Pelagic Fisheries Research Program:

Ten Years of Excellence

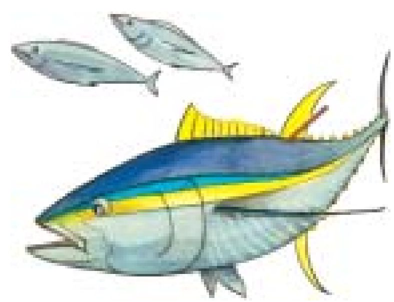
Research and writing: Noreen M. Parks
Editing: John Sibert
Layout: May Izumi

Cover Photo: Richard Herrmann

Executive Summary

This report highlights the accomplishments of the Pelagic Fisheries Research Program (PFRP) over the period 1993–2003. Operating from the University of Hawaii-Manoa, the program supports the scientific research needs of the Western Pacific Regional Fishery Management Council, in conjunction with the National Oceanic and Atmospheric Administration. More than 70 projects have been funded to address questions in fisheries biology, oceanography, statistics and modeling, genetics, protected species, fisheries economics and socio-cultural issues.

The PFRP has played a leading role in promoting research in support of the ecosystem approach to fisheries. Through its links with the University of Hawaii, the PFRP is able to assist in training new fisheries scientists. In its scientific collaborations and participation in multinational forums for fisheries management, the PFRP also has played an important role in fostering international cooperation for the sustainable management of pelagic fisheries throughout the central and Western Pacific. Responding to emerging scientific needs for responsible fisheries stewardship, the program continues to sponsor cutting-edge, multidisciplinary research.



THE PACIFIC OCEAN—HEART OF THE BLUE PLANET, HOME TO THE WORLD'S RICHEST FISHERIES

If you hitched a ride on a space shuttle circling the globe, during much of the voyage the Pacific Ocean would dominate your view of Earth. (Courtesy of NASA.)

If you hitched a ride on a space shuttle circling the globe, during much of the voyage the Pacific Ocean would dominate your view of Earth. Our "blue planet" owes much of its liquid character to the Pacific, which covers nearly one third of the globe—an area larger than all the landmasses combined. More than twice the size of the Atlantic Ocean, the Pacific encompasses over 64 million square miles, spanning from pole to pole and stretching more than 9,000 miles along the equator from Asia to the Americas. Simply put, the Pacific Ocean is Earth's largest geographic feature.

The central and western reaches of the Pacific—from 150° west longitude (just east of Hawai'i) to the shores of Japan, Southeast Asia, Australia and New Zealand—comprise about 40 percent of the entire ocean area. This vast realm contains the planet's highest diversity of marine life, including fisheries that supply direct economic benefits to some two dozen countries and food to millions of people around the world. The character of these fisheries relates closely to that of the 200-plus high islands and about 2,500 low islands and atolls sprinkled sparsely across this ocean sector. Most of these specks of land rise steeply from the seafloor, have no continental shelf, and generally lack the lakes and streams that provide nutrients to support ocean life in the coastal waters of larger landmasses. Thus while nearshore fisheries are immediate and significant resources for Pacific island peoples, they represent only a tiny fraction of the region's marine wealth.

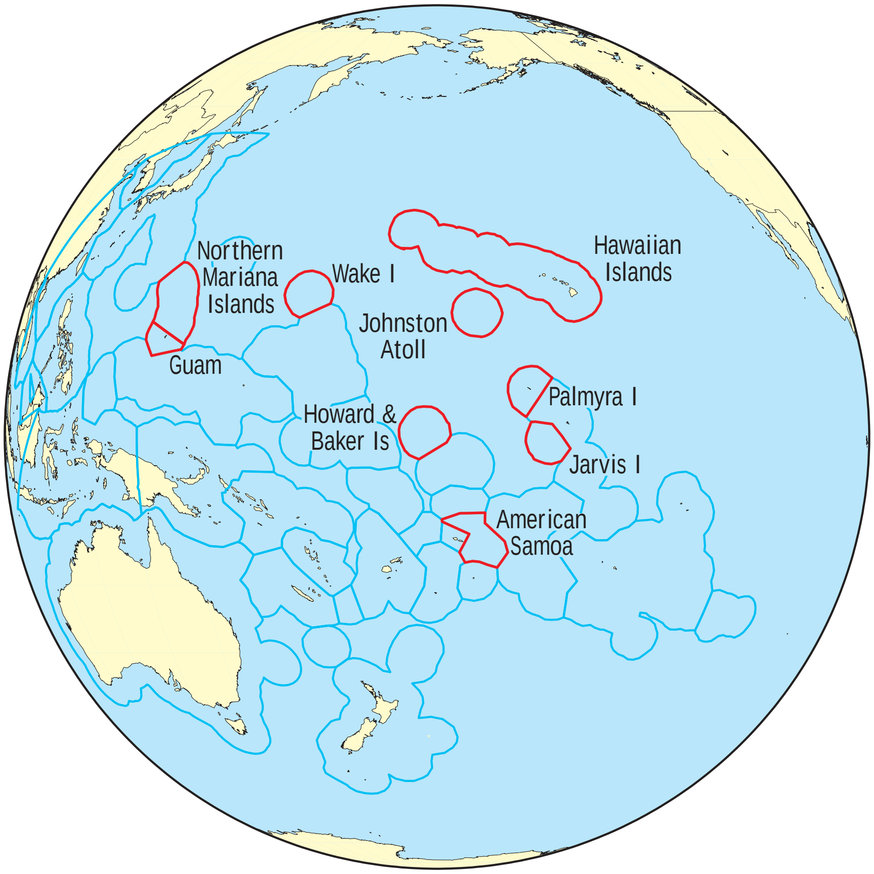
Tunas and billfish (such as swordfish and marlins) are sometimes called the "petroleum of the Pacific" for their economic importance. Their delectable meat and prowess make them some of the most popular fish sought for food and sport. In contrast to fish that dwell near the seafloor or spend much of their lives near land, these "pelagic" fish are masters of the high seas, ranging freely throughout the upper waters of the open ocean. While each species has unique traits and behaviors, in general tunas and billfish grow rapidly and possess champion-like stamina. Clocking speeds of up to 30 miles an hour, they migrate over distances of many hundreds of miles, guided principally by seasonal changes in ocean temperatures and concentrations of prey. During warm seasons some of these streamlined nomads travel as far as northerly latitudes on par with Japan and southerly latitudes of New Zealand. Another key feature of these fishes is their prolific reproduction. Spawned mainly in the open seas, their larvae ride on ocean currents far and wide. Thus, the fisheries targeting these species span the Pacific, and understanding their ecology and sustainably managing those fisheries poses a huge and complex challenge.

The tuna fisheries are by far the most valuable component of the commercial pelagic fisheries of the central and western Pacific (CWP), producing roughly three-quarters of the ocean-wide catch each year. Over the last two decades, tuna catches have expanded steadily, chiefly due to the growth of the purse seine fishery. Throughout the 1990s CWP tuna catches averaged about 1.6 million metric tons (mt)* annually, with an all-time record set in 1998 at 2.04 million mt. The preliminary estimate for 2002 was nearly 1.9 million mt—almost half of the estimated world tuna catch.

Geopolitics and Fisheries Management

The total landmass of the Pacific island nations and US Pacific holdings represents only a tiny fraction of the CWP. However, each political entity has jurisdiction over an exclusive economic zone (EEZ) extending 200 miles offshore, and this combined area amounts to 28 percent of all EEZs worldwide. The substantial US stake across the region includes the State of Hawai'i—

*one metric ton = 1.102 US "short" tons (2204 pounds)



Exclusive economic zones (EEZs) of Pacific Islands. Western Pacific Regional Fisheries Management Council jurisdiction shown in red. (Courtesy WPRFMC)

extending about 1500 miles, from Hawai‘i Island to Kure Atoll—Guam; the Northern Mariana Islands; American Samoa; Johnston Atoll; Palmyra; and Wake, Jarvis, Howland and Baker islands. Together, the economic zones of these far-flung territories is about 1.5 million square nautical miles—nearly half of the EEZ waters under US control.

Adding to the political complexity of the region are the fishing interests of other countries (Japan, China, Taiwan, Korea, Philippines, Indonesia, Spain and others) that operate “distant-water” fleets in the CWP under license agreements with local governing authorities. And, interspersed within and around this mosaic of marine jurisdictions are areas of international waters—the unregulated “high seas” where a lack of official control seriously hampers effective fishery management.

The interests of the stakeholder nations of the CWP and their abilities to exploit fish resources vary considerably, from the developing island nations whose fisheries represent the bulk of natural resource wealth; to the countries whose primary aim is to maximize commercial catches destined for international export; to the industrialized United States, whose stated policy goals include sustainable fisheries and the conservation of marine resources. Notwithstanding these disparities, the management of shared stocks of highly migratory species can succeed only with multinational cooperation and participation. Achieving effective, sustainable fisheries management demands timely and accurate scientific information. With its highly developed capacity for research, the United States has played and must continue to play a leading role in providing a scientific foundation for fisheries policy and facilitating international cooperation.

The declining state of world fisheries further underscores the critical need for sustainable management of Pacific fish populations. Globally, fish provide approximately one fifth of animal protein in the human diet, and about one billion people rely on fish as their primary protein source. Humans directly consume about 80 million mt of fish annually, and the United Nations Food and Agriculture Organization expects demand to increase by as much as 50 percent over the coming decade as the world population grows. At the same time, several decades of increasing fishing pressure have left the majority of important fish stocks depleted or in decline. Recent projections suggest the contribution of fish to the global food supply will likely decrease over coming years as demand for fish rises and production levels out and then falls. In addition, growing concerns over the effects of industrial fishing on marine ecosystems—in particular the discarded bycatch and incidental catches of protected species—have sharpened the urgency of improving our understanding and stewardship of ocean resources.

The essential function of the CWP pelagic fisheries in world food supplies and their unique and highly migratory character makes US leadership in the scientific management of these fisheries vital and inescapable.

The Pelagic Fisheries Research Program—A Unique Program to Meet Unique Needs

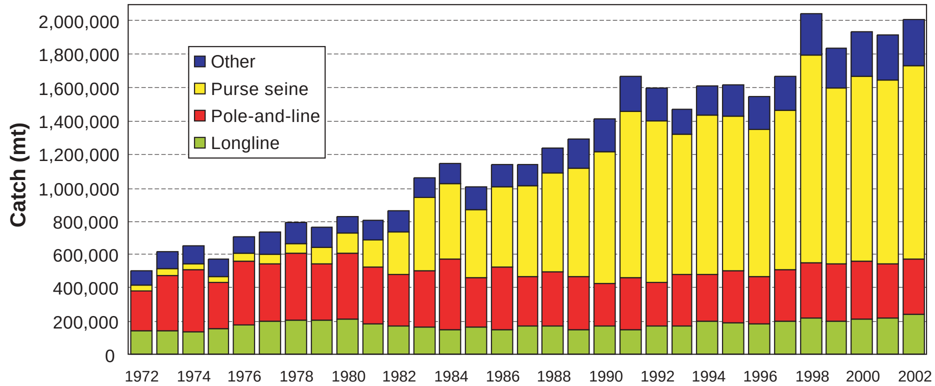
Responsibility for US fisheries management in CWP waters lies with NOAA Fisheries and the Western Pacific Regional Fisheries Management Council (WPRFMC), headquartered in Honolulu. When the council was established under the Magnuson-Stevens Fishery Conservation and Management Act in 1976, fisheries for highly migratory species in the Pacific were relatively undeveloped, and the council received no explicit authority for regulating them. Elsewhere in the world, international fisheries organization played a role in managing fisheries, but in the CWP no such groups existed. During the 1980s as Pacific pelagic fisheries rapidly expanded, the fisheries council recognized this uncontrolled growth could have potentially disastrous effects and the council urged Congress to amend the MSFCMA to include tunas and billfish.

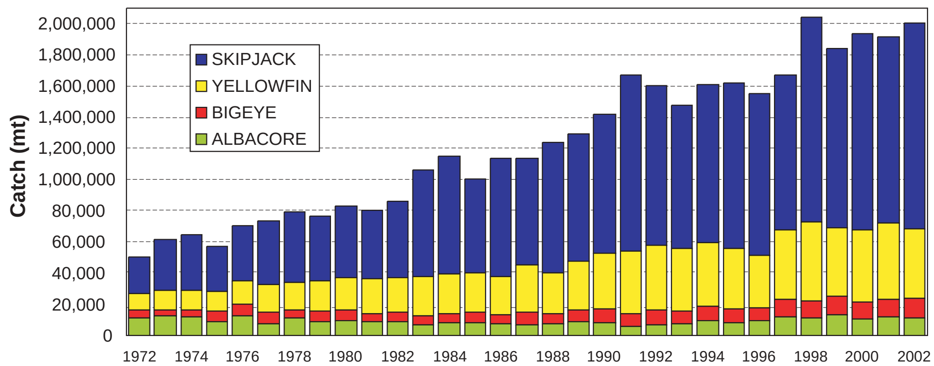
In 1992 Congress made this historic move, at the same time earmarking funds for a dedicated research program to assist the council with the scientific information needed for carrying out its vastly enlarged duties. With a start-up budget of $1.7 million, the Pelagic Fisheries Research Program (PFRP) was launched, with a mission "to foster and sponsor multidisciplinary, collaborative research that addresses critical issues in pelagic fisheries and marine conservation in support of scientifically based fishery management policy."

The Joint Institute for Marine and Atmospheric Research (JIMAR) administers the program under the University of Hawai'i's School of Ocean and Earth Science and Technology. JIMAR is one of eleven joint and cooperative institutes established by NOAA to foster collaboration between academic researchers and the agency's scientists.

The PFRP operates under the general direction of a six-member steering committee, composed of the executive director of fisheries council and the chair of its scientific and statistical committee; the dean of the UH School of Ocean and Earth Science and Technology; and the directors of JIMAR, the National Marine Fisheries Service (NMFS), Pacific Islands Fisheries Science Center, and the Pacific Islands Regional Office. The composition of this steering committee assures that research sponsored by the PFRP meets the highest scientific standards, is pertinent to fishery council priorities, and complements NMFS research programs. Dr. John Sibert has served as fulltime program manager since PFRP's inception.

The PFRP funded its first research project in 1994. Since then, more than 70 projects initiated by individuals and teams of researchers have received funding. The program periodically solicits research proposals to address priorities established by the steering committee. The most competitive proposals undergo rigorous review by the committee and independent scientists. Selected proposals are funded for periods of one to three years. Continuation of projects after their first year depends on evidence of satisfactory progress and availability of funds. Project scientists meet at least once a year to discuss their research and share results. These meetings serve to foster collegiality and help identify new areas of research.





Tuna catches in the WCPO have increased steadily since the 1970s and have been near 2,000,000 metric tons since the late 1990s. The combined United States tuna catch in 2002 accounts for about 7% of the total. Most of the growth in yield is due to the rapid expansion of purse seine fisheries for skipjack and yellowfin in the 1980s. The smaller and more valuable longline fishery for bigeye has also been growing slowly since the 1990s. The results of assessment models developed with PFRP funding show that populations of skipjack and albacore are sustainable at these levels, but that by-catch of juvenile bigeye and yellowfin in the purse seine fishery should be reduced. (Anonymous [2004]. Report of the Sixteenth Meeting of the Standing Committee on Tuna and Billfish (SCTB16), 9-16 July 2003, Mooloolaba, Qld., Australia. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Secretariat of the Pacific Community (SPC). (available at http://www.spc.int/OceanFish/Html/SCTB/SCTB16/sctb16_final.pdf).

A tuna seiner circling a school of tuna as seen from spotter aircraft. Courtesy of NOAA.

Highly migratory pelagic fish are targeted and incidentally caught in several US fisheries. The major ones in the CWP are as follows.

- The purse seine fishery for skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) tunas.
- The longline fishery for large tunas (bigeye and albacore) and swordfish (*Xiphias gladius*).
- The distant-water troll fishery for albacore (*Thunnus alalunga*).
- The troll-and-handline fishery for other tunas, blue and striped marlins (*Makaira mazara*, *Tetrapturus audax*), mahimahi (also known as dolphinfish or dorado: *Coryphaena hippurus*) and other pelagic species.

In 2002, about 170 US-licensed commercial vessels operated on the high seas in the first three of these fisheries, and roughly 2,000 small vessels (under 45 feet long) participated in the troll-and-handline fishery in nearshore waters.

The combined total catch for US fisheries in the CWP during 2002 was nearly 139,000 mt (approximately 306 million pounds). This represents about 7 percent of the total estimated catch for all countries operating in the CWP (roughly two million mt). The 2002 catch consisted predominantly of skipjack tuna (63 percent) and yellowfin tuna (22 percent).

Purse Seine Fishery—The purse seine fishery uses huge nets to encircle and capture entire schools of fish. It is the largest US fishery in the CWP. However, because of domestic regulations and international treaty arrangements, it is largely outside the jurisdiction of the WPRFMC.

