undertaken by only a few dedicated fishermen, and the catches of these fisheries are insignificant contributors to the total swordfish catch. In fact, there are "virtually no recreational fisheries for swordfish anymore" (Leech, 1994).

The recreational swordfish fishery, as currently practiced, developed off Florida during the late 1970s. Interest in the recreational possibilities presented by swordfish was spurred by Cuban fishermen fishing from small boats at night with small longlines and lighted hooks. A single instance of landings of two fish in the 125- to 140-kg (276- to 309-pound) range brought an immediate response from Florida billfish fishermen, who saw the swordfish as a new challenge. This led to a series of swordfish tournaments off Florida during the 1977-1983 period, which saw participation ranging from about 10 to 50 boats with 13 to 100 anglers. The catch rates dropped from 0.22 to 0.45 fish per boat in the early tournaments to 0.00 to 0.09 fish in the later ones.

The recreational swordfish fishery in California began earlier than that in the Atlantic, as an offshoot of the harpoon fishery (Bedford and Hagerman, 1983). Prior to 1971, when the California Department of Fish and Game restricted harpoons to use in commercial fisheries, recreational fishermen could use either harpoon or rod-and-reel gear to catch swordfish. This fishery, which occurred during daylight hours, was directed at swordfish basking at or near the surface. Regardless of the method of capture, this fishery has been an insignificant contributor to the catch of Pacific swordfish: Bedford and Hagerman (1983) reported an average annual catch of 29 swordfish by California rod-and-reel fishermen during the 1967-1980 period. The peak catch was 130 fish taken in 1978. At present, recreational fisheries for swordfish in the Pacific, as well as around the world, are virtually non-existent, with only occasional fishing directed at swordfish and catches of this species (Sakagawa, 1989; Hanan *et al.*, 1993; Leech, 1994). The current top recreational swordfish fisherman has a lifetime catch of 48 fish.

Commercial

Sakagawa (1989) has reviewed the geographical distribution of the centers of the swordfish fisheries of the Pacific Ocean. The primary ocean zones with fish concentrations high enough to support commercial fisheries are shown in Figure 17. These regions are typified by convergence of warm and cold currents and relatively high primary production, which may lead to trophic regimes capable of supporting large pelagic predators, such as swordfish.

The principal commercial swordfish harvests are made by longline, gillnet and, historically, harpoon fisheries. Descriptions of these gears are found in Bedford and Hagerman (1983), Kawamoto *et al.* (1989), Sakagawa (1989), Nakano and Bayliff (1992), Boggs and Ito (1993), and Hanan *et al.* (1993). Data compiled by the Food and Agriculture Organization of the United Nations (FAO) (Anonymous, 1993a; Grainger, 1994) show that collectively these fisheries have produced catches of Pacific swordfish increasing from about 18,600 metric tons (mt) in 1982 to an estimated 30,600 mt in 1992. (A metric ton is equal to 1.1 short tons.) At the same time, the world catches of swordfish increased from about 44,000 mt in 1982 to about 73,000 mt during the early 1990s, with a peak catch of 81,000 mt in 1988. Of the 142,200 mt of Pacific swordfish harvested during the 1988-1992 period, Japanese fisheries accounted for the majority of the catch (42 percent), with significant harvests also made by vessels of Chile (20 percent), the Philippines (13 percent), the United States (10 percent), and the Republic of China (9 percent) (Table 3).

<u>Japan</u>

The Japanese tuna longline fishery has accounted for 73 to 93 percent of that nation's annual swordfish catch since 1975 (Figure 18). The principal target species of this Pacific-wide fishery was, prior to the mid-1970s, yellowfin tuna. Since then, deep longline gear has been increasingly used in the Pacific to catch highly-valued, deeper-swimming, bigeye tuna (Nakano and Bayliff, 1992). Most longline sets are made early in the day, so that the gear fishes during the daylight hours, with retrieval occurring at or near dusk. Sakagawa (1989) hypothesizes that the swordfish caught by this gear are taken while the gear is being retrieved during periods of darkness.

During the 1952-1962 period, components of the Japanese longline fleet directed their effort at swordfish by fishing at night with squid, rather than saury or other baitfish, for bait (Bartoo and Coan, 1989). This practice takes advantage of the fact that swordfish tend to rise to the surface during the night and sound during the day (Carey and Robison, 1981). This type of fishing was first employed in the eastern Pacific in 1963 (Kume and Joseph, 1969a). It was possible to distinguish effort directed at swordfish from other effort with records on the type of bait used. During the late 1960s, "however, this distinction [was] clouded by the increasing use of squid for bait in ordinary (daytime) sets" (Shingu *et al.*, 1974).

Japanese longline fishing effort in the Pacific ranged from about 275 to 300 million hooks during the 1970-1975 period, and from about 325 to 375 million hooks during the 1976-1987 period (Nakano and Bayliff, 1992). They report that the effort in the eastern Pacific was about 70 to 100 million hooks during 1970-1975, about 100 to 140 million hooks during 1976-1985, and about 190 million hooks in 1987 (Figure 19).

Lesser amounts of swordfish are taken by drift gillnet and harpoon fisheries (Ueyanagi *et al.*, 1989). The gillnet fishery, which has existed since the 1800s, was initially conducted in nearshore waters, which yield peak catches during July to October (Sakagawa, 1989). With the development of drift gillnet technology, the fishery expanded to include more distant waters. Drift gillnet vessels participate in various fisheries, and, though they directed their effort at billfish during the early 1970s, they later shifted to tunas, particularly albacore. The swordfish catch by Japanese drift gillnet vessels has ranged from less than 200 mt in 1972 to 3,600 mt in 1976. Since then the annual swordfish catch by Japanese drift gillnet vessels has dropped to about 1,000 to 2,000 mt per year (Ueyanagi *et al.*, 1989; Nakano, 1994) (Figure 18). During the period leading up to the 1970s, Japanese harpoon fisheries operating in nearshore waters annually harvested about 1,000 to 2,000 mt of swordfish. When Japanese drift gillnet fishermen began directing their effort toward billfish, the catch by the Japanese harpoon fisheries dropped to several hundred tons of swordfish annually (Figure 18). Sakagawa (1984) attributed this decrease to competition with the gillnet fishery "for available swordfish in coastal waters."

Chile

Ponce Martínez and Bustos (1991) have described the increasing importance of Pacific swordfish to Chilean artisanal fisheries and international commerce. With developing markets for fresh and frozen swordfish in the United States in the 1980s, the annual swordfish catches increased from about 200 to 300 mt prior to 1985 to 800 mt in 1986 and then to a peak of 7,000 mt in 1991 (Table 3). The 1992 catch was 6,400 mt. The Chilean artisanal fishery for swordfish operates 15 to 150 nm off northern and central Chile. More than 90 percent of the vessels are less than 18 m (60 feet) in length (Table 4) and fish with drift gillnets. A small part of this fleet continues as a traditional harpoon fishery. As vessel size has increased, an increasing proportion of the fleet has been licensed for and has fished with both drift gillnet and longline gear. Data presented by Ponce Martínez and Bustos (1991) indicate that most of the Chilean swordfish catch is made during January to June, with the peak occurring from March to May. Because of low catch rates, the fishermen switch to other species by July or August (Lizama F. and Naranjo G., 1989).

Philippines

In the Philippine fisheries, swordfish are caught principally by handline and gillnet gear, with longline and other gears contributing lesser amounts to the catch (Anonymous 1994a). The Philippines government classifies the fisheries of that country as municipal or commercial, based on vessel tonnages: vessels of less than three gross tons are classified as municipal (Barut and Arce 1991). During 1981-1989, the municipal fisheries landed over 92 percent of the swordfish catch of the Philippines, and during 1981-1987 (the period for which data are available) handline and gillnet fisheries accounted for an average of 85 percent of the catch. During 1980-1992 the annual catch of swordfish by Philippine fisheries has averaged about 2,900 mt, ranging from 1,720 mt in 1980 to 4,300 mt in 1992 (Figure 20).

United States

The principal U.S. Pacific swordfish fisheries are the drift gillnet fishery and the longline fishery.

Prior to the late 1970s, the only significant U.S. swordfish fishery was the harpoon fishery conducted off Southern California during the late summer and fall. Bedford and Hagerman (1983) describe the history of this fishery, which was operating by the early 1900s and which peaked in importance and total catch during the 1970s. They note that the long-term average annual catch in the California harpoon fishery during the 1908-1980 period was about 400 mt, or 3 percent of the average annual Pacific swordfish catch. Since the 1978 peak catch of about 1,500 mt, the annual catch in this fishery has dropped to about 100 to 200 mt.

The drift gillnet fishery, which is conducted off Southern California in the same waters and during the same season as historically fished by the harpoon fishery, has dominated the U.S. mainland swordfish catch since 1981, when its catch first exceeded that of the California harpoon fishery (Figure 21). Hanan *et al.* (1993) describe the increasing significance of swordfish in the catches of this fishery, which was originally directed at sharks, but which is now directed seasonally at swordfish. During this period the average mesh size increased from 13 to 14 inches (33 to 36 cm) during 1981-1983 to 18 to 19 inches (46 to 48 cm) during 1986-1991 (Hanan *et al.*, 1993: Figure 6). During the first few years following this shift in fishing strategy, the annual swordfish catch by drift gillnets increased to a peak of about 1,500 mt in 1984 and 1985. Subsequently the catches decreased to about 700 mt in 1990 and 1991, but then increased to about 1,100 mt per year in 1992 and 1993. Approximately 80 percent of the drift gillnet catch of swordfish is made during September through December.

The most recent significant changes in the U.S. fishery for Pacific swordfish have been in the longline fishery operating from Hawaii and, more recently, Southern California. Prior to 1989, swordfish were an incidental catch of this fishery, which was directed at tunas and took place primarily within the U.S. Exclusive Economic Zone (EEZ) around Hawaii (Kawamoto *et al.*, 1989). Swordfish comprised only about 1 percent of the catch (Yoshida, 1974), with an annual harvest of less than 120 fish (Uchiyama and Shomura, 1974). This situation continued until the early 1990s. At that time, U.S. vessels from the Atlantic coast, using fishing strategies developed for fishing Atlantic swordfish, including night sets of shallow gear with lighted hooks, entered the Hawaii-based fleet (Ito, 1992). The present longline fishery exhibits a complexity resulting from vessels fishing for swordfish, tunas, or a mixture of species (Dollar, 1992; Ito, 1992). As the fishing effort has increased with the addition of vessels (Figure 22), there has also been an expansion of the fishery to include significant effort in international waters outside the U.S. EEZ around Hawaii. The catch by the longline fleet based in Hawaii increased ten-fold, from about 200 mt in 1989 to about 1,900 mt in 1990, and then doubled to about 4,500 mt and 4,950 mt in 1991 and 1992, respectively. These catches are made mostly during the January-June period: of the swordfish caught in 1991, 28 percent were taken during the first quarter and 41 percent during the second (Dollar, 1992).

In late 1992, longline vessels which had been fishing in the Atlantic Ocean and the Gulf of Mexico began operating in the Pacific Ocean from Southern California ports. These vessels are reportedly fishing primarily in international waters. Only two or three of these vessels were fishing in 1992, but they have continued to operate, with increasing effort, and by July 1994 the number of vessels had increased to at least 23. Several vessels have fished throughout the year to attempt to determine how best to operate, and other vessels have fished only when good fishing has been reported. As is the case for the Hawaii-based fleet, these vessels also fish for tunas, and direct most of their effort toward swordfish when swordfish are most abundant or easiest to catch. The catch of swordfish has been averaging about 2.5 mt per trip, with some trips producing significantly more than that. The total catches of swordfish were reported to be about 50 to 60 mt 1993 and about 150 mt during the first seven months of 1994. It is expected that the catches will increase as the fishermen gain experience.

Mexico

While the Mexican fishery accounted for only 4 percent of the 1988-1992 swordfish catch in the Pacific Ocean, it is described here because it is conducted adjacent to waters in which part of the U.S. fishery is conducted, and it is likely that both fisheries capture fish from the same component of the Pacific swordfish population (Bedford and Hagerman, 1983). The Mexican swordfish fishery had its inception following Mexico's adoption of a 200-nm EEZ and restriction of foreign fishing operations within that zone. Squire and Muhlia-Melo (1993) noted that, prior to this time, high catches of billfish, including swordfish, were taken by the longline fisheries of distant-water fishing nations, such as Japan, the Republic of China, and the Republic of Korea, in what is now Mexico's 200-nm EEZ. During the 1980-1989 period Mexico authorized joint-venture longline fisheries operating under the Mexican flag. During the early 1980s the effort exerted by this fishery was low, but by the end of the decade about 10 to 15 vessels were participating in the fishery on an annual basis. Fishing effort (hooks fished) varied widely during the period of this fishery, ranging from a low of about 260 thousand hooks in 1984 to a high of about 3.8 million hooks in 1988 (Table 5). The total swordfish catch made during the period this fishery existed was about 1,800 mt, with annual catches ranging from about 5 mt in 1984 to 470 mt in 1981 (Table 5).

Since the elimination of the joint venture-longline fisheries for billfish, a drift gillnet fishery for billfish within the Mexican EEZ has developed. It is estimated that by 1990 about 25 vessels from 16 companies were operating and that these numbers nearly doubled to about 44 vessels from 37 companies by 1992. The swordfish catch by these vessels was about 790 mt in 1990, 1,040 mt in 1991, 700 mt in 1992, and 500 mt in 1993. Squire and Muhlia-Melo (1993), however, reported that in 1992, 27 permits had been issued for this fishery and 24 boats were operating. They estimated that 1991 catch by this fishery was about 900 to 1,400 mt. The peak catches are made during the late fall and winter.

Republic of China

The high-seas and coastal longline fisheries and the harpoon fishery of the Republic of China (ROC) are described by Sakagawa (1989) and Ueyanagi *et al.* (1989). Swordfish is an incidental catch of ROC fisheries directed at tunas and other billfishes. Of these fisheries, the least important contributor to Pacific swordfish catch is the high-seas longline fishery, which principally operates in the southern hemisphere and is directed primarily at albacore. It should be noted, however, that prior to 1982 this fishery harvested up to 27 percent of the catch of Pacific swordfish by vessels of the ROC. During the 1987-1991 period, high-seas longlines fished a total of 162 million hooks in the Pacific, with a low of about 17.5 million in 1987 and a high of about 39.6 million in 1991. The total swordfish catch by this gear during the period was about 306 mt, with annual catches ranging from about 28 mt in 1987 to about 93 mt in 1990 (Anonymous, 1992a). Recent effort and swordfish catch statistics for the coastal longline and the harpoon fishery are not available, but by subtracting the high-seas longline catch from FAO total catch statistics, it is possible to estimate the combined total catch of these two gear types since 1986. Available data for the 1972 through 1986 period (Sakagawa, 1989; Anonymous, 1992a) show that the coastal longline fishery once accounted for an average of 75 percent of the catch. Since 1986, the coastal longline and harpoon fisheries have accounted for over 95 percent of catch of Pacific swordfish by vessels of the ROC (Figure 23).

Other nations

Small contributions to Pacific swordfish annual catch are currently made by various other fisheries. On average, these fisheries contribute less that 500 mt. Among these fisheries are those of Ecuador (200 to 300 mt), the Republic of Korea (100 to 150 mt), and Colombia, Costa Rica, French Polynesia, and Peru (5 to 15 mt each).

MARKETING AND UTILIZATION

The swordfish market is global in scope, and as a result it is difficult to document the exact position of Pacific swordfish within the market with readily-available trade statistics and information. Sakagawa (1989) has summarized the development of the global swordfish markets through 1986. In 1986, the principal markets for swordfish were western Europe, Japan, and the United States. At that time, the United States was consuming about 22 percent of the world swordfish supply, with about half of this consumption being met by domestic production and half by imports.

The growing U.S. demand for swordfish projected by Lipton (1986) was met during the late 1980s by increasing domestic production of Atlantic swordfish and increasing imports of swordfish. The domestic production of Atlantic swordfish increased from about 3,000 mt in 1986 and 1987 to a peak of about 6,600 mt in 1990, and the imports exceeded 7,400 mt in 1990 (Figure 24). The percentage of the U.S. swordfish consumption which was imported ranged from 38 to 51 percent, and averaged 44 percent, during the 1985-1992 period. Since 1990, the annual U.S. consumption of swordfish has averaged about 16,800 mt. It is interesting to note that during the 1990-1992 period the decreased catches by U.S. vessels in the Atlantic (6,600 mt in 1990 and 3,300 mt in 1992) were almost exactly offset by increased catches by U.S. vessels in the Pacific (3,100 mt in 1990 and 6,600 mt in 1992).

The principal exporters of Pacific swordfish to the United States since 1985 have been Chile and the Republic of China. In 1986-1987 these two nations provided about 40 percent of the U.S. imports of swordfish and by 1989-1990 this had risen to about 70 percent. Since 1990, Chile has provided over 90 percent of the imports of swordfish to the United States. The United States has utilized an average of 18 percent of the annual global swordfish production during 1985-1992, and about 42 percent of the Pacific swordfish production during 1990-1992.

FISHING REGULATIONS

The following summary of regulations for fishing for swordfish was compiled from various sources. Because it is only a summary, persons wishing to participate in one or more of the fisheries for swordfish should obtain detailed information on regulations from the agencies which have jurisdiction in the areas in which they plan to fish.

United States

California Department of Fish and Game (CDFG)

The information is this section was obtained from CDFG Commercial Fishing Provisions, 94-18 (Swordfish-Harpoon) and 94-03 (Drift Gill Net Shark/Swordfish), and California Sport Fishing Regulations (March 1, 1994-February 29, 1996).

Commercial fishery

Harpoon fishery

The owner or operator of a vessel taking swordfish for commercial purposes must have a swordfish permit, which costs $330.00 per year. In addition, all crew members must have commercial fishing licenses. Swordfish may be taken only by harpooning or hand-lining. Assistance from aircraft in locating swordfish is permitted. Records of fishing activities must be kept for use by the CDFG.

Drift gillnet fishery

The owner or operator of a vessel participating in the drift gillnet fishery for sharks and swordfish must have a drift gillnet shark and swordfish permit and a trammel net permit, each of which costs $330.00 per year. Each permittee is required to maintain and submit a record (logbook) of all gillnet fishing activities. In addition, all crew members must have commercial fishing licenses. Drift gillnets may not exceed 6,000 feet (1,829 m) in length, and the minimum stretched mesh size is 14 inches (35 cm).

The following regulations are effective only until January 1, 1995, at which time amended regulations will take effect. Fishing is not permitted within 12 nautical miles (nm) of the mainland south of Point Arguello or east of an imaginary line between Point Reyes and the Farallon Islands at the mouth of San Francisco Bay. In addition, the following seasonal restrictions apply: December 15-January 31, fishing not permitted within 25 nm of the mainland; February 1-April 30, fishing not permitted at all; May 1-August 14, fishing not permitted within 75 nm of the mainland. Also, there are numerous areas off Southern California in which fishing with drift gillnets is not permitted. If a marlin is caught, the operator must not remove it from the boat, and he must immediately notify the CDFG, which will remove it for distribution to public institutions.

Recreational fishery

The possession limit for swordfish is two fish.

U. S. National Marine Fisheries Service (NMFS)

Pacific Ocean

The information is this section was obtained from Part 685--Pelagic Fisheries of the Western Pacific Ocean, dated June 3, 1994, furnished by the U.S. NMFS, Terminal Island, California. The U.S. NMFS regulations for the Pacific Ocean which affect swordfish, except for the Marine Mammal Protection Act discussed below, apply only to the U.S. Exclusive Economic Zone (EEZ) of the western Pacific Ocean (Hawaii, American Samoa, Guam, and other territories under U.S. administration).

