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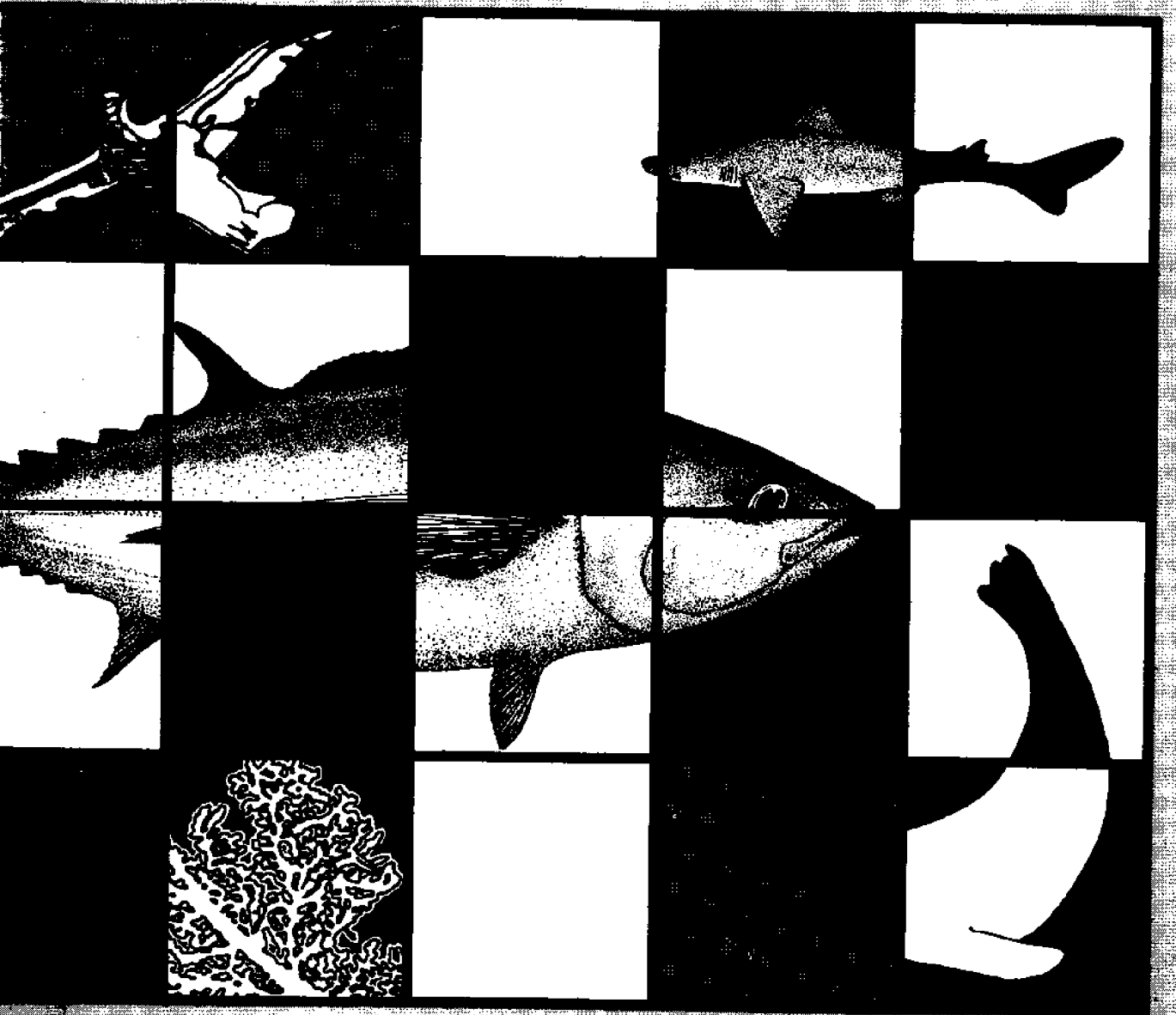
Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands

Volume 1

May 25-27, 1983



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PROCEEDINGS OF THE SECOND SYMPOSIUM ON RESOURCE INVESTIGATIONS IN THE NORTHWESTERN HAWAIIAN ISLANDS

VOLUME 1

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May 25-27, 1983
Campus Center Ballroom
University of Hawaii
Honolulu, Hawaii