In 2002, 29 purse seine vessels landed 119,000 mt of tuna, accounting for 86 percent of the total catch for all US fishers in the region. The estimated CWP catch for all purse seine vessels in 2002 was 1.16 mt—the second highest on record for the region. Skipjack tuna comprised about three-quarters of the catch, yellowfin tuna nearly a quarter, and bigeye tuna around three percent. More than 90 percent of the 2002 catch was delivered to the American Samoa canneries.

Longline Fishery—The second most prominent US fishery in the CWP is the longline fishery, with vessels based primarily in Honolulu and at California ports. Longliners set lines up to 60 miles long, with thousands of branch lines attached that bear baited

Comparisons of U.S. catch of highly migratory species by gear type and by composition for the years 1998-2002 in the central-western Pacific (from a working document by Ito, Hamm, Coan, and Childers for the 16th Standing Committee on Tuna and Billfish, Mooloolaba, Australia, July 9–16, 2003).

Total pelagic landings in lbs in the Western Pacific Region in 2002*

Species	Am Samoa	Guam	Hawaii	CNMI
Swordfish	37,101		461,000	
Blue marlin	74,257	53,553	1,001,000	1,261
Striped marlin	3,850		558,000	
Other billfish	12,347	2,285	371,000	18
Mahimahi	86,513	172,674	1,164,000	17,937
Wahoo	358,238	71,810	620,000	8,160
Opah (moonfish)	6,762		915,000	
Sharks (whole wgt)	6,540	0	388,000	
Sharks fins				
Albacore	13,104,279		1,522,000	
Bigeye tuna	431,711		10,266,000	
Bluefin tuna			2,000	
Skipjack tuna	520,265	175,836	986,000	177,487
Yellowfin tuna	1,079,598	44,932	2,462,000	29,394
Other pelagics	11,299	12,765	676,000	19,017
Total	15,732,759	533,855	21,392,000	253,274

*Does not include purse seine landings.

hooks. Typically the lines are set at depths of 100-300 meters (about 300–1000 feet) and are left in place for periods ranging from several hours to a couple of days. The configuration of the lines, including the addition of floats and weights, is tailored to different species and habitats.

From the late 1970s to the late ‘80s, the size of the Honolulu-based longline fleet tripled—primarily due to an increased focus on swordfish—and by 1992 the fishery was a major supplier of fresh tuna and swordfish to North America and Europe. (Almost all of this catch is sold at auction in Honolulu and shipped from there.) The dramatic growth of the longline fishery brought with it a substantial increase in the incidental catch of protected sea turtles and seabirds, resulting in critical fishery management issues. In November 1999 a federal court issued an injunction to close 16.5 million square miles in the EEZ to the Hawai‘i longline fishery to reduce impacts on federally protected sea turtles, which prompted many longliners to relocate to California.

The 100 longline vessels currently based in Honolulu and 23 in California accounted for approximately 56 percent of the 2002 US longline catch (about 9,100 mt). While the longline portion of the US regional catch is only about 7–12 percent, high-value products such as sashimi-grade bigeye tuna significantly boost the fishery’s economic impact. In 2002 swordfish catches declined by two-thirds compared to the previous year, but landings of bigeye and albacore rose by 83 percent and 42 percent respectively. Hawai‘i longliners now fish almost exclusively for large tunas in the EEZ and international waters, while California longliners primarily target swordfish in international waters. American Samoa’s longline fleet, which focuses primarily on albacore and operates exclusively in the South Pacific, has expanded greatly during recent years. Its 60 vessels accounted for 44 percent of the entire US longline catch in the CWP in 2002. Also, a few US longliners fish in the waters of the Federated States of Micronesia, Marshall Islands, Fiji, and Cook Islands, generally targeting bigeye and yellowfin tuna.

A section of the fishing fleet at Honolulu Harbor. Courtesy of NOAA.

Yellowfin tuna coming aboard during pole and line fishing operation. Courtesy of NOAA.

Distant-water Troll Fishery—The distant-water troll fishery for albacore primarily involves vessels based in Oregon, Washington and California that operate in the North and South Pacific. The number of US vessels in the CWP has decreased by almost 60 percent since 2001 (to 14 vessels) because of depressed albacore prices, and catches have fallen by roughly half. Albacore landings in 2002 were approximately 1,000 mt, with catches split between deliveries to American Samoan canneries and transshipment elsewhere.

Troll and Handline Fishery—Nearly 2,000 small vessels troll and use handlines to catch fish in Hawai‘i, American Samoa, Guam and the Northern Mariana Islands. Hawai‘i-based boats make up almost 80 percent of the fishery. Troll and handline catches decreased 29 percent to about 2,100 mt in 2002. The catch was predominantly yellowfin tuna, skipjack tuna, and mahimahi (also known as dolphinfish or dorado, *Coryphaena hippurus*). These fish are sold mainly at local markets.

Longliner docking in Pago Pago, Samoa. Courtesy of NOAA.

Well into the 21st century, the Food and Agriculture Organization of the United Nations has warned the world that more than 75 percent of the major fish stocks in our oceans are depleted, over-exploited or fully exploited. The tropical tuna stocks of the central and western Pacific Ocean are considered to be hopeful exceptions to this otherwise bleak situation. However, fishing pressure on these stocks has intensified over recent decades, the responsible agencies face the challenge of managing them on the knife-edge between sustainability and disaster.

Essentially, fishery management is the practice of manipulating the fishing community to achieve some social or political goal. This generally entails restrictions on the activities of fishers, toward the goals of sustainable use, and conservation of the resource. Other goals of fishery management may be equally important and legitimate, however. For instance, a coastal state may adopt a policy of restricting foreign access to increase the value of fishing licenses and, in turn, revenues from foreign fishing. Or a coastal state may adopt policies that favor access to local fishers—perhaps even at the expense of the resource—to foster development of local fishing fleets. Or one resource user may adopt a goal that restricts activities of other resource users in order to reduce competition both in the market place and on the fishing grounds. Or, as with the United States, the goal of fishery management may be "optimal use."

The aims of various user groups frequently are incompatible, and fishery management requires balancing conflicting values on the basis of incomplete and often faulty information. The information required to support management depends on the goals. Integrated fishery research is a means for inserting additional information into the analysis of fisheries and supplying the results to managers in a useful format. While the notion that policy makers and fishery managers should be completely informed to make important decisions is not novel, in practice it is extremely demanding to generate the required information and to present it to decision-makers in a timely and useful form.

Fishery management for the 21st century demands carefully designing integrated and multidisciplinary research for improving and applying tools for the analysis of fisheries and development of effective management policies. This imperative has been the operating principle for the Pelagic Fisheries Research Program in providing scientific information for the development of pelagic fishery management policies by the Western Pacific Regional Fishery Management Council (WPRFMC).

Management Challenge: The Hawai‘i Longline Fishery

The history of the Honolulu-based longline fishery from the 1980s to the late ‘90s offers an example of the complexity of management problems faced by the WPRFMC (and other management bodies throughout the world). It illustrates the types of information required to manage fisheries and introduces a framework for guiding integrated multidisciplinary research on pelagic fisheries.

The Hawai‘i longline fishery dates back to the 1940s. In the 1970s, catches by the Honolulu-based longline fleet began to expand, and in 1983 longline landings surpassed the previous historical record, set in 1948. During the late 1980s the size of the longline fleet tripled as nearly 100 vessels and their crews migrated to Hawai‘i, mainly from US ports in the Atlantic Ocean and Gulf of Mexico, where swordfish stocks were declining. Broadbill swordfish (*Xiphias gladius*) became a primary target of the Hawai‘i longline fleet, which quickly developed into the largest supplier of swordfish to domestic markets.

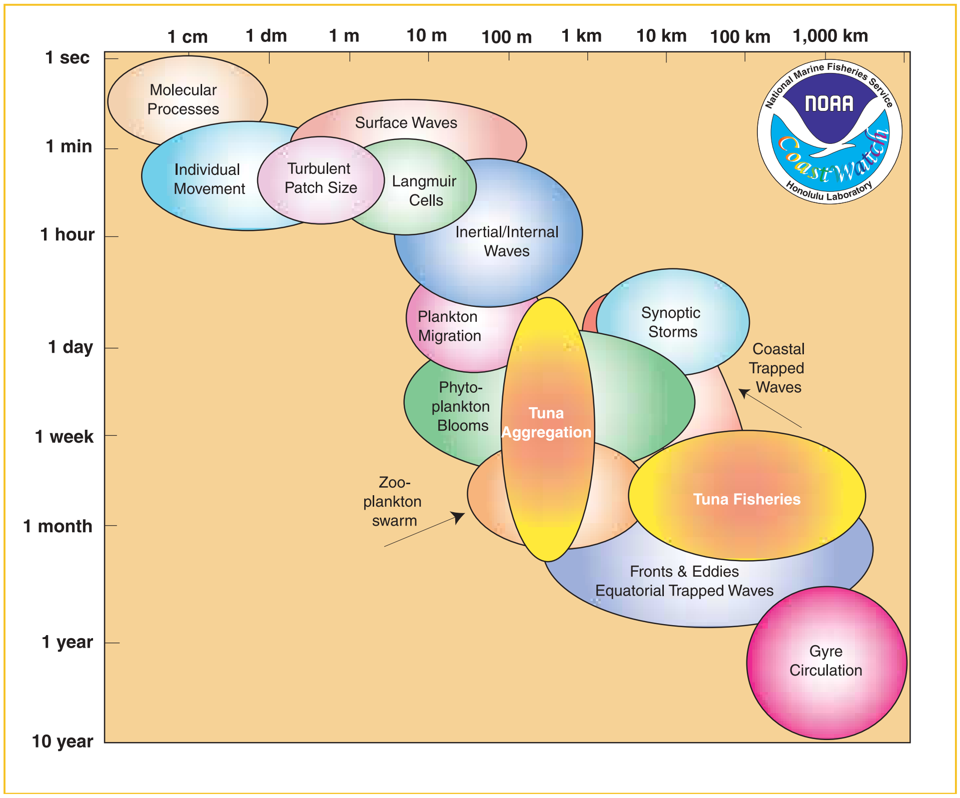
This rapid influx of fishing power and crews naturally caused problems for fishery managers. There were the usual resource questions: Was the swordfish resource capable of sustaining high levels of exploitation? (This was a particularly urgent question given the decline of the Atlantic swordfish fishery.) Considering that the longline fleet also catches significant numbers of yellowfin and bigeye tuna, were tuna resources capable of sustaining higher levels of exploitation? Would tuna harvesting by longliners impact the ability of commercial trollers and handliners to catch tuna? If the swordfish stock declined would the longliners begin to target tunas, further intensifying pressures on local tuna stocks? (This question concerned the users of the resource as well as the resource itself.) And finally, were there "local" tuna stocks in the vicinity of Hawai'i?

There were also sociocultural concerns. Local longliners had established relationships with other pelagic fishers, such as trollers and recreationists. There were informal divisions of fishing grounds and few conflicts. The newly arrived longliners did not share these common cultural values, and there were confrontations.

In 1991 the fishery council set a moratorium on new entries to the fishery, and some areas were closed to longlining to minimize the increasing number of interactions with the federally endangered Hawaiian monk seal. These actions calmed the social situation and allowed time for development of more thoughtful management strategies. Unfortunately, there were few data on the north Pacific swordfish population, none on longline economic performance, and only fragmented data available on tuna populations to inform management considerations.

A decline of swordfish catches in 1994 reinforced the worst fears of many people associated with the fishery. The causes of the decline were not clear, however. An *ad hoc* interdisciplinary group of biologists, economists, and oceanographers from the PFRP and the NMFS Honolulu Laboratory assembled to investigate the problem, focusing on three hypotheses:

1. Absolute abundance had declined, due to fishing pressure, swordfish population changes (e.g., changes in the survival of young or increases in mortality), or a combination of these two factors.
2. Availability of the swordfish had become limited due to changes in their distribution (e.g., changes in migration patterns).
3. Fishing power had decreased, due to fewer fishers participating in the fishery, or fishers switching to other target species.



Spatial and temporal scales of ocean processes in relation to the scales of tuna populations and fisheries.

The researchers examined the limited economic and other data on the fishery that had accumulated since 1991 and discovered many confounding facts. The catch-per-unit-effort (CPUE) of the swordfish-directed segment of the longline fleet fell between 1992 and 1994, but then recovered sharply in 1995. The size distribution of the fish caught did not change in any way that suggested high levels of exploitation. The group suspected that overall swordfish abundance may have been reduced, but that made it difficult to explain the rapid recovery in 1995. Participation in the fishery also had changed, which partially accounted for the decline in total catch and effort and possibly for changes in CPUE after the departure of some of the fleet's "high-liner" fishing vessels. The spatial distribution of the catch also had varied year by year, further increasing the difficulty of reaching general conclusions about the fishery. A potentially important factor in explaining the observed decline and subsequent recovery of swordfish catches was the variability in the strength of the convergent oceanographic front near the fishing grounds. In the end, the group very cautiously concluded the most likely explanation for the decline was a change in the ocean environment that affected the availability and/or catchability of swordfish.

Fisheries as Globally Coupled Systems

The swordfish anecdote demonstrates how rapidly distant events may impact local conditions. US longline vessels had moved from one ocean to another. The move was not predicted and indeed happened so swiftly it was essentially complete before fishery managers could react. Migration of pelagic fishing fleets is not uncommon. In the early 1980s large purse-seiners moved from the eastern to the western Pacific and from the Atlantic to the Indian Ocean. Large-scale fleet movements confront local fishery managers with social and resource problems, with the challenges arriving as suddenly as the vessels. Thus fishery management—at least with respect to pelagic fisheries—has acquired global dimensions.

The swordfish example also illustrates that analysis of fishery management problems must be a multidisciplinary enterprise. Social and economic changes in the fleet interact with environmental changes to cause changes in catches and catch rates that are difficult to understand. Fisheries inextricably couple human and natural systems. The productivity of fisheries resources depends on the dynamics of the species and on environmental constraints imposed by the ocean ecosystem. The exploitation of fisheries resources depends on economic and cultural forces. The act of exploitation couples natural production systems to human social systems and induces additional layers of uncertainty. The fact that these systems and the nature of the coupling are incompletely understood further heightens the complexity, and added complications emerge as the scope of these systems expands from local to global.

Policy development requires a means of discriminating among alternative policies in the context of management goals. Decisions made imply that some management scenarios are "better" or "worse" than others. The Magnuson-Stevens Fishery Conservation and Management Act specifies "optimal use" as a goal of fishery management. Since optimality is an inherently quantitative concept, a critical requirement for developing optimal policy is a consistent measure, or yardstick, that can be applied to objectively compare policies.

The information required to develop optimal fishery management policies is essentially the same as that required for predicting catch. Prediction of catch obviously requires the ability to make predictions about the resource, but catch ultimately depends on the resource users (fishers). Therefore, the prediction of catch also requires the ability to make predictions about the fishers.

Resource (THE FISH)	Users (FISHERS)
Identify and Characterize	Identify and Characterize
Movement Between Fishing Grounds	Movement Between Fishing Grounds
Response to Exploitation	Response to Change in Resource
Response to Environment	Response to Economic Conditions
	Response to Changes in Policy
Forecast Population	Forecast Effort

The information needed to make these two types of predictions should guide research for fishery management. Taking this a step further, predicting the effects of management actions on the resource and its users is essential in evaluating policy. These two branches of inquiry concern the resource on one side and the users of the resource on the other. The PFRP is based on this vision of fisheries research as a set of parallel inquiries directed at the resource and its users.

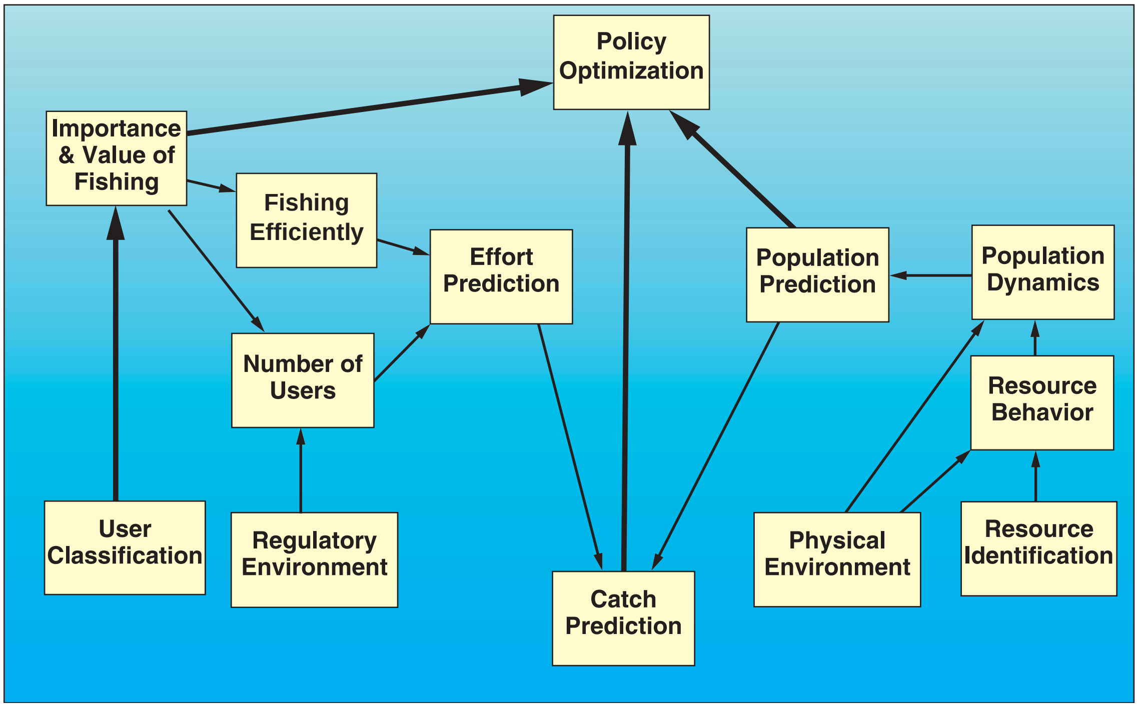
A Catch Prediction Model

Models are valuable—some would say essential—components of scientific research. In the most general sense, models outline the conceptual understanding of the phenomenon under study. Using a model to shape a research agenda for resource management focuses attention on processes rather than problems. Understanding processes enables researchers and managers to anticipate problems before they occur instead of reacting to them in an ad hoc way.