Longline fishery

The owner or operator of a vessel participating in the longline fishery for tunas and billfishes must have a "Hawaii longline limited entry permit" or a "longline general permit." In addition, "experimental fishing permits," which allow the permit holders to take limited amounts of species which are otherwise protected, are also available. Longline fishing is prohibited in waters close to the principal Hawaiian Islands (Figure 25). Records of fishing activities must be kept for use by the NMFS. These records must include, among other things, information on (1) fishing effort, (2) catches of unprotected species, including releases and discards, and (3) catches of protected species which are released or discarded and sightings of protected species, other than birds. "Protected species" are animals "protected by the Marine Mammal Protection Act of 1972, as amended, listed under the Endangered Species Act of 1973, as amended, or subject to the Migratory Bird Treaty Act, as amended." The vessels must carry NMFS observers when requested to do so. An electronic system for monitoring the positions of all vessels at all times is being prepared.

Drift gillnet fishery

Fishing with drift gillnets is prohibited in the U.S. EEZ of the western Pacific Ocean.

Amendments to the Marine Marine Mammal Protection Act of 1972 (U.S. Public Law 92-522) adopted in 1988 (U.S. Public Law 100-711) require vessel "owners in the drift gill net fishery [of California], which was considered likely to have marine mammal interactions, to obtain and display Federal MMPA exemption permits, report marine mammal kills, and allow Federal observers to board and observe fishing operations" (Hanan *et al.*, 1992).

Atlantic Ocean

The information is this section was obtained from Part 630--Atlantic Swordfish Fishery, dated June 23, 1993, furnished by the U.S. NMFS, Silver Spring, Maryland. The regulations are the result of recommendations based on the research described in the section of this report entitled STOCK ASSESSMENT.

Recreational fishery

Permits are not required for persons fishing for swordfish with rod-and-reel gear. Swordfish caught by recreational fishermen may not be sold.

Commercial fishery

The owner or operator of a vessel registered in the United States which catches swordfish commercially in the Atlantic Ocean north of 5°N must have a permit. This regulation applies to the owners or operators of commercial vessels which catch swordfish incidentally when fishing for other species, even if the swordfish are not retained. It does not apply, however, to owners or operators of vessels fishing "shoreward of the outer boundary of the EEZ around Puerto Rico and the Virgin Islands with only handline gear aboard."

The following quotas for swordfish applied to U.S. fishermen during 1994:

- directed fishery - 7,000,000 pounds (dressed weight)
  - drift gillnet fishery - 69,286 pounds during the January 1-June 30 period and the same amount during the July 1-December 31 period
  - longline and harpoon fisheries - 3,430,714 pounds during the January 1-June 30 period and the same amount during the July 1-December 31 period
- incidental catch - 560,000 pounds (dressed weight)

When a quota is reached a closure goes into effect for the gear in question, and additional catches of swordfish by that gear are counted as incidental catches. During a closure the limit on incidental catches of swordfish is two fish per vessel per trip.

It is unlawful to fish for swordfish with a drift gillnet 2.5 km (1,367 fathoms) or longer.

The minimum legal size for swordfish is 31 inches (78.7 cm), measured from the cleithrum (collarbone) to the anterior portion of the caudal keel (the bony structures on the sides of the fish just anterior to the tail). However, up to 15 percent, by number, of the swordfish landed from a trip may be smaller than the legal limit.

Records of fishing activities must be kept for use by the NMFS. These records must include, among other things, information on fishing effort and catches of other species which are retained. The vessels must carry NMFS observers when requested to do so.

Vessels fishing with gear other than drift gillnets, longlines, or harpoons may not direct their efforts toward catching swordfish. The limit for possession of swordfish by such vessels is five fish for squid trawlers and two fish for all other vessels.

Hawaii Division of Aquatic Resources

The information in this section was obtained from Hawaii Fishing Regulations, dated July 1994, published by the Division of Aquatic Resources, Department of Land and Natural Resources, of Hawaii. It is unlawful to engage in longline or drift gillnet fishing within state waters. State waters include waters within 3 miles of the Hawaiian Islands, including those which extend westward from Kauai to about 179°E.

Mexico

The information in this section was obtained from the Diario Oficial of Mexico of August 28, 1987. Commercial fishing for billfishes is not permitted within 50 nm of the Pacific coast of Mexico nor within two areas which are more than 50 nm offshore (Figure 26). (Parts of the law are written as if longlines take only marlins and drift gillnets take only swordfish, whereas actually large amounts of tunas and smaller amounts of other species, including swordfish, are taken by longlines, and sharks and other species are taken by drift gillnets.)

Commercial fishery

A fishery directed at marlins and sailfish may be conducted with longlines. Longline fishing may be conducted with a maximum of 2,000 hooks per boat, and the maximum annual effort permitted for the entire fleet is 6,250,000 hooks. A fishery directed at swordfish may be conducted only with drift gillnets.

Licenses are required for fishing for billfishes, and these are issued only to Mexican citizens and Mexican business enterprises. A license is issued only upon presentation of a plan which estimates the annual catches by the license holder and describes how the fish are to be marketed. All fish caught, especially sharks, must be landed for utilization. The license holders must make reports on their activities to the Mexican government, including daily radio reports of the positions of the vessels and annual reports of the amounts of fish caught and the amounts sold to specific buyers. Scientists and observers designated by the Secretaría de Pesca must be permitted aboard the vessels. Transshipment of fish is not permitted without permission from the Secretaría de Pesca.

Recreational fishery

The regulations empower the Secretaría de Pesca (1) to establish, in consultation with the Secretaría de Desarrollo Urbano y Ecología, areal and seasonal closures, and (2) to establish, on the basis of studies carried out by the Instituto Nacional de Pesca, limitations on the amounts of fish caught or the numbers of individuals fishing and the amounts of fishing gear permitted.

Licenses are issued to persons intending to fish for billfishes in their own boats or intending to charter their own boats to recreational fishermen (who need not be Mexican citizens). The owners of charter boats must make reports of their activities to the Mexican government.

Chile

The information in this section was obtained from Ponce Martínez and Bustos R. (1991) and Capurro (1993). Vessels more than 28 m (92 feet) in length may not fish within 120 nm of the coast.

Drift gillnet fishery

The maximum length permitted for drift gillnets is 2,470 m (1,350 fathoms). The maximum surface area permitted is 83,605 square meters (25,000 square fathoms) for vessels 28 m or less in length and 125,633 square meters

(37,500 square fathoms) for vessels more than 28 m in length. (The maximum depths permitted for 2,470-m nets used within 120 nm of the coast and more than 120 nm of the coast would be 33.8 and 50.8 m (18.5 and 27.8 fathoms), respectively.)

Longline fishery

The maximum numbers of hooks which may be deployed by vessels up to 28 m in length and vessels more than 28 m in length are 1,200 and 2,000, respectively.

STOCK ASSESSMENT

Fish are renewable resources, and their abundance is affected by natural factors and human activities. Many species support major commercial and/or recreational harvests. The rates at which they are harvested affects their abundance, and consequently the rates at which they replace themselves. It is frequently possible to increase or decrease the level of abundance of a population of fish by controlling the rates at which it is harvested. Theoretically, if it were not for the "noise" introduced by natural variability, it would be possible to sustain a stock of fish at any level (provided this did not exceed the capacity of the environment), and thereby to sustain the harvest at a desired level. In an historical perspective, the level of sustainable exploitation sought for most species or stocks has been the maximum harvest, in terms of weight, that the species or stock is capable of supporting on a continuous basis, taking into account the effect of the environment on the abundance and productivity of that species or stock. This is generally termed the maximum sustainable yield (MSY). Economists have long argued that MSY is undesirable as a management objective from an economic point of view because the potential "rents" are dissipated. They note that the rent from a resource can be maximized by maintaining the level of investment or harvesting costs below the point at which the change in the rate of "marginal returns" is zero.

There has been a tendency, in recent years, to regard optimum yield (OY) as a management objective. OY is a general term which can be any yield between zero, as is the case for the great whales, and some level greater than the MSY, as is the case for some fisheries in developing countries for which the objective is to maximize employment of fishermen. In the Magnuson Fisheries Conservation and Management Act (MFCMA) of 1976, "optimum yield" means the amount of fish:

"a) that will provide the greatest overall benefit to the Nation, with particular reference to food production and recreational opportunities; and
b) that is prescribed as such on the basis of the maximum sustainable yield, as modified by any relevant economic, social or ecological factor."

The definition is so broad and vague that it permits levels of harvest to be negotiated and set between zero and levels greater than the MSY. Although not called for in the MFCMA, prudence would demand that the OY never be set at a level that would reduce the abundance of the fish to below the level at which the stock could sustain maximum yields. Furthermore, if a stock of fish is below the MSY level, the level of harvest should be set below the current replacement level to allow restoring of the stock to the MSY level.

Regardless of what level of harvest is set as a management goal, information must be collected to assess the abundance of the species or stock in question. Such information would include data on catch and effort, reproduction, growth, mortality, and movements of the fish. Various models which use that information to assess the impact of fishing on the abundance of the species or stock are discussed briefly here.

Production models

Production models, which make use of data for the stock as a whole, rather than for individual fish, are fairly simple to use, as they require only data on catch and fishing effort. When a stock of fish has not been exposed to a fishery it is at the maximum size that the environment permits. Lack of food, lack of suitable living space, presence of predators, *etc.*, prevent the population from growing beyond that maximum. When, over the long run, gains to the population by recruitment and growth are balanced by losses due to natural mortality the stock is said to be in equilibrium. There may be years of especially favorable environmental conditions when the population is greater than average and years of especially poor environmental conditions when the population is less than average, but these can often be ignored when looking at long-term trends.

If one or more fishing boats began to fish on the stock the catch per unit of effort (catch per day of searching, for example), which is assumed to be proportional to the size of the population, would initially be relatively high, as the population would be at its maximum. The gains to the population would still be due to recruitment and growth, but the losses to the population would be due not only to natural mortality, but also to fishing mortality. Thus the population would be reduced. In response to the reduction in population the rates of recruitment, growth, and/or natural mortality would change, the gains from the first two exceeding the losses from the third. If the boats stopped fishing this net gain would cause the population to increase gradually to its original size. As the population approached that size the rates of recruitment, growth, and/or natural mortality would gradually approach their previous levels until they were the same as before the fishery began. The population would thus be restored to equilibrium at its maximum size. If the boats continued to fish at the same rate, however, the population would eventually come into equilibrium with different rates of recruitment, growth, and/or natural mortality and a population size which was less than the original population size. The catch per unit of effort (CPUE) would still be proportional to the population size. If there were only a few boats the population size would be only slightly reduced and the CPUE would be relatively high, but if there were many boats the population would be considerably reduced and the CPUE would be much lower.

The total catch would be the product of the CPUE and the total effort. If the fishing effort were relatively low, modest increases in effort would more than offset the corresponding decreases in CPUE, resulting in greater catches, but at greater levels of effort such would not be the case. At some intermediate level of effort the product would be at its maximum. If the objective of management is to obtain the MSY the fishing effort should be maintained at that level. If the object is maximum economic yield (MEY) the effort should be somewhat less (assuming that the price remains constant), and if the object is maximum employment of fishermen the effort should be somewhat greater. If the effort is less than whatever optimum is selected, the stock is said to be underfished, and if the effort is greater than that optimum, the stock is said to be overfished.

Figure 27 is a graphical representation of a production model, showing both MSY and MEY.

It is easiest to consider the interrelationships of effort, catch, and CPUE at equilibrium conditions, but it must be recognized that such conditions are rarely present. For example, if the population is at equilibrium near its maximum and the effort is suddenly increased the CPUE will gradually decrease for a period before a new equilibrium point with a lesser CPUE is reached. The catches will be greater during the period of transition than at the new point of equilibrium. Likewise, if the population is at equilibrium at a low level and the effort is suddenly decreased the CPUE will gradually increase for a period before a new equilibrium point is reached with a greater CPUE. The catches will be less during the period of transition than at the new point of equilibrium.

There are a number of assumptions and conditions that must be fulfilled for production models to be applicable. The most important of these is that the amount of mixing between the fish in the area of exploitation and fish in adjacent areas must be low relative to the level of exploitation.

Assuming that production models are applicable, that fact can be detected only if (1) there are catch, effort, and CPUE data available for a wide range of levels of fishing effort, preferably including periods of both underfishing and overfishing, and (2) the perturbations caused by fluctuations in environmental conditions are not so great as to mask the changes in abundance caused by fluctuations in fishing effort.

As already mentioned, if production models are applicable, they are easy to use, requiring only information on the amount of fish caught and the amount of fishing effort exerted to make that catch. Collection of usable data on fishing effort is not as easy as it may seem, however, as a fishery may be directed toward more than one species and may shift its emphasis from one species to another from time to time. Also, if changes in gear or fishing methods occur, these changes must be accounted for in the analyses. Because the assumptions which are required when using production models are not always fully satisfied, they often provide less precise estimates of the effects of fishing than do more sophisticated models.

Age-structured models

Age-structured models require data on recruitment and on the growth and mortality rates of individual fish, which are often difficult to obtain, but they often produce better results than do production models. Estimates of these parameters are obtained from analyses of size and age data from fish in the catch and from tag-and-recapture experiments. The differences in growth and longevity of males and females can be incorporated into age-structured models.

Cohort models

The most commonly used age-structured models are cohort or virtual-population models. To use these models, it is necessary to estimate the numbers of fish of each age caught during each of a series of years. An estimate of the fishing mortality for at least one year and an estimate of the natural mortality are required. The models track cohorts or age groups of fish as they move through the fishery, and estimate the fishing mortality for each time interval. With this information, the abundance, in numbers of fish of each age group, can be estimated. Estimates of the corresponding weights can be made, using information on the weights of the fish at each age. By working backward in time, the numbers of fish recruited to the fishery can be estimated.

Cohort models provide a more complete picture of the dynamics of a stock of fish and, in general, are more useful in making management decisions than are production models. However, they require more detailed data than do production models.

Yield-per-recruit models

In addition to cohort analyses, yield-per-recruit analyses are used in the assessment of many fisheries. The general idea is to maximize the yield of fish by catching them at the size at which the total weight of the cohort to which they belong is at its maximum. For example, when the fish of a cohort are young, the total weight increases because the growth in weight of the individual fish is rapid, while the losses to the cohort due to natural mortality are moderate. Later, as the fish grow older, their growth rate becomes slower, while the natural mortality continues to be about the same. Thus the losses to the total weight due to natural mortality at that time are greater than the gains due to growth, and there is a net loss to the total weight. Eventually the cohort disappears. This is depicted graphically in Figure 28. The ideal way to obtain the maximum yield in weight from a cohort of fish (assuming, for this discussion, that this is the object of management) would be to harvest each fish just before it died a natural death. This is not possible, of course. The second alternative would be to harvest all the survivors at the age or size at which the loss to the total weight by natural mortality exactly balances the gain to it by growth (the "critical age" or "critical size"). This is possible for some animals, such as oysters or clams which are exposed at low tide and can be easily harvested at that time. When the manager of a bed of oysters or clams surveys it at frequent intervals and removes the individuals which have reached the critical size he is exerting an infinite amount of fishing effort on the animals which have reached that size, which maximizes the yield per recruit. It is obvious that this alternative is not practical for most species of fish.

Intuitively, it seems that if the second alternative is not possible harvesting should begin on fish which have not yet reached the critical size. This is the third alternative, and the only practical one for most species of fish. It is assumed, for the moment, that the size at entry (*i.e.* the size of the smallest fish caught) can be efficiently controlled. If the fishing effort is high a size at entry only slightly less than the critical size would be selected, most of the fish caught would be close to the critical size and age, and the yield would be almost as great as under the second alternative. If the fishing effort is lower a size at entry considerably below the critical size would be selected, the fish caught would exhibit a wider range of sizes and ages, and the yield would be considerably less than it would under the second alternative (but still the maximum possible without increasing the effort).

It may not be possible, however, to control efficiently the size at entry. If so, the only way to manage the fishery is to control the effort. If the size at entry is greater than the critical size unlimited effort can be permitted, but if the size at entry is less than the critical size restriction of the effort may increase the yield.

So far it has not been mentioned that at least some of the individuals of a cohort must be allowed to spawn at least once before they are harvested. There is probably no danger from this standpoint if spawning occurs well before the fish reach the critical size, but if spawning does not occur until after the fish have reached the critical size, and the fishing effort is high, there is a possibility that the number of spawners would be so reduced that the recruitment in subsequent years would be reduced. Therefore a fishing strategy designed to produce the maximum yield per recruit will not necessarily produce the maximum yield. If the fishing pattern has an impact on the future recruitment, the maximum yield will be obtained by controlling the fishing to optimize the cohort size and yield per recruit simultaneously. (It should not be assumed, however, that a modest reduction in spawners would reduce the recruitment in subsequent years, as this does not appear to be the case for most species of fish.) The yield-per-recruit model, as described here, does not take into account the possibility of changes in recruitment, but this is an integral part of the production models discussed above.

Also, it has not been mentioned that the growth of the individual fish may be slower, or the natural mortality may be greater, when a population of fish is dense than when it is less dense. Accordingly, the loss due to harvesting of some fish at less than the critical size may be at least partially compensated for by faster growth and/or lesser natural mortality of the remaining fish. In addition, if the growth or natural mortality rates are affected by population density the critical size and age will vary according to population density. This is another complication not taken into account in the yield-per-recruit model as described here, but it is automatically compensated for in production models.

<u>Spawner-recruit models</u>

Spawner-recruit models are based upon comparisons of the relationships between abundance of spawners and subsequent abundance of eggs, larvae, juveniles, or recruits to the fishery. The differences in growth and longevity of males and females must be incorporated into spawner-recruit models. For many years it was thought that spawning and recruitment are rarely correlated for marine fishes with high fecundities, but recent studies involving longer series of data with wide ranges of abundance of spawners indicate that such correlations occur more frequently than previously supposed.

In summary, it has been pointed out that there are three types of models used to assess the abundance of fish populations and the impact of fishing on such populations. Production models are relatively simple and straightforward, and do not require as sophisticated a data base as do age-structured models. Age-structured models provide a more complete picture of the population dynamics of the fish, and usually provide better information for making management decisions. Spawner-recruit models are useful only if the abundance of spawners has been reduced sufficiently to reduce the recruitment in subsequent years. Fisheries scientists have used these models both independently and jointly to provide scientific advice to managers.

Stock assessment of swordfish

Both production and age-structured models have been used extensively to study the population dynamics of swordfish. Most of this work, however, has been done with Atlantic swordfish.

Pacific Ocean

Joseph *et al.* (1974) examined trends in longline CPUE for swordfish in the eastern Pacific Ocean for the 1963-1970 period. These unadjusted CPUEs showed two areas of high apparent abundance, one near the Mexican coast between 20°N and 30°N and the other near the coasts of Ecuador and Peru between 10°S and the equator. In both areas the trends in CPUE were constant until the mid- to late 1960s, at which time the CPUEs increased. The upward trends in the CPUEs were most likely due to increased efficiency as a result of increased night sets, using squid as bait, and concentration of effort on the more productive swordfish grounds. Although the data suggested that increased swordfish catches could be sustained, it would be necessary to adjust all the data for the effect of night sets before the longline CPUE data would provide a reliable indicator of the abundance of swordfish.

Sakagawa and Bell (1980) examined data for the Japanese longline fishery for the 1952-1975 period. They proposed two stock hypothesis: (1) a single Pacific-wide stock and (2) three separate stocks, with centers of concentration in the northern, southwestern, and south-central regions of the Pacific Ocean (Figure 1). They examined the trends in the CPUEs on a Pacific-wide basis, and showed that there was a general decline between 1958 and 1968, followed by stability thereafter. The CPUEs during the later period were about 60 percent of those of the earlier period. They attributed this change to a cessation of night fishing with longlines in the productive northwestern region of the fishery, rather than to a decline in swordfish abundance. Using production models and the 1952-1963 data set, they estimated the Pacific-wide MSY to be about 20,000 metric tons (mt) per year. The average annual catches were about 14,000 mt at that time, so they concluded that the fishery was not overexploiting the stock, and that it was in good condition.

Bartoo and Coan (1989) extended the analyses of Sakagawa and Bell (1980) to include data for the Japanese longline fishery through 1980. They first examined the data as a single Pacific-wide stock with several areas of high catches. The CPUEs in the target areas showed a slight increasing trend through 1963, and thereafter the values dropped to about two thirds of that level and remained there. This decrease was attributed to the change in fishing methodology mentioned above. For their second examination of the data, they assumed that there were stocks centered in areas similar, but not identical, to those of Sakagawa and Bell (1980) (Figure 3). The trends in apparent abundance in each area, as reflected by the CPUEs, were similar to those for the single-stock case. They concluded "that the stocks do not appear to have been exploited heavily enough to cause a declining trend in CPUE and, by extension, in abundance, through 1980."