Edited by

Richard W. Grigg

Karen Y. Tanoue

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Sea Grant Miscellaneous Report
UNIHI-SEAGRANT-MR-84-01

April 1984

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PREFACE

For more than a decade, the state of Hawaii and the nation have recognized the urgency to survey and assess the marine resources of the Northwestern Hawaiian Islands (NWHI). Recommendations for resource surveys of the Hawaiian Archipelago were made by a task force of the Governor of Hawaii in Hawaii and the Sea in 1969 and again in 1974. In 1975, a formal agreement between the National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (FWS), and the Division of Fish and Game (since renamed Division of Aquatic Resources) of the Hawaii Department of Land and Resources was established to conduct a 5-year survey and assessment of the marine resources of the Northwestern Hawaiian Islands (Nihoa to Kure Atoll). This agreement, known as the Tripartite Cooperative Agreement, names NMFS as the lead agency and attributes responsibility for research on offshore, bank, and seamount resources to NMFS, nearshore resources to DAR and seabird resources to FWS. The University of Hawaii through its Sea Grant College Program, with matching assistance from the Office of the Marine Affairs Coordinator, joined the study in 1977. The major objective of the joint investigation was resource assessment and ecology for the purpose of protecting unique wildlife and managing potential fishery resources. Since the inception of the joint venture, the participating agencies have attempted to maximize cooperative use of facilities and maintain open interagency communication.

In 1979, it was decided by the heads of the tripartite agencies and the UH Sea Grant College Program that sufficient progress had been made to convene a symposium to interchange research results and ideas and to incorporate this information in planning the remaining 3 years of research. The agency heads who served as members of the steering committee to organize the symposium were Mr. Richard Shomura, Southwest Fisheries Center Honolulu Laboratory of NMFS; Mr. Kenji Ego (replaced by Mr. Henry Sakuda in 1980), Division of Aquatic Resources, Hawaii Department of Land and Natural Resources; Mr. Dale Coggeshall, Pacific Islands branch of the U.S. Fish and Wildlife Service; and Dr. Jack Davidson, University of Hawaii Sea Grant College Program. Dr. Richard Grigg of the Hawaii Institute of Marine Biology at the University of Hawaii, and project leader of the Sea Grant Northwestern Hawaiian Islands research program, chaired the committee and was the convener and moderator of the symposium.

The symposium was held on April 24-25, 1980 at the Campus Center Ballroom on the Manoa campus of the University of Hawaii. Twenty-seven papers were presented at the symposium. Authors were asked to give the original objectives of their studies, describe progress to date, and address future research needs. The symposium was attended by 151 invited representatives of governmental agencies, industry, the University of Hawaii, environmental groups, and the private sector.

Manuscripts of the papers delivered at the first symposium along with panel discussions, the keynote and luncheon addresses, and the concluding remarks were all published in a proceedings in 1980 (Grigg and Pfund, eds., 1980; UNIHI-SEAGRANT-MR-80-04). After the first symposium, research continued in the NWHI for another 3 years and the steering committee for organizing the research, Council for Coordinating Research in the NWHI (CCR-NWHI), continued to meet monthly. In late 1982, the council decided that a second and final symposium should be held. The date was set for May 25-27, 1983. The council also decided that a film documenting the entire program should be made. All four participating agencies provided equal financial support for its production. A subcommittee responsible for producing the film was appointed by the council. Its members were Jeffery Polovina, Robert Shallenberger, and Reg Gooding. The film, produced by Cinepac Hawaii, is entitled "The Northwestern Hawaiian Islands: A Five-Year Study of Ecology and Fisheries."

The second and final symposium was attended by 211 registered individuals representing state and federal agencies, academia, and the private sector, particularly fishermen and environmentalists. This proceedings contains full-length papers or abstracts of papers presented at the 3-day meeting in 1983 along with the introductory speeches, luncheon addresses, panel discussions, and concluding remarks. It also contains reports on research conducted in the NWHI. The papers delivered at the symposium were designed to be overviews of the research conducted in the NWHI on each major topic of concern. Thus, the symposium papers tend to be summaries, while the reports are detailed descriptions of more specific subject areas.

Also contained in this proceedings are unpublished abstracts and copies of abstracts of papers published in the scientific literature prior to the second symposium. The abstracts are produced herein in an attempt to make these volumes as complete a reference document as possible on the results of the tripartite-Sea Grant 5-year study.