The flow diagram below outlines a conceptual model for policy optimization and catch prediction. This model explicitly includes the idea that exploitation of the fishery couples two complex and disparate systems—resource and users—and attempts to break down the problem of catch prediction into component problems. Though obviously an oversimplification, it serves to illustrate how analysis of a general model leads to specific information requirements. Each of the boxes and arrows in the diagram can be further broken down to yield specific research problems. The PFRP has supported more than 70 research projects that have addressed topics in the majority of boxes.

The diagram reveals two essential pieces of information required to predict catch: population size and fishing effort. Over the past 20 years, researchers have spent considerable effort toward creating models that explicitly include the structure and movement of fish populations through space and time. Such models are extremely promising starting points for the development of catch prediction models. However, some substantial difficulties remain to be solved. It is at this point that models are of great value in shaping research priorities.

Measuring the amount of fishing—The ability of models based



Conceptual model of catch prediction and policy optimization. Courtesy of John Sibert.

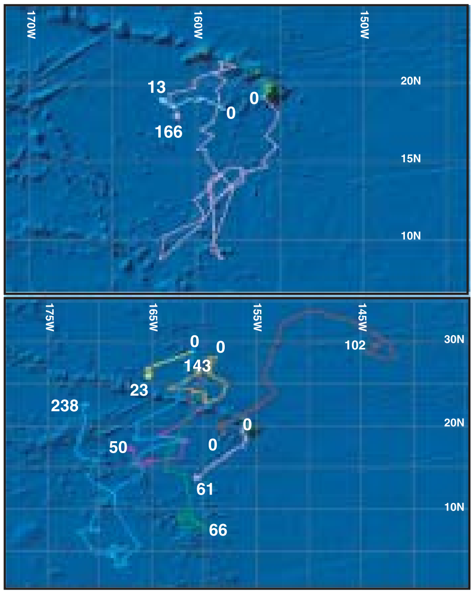
on population movements to predict catches depends on knowing the distribution and intensity of fishing. The population dynamics components of the models predict the general distribution of the population, but specific catch predictions depend on the amount of fishing at a particular time and place. These models "hindcast" catches, provided adequate fishing effort data are available. The ability to "forecast" catches depends on the ability to "forecast" fishing effort. This emphasizes the critical need not only for collecting detailed information from the fishery on the time and place of fishing, but also for research into fishing practices. Understanding how fisheries policy, economic and social factors, and resource abundance interact in determining the time and place of fishing is a critical but sadly neglected research need.

Ecology and habitat—Fisheries population models traditionally have included only the classic processes of population growth, mortality, and exploitation. Newer models include large-scale population movements—both well-defined seasonal migrations and movements in response to changes in critical environmental characteristics such as temperature, oxygen and prey.

Toward a Comprehensive Theory of Fishery Dynamics

Computational and mathematical tools that were almost unimaginable 50 years ago are now available for use in research that supports fisheries management on huge geographic scales. It is possible to conceive of population models that integrate all the important features of population dynamics, with the realistic expectation of estimating these parameters directly from fisheries data. Thus researchers can test how notions of growth, mortality, movement and exploitation interact, extending ideas about the dynamics of exploited fish populations to embrace the dynamics of whole fishery systems. In short, it's now possible to build a comprehensive theory of the dynamics of fisheries systems. The overriding challenge of the 21st century likely will be to manage the world's fisheries at full exploitation. To meet this challenge we need tools that explicitly include the broad-scale complexities inherent in the coupling of global systems. The types of models nurtured by the PFRP are clearly important steps in that direction.

GETTING TO KNOW THEM—THE BIOLOGY AND ECOLOGY OF PELAGIC FISHES



Pop-off archival tags, or PATs, store information on an animal's environment, detach from the fish (pop off), and transmit the information back to the research via satellite. PFRP researchers have been monitoring shark movements with PATs near Hawaii to determine the fate of animals released from hooks. The numbers on the figure indicate the history of the track. "0" indicates the position of the fish when tagged (day zero), and the second number indicates the number of days at liberty. Upper panel shows two oceanic white-tip sharks, *Carcharhinus longimanus* and the lower panel shows four blue sharks, *Prionace glauca*.

When Congress expanded the mandate of NOAA Fisheries and the fishery councils to manage pelagic fish stocks in 1992, basic scientific knowledge about highly migratory species was in many respects rudimentary. Since then, more than a third of the PFRP's 70-plus projects have focused on unraveling the mysteries of the fundamental biology and ecology of these fish. Researchers have tackled complicated but essential questions such as these:

- What are the general "lifestyles" of the various species and the behaviors that affect their population numbers, movements, and distributions?
- How big are the populations of the major species? Are they growing or shrinking?
- Where are the fish stocks (subunits of populations) concentrated?
- Can individual stocks sustain current levels of fishing, or are they being overfished?

Getting our Arms Around the Fish Population Problem

Since the end of World War II, ever-expanding numbers of fishers—from small-scale subsistence and recreational fishers to industrial domestic longliners to factory ships from Asia—have competed over stocks of bigeye and yellowfin tuna around the Hawaiian Islands. Gauging the impacts of these often conflicting fisheries from area to area requires the most accurate information possible on movement patterns for these wide-ranging fish. A series of PFRP projects utilizing fish "tags," ranging from simple to high-tech, has enabled researchers and fisheries managers to begin to map out the complexities of fish migrations.

In the first such effort, the Hawai'i Tuna Tagging Project, researchers attached conventional plastic tags with identification numbers to more than 17,000 yellowfin and bigeye tuna captured around the Hawaiian Islands and released them. Enticed by a publicized reward, fishers returned more than 16 percent of the tags from recaptured fish, along with geographic and other details of their recovery. This allowed researchers to approximate overall fishing mortality for these species and rates of mortality for fish of different ages and sizes. The project results also provided fresh insights on the numbers of fish moving between various fishing grounds.

Other PFRP researchers have experimented with attaching sophisticated "pop-up" archival tags to the backs of swordfish, yellowfin tuna and blue sharks. With the fish's release, these miniature electronic devices begin recording and storing data on its route, swimming depths and the water temperature of its surroundings—all of which provide clues on its preferred habitat. After a preprogrammed interval (a few to several months) these "smart" tags detach from the animal, pop up to the surface and transmit their data to an orbiting satellite.

These data have enhanced fisheries models used in making stock assessments. For example, since the 1970s the longline catch of bigeye tuna has fluctuated, while the catch per unit of effort (CPUE) has declined steadily, particularly in the area east of 160°W, where the largest numbers of bigeye are caught. Some models have suggested that longline catches are exceeding the bigeye's ability to sustain its numbers, leading to speculation that the stock of mature bigeye tuna has been fully exploited, if not over-exploited. The rapid increase in purse seine catches of juvenile bigeye since the mid-'90s has created further uncertainty about the sustainability of the current fishing levels. Since the early days of the program PFRP-supported researchers have been working on a new approach in modeling Pacific-wide populations of bigeye and yellowfin tunas. The MULTIFAN-CL stock assessment tool uses data on the sizes and ages of fish in catches, the numbers taken in various areas, and the continuing stream of information from tagged and recaptured tunas. This model will be the tool of choice for assessing and managing tuna fisheries in the CWP for the foreseeable future.

Tuna Movements and Biology

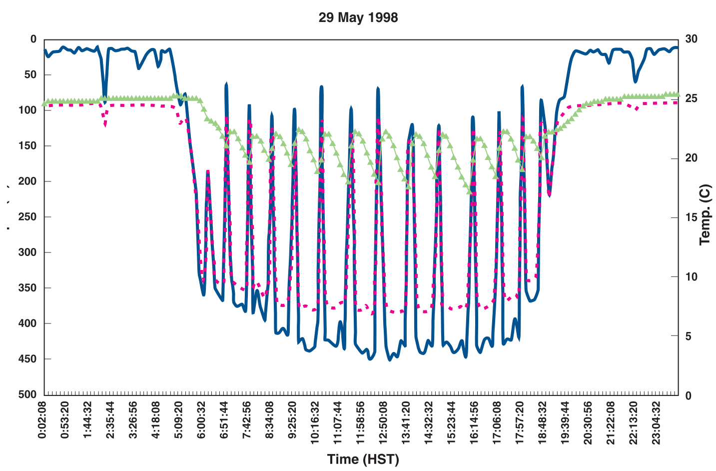
Fisheries scientists agree that the geographic ranges of the four main tuna species in the CWP span much of the Pacific, and their large-scale distributions often overlap. However, effective fisheries management requires more precise knowledge about where individual species occur in space (geographic locations and water depths) and time (of day and by season). The vertical and horizontal boundaries of a fish's world are principally linked to aspects of its biology, so research in this area is basic to improving the understanding of the abundances and distributions of pelagic fishes.

Traditionally, fisheries managers have assumed that the "catchability" of a species is essentially constant, and they have used information on the amount of catch per unit of human effort (CPUE) to infer the movements of fish and assess their populations. But this approach leaves out other factors that might affect catchability—such as variations in fishing tactics and gear and fluctuations in the marine environment. This has made it difficult to differentiate between overfishing, changes in fishing tactics, and altered environmental conditions.

It is generally accepted that factors such as the abundance of prey and the temperature and oxygen content of ocean water influence tuna movements, but pinning down how these factors interact is very tricky. To improve models that describe tunas' movements and reflect changes in their populations, it is necessary to understand the influence of variable oceanographic conditions on tunas.

By attaching ultrasonic transmitters with depth recorders to tunas, PFRP researchers observed that skipjack and yellowfin prefer warm surface waters of the ocean (at least 60° Fahrenheit) and typically don't descend below 100 meters (about 350 feet). In contrast, bigeye tunas seem to relish colder waters, swimming to depths of 100–500 meters (about 500–1600) feet, often visiting waters with low oxygen levels. This gives the bigeye access to food resources unavailable to its kin. But how does the bigeye withstand these arduous conditions?

The oversized eyes that give the bigeye its name are a major advantage for foraging in dimly lit depths. PFRP laboratory experiments revealed another: Bigeye tunas and other fish are equipped with a special circulatory system that conserves heat and allows their muscles to work in waters considerably colder than their body temperature. The trade-off for most fish is that this adaptation affects the offloading of oxygen from blood to muscles, so typically fish that spend a lot of time in low-oxygen waters are sluggish. But bigeye blood apparently has a unique property that allows the binding and releasing of oxygen in quantities sufficient to power their regular swimming and feeding at oxygen-sparse depths. From historical catch statistics (which indicate the depths where fish are caught) researchers had surmised the bigeye was tolerant of low oxygen, but these PFRP findings were the first to explain the underlying physiological reasons.



Data from depth recorders on tagged bigeye tuna show that the bigeye follows a very repetitive daily pattern. This graph shows swimming depth (blue line) and internal (yellow triangles) and external (red dots) body temperatures, recorded every 8.5 minutes since the fish's tag and release by NMFS scientists.

Fish Swim Down, Fish Swim Up: The Heart Connection

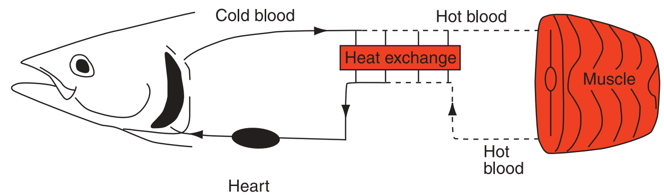
In another eye-opening study, PFRP scientists discovered that heart temperature plays a key role in limiting yellowfin and skipjack movements up and down the water column. Researchers had observed that both adults and juveniles of these species spend most of their time in warm, oxygen-rich surface waters. This contradicted the logic that the cooling of muscles in older, more massive fish should be slower than in smaller young fish, and adults should therefore be able to spend more time in deeper, colder water. But closer scrutiny of the tuna circulatory system revealed that—unlike its other muscles—the heart is on the "cool" side of its vascular heat conservation system, so heart temperature directly reflects the surrounding water temperature regardless of the tuna's size. As colder water slows down the heart rate in skipjacks and yellowfins, their ability to swim and move downward is curtailed. Amplifying the effect, at less than 60° Fahrenheit these tunas lose their capacity to boost their heart rate and increase blood flow and oxygen to their muscles. Although the researchers haven't yet learned the bigeye's secret for getting around the heart temperature limitation, they have recently discovered that swordfish and bigeye thresher sharks also tolerate very low-oxygen waters.

These findings on the physiological reasons underlying the bigeye tuna's habitat preferences have helped scientists improve estimates of their relative abundances as well as the effectiveness of the longline fishing tactics. Using a model that incorporates information on the bigeye's favored depths and the distribution of longline gear with oceanographic and other data, modelers found that the effectiveness of longline fishing efforts in the CWP increased by 43 percent between the late 1960s and the late '80s. They attributed the improvement primarily to more efficient techniques, such as setting gear deeper, rather than an increase in the amount of fishing effort.

Yellowfin Tuna: Champion Spawners

Understanding the basics of tuna reproduction—when they become sexually mature, the frequency and timing of egg-spawning and other details—is essential for evaluating the health of tuna stocks and differentiating between natural environmental effects on tuna populations and human-caused effects. To gain insights into yellowfin reproduction, PFRP-funded researchers examined several thousand samples of ovary tissue collected from female yellowfin in a range of sizes caught around the CWP.

It turns out that female yellowfin spawn energetically, releasing millions of eggs on a daily basis for prolonged periods and then stopping for a well-deserved rest. Peak spawning occurs at different seasons across the CWP, apparently related to water temperatures, weather patterns and other environmental conditions. Around the Hawaiian Islands spawning climaxes during summer months, when sea surface temperatures are warmest, whereas the height of spawning in equatorial regions seems to coincide with plentiful food for larvae, as well as weather patterns and other conditions. The study results also enabled the researchers to define the varying sizes at maturity for yellowfin in different areas. During spawning both females and the males attracted to them are far more vulnerable to fishing, so these findings could assist fisheries managers in designing regulations to protect spawning stocks, if necessary. The results also give modelers needed data for estimating yellowfin populations and their productivity in equatorial waters where the majority yellowfin are caught.



In fishes other than tunas (and a few shark species), heat is picked up by the blood as it passes through the warm muscles and lost to the water when the blood passes through the gills. In tunas, vascular countercurrent heat exchangers are interposed between the muscles and the gills. The resultant venous to arterial heat exchange acts as a thermal barrier allowing tunas to maintain their muscles significantly warmer than the surrounding water.

Tuna Feeding: They Do it in Schools

Another aspect of fish behavior relevant to fishing and fisheries management is their feeding, or foraging, habits. More than 75 percent of the Pacific tuna catch are fish that form schools—presumably to find prey—around floating logs, seamounts (underwater mountains) and man-made fish aggregation devices (FADs) such as drifting rafts and anchored deepwater buoys. Deployment of these fish attractors has increased steadily over the last 25 years, and has become rampant over the last decade. Until recently little attention was paid to the ecological impacts of this fishing practice. Understanding tuna feeding behavior and the amount of time they spend in open-water schools, compared to schools associated with seamounts or FADs, is critical to accurately assessing stocks and discerning the impacts of FADs on tuna distribution, their vulnerability to fishing gear and their general well-being. A sizable proportion of tuna caught by purse-seining around FADs are immature sub-adults and juveniles, which raises concerns over the effects on the adult population. Also, the presence of large numbers of FADs may alter tuna movements and deter the fish from traveling to areas of high food abundance. Recognizing concerns over the growing exploitation of yellowfin and bigeye stocks in the CWP, in 2001 the Standing Committee on Tuna and Billfish recommended that mortality of juveniles not be allowed to increase. However, no institution exists yet to implement that recommendation.