In summary, stock assessments of swordfish in the Pacific have employed only Japanese longline data and production modeling. Fortunately, about 75 percent of the annual Pacific catch of 20,000 mt of swordfish prior to the late 1980s was taken by Japanese longline vessels, and the Fisheries Agency of Japan does an excellent job of collecting statistical and biological data for the Japanese high-seas longline fishery. This information formed the basis of the three analyses reviewed above. The results probably adequately reflect the trends in the fishery and the condition of the Pacific-wide swordfish stock during the years included in the analyses. The fisheries have changed since then, however. By 1992, the swordfish catch in the Pacific Ocean had reached nearly 31,000 mt, a 50-percent increase since 1986. The Japanese share of this catch declined from about 75 percent to about 35 percent, so the Japanese fishery may no longer provide coverage adequate to monitor the entire fishery. Data for the coastal fisheries of Chile, Costa Rica, Ecuador, Mexico, the Philippines, the United States, and other nations should be included in future analyses. Because the fisheries are expanding, it is important to initiate such analyses as soon as possible.

Atlantic Ocean

It is important to review the studies which have been conducted in the Atlantic Ocean, as the fishery of the Pacific Ocean is developing similarly to the way that the fishery of the Atlantic developed during the 1970s and 1980s. Stock assessment and management of the Atlantic fisheries are carried out internationally under the auspices of the International Commission for the Conservation of Atlantic Tunas (ICCAT).

Swordfish are captured in the Atlantic Ocean and adjacent seas between about 50°N and 50°S. Although fisheries for swordfish have taken place in the Atlantic Ocean since the 1800s, and even before that in the Mediterranean Sea, it was not until the late 1970s and early 1980s that fishing effort began to increase to the present levels. At first the catches increased with increasing effort, but then they began to decline. In some fisheries the average sizes of the fish caught also declined.

The catch in the Atlantic reached an historic high of about 33,500 mt in 1989, but by 1992 it had declined by 30 percent to 23,500 mt. For the north Atlantic, the area north of 5°N, the catch peaked at nearly 20,000 mt in 1987, but by 1992 had declined by about 34 percent to 13,200 mt. The peak catch south of 5°N, 16,600 mt, was taken in 1989, but by the end of 1992 the catch in this area had declined by about 37 percent to 10,400 mt. In the Mediterranean Sea the catch peaked at 20,300 mt in 1988, and thereafter declined; in 1992 it was about 13,500 mt, a decline of about 33 percent.

These declines were a matter of growing concern for the governments of the nations whose vessels participated in the fishery. This was particularly true for the United States and Spain, whose fleets rapidly expanded their operations from coastal waters to the high seas of the central Atlantic, where the two fleets share the same fishing grounds. These concerns resulted in intensive scientific investigations, under the auspices of ICCAT, of the status of swordfish in the Atlantic Ocean and Mediterranean Sea.

The stock assessment carried out for the north Atlantic (Anonymous, 1993b) is the most comprehensive to date for any swordfish stock in the world. Because of the shorter period of exploitation and lack of reliable CPUE data for the south Atlantic and limited statistical and biological data for the Mediterranean, analyses of the condition of swordfish in these areas are less reliable than that for the north Atlantic.

The scientists conducting these analyses reached a number of conclusions regarding the fishery of the north Atlantic, the most important of which were:

1. The virtual-population analyses showed that the fishing mortality rate on 1- to 4-year-old swordfish generally increased through 1988, and then declined during 1989-1991. The pattern for the older fish was similar.

2. The virtual-population analyses showed some increases in abundance of adults during the early 1990s as the apparent result of increased recruitment during the late 1980s and reduced catches since 1987.

3. Production modeling produced estimates of MSY of 13,100 to 14,300 mt, with a "base-case" estimate of 14,200 mt. The 1991 catch of 13,200 mt was less than the MSY, but about equal to the "equilibrium catch," *i.e.* the catch that could be harvested on a sustained basis at the current population size. The current abundance of swordfish was estimated to be approximately 15 percent less than that which would produce the MSY, indicating overfishing.

Based on these analyses, the scientists involved noted that the decline in swordfish abundance had slowed or stabilized. However, they expressed concern about the status of the entire Atlantic population, especially in view of the recent rapid increases in the catches in the south Atlantic. Accordingly, ICCAT recommended a number of management measures for swordfish designed to halt the apparent decline in abundance and to restore the stocks to levels of abundance which would support greater catches. The ICCAT recommendations for swordfish in the Atlantic, which took effect in mid-1991, were *inter alia*:

1. For the fleets of nations with major catches of swordfish fishing for swordfish as a target species in the north Atlantic: a reduction in fishing effort sufficient to reduce the fishing mortality on fish larger than 25 kg (55 pounds) by 15 percent.

2. For the fleets of all nations fishing anywhere in the Atlantic Ocean: a prohibition against capturing and landing swordfish less than 25 kg, with a maximum 15-percent incidental allowance in numbers of fish.

3. For the fleets of nations with minor catches of swordfish fishing for swordfish as a target species anywhere in the Atlantic Ocean: a limit on the catches to the levels of 1988.

4. For the fleets of all nations which are members of ICCAT fishing anywhere in the Atlantic Ocean for species other than swordfish: a limit on the incidental catches of swordfish to no more than 10 percent of the entire catch by weight.

DISCUSSION AND CONCLUSIONS

After a decline in the catches of swordfish in the Pacific Ocean during the early 1960s, when the Japanese longline fleet in the northwestern Pacific began to direct its effort toward species other than swordfish, the Pacific-wide catch began to increase (Table 3). Between 1964 and 1992, it increased, on the average, by nearly 800 mt per year. Based on the growing world demand for swordfish and the steady increase in catches in the Atlantic and Mediterranean, it is expected that the catches in the Pacific will continue to increase as long as the abundance of the fish will support that increase. If the catches continue to increase, it is likely that, based on the Atlantic experience, the abundance of swordfish will be reduced to the point that the catches will eventually decline. The decline would probably be accompanied by a decline in the average size of swordfish captured by the fishery. In fact, it appears that a decline in average size of the fish took place in the northwestern Pacific during the 1948-1949 to 1955-1956 period (Figure 15). A decline in the average size of the fish does not necessarily indicate overfishing, however.

The question arises as to how overfishing might be avoided, that is how exploitation can be kept in balance with the ability of the swordfish population to support the catches. The answer, of course, is that we must gain sufficient understanding of the population dynamics of swordfish and possess the political will and administrative ability to utilize this understanding for purposes of management.

Scientific issues

There are a number of technical requirements that must be met to ensure adequate stock assessment research.

The most fundamental requirement is collection of comprehensive catch and effort data. For each fishery, data are needed on the catches for small areas and short time intervals, along with measures of fishing effort, such as numbers of vessels operating, numbers of hooks set per day, hours of deployment for drift gillnets, including corresponding information for recreational fisheries if and when the catches by those fisheries became important. A practical way to collect such information for commercial fisheries and recreational charter boats is through the establishment of a logbook system to be maintained by vessel captains or crew members, complemented by an observer program. Other systems, such as monitoring of important landing locations, could be developed for smaller vessels.

With this sort of data, analyses utilizing production models could be carried out. Although limited in scope, these models could provide initial estimates of potential catches and early warnings of overfishing. However, to utilize more comprehensive approaches, data on the ages of the fish caught and estimates of various biological parameters would be required.

The most fundamental information needed for more comprehensive approaches are measurements of the lengths and/or weights of fish in the catch. A program to collect such data would have to include sampling at most of the major landing sites of the commercial fisheries, and perhaps the recreational fisheries as well. Samples would have to be collected on a regular basis for an extended period of time.

In addition to the collection of catch, effort, and size data, additional information on the biology of swordfish is necessary to understand the population dynamics of the stock(s). Programs designed for this purpose should include studies on the growth, rates of natural and fishing mortality, movement of individual fish within and among areas, and reproductive characteristics, such as sex ratio, fecundity, frequency of spawning, and location of spawning areas.

One of the most important prerequisites for management is an understanding of the stock structure of the stocks of swordfish that are the object of exploitation. It must be known whether the fish which are the object of a particular fishery mingle with fish which are the objects of other fisheries and whether they interbreed with those fish, as attempts to manage one fishery would not be effective if fish moved from that fishery into other fisheries where there were no similar or complimentary management measures. It is therefore necessary to understand the stock structure of the species in question before the models described above can be applied with confidence.

There are a number of techniques that can be utilized to obtain information on stock structure, but collection of the material and data is difficult and expensive, and the analyses require highly-trained personnel and costly equipment. These techniques include the use of information on heritable characteristics of fish obtained from studies of blood-group systems, serum protein systems, and mitochondrial DNA restriction-enzymes. Non-genetic techniques hold potential also. These include morphometric and meristic analyses, wherein body form and shape and counts of fin rays, vertebrae, *etc.*, of swordfish can be compared among fish caught in different areas, the frequency of parasites occurring in swordfish in areas outside of the normal ranges of those parasites, and the composition of chemical elements incorporated into bones of fish from different areas, which are believed to differ because of differences in the characteristics of the ocean and/or the chemical composition of the prey of swordfish.

The most direct way to measure the physical exchange of individual fish among areas is through the use of mark-and-recapture experiments. In addition to providing information on movements, properly-designed tagging studies can also yield invaluable data for estimating growth and mortality. Tagging studies have been utilized for these purposes for many stocks of fish, and they afford a promising tool for swordfish, although their use has so far been limited for this species.

One of the shortcomings of conventional tagging studies is that only two bits of information on movement are obtained--where and when the fish was released and where and when it was recaptured. The whereabouts of the fish in the interval between release and recapture is unknown. To help close this gap, a new type of tag, the archival tag, which stores information on time, temperature, depth, and light has been developed. When the tag is recovered a daily record of where the fish has been can be retrieved. These tags are adding a new dimension to fisheries research. Unfortunately, however, they cost about $1000.00 each, but as the demand increases the prices will probably decrease, making it more practical to use them for studying the movements and behavior of swordfish.

Non-scientific issues

Technical requirements

Assuming that an adequate understanding of the population dynamics of swordfish is available, there are, nevertheless, several non-scientific issues that may complicate the implementation of management. These have to do with an ever-increasing awareness of and concern over "bycatch" (capture of species other than the "target" species), conflicts among commercial fishermen using different types of gear, conflicts between commercial and recreational fishermen, and the eventual problems of allocation of catches among nations. (In this report the definitions of Alverson *et al.* (1994) are used. His definitions are as follows: "Target Catch -- The catch of a species or species assemblage which is primarily sought in the fishery ...; Incidental Catch -- Retained catch of non-targeted species; Discarded Catch -- That portion of the catch which is returned to the sea as a result of economic, legal, or personal considerations; Bycatch -- Discarded catch plus incidental catch." The principal target species are tunas and billfishes for the longline fisheries and swordfish and sharks for the drift gillnet fisheries. It should be noted that much of the discarded catch consists of fish and other animals which are released alive.)

Longlines and drift gillnets take the greatest amounts of swordfish in the Pacific Ocean. The probability of capturing swordfish can be increased by altering the locations in which the gear is deployed, the configuration of the gear, *etc.*, but in no case can catches of only swordfish be assured. Longlines and drift gillnets normally capture a variety of large pelagic fishes, such as tunas, marlins, and sharks, along with swordfish. Marlins are less common in the catches of gillnet vessels than in those of longline vessels. In addition, a few marine mammals and turtles are occasionally taken by both longline and gillnet vessels.

The actual and perceived capture of marine mammals, turtles, and birds by longlines and marine mammals and turtles by drift gillnets has resulted in action on the part of some environmental organizations to limit the use of these types of gear. It is imperative, if this perceived problem is to be resolved, that information be collected on the numbers and kinds of animals taken as bycatches. (Data on the bycatches of drift gillnet vessels operating off California have been published by Perkins *et al.* (1992), Hanan *et al.* (1993), Julian (1993), Peltier *et al.* (1993), and Peltier *et al.* (1994). Some of these data are shown in Table 6.) Hand and hand with these efforts to collect data should be a major effort to design, develop, and implement modifications to fishing gear, if it is shown that the longline or drift gillnet fisheries have significant impacts on the species making up the bycatches.

The other major issue that must be dealt with is allocation--who gets what? This is the crux of most fisheries problems, and in an international fishery in which vessels of a number of nations participate it is the most difficult to solve. The problem occurs at several levels.

At the national and local level, conflict will develop over the right to harvest swordfish among commercial fishermen using different gear types.

Conflicts between commercial and recreational fishermen may escalate; in fact, there have already been disputes over allocation in Hawaii, California, Mexico, and Australia. The confrontation will center not so much on swordfish *per se*, but on the catches of other species of billfishes and of sharks. Few swordfish are taken by recreational fishermen anywhere in the world, as swordfish do not readily take a baited hook or lure at the surface. In the Pacific Ocean, for example, probably less than 100 swordfish are taken annually on rod-and-reel gear, compared to the commercial harvest of hundreds of thousands of fish. Marlins, on the other hand, are the basis for a large recreational fishery in many coastal resort areas around the Pacific basin. Important tourist facilities in California and Baja California include opportunities to fish for marlins. It is perceived by sportsmen and investors involved in the tourist and recreational fishing industry that longline and, to an extent, drift gillnet fisheries for swordfish and sharks reduce the abundance of marlins in the areas where the recreational fishery takes place.

In response to this, longline and drift gillnet fishing is not permitted in certain areas off California and Baja California. Resolution of such disputes will require gathering of information to obtain estimates of the bycatches of the various species and development of fishing gear and methods that reduce or eliminate the bycatch of marlins.

Many nations are involved in the swordfish fishery of the Pacific. In the eastern Pacific, there are at least 10 nations whose vessels fish for swordfish. Some of these nations are coastal states whose fleets fish inside their own Exclusive Economic Zones (EEZs), and others are coastal states whose vessels fish both inside and beyond their EEZs. Still others are non-coastal nations whose vessels fish only on the high seas. Each of these perceives its rights to access to the swordfish stocks in a different manner, but all claim rights to such access in one form or other. As fishing effort continues to expand, competition among fleets will increase, and there will be increasingly greater pressure to develop a framework within which the fleets can operate. Within such a framework, control over the fisheries within the EEZs will reside with the coastal states. On the high seas, however, controls must be determined through international cooperation among the involved parties.

Institutional requirements

A proper institutional format for managing the swordfish resources of the Pacific must be responsive to the unique characteristics of swordfish and the fisheries for them.

It has been noted that swordfish are distributed widely throughout the tropical, subtropical, and temperate waters of the Pacific Ocean. Although there is not a great deal of information on the degree to which fish from different parts of the Pacific Ocean mix with one another, some assumptions, based on information from the Atlantic, may be made. On one hand, data for tag-and-recapture experiments conducted in the Atlantic Ocean suggest that most swordfish do not move more than about 600 miles from the area of release. On the other hand, recently-collected data on mitochondrial DNA, length frequencies, and CPUE trends indicate similarities among swordfish from widely-scattered locations of the Atlantic. Though swordfish apparently do not migrate as extensively as bluefin tuna, for example, which make regular transoceanic migrations, fish frequently move from the EEZs of various nations to the high seas and *vice versa* and across national boundaries from one coastal state to another. At least half of the total Pacific catch of swordfish is probably taken on the high seas beyond the EEZs of any nation.

The fleets that fish for swordfish are at least as mobile as the fish, and probably more so. Longline vessels from Japan may fish in the northwestern Pacific for swordfish during part of the year and in the southeastern Pacific during another part of the same year. Vessels from California, Hawaii, and Japan fish side-by-side for swordfish on the high seas midway between Mexico and Hawaii. Spanish longliners fish for swordfish in the Pacific Ocean off Chile.

The market for swordfish is international. Swordfish from Chile, for example, may end up in Japanese, European, or U.S. markets, depending on supply, demand, and price.

Research on swordfish is conducted by several national research institutions on stocks or portions of stocks of concern to the respective nations. International research is conducted in the eastern Pacific Ocean by the National Research Institute of Far Seas Fisheries of Japan and the Inter-American Tropical Tuna Commission (IATTC).

Considering the characteristics of swordfish and the fisheries for them in the Pacific Ocean, it is clear that cooperation among the interested nations is required for proper management of these resources. This is not a new concept. In fact, the United Nations Convention on the Law of the Sea calls for such cooperation in the management of highly-migratory species. Article 64 of that Convention states:

"1. The coastal State and other States whose nationals fish in the region for the highly migratory species listed in Annex I shall cooperate directly or through appropriate international organizations with a view to ensuring conservation and promoting the objective of optimum utilization of such species throughout the region, both within and beyond the exclusive economic zone. In regions for which no appropriate international organization exists, the coastal State and other States whose nationals harvest these species in the region shall cooperate to establish such an organization and participate in its work.

"2. The provisions of paragraph 1 apply in addition to the other provisions of this Part."

(Swordfish is included in Annex I of that document.)

Most of the nations whose fleets harvest swordfish in the Pacific Ocean are signatories to the treaty or are members of international fisheries organizations that have responsibility for the scientific study and management of highly-migratory species. The government of the United States has been a leader in the creation of international fisheries organizations, and is party to both the IATTC and the International Commission for the Conservation of Atlantic Tunas, the two organizations currently dealing with tunas and billfishes in the eastern Pacific Ocean and the Atlantic Ocean.

The IATTC is the only Article-64 type organization concerned with tunas and billfishes in the Pacific Ocean. This organization, which was created in 1949, has responsibility for the scientific study of tunas and other fishes taken by vessels fishing for tunas in the eastern Pacific Ocean and for making recommendations for management of the fisheries for these species. The Convention establishing the IATTC does not define the limits of the eastern Pacific Ocean, but it conducts most of its studies of tunas, billfishes, and marine mammals in the area between the mainland of the Americas and 150°W.

No Article-64 type organization for tunas and billfishes exists in the the western Pacific Ocean, with the exception of the newly-created body for southern bluefin tuna whose jurisdiction is restricted to the southern hemisphere, and particularly to waters of the Southern Ocean south of about 35°S. The Forum Fisheries Agency (FFA), which represents the coastal states of the South Pacific region, is concerned primarily with access agreements and the harmonized exercise of jurisdiction over the EEZs of its member states. Non-coastal states, even though they may have fleets operating in the region, cannot be members of FFA.

The South Pacific Commission (SPC) is a regional consultative and advisory body to participating governments on matters affecting economic and social development. One of its programs, the Tuna and Billfish Assessment Programme, collects and analyzes data on these species in the southwestern and south-central Pacific. The SPC does not have management responsibility.

There are a number of options for institutional arrangements for swordfish in the Pacific Ocean. Some of these which could be used in combination with Pacific-wide management of swordfish are:

1. Creation of a Pacific-wide Article-64 type organization. However, because of the position of the FFA regarding distant-water fishing nations and non-coastal states, it is not likely that this approach would be successful over the near term.

2. Creation of two independent organizations in the western Pacific, one including the member nations of the FFA and the other including the rest of the interested nations. The boundaries for the two organizations might bear no resemblance to the natural boundaries of the swordfish stocks, however.

3. Creation of a new organization in the eastern Pacific which would deal only with swordfish. This would be redundant, as the IATTC, an Article-64 type organization with responsibility for tunas and other fishes caught by vessels fishing for tunas, is already in existence and is currently working on swordfish.

These are only a few of the options that might be considered for swordfish. Regardless of which option is chosen, there are certain criteria that must be met if effective research and management are to become realities. The most important of these criteria is that the studies and management, as already noted, must apply over the entire range of the stock being exploited. Coordination must be exercised to ensure that adequate statistical and biological data are collected by the various research programs of the nations involved. All nations which participate in the fisheries must be party to any agreement for management.

It is only through such international cooperation, as called for in the United Nations Convention on the Law of the Sea, that the swordfish stocks of the Pacific Ocean can be maintained in a healthy condition, which would be beneficial to everyone concerned.