For a clearer understanding of these issues, PFRP researchers are investigating the feeding habits of yellowfin and bigeye tuna in Hawaiian waters and, specifically, how they fare when associated with seamounts and FADs. Preliminary results from analyzing the stomach contents of some 1400 tuna show that feeding habits seem to vary with species, size and circumstances. For example, bigeye and yellowfin of the same size have markedly different diets even when caught in the same place. Bigeye tuna hunt more effectively around seamounts than do yellowfin. And while big yellowfin sometimes feed well at offshore FADs, smaller ones do better at nearshore FADs that offer alternate prey. The researchers are using small electronic tags attached to tuna for monitoring their movements between FADs around the island of Oahu. Integrating such information on feeding and movement patterns is greatly improving the understanding of the influence of FADs on tuna ecology and behavior. This, in turn, should result in improved resource assessment and management.

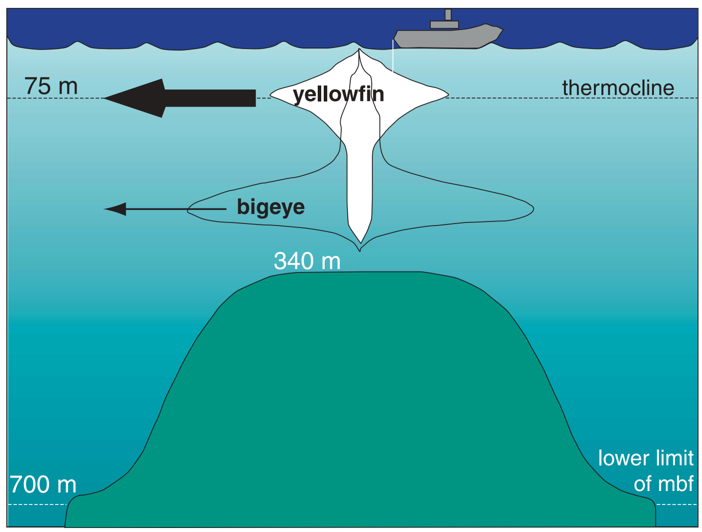
The Secret Identities of Pelagic Fishes

Genetic techniques are powerful tools for investigating the hereditary makeup of populations and migratory movements of animals. By comparing genetic material (DNA) from diverse groups of animals and determining how similar it is, scientists can gauge how closely related the groups are. For fisheries, knowing whether a population consists of one homogenous (genetically identical) stock or many stocks associated with different geographic areas assists fisheries managers in designing suitable stock management plans. For example, if swordfish—which can migrate thousands of miles—all belong to a single stock, then a management strategy that treats the entire geographic range is appropriate. However, if several different stocks exist (e.g., North Pacific, South Pacific, etc.), then policies aimed at too broad a geographic area could lead to losses of genetically diverse regional stocks, with potentially serious consequences for the population as a whole. On the other hand, management efforts divided on too fine a scale (such as within a stock) could potentially be overly restrictive and fail to address the needs.

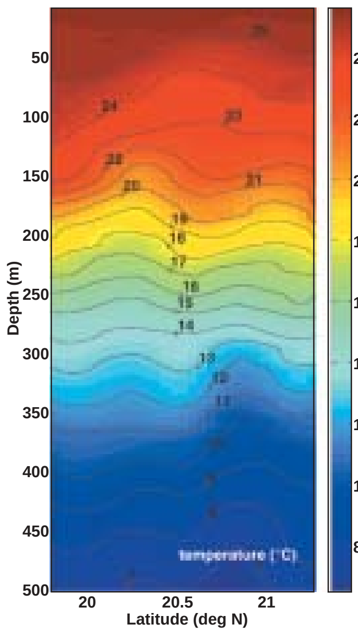
Several PFRP projects have used genetic analysis of DNA to shed light on the population structures of pelagic fish species. Some preliminary findings are these:

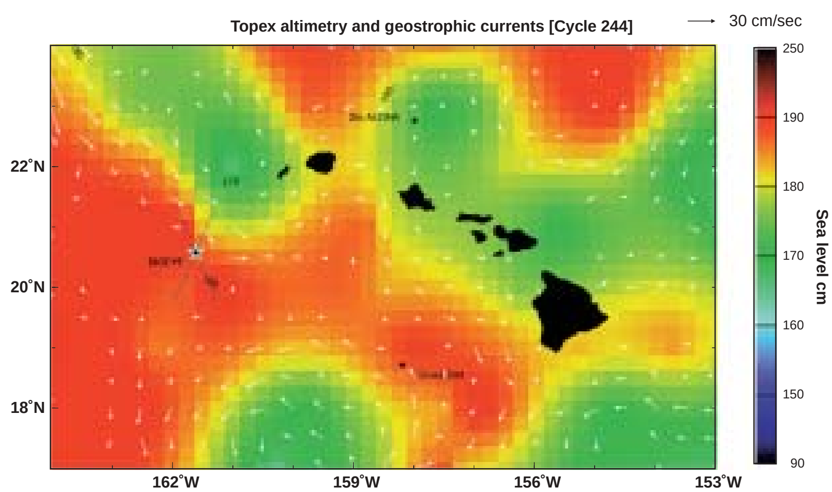
- Blue marlin in the Pacific Ocean appear to belong to a single genetic stock that also extends into the Atlantic Ocean. A second, less widely distributed genetic stock is found only in the Atlantic.
- Researchers have identified several genetic stocks of swordfish in the Pacific Ocean alone.
- For dolphinfish (mahimahi), which inhabit tropical waters around the world, researchers have identified 13 genetic types. One occurs commonly worldwide, and the other 12 are quite rare.
- DNA samples from more than 800 bigeye tuna caught at widely separated locations indicated that the Pacific Ocean has a single, "wall-to-wall" stock of bigeye.

FADs play a critical role in recreational and commercial fishing by attracting target species to known locations. This simple function may soon be augmented with a new class of FADs equipped with sonar, for tracking the nearby movement of schools and individual fish, and other electronic devices for monitoring the activity of tagged fish. PFRP has funded a project to use "smart" FADs to explore the dynamics of fish aggregations. (Courtesy of David Itano.)



Tagging techniques can elucidate the biology and exploitation patterns of aggregated pelagic fishes. (Holland, K.N., S. M. Kajiura, D.G. Itano and J. R. Sibert, 2001. In *Island in the stream: oceanography and fisheries of the Charleston Bump.* G. R. Sedberry, editor. American Fisheries Society, Symposium 25, pp. 211-218.





Examples of oceanographic information recorded by drifting buoys, moored instruments, research ships and satellites. Top frame: Water temperatures to depths of 1650 feet (500 meters) recorded on a transect of a NOAA research ship from 20‹21¡ north latitude. Bottom frame: Map of sea level height around the main Hawaiian Islands, as measured from instruments aboard the TOPEX-Poseidon satellite. The arrows represent the velocity of currents driven by differences in salinity and temperature. (Length of arrow indicates current strength.)

The complex and continuously changing ocean environment influences marine life in countless ways. Large pelagic fish like tunas and billfish have specific requirements for fulfilling basic needs related to survival, feeding, and reproduction. Sound fisheries management demands not only understanding the variable needs and habits of the fish themselves, but also how they tie into the features and conditions of the ocean environment. PFRP research has penetrated to the depths of interactions between the fish and their environment by focusing on questions such as these:

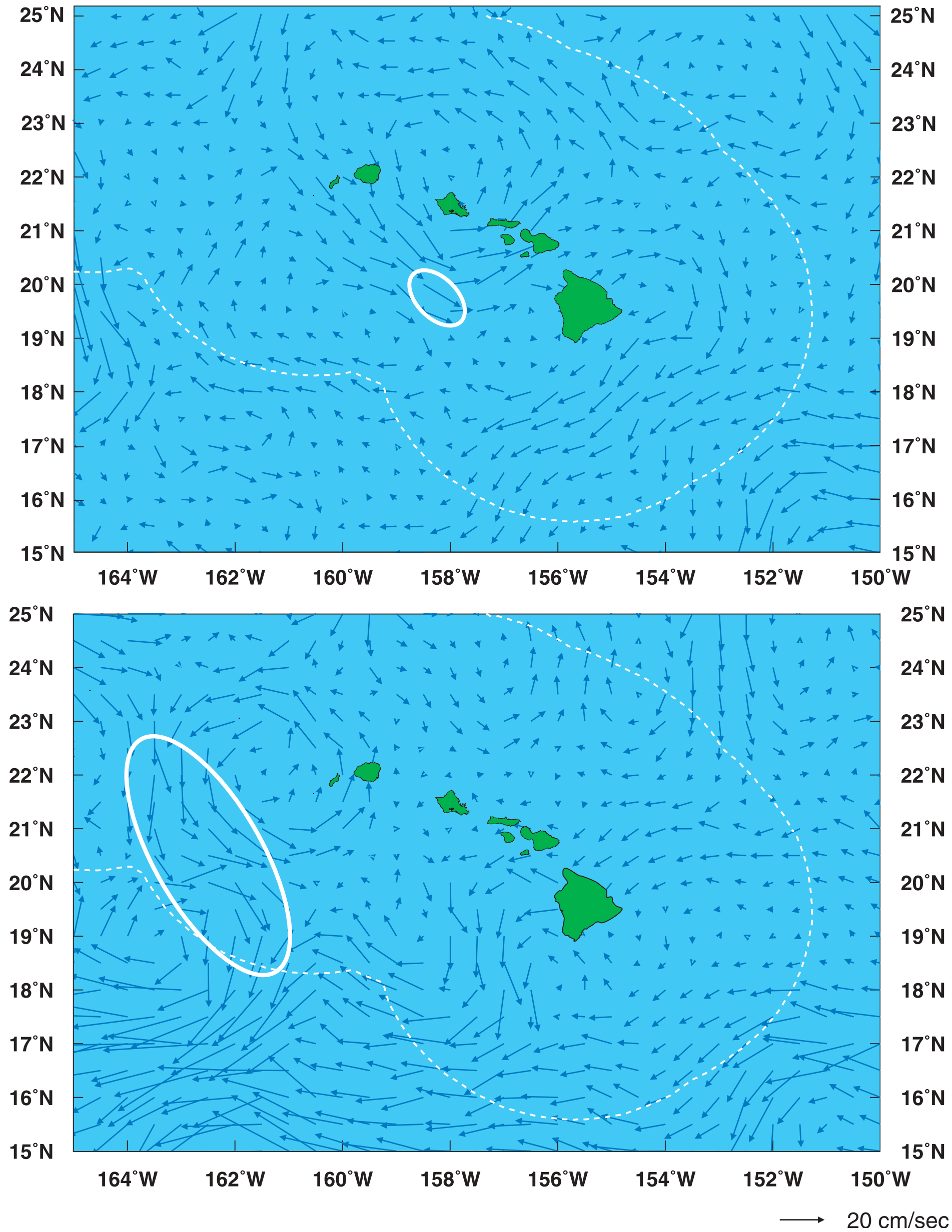
- How does the changing ocean environment influence the distribution and behavior of the pelagic fish species?
- What ocean features are associated with the fish and the ecosystems that support them?
- How do changes in the environment affect fishing success?

Tracking Fish by Mapping Ocean Features

The physical ocean influences the distribution of fish and other marine life in two basic ways. First, water motion (currents, eddies, etc.) transports marine life from place to place. Second, factors such as water temperature, oxygen content and proximity to land may attract or repel marine life. Understanding these influences is necessary for defining fish habitat and forecasting fish abundances and distribution. To study in detail the physical characteristics of Hawai‘i waters, researchers deployed 100 drifting buoys equipped with instruments that recorded water temperature, wind strength, changes in the ocean surface and geographic position. The researchers collected the data for two years, via an orbiting satellite, and compiled it into a database. The results led to the discovery of the eastward Hawai‘i Lee Counter Current, an ocean circulation feature found at 19° north latitude that spans more than a thousand miles from west to east. The drifting buoys also revealed that eddies (whirlpools that mix water and may bring nutrients to the surface) are roughly ten times stronger in leeward waters of the islands than in windward waters. The database has also made possible estimates, or “nowcasts,” of physical water conditions in areas of Hawaiian EEZ, used by fishers, recreational boaters and others.

In a related project, PFRP researchers used satellite instruments to detect and map ocean features that signal locations of fish and other marine life. Subtropical fronts—convergence zones often spanning hundreds of miles, where cold masses of subarctic water slide beneath warm tropical waters—are particularly rich areas for swordfish. The cold water carries microscopic algae that are fed upon by tiny zooplankton that in turn become meals for small fish, which squids prey on. The squids attract swordfish and other predatory fish. To learn more about the relationship between swordfish and the Subtropical Frontal Zone west of the Hawaiian archipelago, the researchers compiled data collected by a satellite sensor that “reads” ocean color (algae-rich cold water appears greenish, clear warm water blue) and an altimeter that measures ocean heights to within an inch. They then used the information to produce maps of the regional ocean currents.

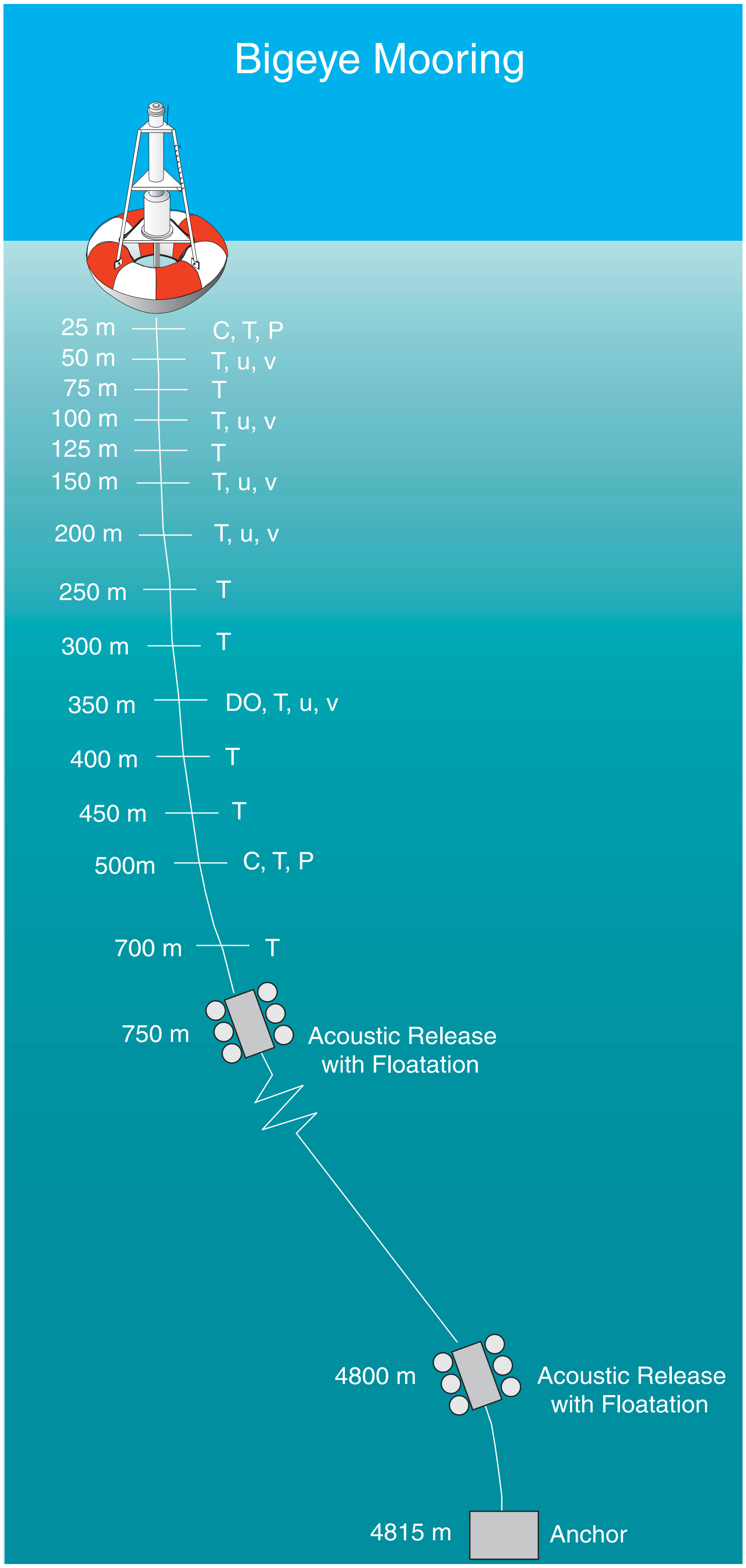
The maps revealed that prime swordfishing grounds lie along a front associated with a large-scale meandering current. Coupling the maps with catch statistics showed that variations in swordfish catches correlated strongly with changes in sea surface height (which reflect fluctuations in the amount of heat in the water column). A drop in surface height indicates the warm water layer beneath the surface is relatively shallow, while rises in sea surface height indicate warm water extends to greater depths. Swordfish feeding activity is apparently linked to water temperature: Catch rates increase when the warm layer is shallow and decrease when it deepens and, presumably, the fish are feeding at greater depths. The study also helped the scientists identify another front north of the swordfishing grounds where protected loggerhead turtles feed and sometimes get hooked on the gear of longline vessels operating in the area.



Maps of estimated currents around the Hawaiian Islands, based on TOPEX-Poseidon satellite data from November 1993 (top) and 1994 (bottom). White ellipses indicate tuna fishing grounds associated with currents, which shifted over that time period.

Variations in the Ocean Environment and Bigeye Tuna

Bigeye tuna (*Thunnus obesus*) is the principal deepwater target species of the Pacific-wide longline fishery, typically yielding total annual catches of more than 150,000 mt. Recent apparent reductions in bigeye stocks are causing fishery managers to consider imposing restrictions on the fishery. It is therefore critical to verity the accuracy of stock estimates. Catch per unit of effort (CPUE) is often used as a rough index of the abundance. However, the relationship between abundances and CPUE also depends on the "catchability" of a species using a specific type of fishing gear and gear configuration under various oceanographic conditions. For example, the depth to which hooks can be set generally depends on the configuration of fishing gear, but currents also can affect gear setting. As with swordfish, another influence on catchability is the depth of the uppermost layer of ocean water, which affects where the temperature-sensitive bigeye is likely to occur. Bigeye tunas often forage around the base of this layer, but return to the surface for short periods between dives. When the warm layer deepens the bigeye's daily vertical migrations are more extensive and the fish are more dispersed, so they are more difficult to catch. Conversely, when this water layer is shallower bigeye are more concentrated with respect to the hooks



Schematic diagram for the BIGEYE oceanographic sensor array. Abbreviations are as follows: C (conductivity), T (temperature), P (pressure), u (east velocity of current), v (north velocity of current) and DO (dissolved oxygen). [figure courtesy of JIMAR and NOAA]

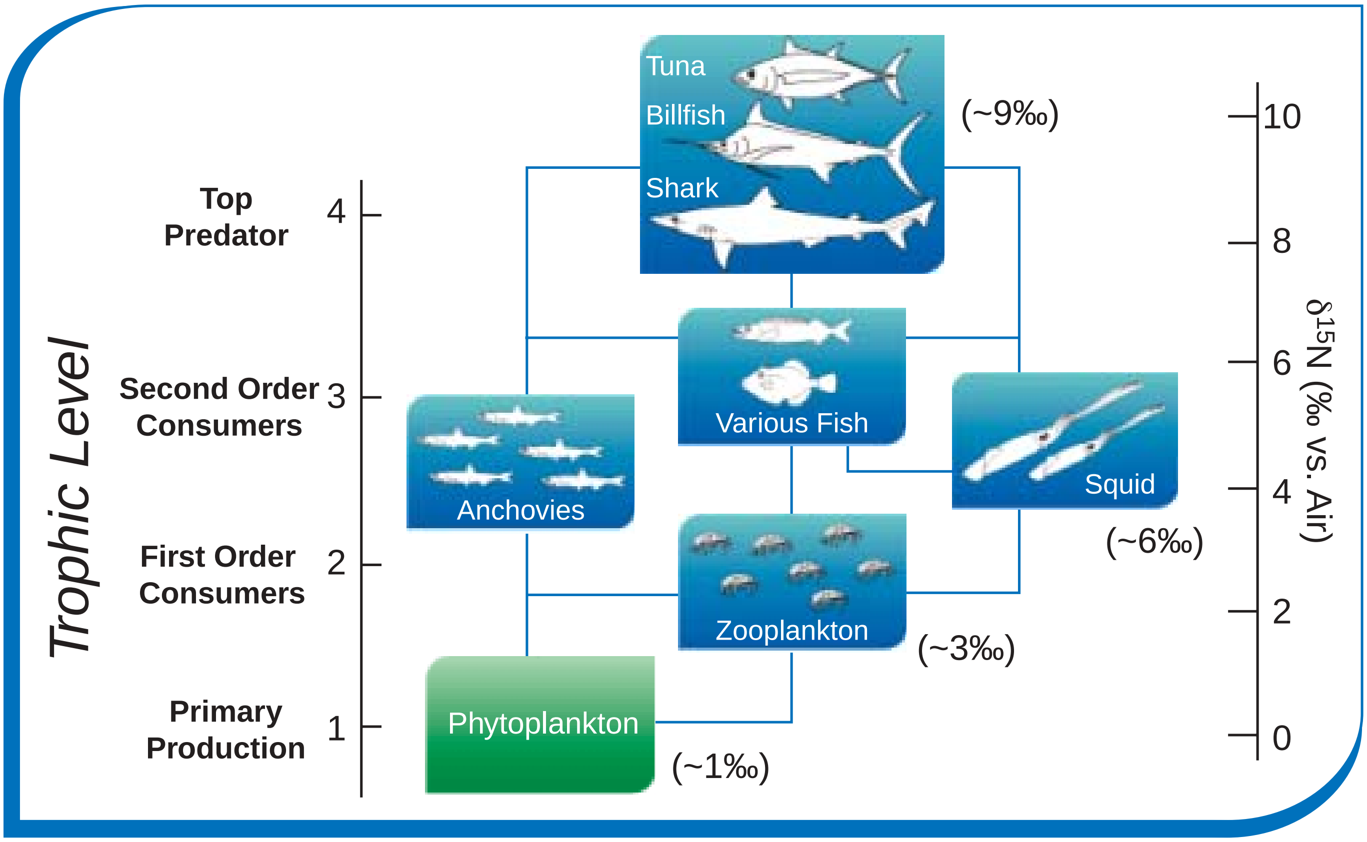
and easier to catch. Environmental data such as temperature and oxygen often are used to standardize catch rates, to produce an unbiased index of relative abundance for use in stock assessments.

PFRP has funded a multi-year project to explore the relationships between key oceanographic features, catches and longline fishing effort south and west of the main Hawaiian Islands. The researchers are using instruments on specially designed moorings, research ships and satellites to measure properties of the upper ocean, including oxygen levels, concentrations of marine algae, salinity, temperature, currents, and the diversity and abundances of plants and animals. Project results to date have confirmed that bigeye catch rates vary as much as fivefold, depending on the season. These variations apparently are linked to north-south migrations of bigeye that coincide with temperature fluctuations in the upper ocean water. Pacific-wide data indicate that catch rates for swordfish, albacore and marlins exhibit similar annual patterns throughout the region. The findings will aid fisheries managers in making more accurate estimates of bigeye stocks and will be applied to other fisheries as well.

You Are What You Eat—Using Chemical Clues to Study Tunas' Diets and Migrations

All life in the oceans is connected via food webs composed of highly abundant primary producers (marine algae), several orders of progressively larger and less numerous consumers (e.g., fishes and squids), and a comparatively small number of predators such as sharks, tunas and billfish. Previous studies have suggested that tuna productivity is linked to the upwelling of cold, nutrient-rich water (which supports the growth of algae) along the equator in the central and eastern Pacific. This area of upwelling forms a cold "tongue" of water extending westward from South America until it meets a large pool of warm water in the western Pacific, where upwelling is absent and algal growth low. Modeling predicts that equatorial tunas feed at

Pelagic Food Web, as determined by nitrogen stable isotopic composition



By measuring the stable isotopic composition of key elements (e.g., nitrogen) in the tissues of marine organisms, PFRP researchers are determining the relationships of those organisms within marine food webs. Adapted from the Secretariat of the Pacific Community.

lower levels of the food web. In contrast Western Pacific tunas are thought to range extensively, seeking bigger, less abundant prey (i.e., feeding at higher levels of the food web). Paradoxically, the largest proportion of the Pacific tuna catch comes from this warm pool, despite its low primary productivity.

To learn more about tunas' diets and the links between primary productivity and tuna movements and populations, a PFRP-sponsored team of scientists is measuring the chemical isotopes (alternate forms) of the elements carbon and nitrogen in tissue samples and stomach contents of tunas and other fish in the cold-tongue, warm-pool region. Different oceanic regions have distinct isotopic "fingerprints" that become incorporated into animal tissues via their diets, and the researchers have discovered that white muscle and liver tissue in fish are replenished at different rates. Thus by comparing the isotope values of these tissues they can gauge how long individual fish have stayed in different regions. For example, if isotope levels in the two tissues are dissimilar, the tuna probably has switched its diet recently or traveled from another area with a different isotopic fingerprint. The initial results of the research support the notion that prey and predators in different regions have distinct fingerprints. Another interesting discovery is that when yellowfin tuna attain a length of about 18 inches they shift their diet rapidly, from shallow-dwelling shrimp larvae to an adult fare of fully developed deep-water shrimp. The next step in the research is to develop an "isotope map" to help determine where tuna have resided and how far they migrate.

This work is enriching the overall understanding of the rich equatorial Pacific ecosystem, the connections between tunas and other members of their food webs. The scientists also expect to learn about the effects of climate variability on the systems; for example, whether the eastward expansion of the warm pool during El Niño events triggers a diet shift in tunas. Such information is important for both fisheries production and ecosystem modeling of the equatorial Pacific.

MEASURING FISHING'S FOOTPRINT

Longliners hauling in lines (top) bring in more than the targeted fish. Non-target species such as the blue shark, protected loggerhead turtles, and commercially valuable opah (moonfish) can also be part of the catch. Photos from NMFS's Hawaii Longline Observer Program.

Around the world, fishing is under increasing scrutiny for its impacts on marine ecosystems. These impacts sometimes have gone unnoticed until they become problems for individual species, ecosystems, or the fishery itself. Under the Magnuson-Stevens Fishery Conservation and Management Act the Endangered Species Act, and the Marine Mammal Protection Act, resource managers are obliged to consider a broad range of fishing impacts when making policy decisions, to minimize ecological impacts as well as effects on the target fish species. The PFRP has expanded knowledge about the effect of fishing and broadened the scientific basis for management options by funding studies that address questions such as these:

- How does fishing activity as a whole affect target species, protected species, non-target species and ecosystems?
- What are the impacts of particular fishing sectors (e.g., purse-seine, longlining, trolling) and specific techniques used within fisheries?
- Why are certain species vulnerable to incidental capture by fishing activities?
- How can mortalities and injuries to protected species be avoided and reduced?

Reality Check: Incidental Catch in the Longline Fishery

Longline fisheries capture significant numbers of non-target fishes as bycatch (which is discarded or otherwise unused) and incidental but commercially valuable catch. For the Hawai‘i-based longline fleet, such non-target species as blue shark, dolphinfish (mahimahi), blue marlin, moonfish (opah), wahoo (ono) and pomfrets comprised almost half of the catch and a major portion of the revenue from 1991–98. All these species are ecologically important, and each species poses unique challenges with respect to understanding fishing effects on its population. For example, until the 2001 federal ban on shark finning longline fishers took about 100,000 blue sharks per year, commonly discarding all but the fins. The reported blue shark bycatch has declined to about 40,000 annually; however, experience has documented that fishery-based documenting of bycatch is less accurate than for target species.

Incidental catch is reported through the NMFS Hawai‘i Longline Observer Program (currently about 20 percent of fishing trips have at-sea observers) and in vessel logbook records submitted to NMFS. To get the most accurate historical information possible, PFRP-sponsored researchers used observer data to develop models for estimating the amount of incidental catch for each species. They then applied the models to vessel logbook data to generate predictions of quantities of incidental catch. By comparing these predictions to sales records from Honolulu fish auctions (where the retained, commercially valuable fish were sold) they have identified discrepancies in the logbook and observer reporting. The methods have also proven useful in detecting the underreporting of blue shark bycatch and the misidentification of marlin species.

The models are being used to further evaluate the quality of reporting and correct catch statistics, which will render stock assessments more accurate. Additional studies on the quality of observer data have helped improve at-sea observer training. The data collected also benefit research on the geographical distributions of incidental catch species, which could help clarify the effectiveness of fishing area closures and other management measures. Project data might also be valuable in identifying environmental and technical (fishing) factors that affect catch rates, which could lead to new and improved ways to reduce bycatch. Finally, the corrected catch histories are essential for other investigations of biology, population dynamics, and fisheries economics.

Release of Large Non-Target Fish: A Life-Saving Measure?

PFRP and NMFS researchers work to collect blood from a blue shark and attach a PSAT to its dorsal fin. Data collected by PSATs help to answer questions about the fate of sharks and other pelagic species. These "tags" transmit information by satellite that enable researchers to differentiate between live and dead animals and shed tags.

Sharks and other top predator fish serve are important components of the pelagic ecosystem, and ecologists consider them to be indicators of the health of our oceans. PFRP-sponsored stock assessment studies have shown that populations of some large predators have declined by as much as 50 percent since the beginning of industrial fishing. Fishery managers are actively searching for effective conservation measures to preserve top predators. Traditionally, fishers and fishery managers have made a variety of unsupported assumptions about the survival of large fish captured in sports fishing or as unwanted bycatch by commercial fishers. The presumption that released fish die regardless of treatment has resulted in fishery models incorporating this unproven premise, and "salvage" practices such as shark-finning (now federally banned).

While large fish frequently are released after capture, whether they survive or die is unknown. Sidestepping the considerable costs and logistic difficulties of a broad-scale tagging program to determine the fate of sharks and other released fish, a team of PFRP-supported researchers focused on pinning down physiological factors associated with mortality in caught-and-released fish. On a series of research cruises, they collected blood samples from dead and live blue sharks hooked by longline gear and attached pop-up satellite archival tags (PSATs) to some of the live sharks before releasing them.

The blood samples provided baseline information on the traumatized condition of captured sharks, including oxygen levels in their blood, stress hormones and a slew of proteins that indicate damage to muscle and organs. The PSATs recorded the daily locations and swimming depths of the released fish, and the water temperature of their surroundings. When the tags automatically detach from the fish after a predetermined time, they transmit recorded data to an orbiting satellite. Combining the biochemical and PSAT data, the researchers have identified biochemical measures that enable them to predict which sharks will live after release and which will likely die. The study was expanded to tag sharks of five other species. Though data spanning several months were recovered from only about half the PSATs, it confirmed that the majority of released sharks survived after being released from longline gear.

The researchers are applying similar techniques to address survival questions for Pacific blue marlin. Commercial fishers catch significant numbers of blue marlins, and the feisty fish also are popular in Hawai‘i's world-renowned fishing tournament industry. The current population level of this species argues against allowing increases in catch, and in some jurisdictions the retention and sale of marlins is prohibited, thus requiring commercial and sport fishers to release them. For these practices to be justifiable management options, there must be a reasonable likelihood that released fish will survive—particularly following protracted contests with anglers.

Longline hook removed from lower jaw of an olive ridley Sea Turtle in Costa Rica (photo by Yonat Swimmer).

However, there is scant evidence to back this assumption, so the researchers are developing measures to assess the physiological changes in captured billfish and identify factors that predict whether they will survive. For the blue marlin the issue is especially pressing, because the sport fishery in the main Hawaiian Islands takes place in an important marlin spawning area. These studies will help fisheries biologists to assess how fishing practices affect populations of large fish, which in turn will improve stock assessments.

The Fate of Sea Turtles Freed from Longline Fishing Gear

All five sea turtle species inhabiting Pacific waters (leatherback, hawksbill, loggerhead, green, and olive ridley) are listed as endangered or threatened under the US Endangered Species Act. While several factors (including poaching of eggs on nesting beaches, turtle harvests and coastal gill net fisheries) are implicated in turtle population declines, incidental capture by longline fishing gear has come under growing scrutiny as a contributing cause. The number of turtles currently hooked by Hawai‘i longliners is considerably lower than in some other fisheries. However, prior to the 1999 closure of a large area of the ocean to the Hawai‘i swordfish fishery, turtle captures had been steadily rising, and the situation had turned so critical it jeopardized the future of the fishery.

Few of these animals are dead when caught; most are de-hooked and released. Nonetheless, injuries sustained due to hooking (particularly in the throat) can be severe, and determining how long released turtles survive has been difficult. In a multi-year project PFRP-funded researchers developed techniques for attaching pop-up satellite archival transmitters (PSATs) to turtles, to collect information on their movements, swimming depths, long-term survival and fitness following capture and release. They trained more than 100 at-sea longline observers in the methods, and since 2001 these observers have taken PSATs to sea on approximately 400 longline fishing trips to maximize the chances for tagging turtles.

The swordfish area closure has reduced the number of turtle interactions and, consequently, opportunities for tagging them around the Hawaiian Islands. As an alternative, researchers and observers have deployed tags on 25–30 loggerhead and olive ridley turtles in the central North Pacific (west of California) and in the waters off Costa Rica and Brazil, where the incidental catch of turtles is extremely high. Data collected from these turtles, combined with remote sensing data on ocean color and sea surface height, have shown that loggerheads move seasonally north and south in concert with changes in sea surface temperatures. They are found in association with fronts, eddies, and large-scale currents, and spend about 40 percent of their time at the surface and 90 percent of their time at depths of less than 130 feet. In contrast, olive ridleys occupy warmer waters and have deeper dive patterns than loggerheads. These findings suggest that a “turtle layer” exists in Pacific waters and if fishers set their lines deeper they can avoid hooking turtles.