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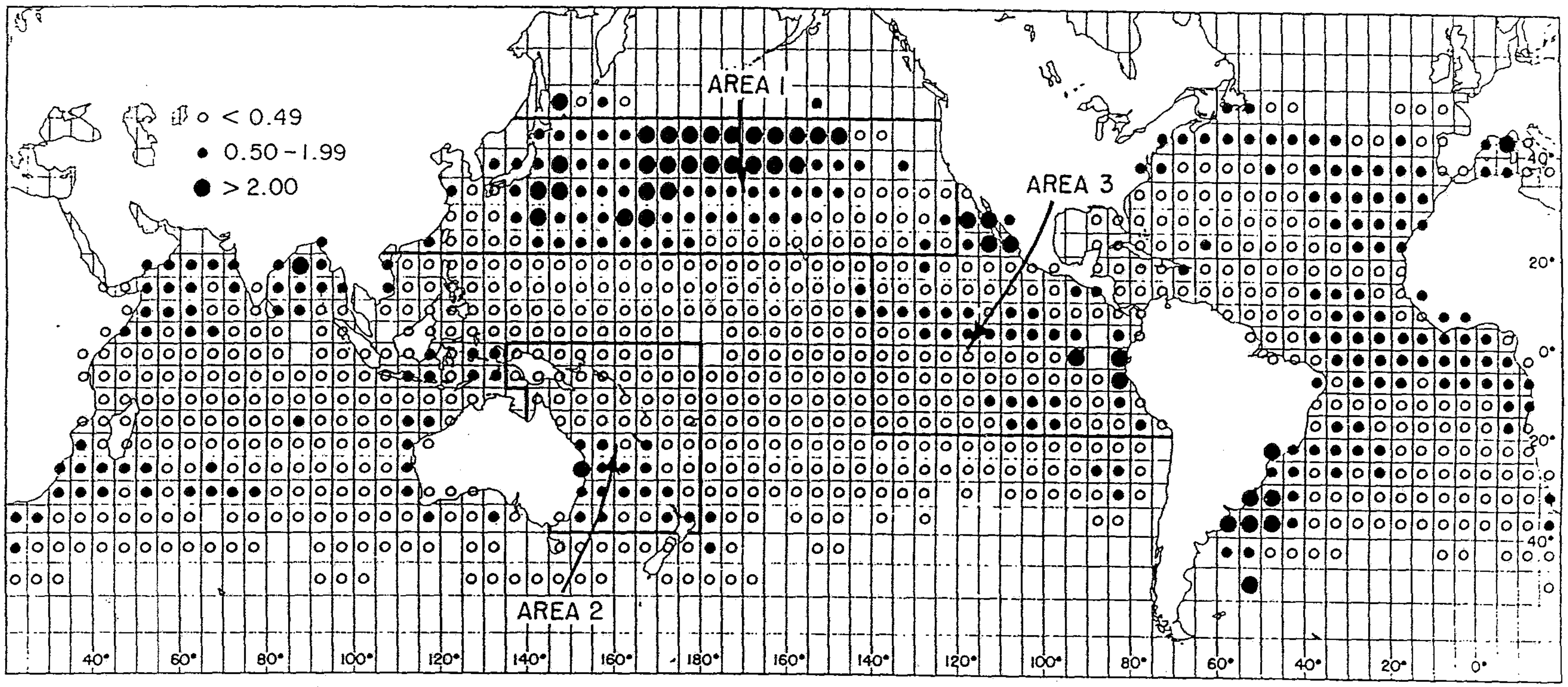

FIGURE 1. Distribution of swordfish, based on catch rates from the Japanese longline fishery. The circles indicate mean catch rates (numbers of fish per 1,000 hooks) (from Sakagawa and Bell, 1980: Appendix Figure 14).

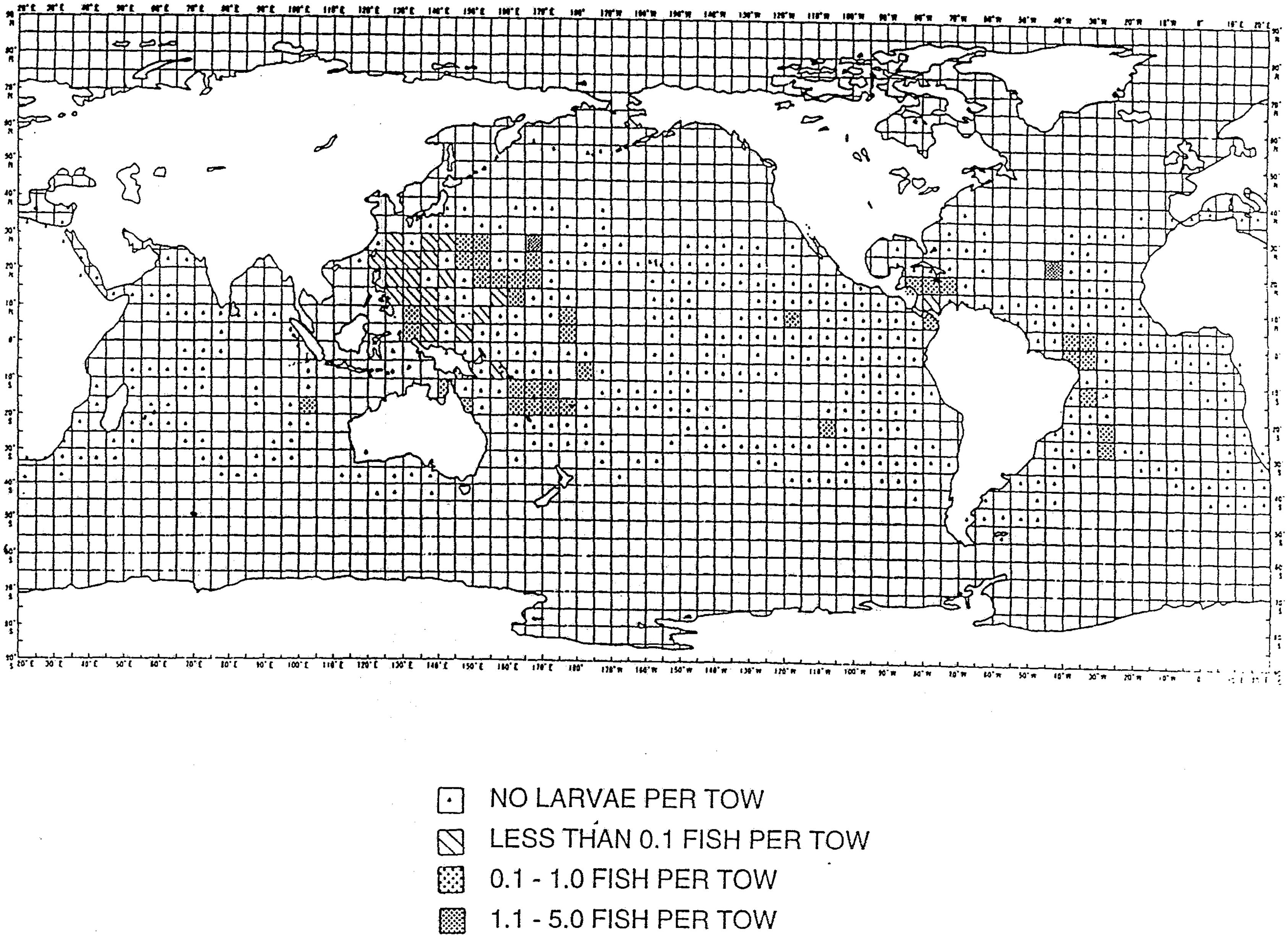

FIGURE 2. Distribution of swordfish larvae (after Nishikawa *et al.*, 1978: 47).

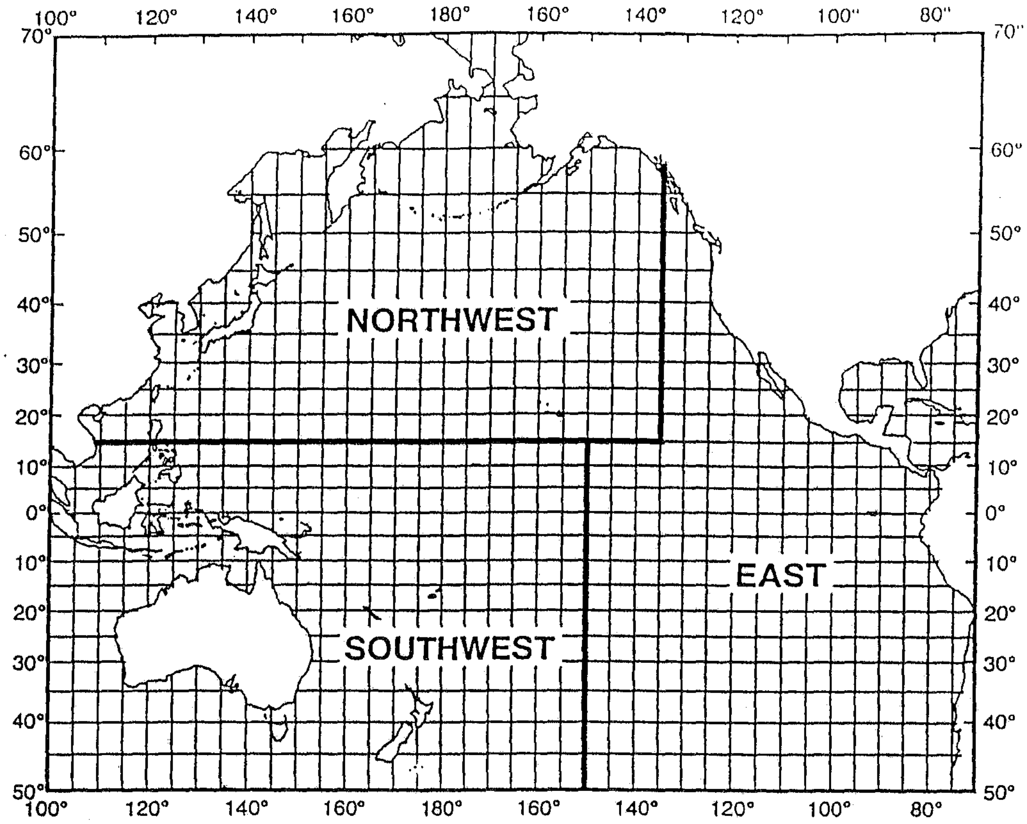

FIGURE 3. Hypothesized stock boundaries for swordfish in the Pacific Ocean (after Bartoo and Coan, 1989: Figure 4).

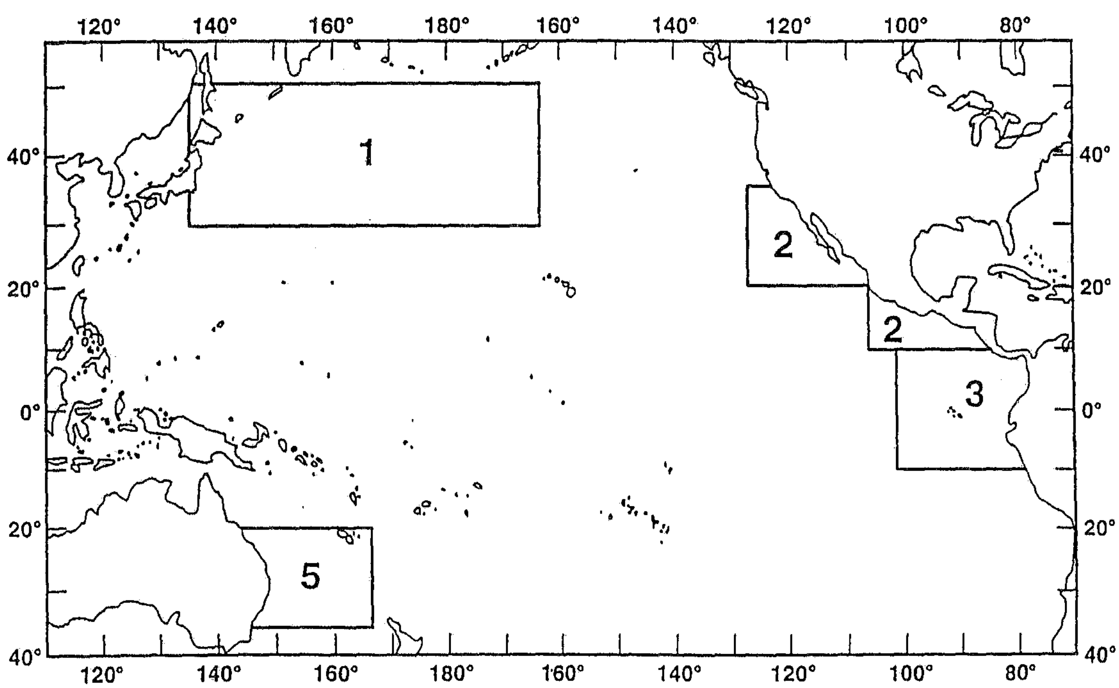

FIGURE 4. Skillman's index areas for swordfish (after Skillman, 1989: Figure 1).

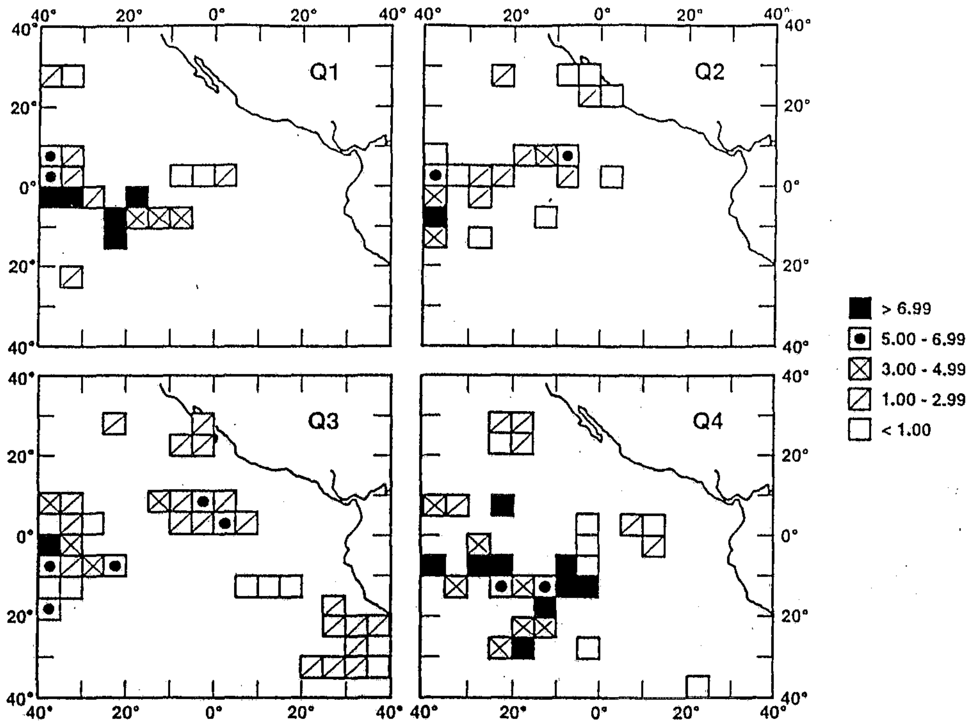

FIGURE 5. Quarterly distributions of average gonad indices for swordfish greater than 150 cm in length, 1971-1980 (after Miyabe and Bayliff, 1987: Figure 42).

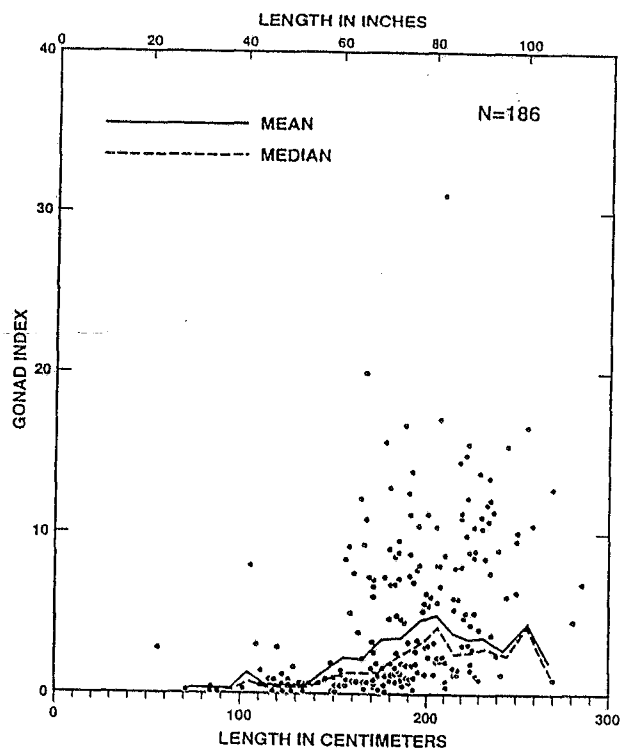

FIGURE 6. Relationship between gonad index and length for female swordfish, 1981-1987 (after Nakano and Bayliff, 1992: Figure 47). "The fish were measured "to the next-highest 5-cm interval from the posterior margin of the orbit to the fork of the tail." "Mean" is a synonym for average. The "median" is the central value, *i.e.* that with equal numbers of values above and below it.

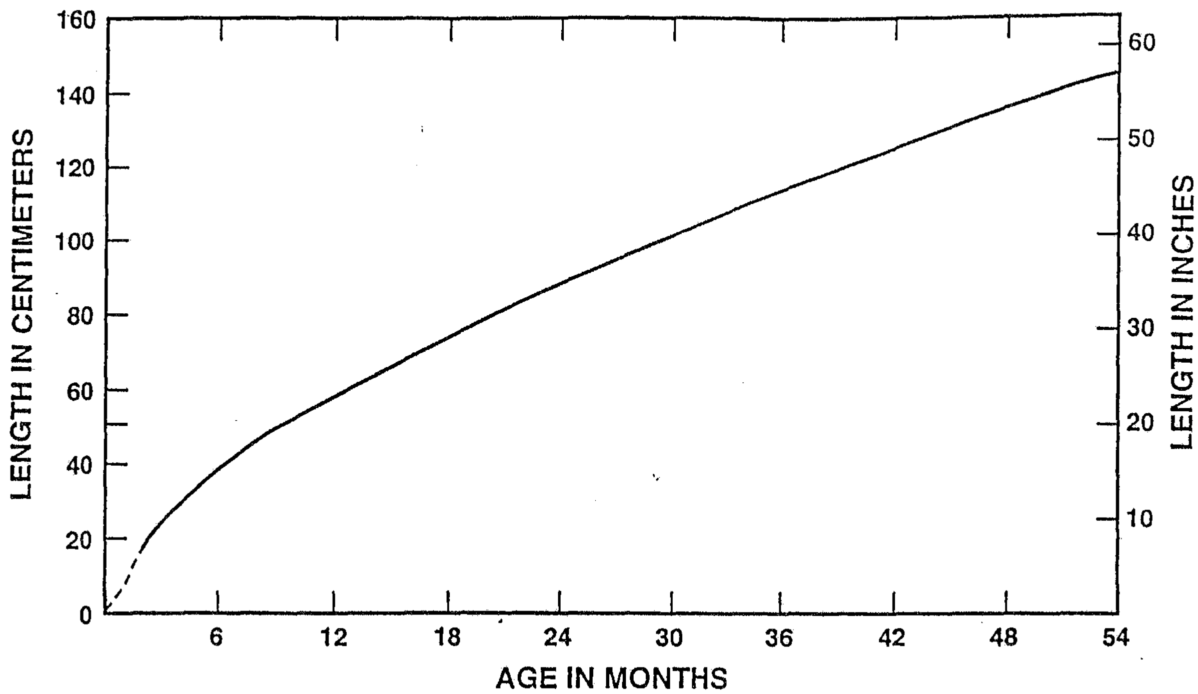

FIGURE 7. Growth of swordfish in the northwestern Pacific Ocean (after Yabe *et al.*, 1959: Figure 28). The body length is defined in Appendix 1.

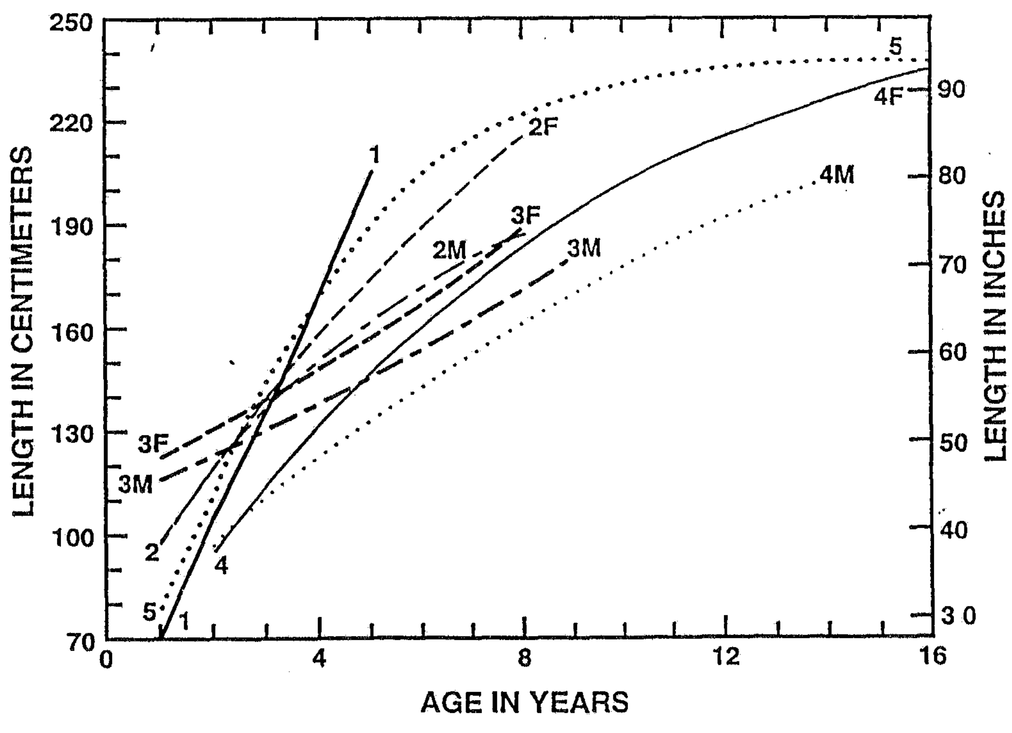

FIGURE 8. Growth of swordfish in the Atlantic Ocean (after Boggs, 1989: Figure 1). The lengths were measured from the anterior tip of the lower jaw to the fork of the tail. The numbers correspond to the following sources of data listed in Table 1: 1, Caddy, 1976; 2, Berkeley and Houde, 1983; 3, Radtke and Hurley, 1983; 4, Wilson and Dean, 1983; 5, Southeast Fisheries Center, 1987.

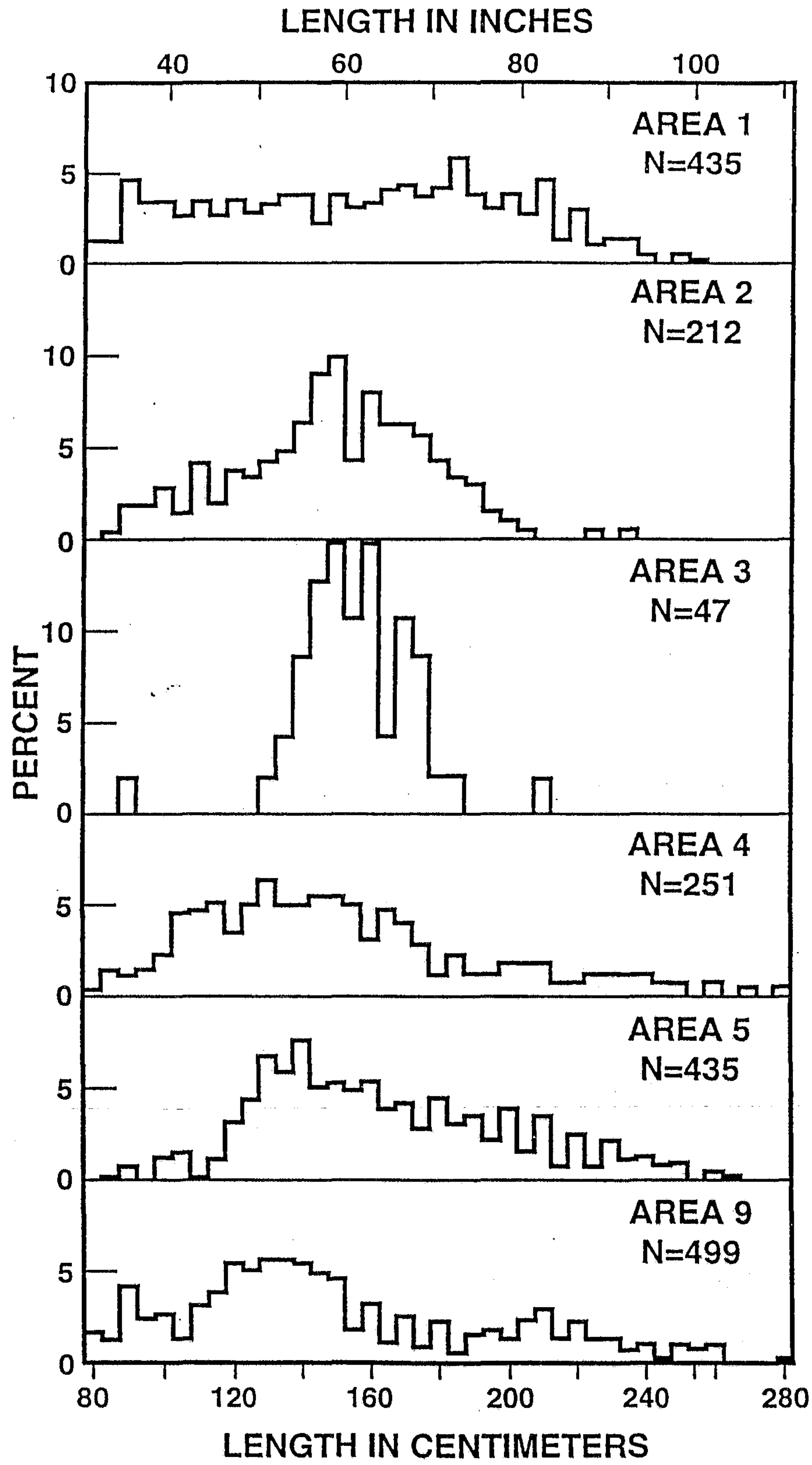

FIGURE 9. Length frequencies of longline-caught swordfish in the eastern Pacific Ocean (after Nakano and Bayliff, 1992: Figure 66). "The fish were measured "to the next-highest 5-cm interval from the posterior margin of the orbit to the fork of the tail." The areas are shown in Figure 10.

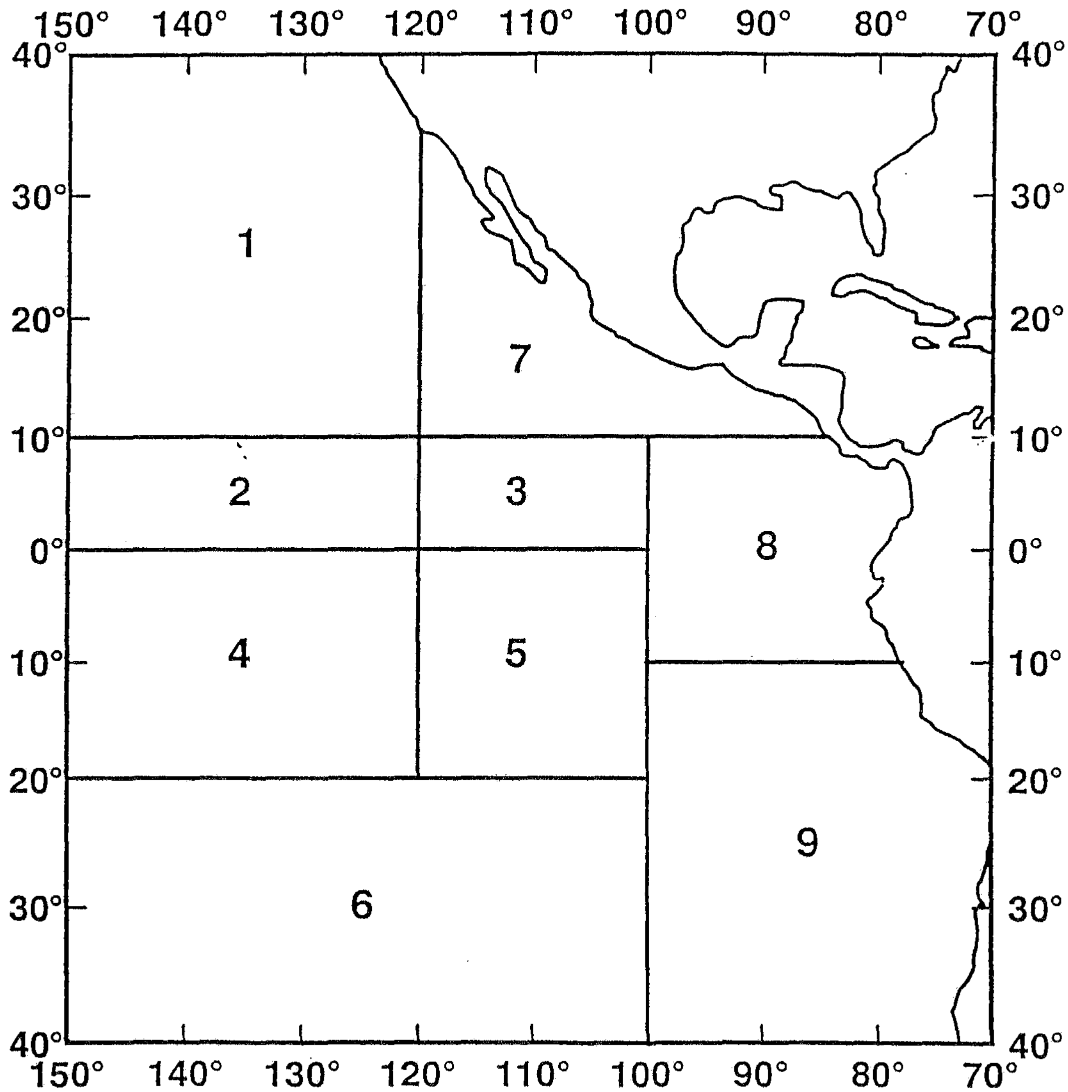

FIGURE 10. Areas designated in Figures 9, 11, and 12 (after Nakano and Bayliff, 1992: Figure 1).

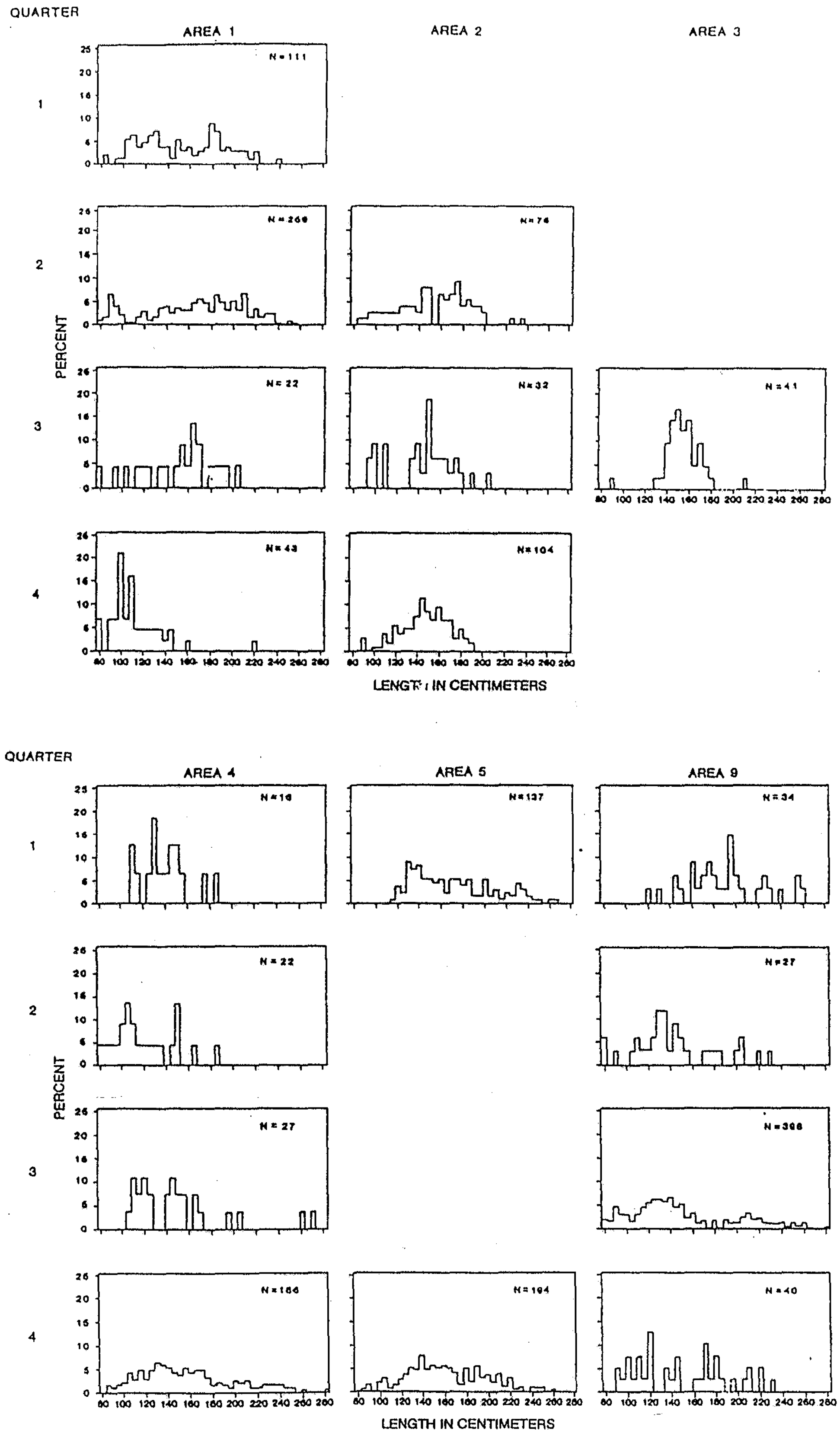

FIGURE 11. Quarterly length frequencies of longline-caught swordfish in the eastern Pacific Ocean (after Nakano and Bayliff, 1992: Figure 67). "The fish were measured "to the next-highest 5-cm interval from the posterior margin of the orbit to the fork of the tail." The areas are shown in Figure 10.

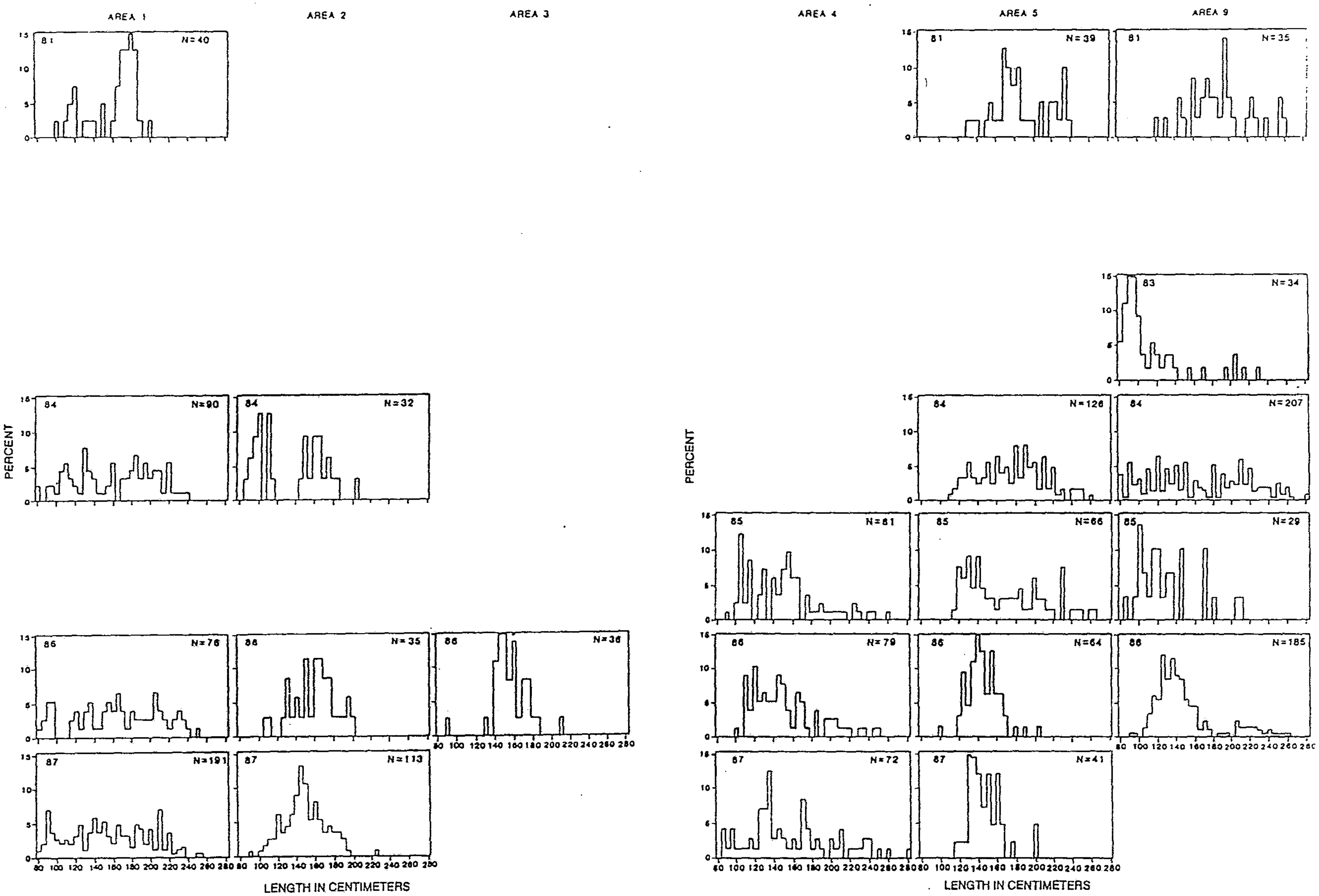

FIGURE 12. Annual length frequencies of longline-caught swordfish in the eastern Pacific Ocean (after Nakano and Bayliff, 1992: Figure 68). "The fish were measured "to the next-highest 5-cm interval from the posterior margin of the orbit to the fork of the tail." The areas are shown in Figure 10.