To date, none of the tagged turtles appear to have died during the first few months after release. These preliminary findings suggest most sea turtles may survive longline hooking. However, the PSAT data also indicate that turtles released after capture have markedly different dive patterns (e.g., remaining in deep cold water during the day) that could affect their feeding and/or reproduction. Furthermore, if a turtle suffers more than one gear-hooking, its chances for survival might decrease. With the ongoing efforts to tag more turtles, it is anticipated that more skillful means of preventing fishery interactions with protected turtles will evolve and be shared with other countries.

THE IMPACTS OF FISHERIES MANAGEMENT ON RESOURCES, FISHERS AND MARKETS

Fisheries management, by definition, constrains human activities. Therefore, understanding the human dimensions of fishing is essential to sound management. Likewise, gauging the effects of fisheries policy on both the resources and humans provides indispensable feedback for developing and modifying appropriate management objectives and effective fishery regulations. The Fisheries Conservation and Management Act mandates that decision-makers set optimum yields for our national fisheries on the basis of maximum sustainable yields, "as modified by any relevant economic, social or ecological factor."

In recent years, economics, public policy studies and the social sciences have contributed much to fisheries management. More than a third of the PFRP research projects have originated from these disciplines. PFRP-sponsored researchers have collected and interpreted fundamental information related to questions such as these:

- What are the key economic issues in the various pelagic fisheries?
- How does regulatory policy affect participation in the fisheries and the conservation of protected species?
- What are the market factors influencing the supplies and prices of Pacific pelagic fish products?
- How do fishing communities vary in Hawai‘i and the US Pacific islands, and how do the social and cultural characteristics of the fishers influence the appropriateness and effectiveness of fisheries policies?

Social and Economic Profiles of Hawai‘i's Fisheries

The Fisheries Conservation and Management Act and the National Environmental Policy Act require evaluations of the impacts on fishers and communities when federal projects and fishery or environmental regulations are proposed. When the PFRP began operations in the mid-1990s, baseline information on the various US fishing sectors in the CWP was sparse at best, and in some cases completely lacking. This prompted the program to fund a number of projects (some ongoing) to compile sociocultural profiles and basic economic studies to aid decision makers in policy considerations. The results of many of these projects were published in PFRP reports and technical papers (see appendix 1). Summaries of some of these projects follow.

- ***HIFIVE***—The Hawai‘i Fleet, Industry and Vessel Economics (HIFIVE) project, begun in 1994, involved economic research on commercial fisheries for tuna, swordfish, blue and striped marlin, and mahimahi and ono. Researchers collected an array of information on longline, commercial troll and handline, and charter boats, as well as the markets associated with these fleets. This multi-year project provided a detailed economic analysis of the Hawai‘i-based longline fishery and perhaps the most comprehensive cost-earnings information every collected on any fishery.
- ***Fishery Economics, Part 2***—During the late 1990s the Hawai‘i longline industry went through substantial changes that affected fleet composition, vessel ownership and fishing operations and practices. In a follow-up to the HIFIVE project, researchers resurveyed more than half of the longline fleet to collect cost-earnings information and identify critical economic differences between 1993 and 2000. Fisheries managers used this updated data in formulating new regulations and assessing their impacts on fishers.
- ***Social and Aspects of Pelagic Fisheries***—This multi-year project described the social organization, historical-cultural background, fishing traditions and ecological knowledge of participants in Hawai‘i's nearshore troll and handline fishery. In the mid-1990s this sector included up to 10,000 small

Tuna longlining in the tropical Pacific. Courtesy of NOAA.

In any given locale, experienced resident fishermen usually have the most detailed knowledge of near-shore fisheries, which can be a vital complement to the geographically broader knowledge of pelagic research scientists and fisheries managers. Shown here are ikashibi fishermen unloading tuna at the Suisan Fish Market in Hilo (left) and at Kewalo Basin in Honolulu (right) (Ikashibi is derived from the Japanese words "ika," for squid, and "shibi," for yellowfin). During the summer yellowfin run, Hawai'i handliners fish around the islands at night, drifting with the current; they can catch large yellowfin and albacore, as well as the occasional swordfish. Their experience in this fishery makes them expert in nocturnal near-shore aggregations and behavior of tuna and other fishes around the Big Island and O'ahu. (Ed.: Big Island refers to the island of Hawai'i, Hawai'i to the entire state.)

boats (under 45 feet long). Of these, only 2,000–3,000 boat owners had commercial licenses required for the sale of fish. Researchers investigated ethnic differences between fishers, their social organization, and networks for distribution of their catches. They also identified fishery issues perceived as important by fishers.

- ***Sociocultural Profile of the Longline Industry***—A project currently underway is compiling in-depth information on the dynamic and ethnically diverse longline industry in Hawai'i. In interviews with vessel personnel and industry-associated businesses, the researchers are soliciting a broad variety of information, including interviewees' knowledge regarding fishing regulations and management, and their adequacy. The results to date reveal that vessel owners and operators are primarily Vietnamese, Korean and Caucasian US citizens (roughly one-third of each). About 80 percent of crewmembers are Filipino, working under transit visas at average salaries of $475 a month. Distinct differences exist in social behavior, community ties and attitudes about the industry both between and within these ethnic groups participating in the fishery.

Markets for Pacific Tuna and Marlin

Understanding fresh tuna quality and market requirements is essential for successful fishing and marketing operations. Fresh tuna is processed into an array of products. In the first step of directing the fish to the most suitable market "niche" (e.g., sushi bar, white tablecloth restaurant, fast food outlet), tuna graders assess the overall appearance of the fish, sample a small section of the meat, and assign a quality grade. Each grade defines a range of acceptable quality. Prices in the Hawai'i market may range from less than 50 cents/lb. to more than $15/lb. depending on the quality of the fish and other market forces of supply and demand.

A PFRP study confirmed that the types of products derived from fresh tuna are highly differentiated, with price varying according to the quality requirements of each end use. The study also showed that fishing methods and the effects of handling and storage affect individual fish quality (grade) which in turn influences tuna market competition. This suggests that better quality control by tuna fishers could increase the proportion of premium-grade fish in landings and improve their economic returns. It also indicates that increasing fishers' awareness of market quality requirements and further diversifying fresh tuna and marlin products could add value to Pacific island fisheries and enhance their economic viability.

Evaluating the Effects of Regulation on Commercial Fisheries

In managing pelagic fisheries NOAA Fisheries and the WPRFMC must balance the sometimes-conflicting goals of maintaining optimal levels of fish stocks while maximizing opportunities for commercial and recreational fishing. Traditionally fisheries managers have used an assortment of measures to achieve these ends, including area closures to rebuild depleted fish stocks, limitations on the number and types of vessels (e.g., size, gear type), catch quotas and license fees. Each of these measures affects the allocation of fishing effort by individual vessels. In turn, changes in overall fishing effort affect fish stocks, fishers' profits, and catches—which influence market prices for each type of fish.

Predicting the impacts of various measures is complex, given the interacting dynamics of fisheries resources, the ocean environment and the fishers. Modeling allows managers to assess different management strategies and approximate their outcomes, which can assist greatly in making optimal policy choices. However, most traditional fisheries economics models have neglected important factors such as temporal and spatial variation in the fish stocks and fishing effort.

PFRP economists are engaged in ongoing efforts to improve upon models for evaluating the effects of fishery regulations. One of the first problems the modelers examined was the resource conflict between longliners and other fishing sectors, such as troll-and-handline fishers, who competed in some nearshore areas around the main Hawaiian Islands (MHI). The model estimated the consequences for possible allocations of fishing access between the two groups. The results for one option, restricting longlining within 75 miles from Hawai'i shores, showed that such an action would have incurred an economic profit loss of nearly a half-million dollars, primarily because longliners would have to travel further to fish. Another application of this model was to evaluate the economic tradeoffs between promoting recreational fishing and maintaining the profits generated from the commercial fisheries. The results suggested an increase of one recreational trip would reduce commercial profit approximately by $12 (at the 1993 effort level).

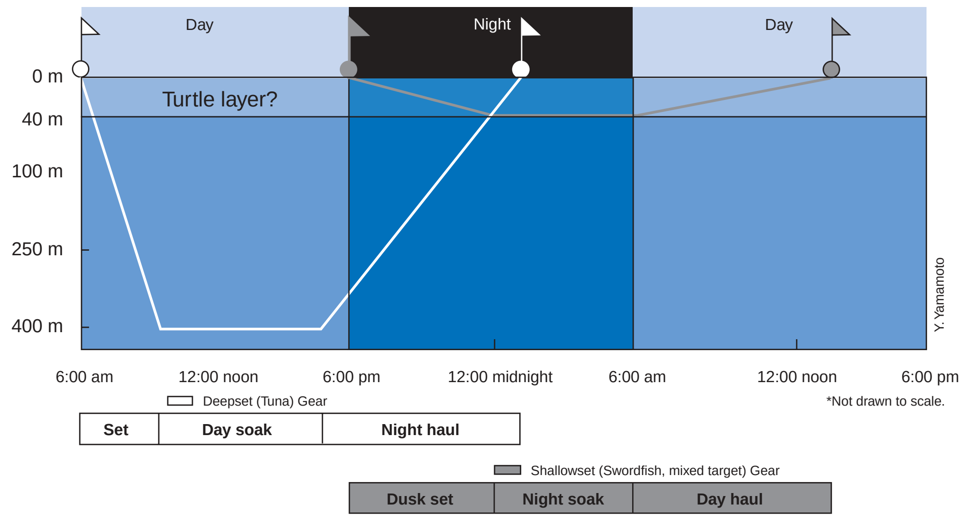
The effects of area closures took front and center stage in fishery policy concerns when a 1999 federal court ruling restricted longlining for swordfish within an area of approximately 6.5 million square miles north of the MHI to protect endangered and threatened species of sea turtles. PFRP researchers developed a spatial economic model that simulates a range of geographically defined area closures and the outcomes. The modeling showed that while nearshore area closures would lead fishers to make fewer trips of longer duration, the swordfish area closure would prompt longliners to relocate to fishing grounds around the MHI. The model forecasted that longline fishing for tunas and striped marlin could increase, possibly reducing catches by handliners and trollers. As information from longline logbooks subsequently showed, many longliners did shift their efforts to the predicted areas.

Tuna being auctioned in Honolulu. With sashimi-quality tuna in high demand, the Pacific-wide catch of bigeye tuna has reached 152,000 t. PFRP research has shown that bigeye belong to a single Pacific-wide stock which is being exploited very close to its maximum sustainable yield. (Courtesy of David Itano)

PFRP economists are continuing to refine the models and make them more flexible in defining fishing areas, which can fluctuate dramatically in terms of fish densities and catchability over small distances. Understanding how regulatory policies would change fishing activity and the associated benefits and costs is critical to sound fisheries management.

Comparing the Environmental Baggage of Longline Fisheries

Worldwide, pelagic longlining has earned a reputation as environmentally harmful for its considerable incidental catch of seabirds and sea turtles. However, longlining is not a single fixed method of fishing. It varies with location (e.g., coastal versus open-water) and operational practices such as how and when gear is set and whether measures are taken to avoid



A summary of key differences in longline fishing methods that impact incidental catch and bycatch rates. Courtesy PacMar, Inc.

interactions with protected species. Thus longlining effects on these species also vary. In a PFRP-sponsored project, researchers assessed and compared the incidental catch rates of sea turtles and non-target fish species in Hawai‘i's longline fishery and other domestic and selected foreign longline fisheries that supply US markets with the same seafood products.

The researchers collected information on the longline gear type, configuration and fishing methods in fleets operating in the Pacific (Australia, California, China, Japan, Taiwan, Mexico and Costa Rica), as well as Brazil and South Africa. They used data from NMFS, the Secretariat of the Pacific Community and scientists in countries where comparisons were made, as well as personal communication with scientists, fleet managers, commercial fishermen and longline gear suppliers.

Comparisons of longline fishing methods revealed that the critical factor in turtle catch is the depth to which hooks are set. Longliners fishing for bigeye tuna typically set hooks to depths of 50–400 meters (about 160–1300 feet), while those targeting swordfish set in depths ranging 35–80 meters (about 115–265 feet). Shallower still are longline gear sets for swordfish, shark and mahimahi in the eastern Pacific, which are commonly 5–30 meters (16–100 feet) deep. According to the data, on average shallow line-setting hooks ten times as many turtles as deep sets.

Next the researchers calculated bycatch-to-catch ratios based on 100 metric tons (mt) of the targeted species. This ratio provides a common denominator for comparing marketed fish caught by different methods. The results showed that Japan and Hawai‘i longliners using deep line-setting for bigeye tuna average about two turtle captures per 100 mt of tuna. Hawai‘i longliners setting shallow for swordfish had approximately 15 turtle takes per 100 mt of swordfish. Longline vessels using shallow sets for a mixture of species (tuna, billfish, sharks and mahimahi) ranged from 7 turtle captures (Australia) to as high as 1,450 (Costa Rica) and 2,320 (Brazil) turtles per 100 mt of target species.

Restricting fishing may transfer the impacts for which regulations are imposed to other regions. This appears to have occurred with the 1999 broad-scale restriction of shallow-set swordfish longlining in Hawai‘i. After the fishery closure, many Hawai‘i longliners simply relocated to California and continued to fish for swordfish in international waters. While NMFS data show that turtle takes declined by nearly one-half (about 340 turtles) after the fishery was closed, at the same time US seafood wholesalers substituted swordfish from other locales to replace the lost supply. This likely resulted in a net adverse impact on turtle populations, as some of the substituted swordfish came from fisheries with substantially higher rates of sea turtle interactions. For example, swordfish fisheries of Mexico, Costa Rica and Panama average 3–100 times higher rates of turtle capture.

The study results suggest that fishery managers should consider the relative ecological trade-offs that result when fishing effort is transferred or the market shifts the supply of fisheries products. The findings also imply that informed consumers can exert market pressure to encourage and support turtle-safe fishing and fishery products.

Area Closures: Do the Predictions Match the Results?

The closure of fishing grounds—either permanently or for discrete periods of time—is a widely used tool of fishery management, employed to protect spawning grounds, depleted stocks and threatened species. However, analysis to determine if these regulatory measures have met the pre-implementation goals has been meager. PFRP-funded researchers examined four such area closures for their effectiveness in achieving the expected biological protection, and compared the predicted consequences on the fishery with the actual results.

Florida Swordfish Closure—During the 1970s and ‘80s swordfish longlining in the Gulf of Mexico and Atlantic Ocean increased dramatically. The average size of swordfish caught steadily decreased as the number of juvenile swordfish discarded in the fishery increased. After considering several alternatives and modeling their effects, NMFS closed selected fishing grounds off the east coast of Florida in 2000. The modeling predicted that catches of juvenile and adult swordfish would fall by 27–38 percent and 11–24 percent respectively. The longline fleet was predicted to either disappear entirely from the region or shift their efforts to the remaining open areas, with a consequent decline in fishing revenues of 9–24 percent.

PFRP researchers found the actual results largely exceeded the modeling

Hawaii Fishing Industry: Economic Breakdown for 1997

Sector	Output ($ million)	Value-Added ($ million)	Wage Income ($ million)	Wage Jobs	Vessel Owner's Income ($ million)	Vessel Owner's Jobs
Swordfish longline	22.67	11.24	4.15	116	1.45	102
Tuna longline	27.37	16.46	7.30	215	2.49	191
Small commercial boats	11.70	6.55	0.29	10	5.40	507
Expense boats	3.94	-0.32	0.00	0	-0.78	1008
Recreation boats	10.30	0.00	0.00	0	0.00	0
Charter boats	14.17	8.39	4.67	175	1.42	67
Total Fishing Industry	**90.15**	**42.33**	**16.42**	**516**	**9.99**	**1875**
Total Hawaii	**58660.04**	**38536.98**	**21626.23**	**615545**	**2087.96**	**126686**

Data courtesy of NOAA Fisheries.

predictions. The 2001 data showed fishing effort fell by nearly 87 percent, and more than 40 of the vessels previously participating in the fishery left the region. This cutback resulted in a surprising 94 percent decline in juvenile bycatch and a 53 percent decrease in adult swordfish landings, which led 2001 fishing revenues to drop 54 percent. Thus the closure achieved the intended outcome for swordfish bycatch, but the accuracy of predictions for the longline fleet fell short.

Mid-Atlantic Bluefin Tuna Seasonal Closure—Responding to a situation of consistently high levels of bluefin tuna bycatch in a portion of the Mid-Atlantic Bight, in 1999 NMFS closed a small part of this area during the month of June. Based on different assumptions of effort redistribution, NMFS modeling predicted a wide range of decreases in bluefin discards (54–100 percent) and landings (18–98 percent). The 2001 data showed that discards and landings decreased by about 81 percent and 60 percent, respectively. The decline in fleet revenue was expected to be a negligible, despite bluefin tuna having a high ex-vessel price. While results for individual vessels varied, the fleetwide prediction proved to be accurate.

Northwestern Hawaiian Islands (NWHI) Monk Seal Closure—The population of the Hawaiian monk seal—a federally endangered species that once ranged throughout most of the Hawaiian archipelago—plummeted by more than 50 percent from the 1950s to the late-70s. The remaining population, of about 1,300 resides primarily in the NWHI. Responding to reports of monk seals bearing hooks used by longliners, in 1991 NMFS prohibited longlining within a zone spanning a 75-mile radius around the NWHI. The action was expected to reduce interactions between fishers and seals and result in an increase in the seal population. As of 2003 no interactions had been documented between the seals and US longliners. However, the overall seal population continues to decline.

Central Pacific Turtle Closure—Bycatch of federally protected sea turtles in Hawai`i waters rose steadily during the 1980s and '90s. NMFS estimated longline-associated turtle captures averaged more than 700 per year from 1996 through 1999. Following a lawsuit over the lack of an environmental impact statement (EIS) of the fishery's effects on the turtles (as required under the Endangered Species Act), NMFS prepared an EIS examining the issue. Measures proposed to address the problem included restrictions on the swordfish fishery. NMFS modeled the selected option for a 6.5-million-square-mile area closure north of the Hawaiian archipelago. The results estimated that interactions would decline by 85 percent, about 22 percent of longline vessels would exit the fishery, and revenues would drop by 10–45 percent.

The actual results matched the estimates relatively well. PFRP researchers found that two years after the closure there were 12 percent fewer vessels, but also a 12 percent increase in fishing effort. At-sea observer reports showed fishery-turtle interactions had diminished by nearly 70 percent. Reflecting the change in targeting by the fleet, the decline in swordfish catches (84 percent) was approximately matched by the increase in bigeye tuna catches (83 percent). Most longline vessels still had positive net returns for 2001.

Conclusions—The researchers concluded that the studied area closures succeeded in their stated pre-closure aims, though outcomes also were influenced by external factors. (For example, oceanographic conditions may change even within the limited temporal and spatial scales of the closures and affect bycatch rates.) They noted that improving the collection of economic data on fishing fleets would allow better economic modeling of proposed management actions, particularly with respect to estimating fluctuations in vessel revenues.

COMMUNICATING RESULTS AND FOSTERING INTERNATIONAL COOPERATION

The results of scientific research are of little value if they are not accessible to potential users. The PFRP has encouraged its affiliated scientists to publish their results widely, and they have published more than 80 articles in the scientific fisheries literature since the program's inception. In addition, more detailed presentations of projects have appeared in JIMAR technical reports and informal workshop reports. (Please see appendices.)

Since 1996 the program has produced a quarterly newsletter that circulates around the world and features results of PFRP-sponsored research as well as relevant science from outside the program. The newsletter goes out to more than 350 fisheries managers, academic and governments scientists, government fisheries agencies, libraries and interested individuals in 38 countries and US territories.

The PFRP's comprehensive Internet site (http://www.soest.hawaii.edu/PFRP/) links to project descriptions, reports and publications, announcements of fisheries research activities, information on project funding, the program newsletter and more. The PFRP office, located on the campus of the University of Hawai‘i-Manoa, serves as the physical hub for program coordination, information and communications.

Recruiting New Fisheries Scientists

Under the administration of the University of Hawai‘i's JIMAR, the PFRP has served as a bridge between the academic and government research worlds, with obvious benefits: Academic scientists are able to understand the practical problems that confront government scientists and can offer complementary points of view. Conversely, the intensely practical nature of government science ensures that academic researchers are well aware of the challenges in applying their findings. Collaborations between the NOAA Pacific Islands Fisheries Science Center (PIFSC) and university researchers also have offered a platform for training students in fisheries science and opening up employment opportunities to them following graduation.

The PFRP has actively promoted graduate education in fisheries to help meet the growing demand for fisheries scientists. Following a recommendation from an academic review of the PFRP economics and social sciences projects in October 2000, the program established two graduate assistantships in fisheries research, one in economics and one in fisheries oceanography. Also, PFRP Program Manager John Sibert assisted in crafting a proposal for a graduate degree program in Coastal and Marine Resources at the University of Hawai‘i-Manoa. The program funds the salary for the coordinator of this program, which will serve its first students during the Fall semester of 2005.

While the majority of PFRP funds has gone to projects originating from JIMAR, other University of Hawai‘i researchers and the NOAA-PIFSC, the program steering committee welcomes all relevant research proposals and has funded projects from many countries. (See sidebar on following page.) This open-door policy serves to attract a bigger pool of relevant proposals and also fosters the sharing of results more directly via institutions affiliated with the researchers.

Working Toward a Sea Change in the Management of CWP Fisheries

The 1990s will likely be remembered as pivotal in the history of the management of highly migratory fish species. In 1992 the UN Conference on Environment and Development (Rio de Janeiro) endorsed the ‘precautionary principle’ with respect to the oceans, specifically pointing to the necessity of "…apply(ing) preventive, precautionary and anticipatory approaches so as to avoid degradation of the marine environment, as well as to reduce the risk of long-term or irreversible adverse effects upon it ..." In August 1994 the UN adopted an agreement for implementing provisions, included in the 1982 UN Convention on the Law of the Sea (UNCLOS), relating to the conservation and man-

Breakdown of PFRP Projects and Funding (by institutional affiliation of the principal investigator), 1992–2003.

Joint Institute for Marine & Atmospheric Research, Univ. of Hawai‘i	
PFRP Administration	2,828,573
Visiting Scientist	1,123,290
Modeling Support	1,113,451
Other University of Hawai‘i researchers	4,927,790
NOAA Pacific Islands Fisheries Science Center	8,077,054
Virginia Institute of Marine Science	239,198
University of California-Davis	202,395
PACMAR, Inc., Honolulu	535,118
Joint Institute for the Study of the Atmosphere and Oceans, University of Washington	236,291
Hopkins Marine Station, Stanford University, California	240,559
Detection Limit Technology, Inc., Honolulu	128,686
Secretariat for the Pacific Community, New Caledonia	662,374
University of Maryland	333,715
University of Guam	254,800
Queens University, Canada	110,250
Inter-American Tropical Tuna Commission, La Jolla, CA (I-ATTC)	105,845
University of Montana and Centre d'Ecologie Fonctionnelle et Evolutive and Centre National De La Recherche Scientifique, France	184,522
University of Florida	100,626
Dalhousie University, Canada	103,488
TOTAL:	**$21,508,025**

agement of highly migratory fish stocks. This historic agreement, dubbed UNIA, emphasizes the management of such stocks throughout the range of their distribution. While the United States has not signed or ratified the UNCLOS, it was the third country to sign and ratify the UNIA, and it has been an international leader in promoting the conservation and management of highly migratory species

These two UN actions cast a sense of urgency on establishing effective arrangements for managing these species and provided an impetus for a higher level of multinational cooperation across the Pacific. In the CWP, governments had organized the South Pacific Forum Fisheries Agency (FFA) to aid in harmonizing management measures taken by individual countries. Also, the South Pacific Commission (now the Secretariat of the Pacific Community) served as a center for data collection and scientific fisheries information. Nonetheless, management of pelagic stocks there remained unconsolidated and inadequate for addressing region-wide needs until the mid-1990s.

Guided by the UNCLOS and UNIA, seven sessions of the Multilateral High-Level Conference on the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific (MHLC) were held from 1994 to 2000. Attended by representatives of Pacific Island and distant-water fishing nations (including the U.S.), the fishing industry and other interested parties, the meetings addressed a range of legal, conservation, scientific and technical issues. In Honolulu in September 2000, the 29 contracting parties adopted the Convention for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific. The convention area encompasses most of the Pacific Ocean west of 150° east longitude. The commission established to implement the convention is scheduled to begin operations in mid–2004. During the interim, participants in a series of preparatory conferences are deliberating on a raft of issues that must be resolved to ensure the convention achieves effective support. The treaty will enter into force and the Commission will begin to function in June 2004.

Category	Year-to-date (FY '92 - FY '04)	YTD %
Administration	2,828,573	13.2
JIMAR Visiting Scientist	1,123,290	5.2
Genetics	502,257	2.3
Biology	6,463,088	30.0
Statistics & Modeling	2,875,421	13.4
Oceanography	2,671,197	12.4
Economics	3,668,263	17.1
Socio-cultural	984,943	4.6
Protected Species	390,993	1.8
Total	$21,508,025	100%

PFRP's Commitment to Multinational Fisheries Management

The PFRP and its affiliated researchers have been actively engaged in discussions on issues of CWP regional research and management since the program's inception. Early on, the program sponsored a symposium on Pacific-wide fisheries research and a workshop on ocean-scale management of pelagic fisheries featuring presentations by economists, social scientists and legal experts. The program also has encouraged the sharing of research results between scientists from numerous countries via the many other meetings and workshops it has hosted. (See sidebar on Fisheries meetings/ workshops.)

In 2001, PFRP Program Manager John Sibert became chair of the Methods Working Group of the Standing Committee on Tuna and Billfish (SCTB), the central clearinghouse for regional fisheries data and research in the Pacific. Dr. Sibert also served as a member of the US delegation to the MHLC and continues participate in the preparatory conferences for the new commission. His frequent reports and articles on the workings of these multinational groups in the program newsletter have helped to keep the PFRP community and newsletter readers abreast of developments in these arenas.

Directions for a New Millennium

In the coming years fishery management will differ radically from current practice. Management goals will give greater emphasis to sustaining entire ecosystems than to maintaining stable harvests of single species. In the Pacific Ocean—where the planet's biggest and most complex ecosystem touches diverse political jurisdictions—specific management actions will take place in a more international context than does unilateral management within a single EEZ.

The PFRP priorities for research have evolved as the program has matured. Having successfully tackled many of the baseline studies needed by the fishery council, program sights have shifted considerably to research in support of ecosystem-based management. This "big picture" approach aims to weave together the best available information on the biology and ecology of marine species (i.e., their functions, processes and interactions), the ocean environment, and the effects of human activity on both. It recognizes that fishery management and exploitation are real and integral parts of marine ecosystems.

While this nascent strategy holds much promise for achieving more holistic conservation and management of fisheries, it demands a much broader base of scientific support than is currently available in the Pacific. In its sponsorship of research on fisheries oceanography, the ecology of non-target commercial species, and the dynamics of critical protected species, the PFRP has laid the groundwork to provide such scientific support. The program's activities in international fisheries research and management also have augmented these efforts.

General ecosystem-related topics that will be addressed in future PFRP research include the following:

- Understanding the relationships between predator populations near the top of the food chain;
- Assessing the impacts of short- and long-term environmental variability on populations of both target and non-target species;
- Determining how populations mix in the Pacific Ocean;

PFRP Involvement in Fisheries Meetings

1992

- PFRP hosted the Pacific Pelagic Fisheries Planning Workshop (March 24-27), University of Hawai‘i-Manoa.

1993

- PFRP funded the Blue Marlin Workshop (April 20–23), Honolulu.
- PFRP hosted the Yellowfin Assessment Model Development Workshop (Nov. 8–12), Honolulu.

1997

- PFRP organized the two-day symposium on Ocean-Scale Management of Pelagic Fisheries: Economic and Regulatory Issues (November 12–13), University of Hawai‘i-Manoa.

1998

- PFRP coordinated the international Pacific Bigeye Tuna Research Coordination Workshop (November 9-10), University of Hawai‘i-Manoa.

1999

- PFRP-affiliated scientists made 8 presentations at the 13th meeting of the Standing Committee on Tunas and Billfish (Feb. 1-3), including a PFRP-coordinated workshop on modeling and bigeye tuna stock assessments.
- PFRP-affiliated scientists made 6 presentations at the 50th Lake Arrowhead (California) Tuna Conference (May 24–27).

2000

- PFRP hosted international workshop on the MUTIFAN-CL stock assessment model (February 1-3), University of Hawai‘i-Manoa.
- PFRP hosted the Second Workshop on Daylight Measurements for Geo-location in Animal Telemetry (February 3–4), University of Hawai‘i-Manoa.
- PFRP co-sponsored the International Symposium on Tagging and Tracking Marine Fish with Electronic Devices (Feb 7–11), attended by more than 100 people from a dozen countries.
- PFRP-affiliated scientists made 7 presentations at the 51st Lake Arrowhead (California) Tuna Conference (May 22–25).
- PFRP-affiliated scientists made several presentations on program-related research at the annual meeting of the Standing Committee on Tunas and Billfish (July 5-12), Noumea, New Caledonia.
- PFRP organized the Marine Turtle Bycatch Reduction Working Group Meeting (September 12-13), Los Angeles.
- Workshop on Exploitation, Predation, and Scales of Spatial Variability in Pelagic Fisheries (PFRP Principal Investigators' Meeting, December 5-7), University of Hawai‘i-Manoa.

2001

- PFRP organized the 2nd Marine Turtle Bycatch Reduction Working Group Meeting (January 9-11), San Diego.
- PFRP-affiliated scientists made 12 presentations at the 52nd Lake Arrowhead (California) Tuna Conference (May 21-25).
- PFRP hosted the Protected Species Population Modeling Workshop (November 13–14), University of Hawai‘i-Manoa.
- Workshop on Ecosystem-Based Management of Pelagic Fisheries held as part of PFRP Principal Investigators' Meeting (December 4-6), University of Hawai‘i-Manoa.
- Publication of proceedings from the 2000 Symposium on Tagging and Tracking Marine Fish with Electronic Devices, as first volume of *Reviews: Methods and Technologies in Fish Biology and Fisheries*, Kluwer Academic Publishers.

2002

- PFRP Program Manager participated in second and third Western and Central Pacific Fisheries Convention Preparatory Conference—“PrepCon”
- PFRP-affiliated scientists made 15 presentations at the 53rd Lake Arrowhead (California) Tuna Conference (May 20–23).
- PFRP co-hosted 15th Standing Committee on Tuna and Billfish (SCTB 15) Meeting, July 22-27, Honolulu.
- PFRP Program Manager participated in the first meeting of the Scientific Coordinating Group of PrepCon, (July 29–31) Honolulu.
- PFRP sponsored the International Workshop on the Current Status and New Directions for Studying Schooling and Aggregation Behavior of Pelagic Fish (October 7–9), University of Hawai‘i-Manoa.
- “Tying One On” Workshop held as part of PFRP Principal Investigators' Meeting, (December 4-6), University of Hawai‘i-Manoa.

2003

- PFRP Program Manager participated in fourth and fifth Western and Central Pacific Fisheries Convention Preparatory Conference
- PFRP-affiliated scientists made 12 presentations at the 54th Lake Arrowhead (California) Tuna Conference (May 20–23).
- PFRP-affiliated scientists made 3 presentations on program-related research at the 15th Standing Committee on Tuna and Billfish Meeting (July 9-16), Mooloolaba, Australia.
- PFRP Program Manager participated in the second meeting of the Scientific Coordinating Group of PrepCon, (July 27–19) Mooloolaba, Australia.
- Workshop on Data Rescue: Discovery, Verification, Documentation and Analysis of Long-Term Data, held as part of the PFRP Principal Investigators' Meeting (December 9-11), University of Hawai‘i-Manoa.

- Devising and evaluating policies suitable for conservation of fish populations on the scale of the largest geographic feature on earth.

A second, related priority involves advancing the knowledge of protected species in the Pacific. The impacts of interactions between fishing operations and protected species have reached the point where fisheries sustainability depends on scientifically quantifying the effects of specific fishing practices and the population dynamics of protected species. The PFRP is seeking to expand the methods used to obtain this critical information and to improve the means for modeling and assessing populations of protected species of seabirds and sea turtles. Work has already begun on some of these topics.

With a ten-year record of considerable scientific accomplishments, the PFRP stands ready to meet the challenges of providing continuing scientific support for 21st century pelagic fisheries management.

Appendix 1: Pelagic Fisheries Research Program Technical Reports

Publication Year 2003

Holland, Kim N. and Melinda J. Braun, 2003. Proceedings of "Tying One On"—a workshop on tag attachment techniques for large marine mammals. SOEST Publication 03-02, JIMAR Contribution 03-349.

O'Malley, Joseph M. and Samuel G. Pooley, 2003. Economics and Operational Characteristics of the Hawaii-Based Longline Fleet in 2000. SOEST Publication 03-01, JIMAR Contribution 03-348.

Wachsman, Yoav, 2003. Externalities and management regimes in fisheries exploitation. SOEST Publication 02-03, JIMAR Contribution 02-346, 19 pp.

Publication Year 2002

Gillett, Robert, Mike A. McCoy, and David G. Itano, 2002. Status of the United States Western Pacific tuna purse seine fleet and factors affecting its future. SOEST Publication 02-01, JIMAR Contribution 02-334, 64 pp.

O'Malley, Joseph M. and Samuel G. Pooley, 2002. A Description and Economic Analysis of Large American Samoa Longline Vessels. SOEST Publication 02-2, JIMAR Contribution 02-345, 24 pp.