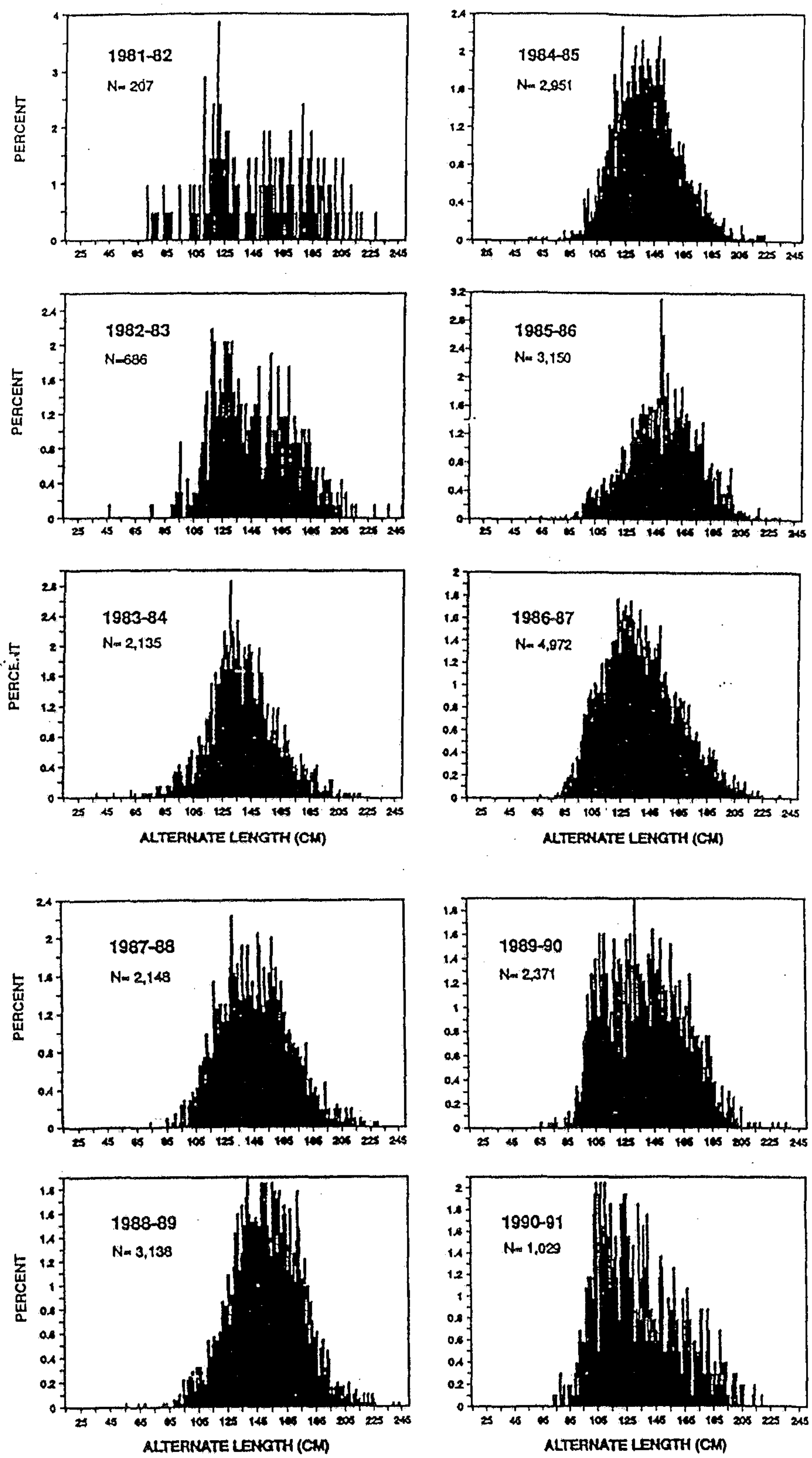

FIGURE 13. Annual length-frequency distributions of swordfish caught off California by gillnets (after Hanan *et al.*, 1993: Figure 27). The alternate length is the length from the anterior margin of the cleithrum (collar bone) to the fork of the tail.

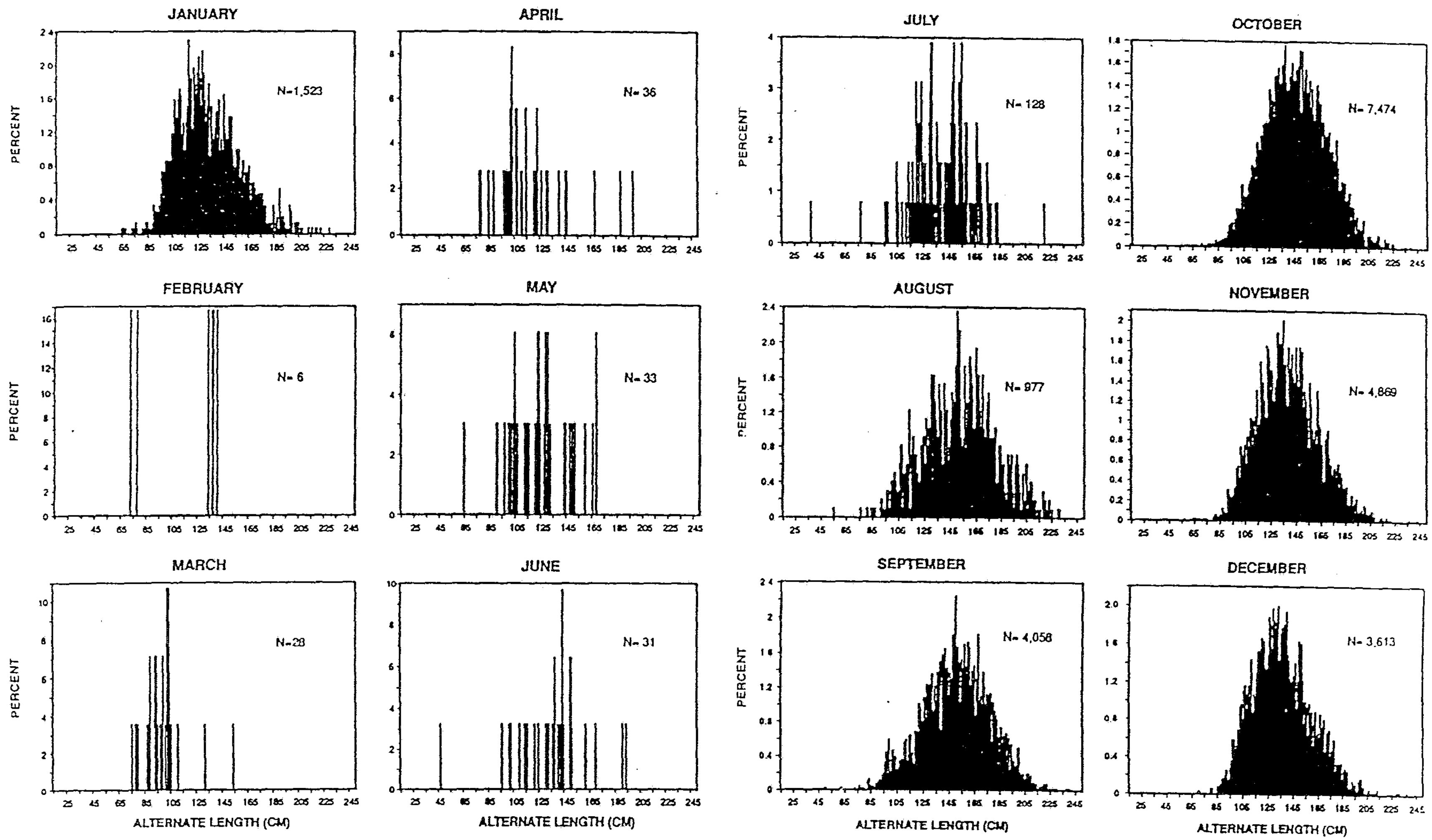

FIGURE 14. Monthly length-frequency distributions of swordfish caught off California by gillnets (after Hanan *et al.*, 1993: Figure 30). The alternate length is the length from the anterior margin of the cleithrum (collar bone) to the fork of the tail.

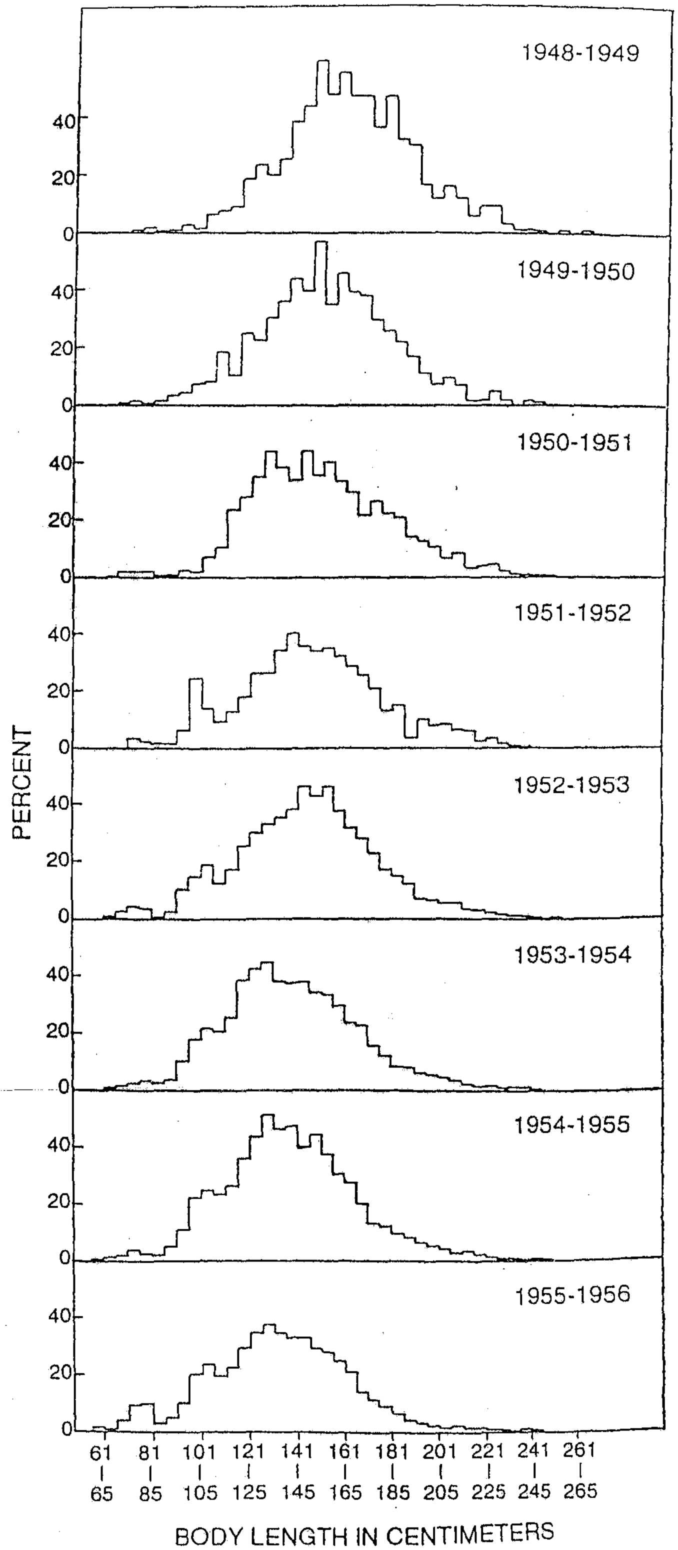

FIGURE 15. Length-frequency distributions of swordfish caught in the northwestern Pacific Ocean by longlines (after Yabe *et al.*, 1959: Figure 25). The body length is defined in Appendix 1.

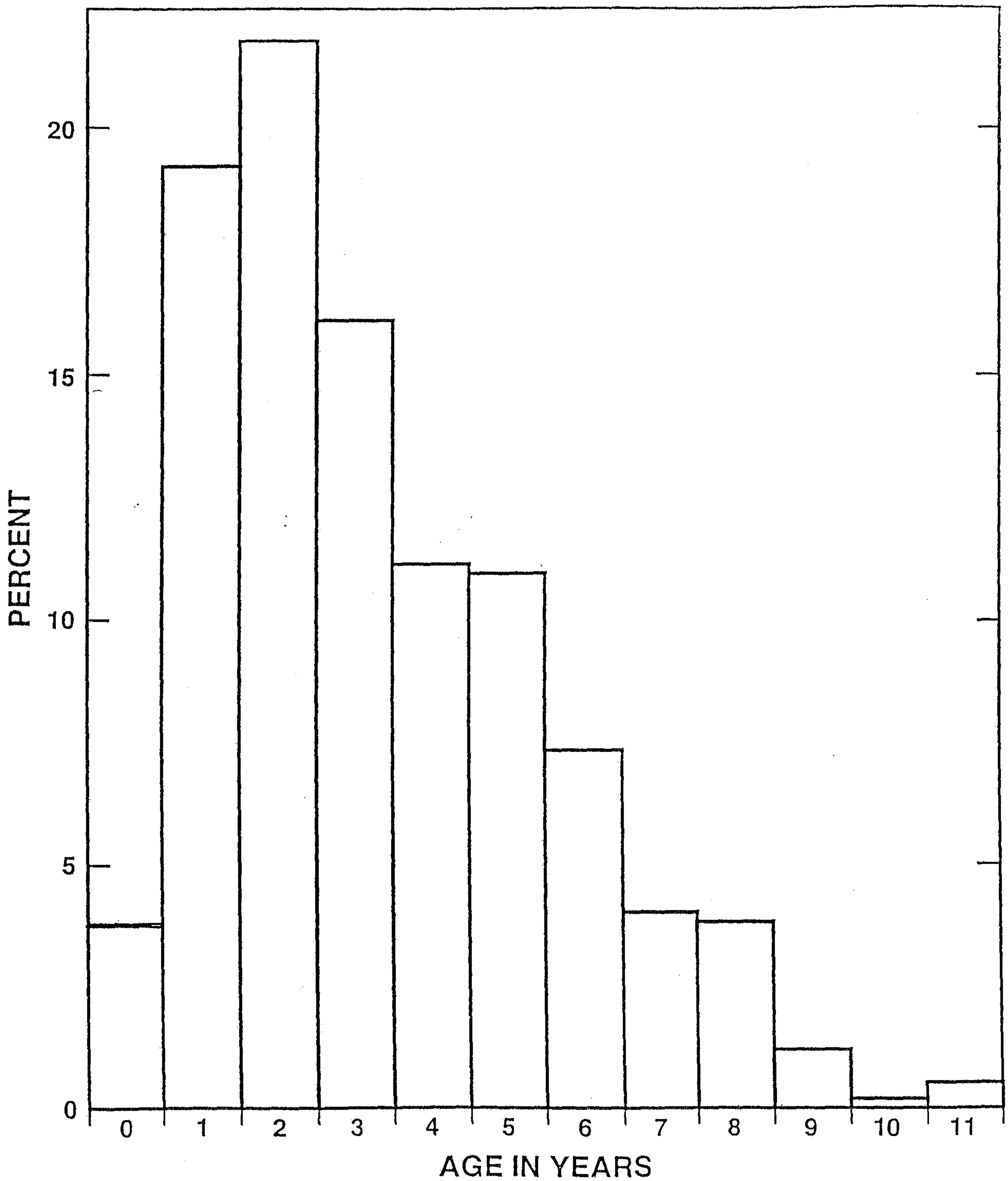

FIGURE 16. Estimated age composition of longline- and recreational-caught swordfish from the Straits of Florida (after Berkeley and Houde, 1983).

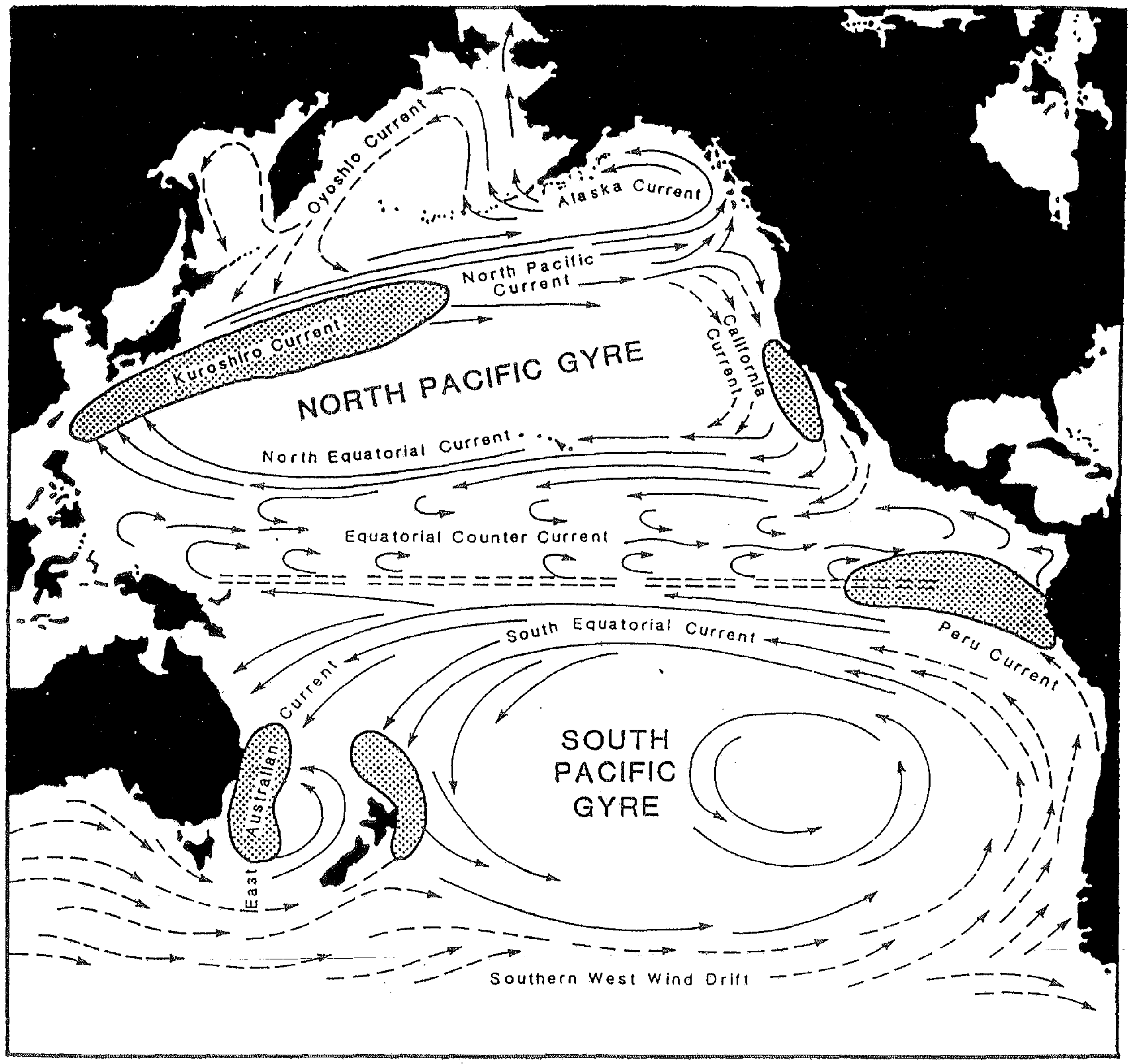

FIGURE 17. Locations of areas in the Pacific Ocean with greater-than-average abundance of swordfish (from Sakagawa, 1989).

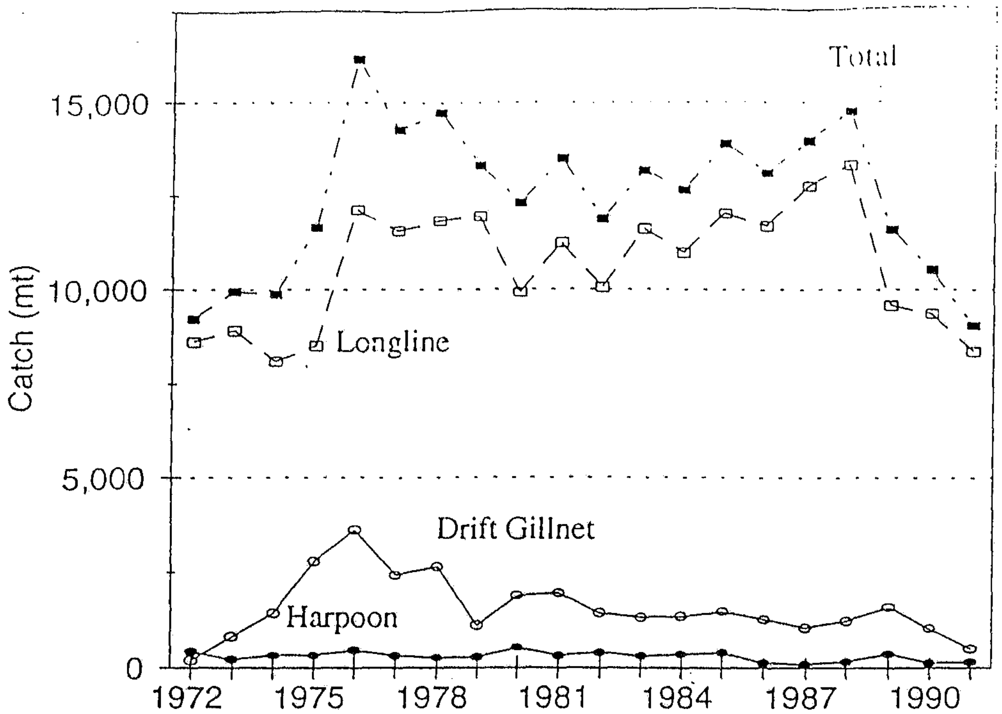

FIGURE 18. Catches of swordfish in the Pacific Ocean by Japanese vessels. The data were obtained from Sakagawa (1989) and Nakano (1994).

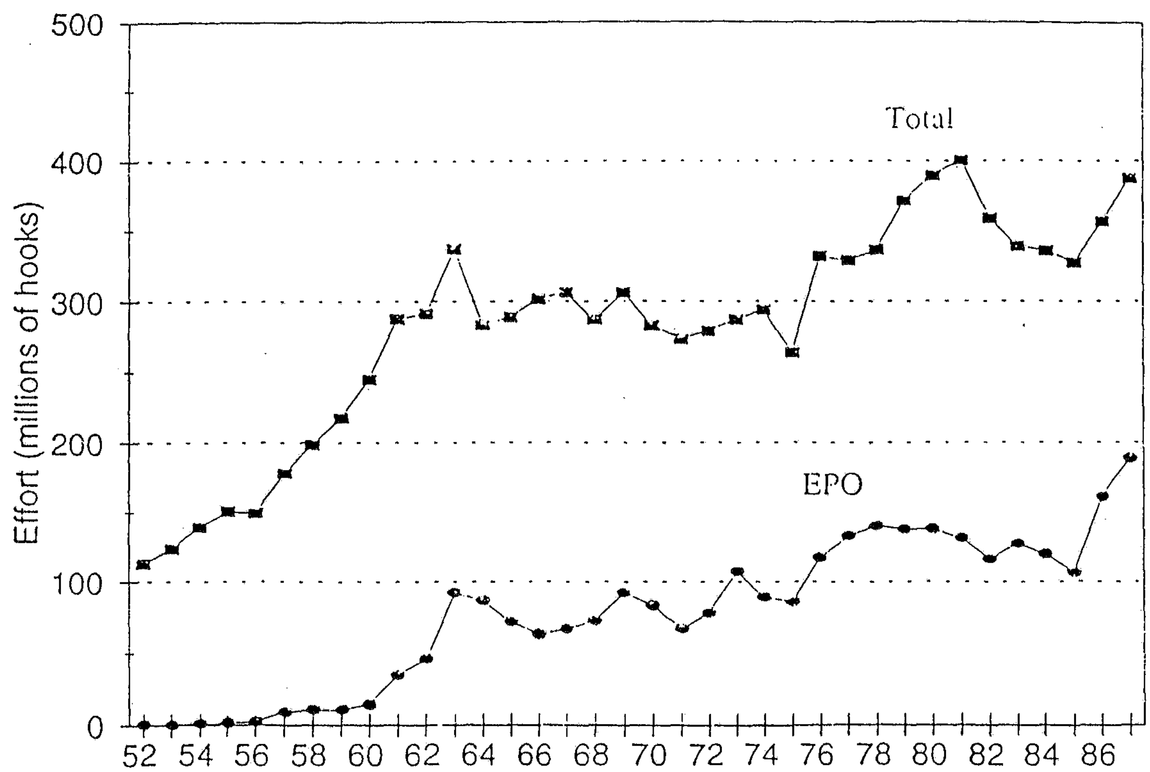

FIGURE 19. Effort by Japanese longline vessels in the eastern Pacific Ocean (EPO) and the entire Pacific Ocean. The data were obtained from Nakano and Bayliff (1992: Figure 2).

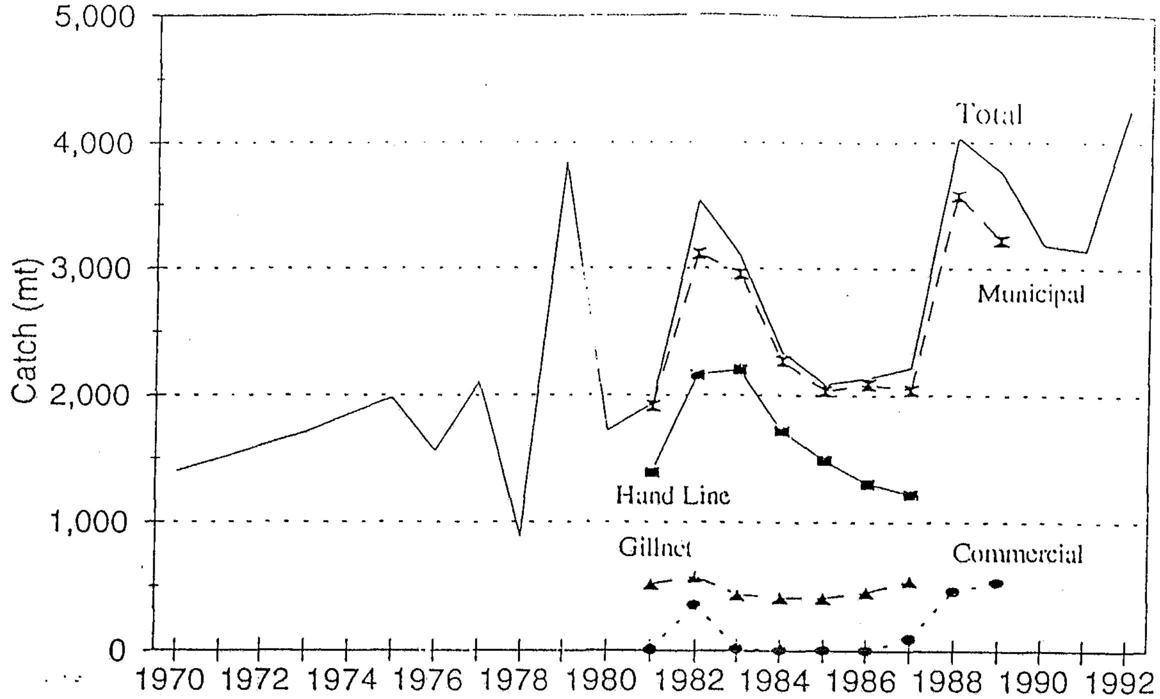

FIGURE 20. Catches of swordfish by Philippine vessels. "Municipal" vessels are those of less than 3 gross tons, and "commercial" vessels are those of 3 or more gross tons. The data were obtained from Barut and Arce (1991) and Anonymous (1994a).

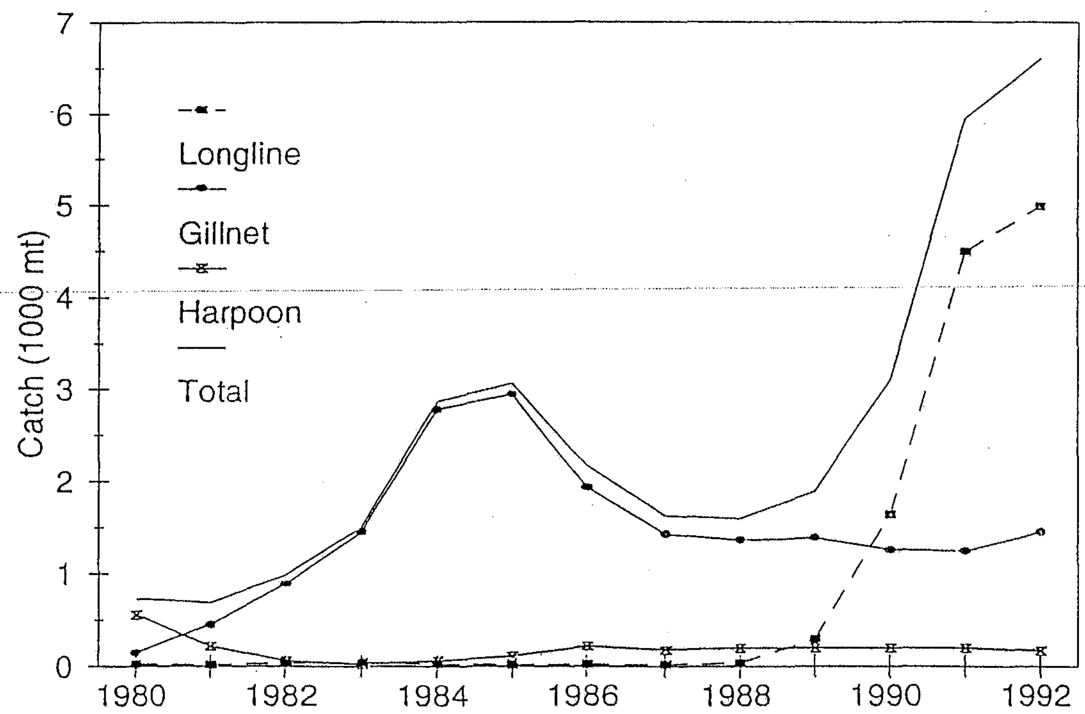

FIGURE 21. Catches of swordfish in the Pacific Ocean by U.S. vessels. The data were obtained from Sakagawa (1989), Ito (1992), Hanan *et al.* (1993), and Anonymous (1994b and 1994c).

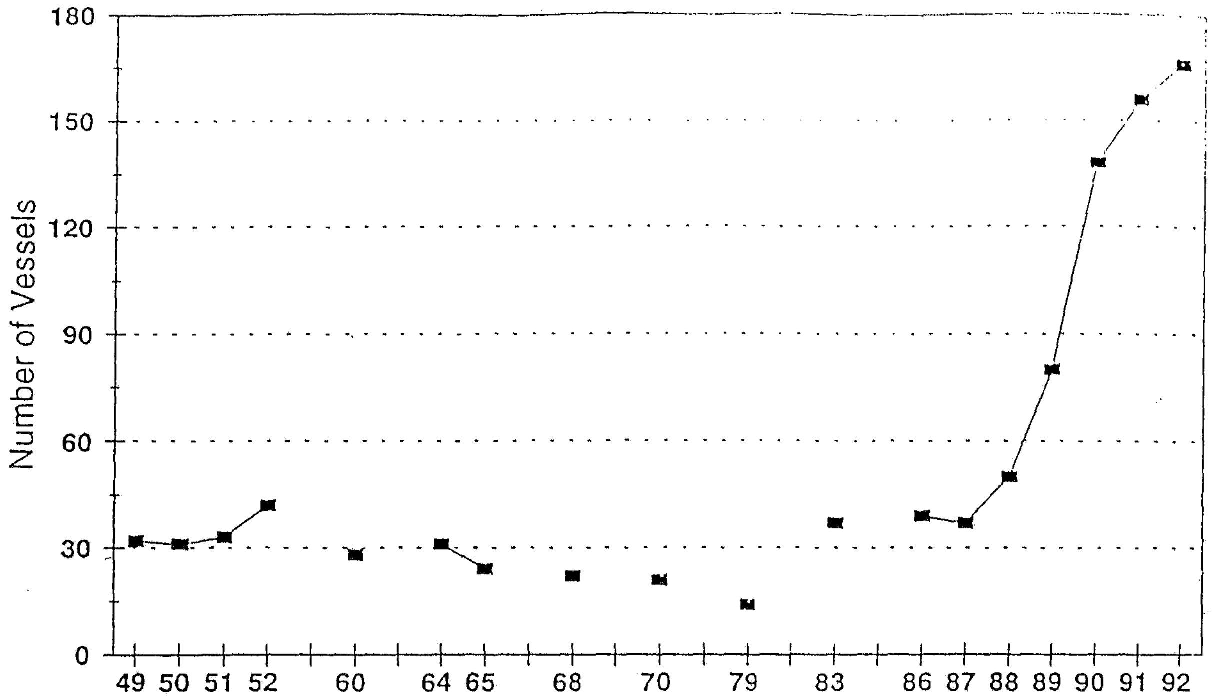

FIGURE 22. Numbers of U.S.-flag longliners operating out of Hawaii. The data were obtained from Kawamoto *et al.* (1989), Dollar (1992 and 1993), and Ito (1992).

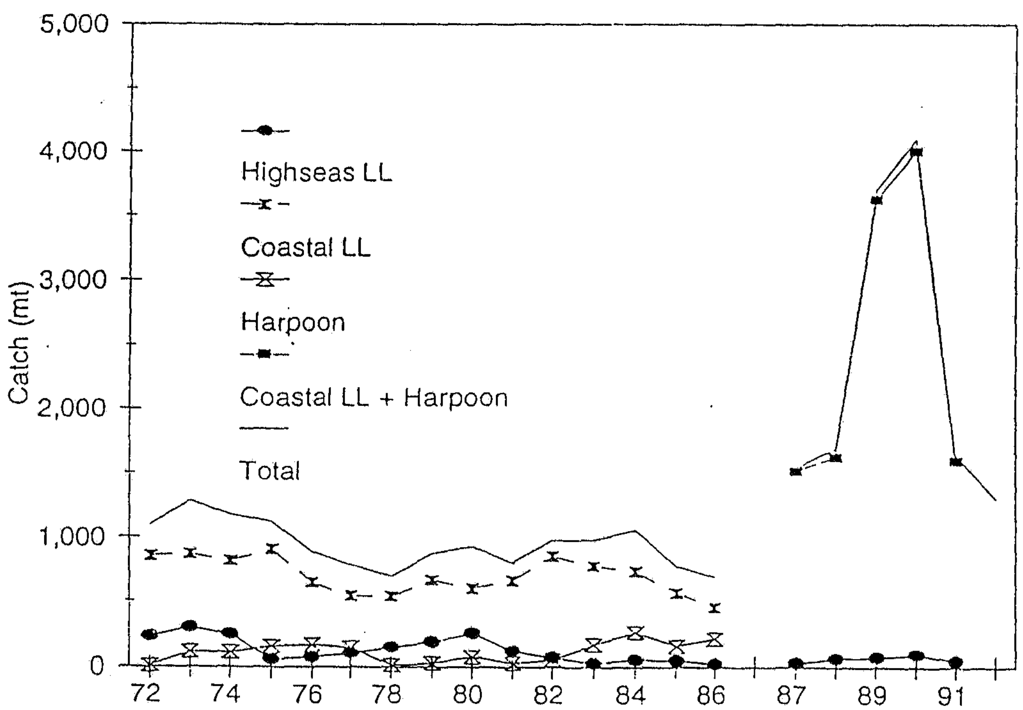

FIGURE 23. Catches of swordfish in the Pacific Ocean by vessels of the Republic of China. The data were obtained from Sakagawa (1989), Anonymous (1992a and 1993a), and Grainger (1994).

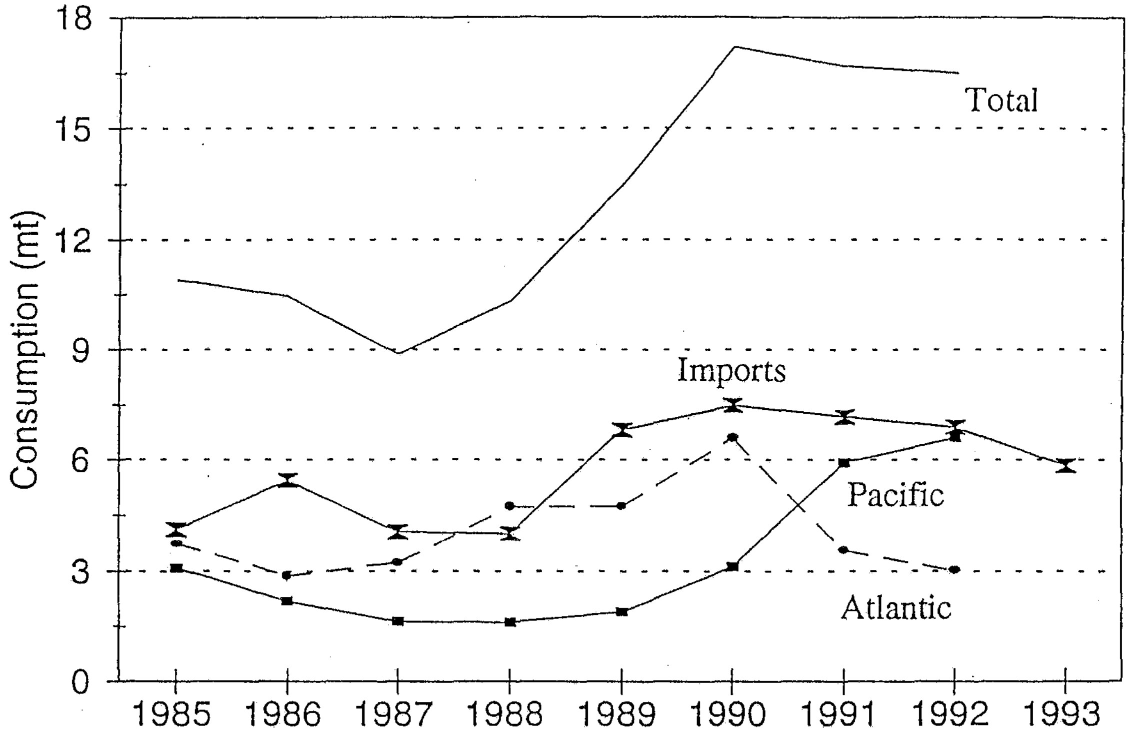

FIGURE 24. Consumption of swordfish in the United States. The data were obtained from Anonymous (1988 and 1992b), Mansilla S. *et al.* (1991), Capurro (1993), and Donley (1994).

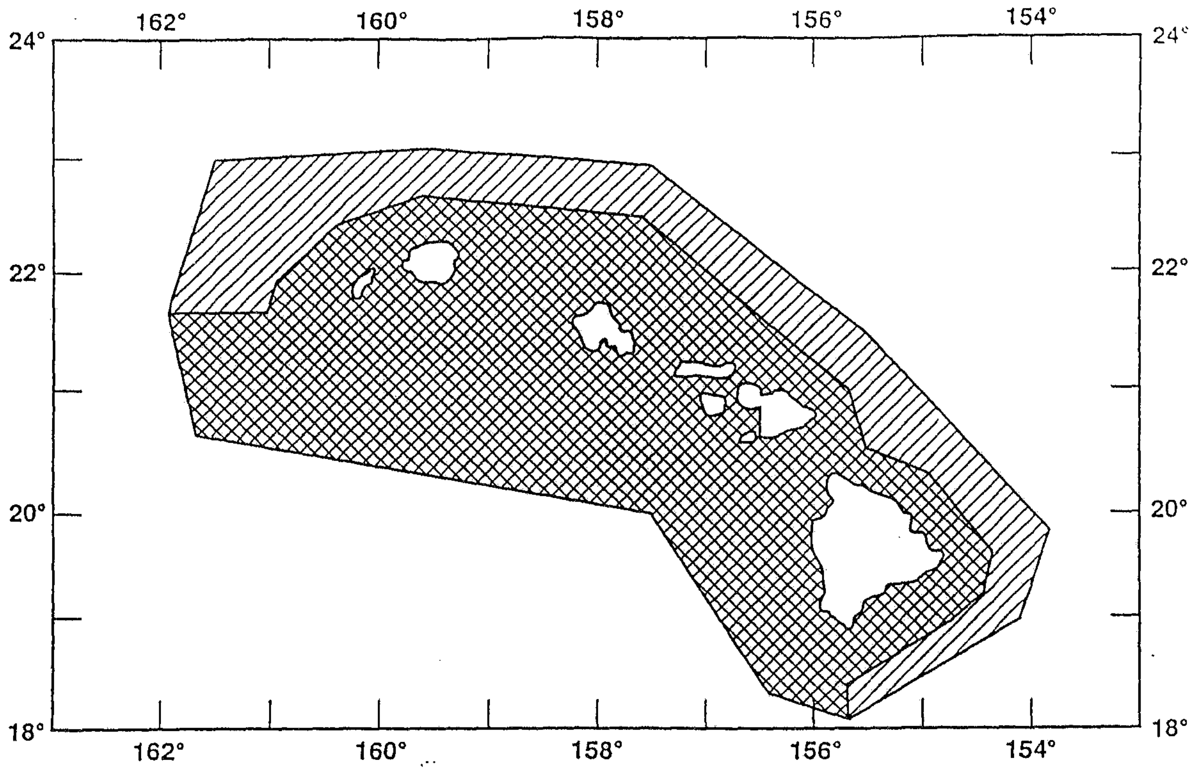

FIGURE 25. Areas around the Hawaiian Islands closed to longline fishing (after Dollar, 1993: Figure 2A). Fishing is prohibited throughout the year in the cross-hatched area and from February 1 through September 30 in the hatched area.