Publication Year 2001

McConnell, Kenneth E. and Timothy C. Haab, 2001. Small boat fishing in Hawaii: Choice and economic values. SOEST Publication 01-01, JIMAR Contribution 01-336, 62 pp.

O'Malley, J.M. and E.W. Glazier, 2001. Motivations, satisfaction and expenditures of recreational pelagic charter fishing patrons in Hawaii. SOEST Publication 01-03, JIMAR Contribution 01-339, 46 pp.

Porter, Richard M., Maribeth Wendt, Michael D. Travis, and Ivar Strand, 2001. Cost-earnings study of the Atlantic-based U.S. pelagic longline fleet. SOEST Publication 01-02, JIMAR Contribution 01-337, 102 pp.

Publication Year 2000

Chakravorty, Ujjayant and Keiichi Nemoto, 2000. Modeling the effects of area closure and tax policies: A spatial model of the Hawaii longline fishery. SOEST Publication 00-02, JIMAR Contribution 00-329, 28 pp.

Hamnett, Michael P. and Cheryl L. Anderson, 2000. Impact of ENSO events on tuna fisheries in the U.S.-affiliated Pacific Islands. SOEST Publication 00-03, JIMAR Contribution 00-330, 27 pp.

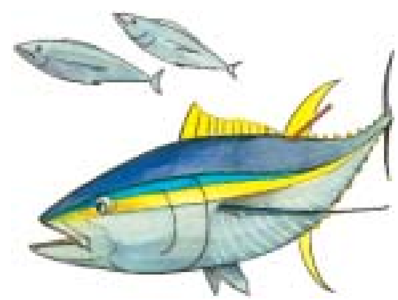
Itano, David G., 2000. The reproductive biology of yellowfin tuna (Thunnus albacares) in Hawaiian waters and the western tropical Pacific Ocean: Project summary. SOEST Publication 00-01, JIMAR Contribution 00-328, 69 pp.

Kaneko, John, Paul Bartram, Marc Miller and Joe Marks, 2000. Local fishery knowledge: The application of cultural consensus analysis to the management and development of small-scale pelagic fisheries. Project final report. SOEST Publication 00-06, JIMAR Contribution 00-334, 34 pp.

Weng, Kevin C.M. and John R. Sibert, 2000. Analysis of the fisheries for two pelagic carangids in Hawaii. SOEST Publication 00-04, JIMAR Contribution 00-332, 78 pp.

Publication Year 1999

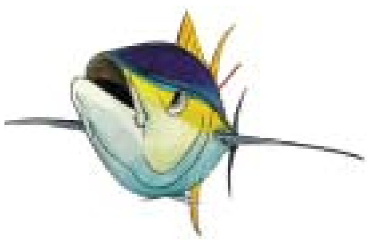
Chakravorty, Ujjayant and John Sibert (editors), 1999. Ocean-scale management of pelagic fisheries: Economic and regulatory issues, (Proceedings of an international workshop organized by the Pelagic Fisheries Research Program, JIMAR, UH, November 12-13, 1997). SOEST 99-01, JIMAR Contribution 99-321, 102 pp.



Glazier, Edward W., 1999. Non-commercial fisheries in the central and western Pacific: A summary review of the literature. SOEST 99-07, JIMAR Contribution 99-326, 48 pp.

Pan, Minling, PingSun Leung, Fang Ji, Stuart T. Nakamoto, and Samuel G. Pooley, 1999. A multilevel and multi-objective programming model for the Hawaii fishery: Model documentation and application results. SOEST 99-04, JIMAR Contribution 99-234, 84 pp. With: Fisheries management decision support system (FMDSS): Users manual, 1999. Omar F. El-Gayar and Fang Ji.

Sharma, K.R., A. Peterson, S.G. Pooley, S.T. Nakamoto, and P.S. Leung, 1999. Economic contributions of Hawaii's fisheries. SOEST 99-08, JIMAR Contribution 99-327, 40 pp.



Publication Year 1998

Grewe, Peter M. and John Hampton, 1998. An assessment of bigeye (Thunnus obesus) population structure in the Pacific Ocean, based on mitochondrial DNA and DNA microsatellite analysis. SOEST 98-05, JIMAR Contribution 98-320, 23 pp.

Hamilton, Marcia S., 1998. Cost-earnings study of Hawaii's charter fishing industry, 1996-1997. SOEST 98-08, JIMAR Contribution 98-322, 105 pp.

McConnell, K.E., I.E. Strand, and R.E. Curtis, 1998. An analysis of auction prices of tuna in Hawaii: Hedonic prices, grading, and aggregation. SOEST 98-03, JIMAR Contribution 98-317, 27 pp.

Stöcker, Sabine, 1998. Cellular automaton models for fish schools: Merging social behavior and hydrodynamics. SOEST 98-02, JIMAR Contribution 98-316, 19 pp.

Publication Year 1997

Bills, Peter J. and John R. Sibert, 1997. Design of tag-recapture experiments for estimating yellowfin tuna stock dynamics, mortality, and fishery interactions. SOEST 97-05, JIMAR Contribution 97-313, 80 pp.

Hamilton, Marcia S., Stephen W. Huffman, 1997. Cost-earnings study of Hawaii's small boat fishery, 1995-1996. SOEST 97-06, JIMAR Contribution 97-314, 102 pp.

Walker, Julie, 1997. Sociology of Hawaii charter boat fishing. SOEST 97-02, JIMAR Contribution 97-309, 50 pp.

Publication Year 1996

Bartram, Paul, Peter Garrod, and John Kaneko, 1996. Quality and product determination as price determinants in the marketing of fresh Pacific tuna and marlin. SOEST 96-06, JIMAR Contribution 96-304, 50 pp.

Hamilton, Marcia S., Rita E. Curtis, and Michael D. Travis, 1996. Cost-earnings study of the Hawaii-based domestic longline fleet. SOEST 96-03, JIMAR Contribution 96-300, 59 pp.

Hamnett, Michael P. and William Sam Pintz, 1996. The contribution of tuna fishing and transshipment to the economies of American Samoa, the Commonwealth of the Northern Mariana Islands, and Guam. SOEST 96-05, JIMAR Contribution 96-303, 38 pp.

Miller, Marc L., 1996. Social aspects of Pacific pelagic fisheries, Phase I: The Hawai‘i troll and handline fishery. SOEST 96-04, JIMAR Contribution 96-302, 120 pp.

Schoen, Christian and John Sibert, 1996. Feasibility of dual mode lidar for pelagic fish surveys. SOEST 96-02, JIMAR Contribution 96-301, 18 pp.

Sibert, John and Mary Nunn, 1996. Pacific pelagic fisheries: Current projects and related research. Abstracts of papers presented November 28-30, 1995. SOEST 96-01, JIMAR Contribution 96-299, 49 pp.

Appendix 2: Peer-Reviewed Journals Papers Related to PFRP-Sponsored Research

1. Adam, M. Shiham, John Sibert, David Itano, and Kim Holland, 2003. Dynamics of bigeye (*Thunnus obesus*) and yellowfin (*T. albacares*) tuna in Hawaii's pelagic fisheries: Analysis of tagging data with a bulk transfer model incorporating size-specific attrition. *Fishery Bulletin*, 101 (2): 215-228.

2. Adam, M. S. and J. Sibert, 2002. Population dynamics and movements of skipjack tuna (*Katsuwonus pelamis*) in the Maldivian fishery: analysis of tagging data from an advection-diffusion-reaction model. *Aquatic Living Resources*, 15: 13-23.

3. Bidigare, Robert R., Claudia Benitez-Nelson, Carrie L. Leonard, Paul D. Quay, Michael L. Parsons, David G. Foley, and Michael P. Seki, 2003. Influence of a cyclonic eddy on microheterotroph biomass and carbon export in the lee of Hawaii. *Geophysical Research Letters*, 30 (6) 10.1029/2002GLO16393.

4. Bigelow, Keith A., Christofer H. Boggs, and Xi He, 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. *Fisheries Oceanography*, 8:3, 178-198.

5. Block, Barbara A., Heidi Dewar, Charles Farwell, and Eric D. Prince, 1998. A new satellite technology for tracking the movements of Atlantic bluefin tuna. *Proceedings of the National Academy of Sciences*, 95:9384-9389, August 1998.

6. Block, B. A., J. E. Keen, B. Castillo, H. Dewar, E. V. Freund, D. J. Marcinek, R. W. Brill, and C. Farwell, 1997. Environmental preferences of yellowfin tuna (*Thunnus albacares*) at the northern extent of its range. *Marine Biology*, 130: 119-132.

7. Braun, Marvin H., Richard W. Brill, John M. Gosline and David R. Jones, 2003. Form and function of the bulbus arteriosus in yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*) and blue marlin (*Makaira nigricans*): Static properties. *Journal of Experimental Biology*, 206: 3311-3326.

8. Braun, Marvin H., Richard W. Brill, John M. Gosline and David R. Jones, 2003. Form and function of the bulbus arteriosus in yellowfin tuna (*Thunnus albacares*): Dynamic properties. *Journal of Experimental Biology*, 206: 3327-3335.

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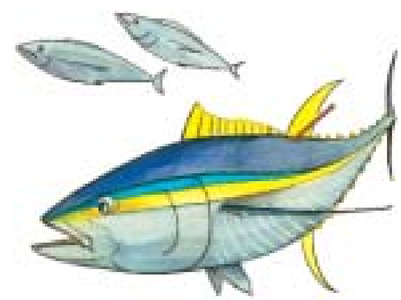
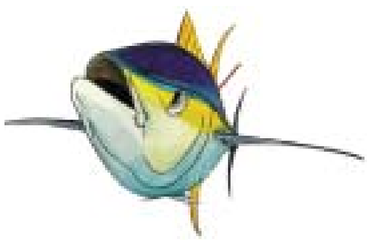
10. Brill, R., et al., 2002. Horizontal and vertical movements of juvenile bluefin tuna (*Thunnus thynnus*), in relation to oceanographic conditions of the western North Atlantic, determined with ultrasonic telemetry. *Fishery Bulletin*, 100: 155-167.

11. Brill, Richard W., and Molly E. Lutcavage, 2001. Understanding environmental influences on movements and depth distributions of tunas and billfishes can significantly improve population assessments. *American Fisheries Society Symposium*, 25: 179-198.

12. Brill, Richard, Yonat Swimmer, Carina Taxboel, Katherine Cousins, and Timothy Lowe, 2001. Gill and intestinal NA+-K+ ATPase activity, and estimated maximal osmoregulatory costs, in three high-energy-demand teleosts: yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*), and dolphin





fish (*Coryphaena hippurus*). *Marine Biology,* 138: 935-944.

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14. Brill, R.W., K.L. Cousins, D.R. Jones, P.G. Bushnell, and J. F. Steffensen, 1998. Blood volume, plasma volume and circulation time in a high-energy demand-high teleost, the yellowfin tuna (*Thunnus albacares*). *Journal of Experimental Biology,* 201, 647-654.

15. Brill, Richard W., Timothy E. Lowe, and Katherine L. Cousins, 1998b. How water temperature really limits the vertical movements of tunas and billfishes—It's the heart stupid. Abstract from the American Fisheries Society, International Congress on Biology of Fish, July 26-20, 1998, Towson University, Baltimore, MD

16. Buonaccorsi, Vincent P., Kimberly S. Reece, Lee W. Morgan, and John E. Graves, 1999. Geographic distribution of molecular variance within the blue marlin (*Makaira nigricans*): A hierarchical analysis of allozyme, single-copy nuclear DNA, and mitochondrial DNA markers. *Evolution,* 53(2), 568-579.

17. Chakravorty, Ujjayant, and Keiichi Nemoto, 2001. Modeling the effects of area closure and tax policies: a spatial-temporal model of the Hawaii longline fishery. *Marine Resources Economics,* 15: 179-204.

18. Curran, D.S., C.H. Boggs, and X. He., 1996. Catch and effort from Hawaii's longline fishery summarized by quarters and five degrees squares. *NOAA Technical Memorandum*, NMFS-SWFSC-225, 68 pp.

19. Curtis, Rita and Robert L. Hicks, 2000. The cost of sea turtle preservation: The Case of Hawaii's Pelagic Longliners. *American Journal of Agricultural Economics,* 82(5):1191 -1197.

20. Firing, E., B. Qiu and W. Miao, 1999. Time-dependent island rule and its application to the time-varying North Hawaiian Ridge Current. *Journal of Physical Oceanography,* 29, 2671-2688.

21. Fonteneau, A, P. Pallares, J. Sibert and Z. Suzuki, 2002. Effect of tuna fisheries on tuna resources and on offshore pelagic ecosystems. In *Ocean Yearbook,* Vol. 16. E. M. Borgese, A. Chircop, and M. McConnell (eds).

22. Fonteneau, A., R. Allen, T. Pollachek, P. Pallares, J. Sibert and Z. Suzuki. 1999. Effect of tuna fisheries on the tuna resources and on the offshore pelagic ecosystems. ICES/SCOR Symposium on Ecosystem Effects of Fishing, Montpellier, France, 16-19 March 1999.

23. Fournier, D., J. Hampton, and J. Sibert. 1999. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to south Pacific albacore, *Thunnus alalunga. Canadian Journal of Fisheries and Aquatic Sciences*, 55:2105-2116.

24. Hamilton, Marcia S., Rita E. Curtis and Michael D. Travis, 1996: Hawaii longline vessel economics. *Marine Resource Economics,* 11(2): 137-140.

25. Hamilton, Marcia, 1999. A system for classifying small boat fishermen in Hawaii. *Marine Resource Economics,* 13: 289-291.

26. Hampton, John and David A. Fournier, 2001. A spatially disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean. *Marine Freshwater Resources,* 52: 937-963.

27. He, Xi, Keith A. Bigelow and Christofer H. Boggs, 1997.

Cluster analysis of longline sets and fishing strategies within the Hawaii-based fishery. *Journal of Fisheries Research,* 31: 147-158.

28. Holland, K. et al, 2001. Five tags applied to a single species in a single location: The tiger shark experience. In J.R. Sibert and J. Nielsen (Eds.), *Electronic Tagging and Tracking in Marine Fisheries* (pp. 237-248). Kluwer Academic Publishers, The Netherlands.

29. Holland, K.N., S. M. Kajiura, D.G. Itano and J. R. Sibert, 2001. Tagging techniques can elucidate the biology and exploitation patterns of aggregated pelagic fishes. In *Island in the stream: oceanography and fisheries of the Charleston Bump*. G. R. Sedberry, editor. American Fisheries Society, Symposium 25, pp. 211-218.

30. Holland, K.N., P. Kleiber and S.M. Kajiura, 1999. Different residence times of yellowfin tuna, *Thunnus albacares*, and bigeye tuna, *Thunnus obesus,* found in mixed aggregations over a seamount. *Fishery Bulletin*, 97:392-395.

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38. Lowe, T.E., R.W. Brill, and K.L. Cousins, 2000. Blood oxygen-binding characteristics of bigeye tuna (*Thunnus obesus*), a high-energy-demand teleost that is tolerant of low ambient oxygen. *Marine Biology,* 136: 1087-1098.

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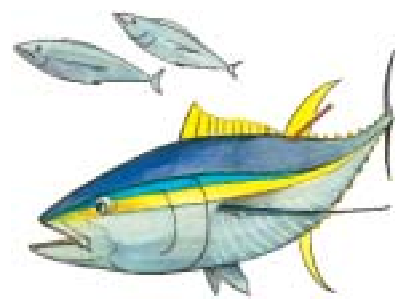
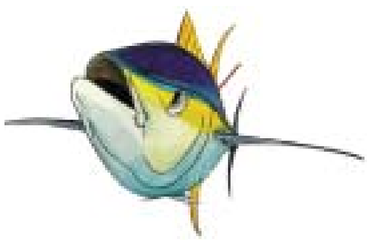
41. Lund S.C., P. Dyment, M.R. Gervais, C.D. Moyes and B.L. Tufts, 2002. Characterization of erythrocyte carbonic anhydrase in an ancient fish, the longnose gar (*Lepisosteus osseus*). Carbonic anhydrase in an ancient fish. *Journal of Comparative Physiology and Biology,* 172: 1467-1476.





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51. Phillips M.C.L., C.D. Moyes, and B.L. Tufts, 2000. The effects of cell ageing on metabolism of nucleated red blood cells. *Journal of Experimental Biology*, 03: 1039-1045.

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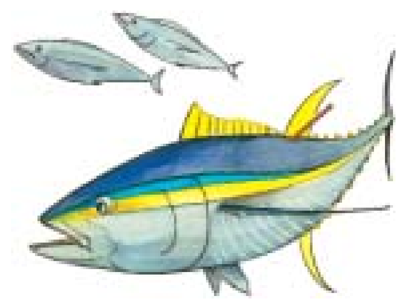

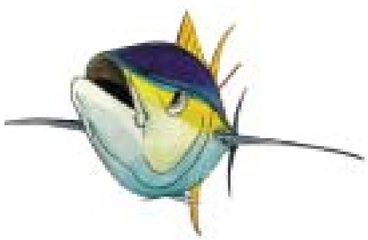

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