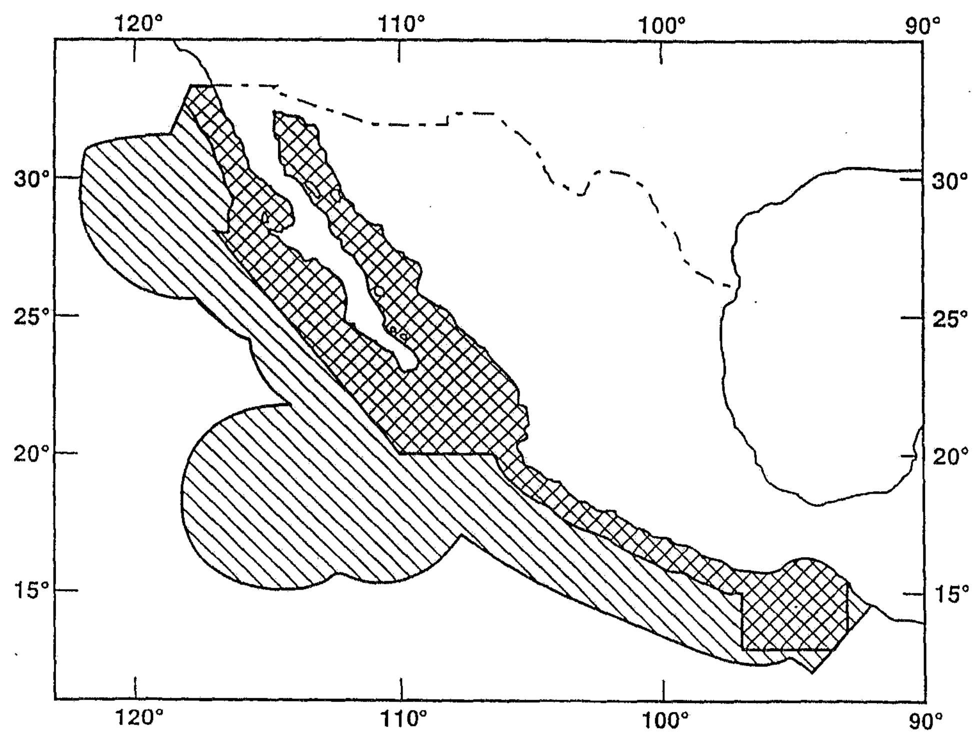

FIGURE 26. Regulatory areas for swordfish off the west coast of Mexico. Recreational fishing is permitted in the cross-hatched area. Both recreational and commercial fishing are permitted in the hatched area.

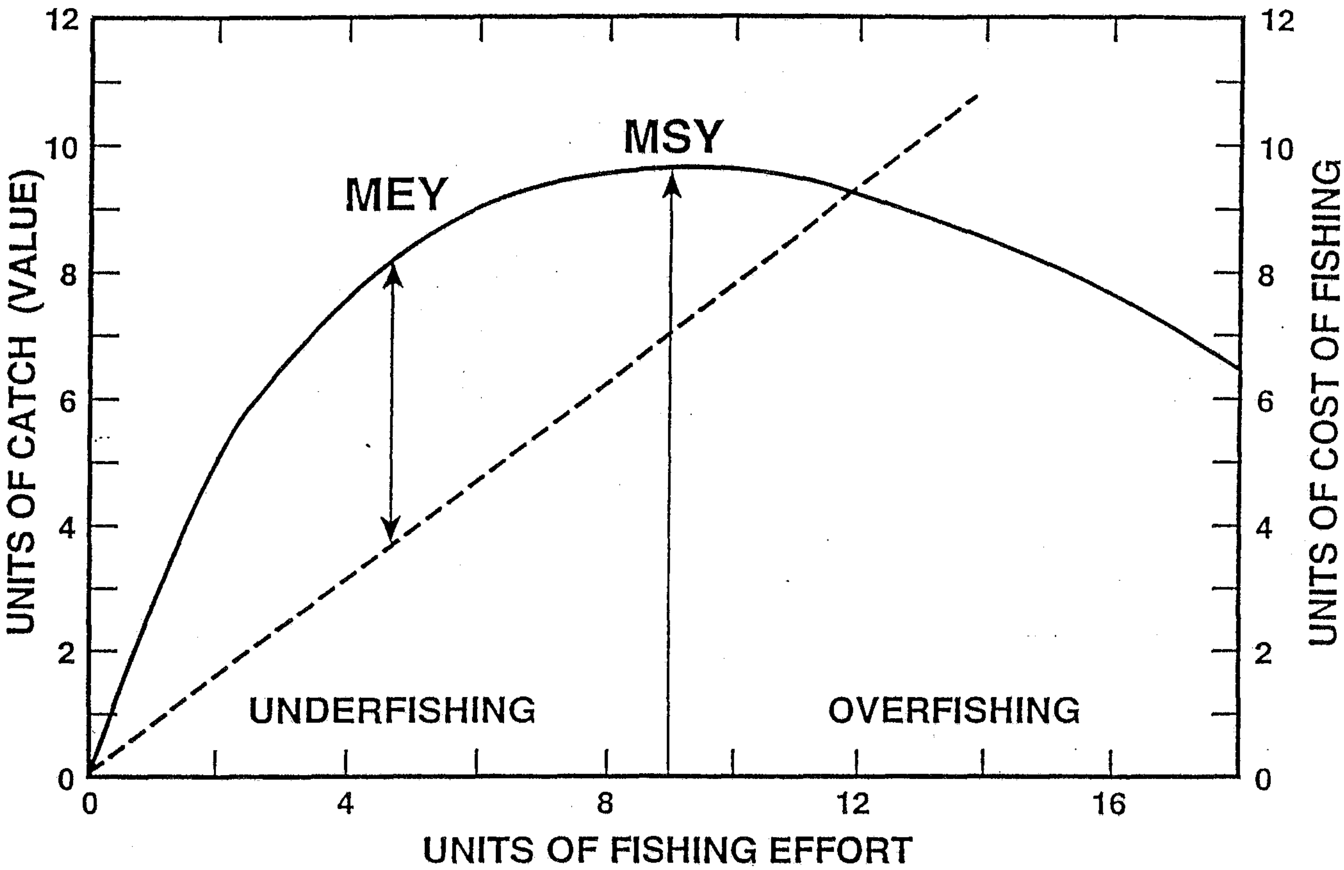

FIGURE 27. Relationships between value of the catch and fishing effort (curve) and between cost of fishing and fishing effort (dashed line). MSY stands for maximum sustainable yield, in value, and MEY stands for maximum economic yield, *i.e.* maximum profit.

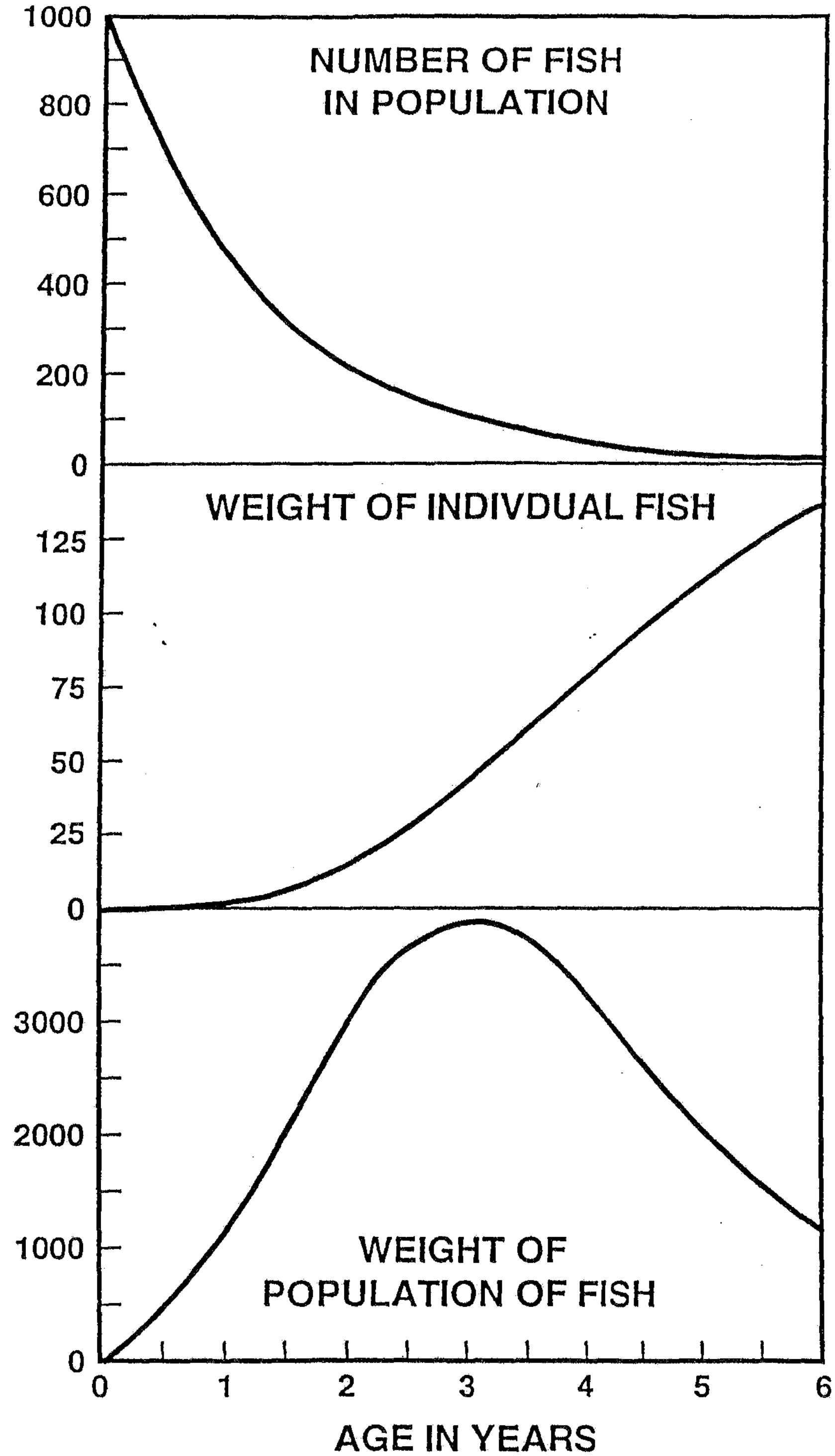

FIGURE 28. Relationships between numbers of fish in the population, weights of the individual fish, and weights of the population of fish.

TABLE 1. Estimates of the parameters of age, growth, and mortality of swordfish (after Boggs, 1989: Table 1).

Method	Number of fish	Sex	Length range (cm)	Source	Parameters of von Bertalanffy growth equation			Coefficient of natural mortality (annual)
					K	t_0 (years)	L_∞ (cm)	
Modal lengths		U	61-245	Yabe et al., 1959	0.124	-1.169	309	0.22
Modal lengths and vertebrae		U	50-260	Caddy, 1976	0.230		365	0.43
Anal spines	275	M	70-270*	Berkeley and Houde, 1983	0.19	-2.04	217	0.35
	164	F			0.09	-2.59	340	0.15
Anal spines	468	M	50-210*	Tsimenides and Tserpes, 1989	0.34	1.22	194	
	506	F			0.25	1.52	220	
Anal spines	263	M	70-270*	Ehrhardt, 1992			281	
	162	F					326	
Otoliths	73	M	88-208	Radtke and Hurley, 1983	0.07	-3.94	277	0.12
	195	F	80-270		0.12	-1.68	267	0.21
Otoliths	39	M	79-209	Wilson and Dean, 1983				
	39	F	102-290					
Tagging data	66	U	100-270	Southeast Fisheries Center, 1987				

* both sexes combined

TABLE 2. Date on the weight-length relationships of swordfish in the Pacific Ocean. The fish were weighed in kilograms and measured in centimeters.

Area	Weight measurement	Length measurement	Number of fish	Size range	loga	b	Source
eastern Pacific	gilled and gutted	eye-fork	10	74.6-231.2	-4.8020	3.0304	Kume and Joseph, 1969b
eastern Pacific	whole	eye-fork	5	131.0-229.0	-4.6754	2.9605	Kume and Joseph, 1969b
central Pacific	probably whole	tip of snout-fork	7	145.2-324.5	-6.6327	3.5305	Skillman and Yong, 1974

TABLE 3. Pacific Ocean and world catches of swordfish, in metric tons. The data were obtained from Anonymous (1964a, 1964b, 1970, 1973, 1976, 1978, 1979, 1987, 1993a), Bartoo and Coan (1989), Sakagawa (1989), and Grainger (1994).

Year	Japan	Chile	Philippines	USA	Rep. of China	Mexico	Other Pacific	Total Pacific	World
1952	11,182			157				11,339	
1953	11,604			85				11,689	
1954	13,301			14	77			13,392	
1955	16,220			80	185			16,485	
1956	12,167			163	254			12,584	
1957	15,771			222	250			16,243	
1958	20,815			279	247			21,341	
1959	19,136			265	262			19,663	
1960	22,944	456		192	273			23,865	
1961	23,636	394		218	432			24,680	
1962	14,037	297		23	544			14,901	
1963	13,775	94		58	300			14,227	
1964	9,703	300		109	300			10,412	
1965	11,955	200		194	300	0	300	12,949	
1966	13,283	200		277	600	0	241	14,601	
1967	13,083	200		181	838	0	1,347	15,649	
1968	12,983	135		118	974	0	833	15,043	
1969	15,612	300		610	1,023	0	1,289	18,834	
1970	11,301	200	1,400	558	1,053	0	2,515	17,027	37,800
1971	9,182	200	1,500	91	1,149	0	315	12,437	23,500
1972	8,846	100	1,600	157	1,095	0	714	12,512	24,300
1973	9,644	400	1,700	363	1,278	0	2,015	15,400	30,400
1974	9,517	218	1,848	383	1,170	0	385	13,521	28,117
1975	11,274	218	1,976	510	1,120	0	273	15,371	32,018
1976	15,843	13	1,558	49	886	0	738	19,087	32,785
1977	13,997	32	2,103	301	789	0	684	17,906	33,360
1978	14,333	56	890	1,536	693	0	634	18,142	40,279
1979	13,091	40	3,845	346	873	7	553	18,755	37,992
1980	11,953	104	1,716	706	932	380	544	16,335	36,402
1981	13,078	294	1,940	674	803	1,575	347	18,711	37,726
1982	11,350	285	3,468	726	984	1,365	347	18,525	43,716
1983	12,511	342	2,974	1,195	979	120	360	18,481	46,587
1984	11,986	103	2,274	2,009	1,056	47	352	17,827	53,517
1985	13,083	342	2,036	2,370	775	18	148	18,772	59,121
1986	14,271	764	2,089	1,585	692	422	69	19,892	61,036
1987	14,867	2,059	2,137	1,221	1,540	550	195	22,569	67,028
1988	15,496	4,455	4,034	1,086	1,690	613	246	27,620	81,036
1989	12,367	5,824	3,756	588	3,692	690	265	27,182	78,074
1990	11,341	4,955	3,187	2,150	4,097	2,650	447	28,827	74,134
1991	9,936	7,255	3,139	4,597	1,645	861	501	27,934	67,581
1992	11,125	6,379	4,256	5,948	1,300	1,160	446	30,614	76,174

TABLE 4. Numbers of Chilean vessels fishing for swordfish (upper panel) and the length composition of these vessels in 1991 (lower panel). The data were obtained from Ponce Martínez and Bustos (1991).

Numbers of vessels					
1986	1987	1988	1989	1990	1991
22	288	440	860	1,200	1,200

Lengths in meters				
Unknown	<= 9	9.1-18	18.1-27.9	>=28
40	63	975	78	50

TABLE 5. Catches of swordfish, in metric tons, and fishing effort, in numbers of hooks fished, by Mexican joint-venture longline vessels. The data were obtained from Squire and Muhlia-Melo (1993).

Year	Catch	Effort
1980	425.1	595,000
1981	1,400.1	2,765,900
1982	836.5	1,808,500
1983	522.6	2,594,700
1984	33.4	262,200
1985	134.2	621,300
1986	781.1	2,006,200
1987	423.5	1,277,000
1988	1,584.0	3,757,100
1989	143.1	607,600

TABLE 6. Observed bycatches and bycatch rates of striped marlin, dolphins and porpoises, whales, and turtles in the California drift gill net fishery (after Hanan *et al.*, 1993). Each retrieval of a net which is monitored by an observer aboard the vessel constitutes an observation.

	1980-1983		1983-1984		1984-1985		1985-1986		1990-1991		Total	
	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate
Observations	226		71		44		66		195		602	
Striped marlin	11	0.048	6	0.085	3	0.068	4	0.061	13	0.067	37	0.061
Seals and sea lions	82	0.364	8	0.113	1	0.023	4	0.061	10	0.051	105	0.174
Dolphins and porpoises	1	0.004			1	0.023	8	0.121	23	0.118	33	0.055
Whales	6	0.027			1	0.023	3	0.45	2	0.010	12	0.020
Turtles			2	0.028							2	0.003

APPENDIX

Yabe *et al.* (1959) measured the "body length" of swordfish, which they defined as the "distance from the posterior end of the upper jaw to the end of the hypural bone [the bone at the posterior end of the vertebral column]."

Kume and Joseph (1969b) stated that "we used 5-cm intervals of the eye-fork length (the shortest distance between the posterior margin of the eye-cavity and the distal tip of the central rays of the tail)." Shingu, Tomlinson, and Peterson (1974) used the same measurement, which they defined as "the eye-fork length which is the distance from the posterior margin of the eye cavity to the fork of the caudal fin." Miyabe and Bayliff (1987) and Nakano and Bayliff (1992) stated that the fish were measured "to the next-highest 5-cm interval from the posterior margin of the orbit to the fork of the tail." Hanan *et al.* (1993) used the "alternate length," which they defined as the distance, in millimeters, "from the anterior margin of the cleithrum [collarbone] to the fork of the tail." They employed this measurement because the fish they were studying had had their heads removed.

Royce (1957: 506) used the "fork length," which he defined as "the straight-line distance from the tip of the snout [anterior tip of the bill] to the tip of center rays of the tail." He calculated equations for converting the lengths of fish measured from the naris (opening of the nasal cavity) to the fork of the tail and from the posterior edge of the orbit to the fork of the tail to fork lengths. Skillman and Yong (1974) used data for lengths of fish measured to the nearest centimeter from the tip of the snout to the fork of the tail plus data for lengths of fish measured in other ways and converted to fork lengths with the equations of Royce (1957) for calculating a weight-length relationship for swordfish.

In the Atlantic Ocean the scientists of the nations which participate in the billfish programs of the International Commission for the Conservation of Atlantic Tunas currently measure swordfish from the anterior tip of the lower jaw to the fork of the tail; this measurement is frequently abbreviated as LJFL. (Hanan *et al.* (1993: Figure 25) refer to this measurement as the "fork length.")

Kume and Joseph (1969b) calculated weight-length relationships for swordfish, using whole weights and gilled-and-gutted weights of the fish.

Royce (1957) used data on weights of fish recorded by dealers at the Honolulu auction market. He stated that "these weights are slightly less than live weights, however, because the swords ... and sometimes the lobes of the tail are removed before delivery to the market. Also large fish are frequently cut in two or more pieces so that they have lost body fluids." Strasburg (1970) did not give any information on the condition of the fish in his analysis, which came from records of the Hawaiian International Billfish Tournament, the Honolulu market, and Japanese longline data. The fish from the billfish tournament were probably weighed whole and those from the Honolulu market were probably in the same condition as those studied by Royce (1957). Skillman and Yong's (1974) fish were probably weighed whole, as they came from the Honolulu market, and the weight-length equation for these fish was compared in their Table 4 to that calculated for whole fish by Kume and Joseph (1969b).