The maps which appear in this proceedings contain several slight place name inconsistencies, viz. Kure Atoll versus Kure Island. For purposes of official reference, the place names in the Hawaiian Islands are as follows: Brooks Banks, French Frigate Shoals (La Perouse Pinnacle, Tern Island, Trig Island, East Island, Whale Island, Skate Island, Shark Island, Gin Island, Little Gin Island), Gardner Pinnacles, Hancock Seamounts, Kure Atoll (Green Island, Sand Island), Laysan Island, Lisianski Island, Maro Reef, Midway Islands (Sand Island, Eastern Island, two Spit Islands), Necker Island, Neva Shoal, Nihoa, Pearl and Hermes Atoll (Grass Island, Little North Island, Seal-Kittery Island, Southeast Island, Bird Island, Planetree Island, Sand Island), Penguin Bank, Raita Bank, St. Rogatien.

The section in the proceedings covering the panel discussions consists of two sessions: the first is entitled

"Optimum Use Scenarios" and the second "Reaction Panel." The first panel was designed to permit recognized experts on various aspects of the NWHI an opportunity to present their views as to optimum use of the islands. The reaction panel, also consisting of recognized experts, was set up to provide the symposium participants with alternative views. Following the panel discussions, the public was invited to participate in the dialog. All three discussions are published in the proceedings verbatim.

The tripartite-Sea Grant study of the NWHI has been a monumental effort. The success of the program is owed to some 200 researchers of various governmental agencies and universities, as well as interested fishermen and lay-persons. The results document one of the largest and most complete multidisciplinary ecological investigations ever attempted. In addition, they have laid the groundwork for a master plan under preparation by the U.S. Fish and Wildlife Service containing management guidelines for a whole variety of commercial as well as endangered or threatened wildlife species. The final measure of the success of the 5-year study perhaps will be the degree to which the master plan successfully meets the needs of preserving wildlife while also providing for limited developmental opportunities throughout the NWHI chain. A number of management plans under preparation by state and federal agencies as well as the Western Pacific Regional Fishery Management Council will be incorporated into the master plan.

Presentation of the symposia as well as publication of the proceedings in 1980 and in 1984 involved the talent and commitment of a large number of people. The staff of the University of Hawaii Sea Grant College Program are largely responsible for both. Particularly valuable contributions during the second symposium were made by Joan Yamada, Nancy Preston, and Rose Pfund (production and overall layout of the proceedings), Joan Choy, Peter Rappa, Wendy Nakano (artist), and Jo Ann Lee. The symposia contents and the proceedings volumes were planned by members of the CCR-NWHI. Considerable logistic support for running the second symposium was provided by Kitty Simonds and the Western Pacific Regional Fishery Management Council staff. Valuable comments were made by reviewers of the papers and reports. Financial support for conducting the symposia and publishing both proceedings was provided equally by the National Marine Fisheries Service, the U.S. Fish and Wildlife Service, the Division of Aquatic Resources of the Hawaii Department of Land and Natural Resources, and the University of Hawaii Sea Grant College Program. The editors gratefully acknowledge these organizations for their professional talent and funding support that together have resulted in an unprecented example of cooperative intergovernmental multidisciplinary research.

The Editors
Richard W. Grigg, UH
Karen Y. Tanoue, UH

ACKNOWLEDGMENT*

At mid-point in the 5-year tripartite-Sea Grant studies I expressed a great deal of concern that if we were going to get to the results, to answer the questions in need of answering, we had to be more adroit and more active in program management. As a result, a Council for Coordinating Research in the NWHI was formulated and the tripartite program was expanded to the tripartite-Sea Grant program to recognize the important role that the University of Hawaii Sea Grant College Program was playing in this endeavor. And by the good graces of Sea Grant Director Jack Davidson and with the willingness of Rick Grigg, we were able to designate Rick as the chairman of the council. I and my conspirators on the council want to acknowledge the key role that Rick has played in helping to keep us on track during meetings and helping to bring together this symposium as well as the first one which occurred at the mid-point of the study period. Also, we would like to acknowledge his contributions as a researcher, as a coordinator of the council, and as the principal person behind the scenes for the development of the two symposia. As we've acknowledged fishermen and individual researchers, I think today we should take a moment to acknowledge Rick Grigg for his valuable contributions.

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*Message read to the symposium participants by Dale Coggeshall of the U.S. Fish and Wildlife Service on the third day during the panel discussions.

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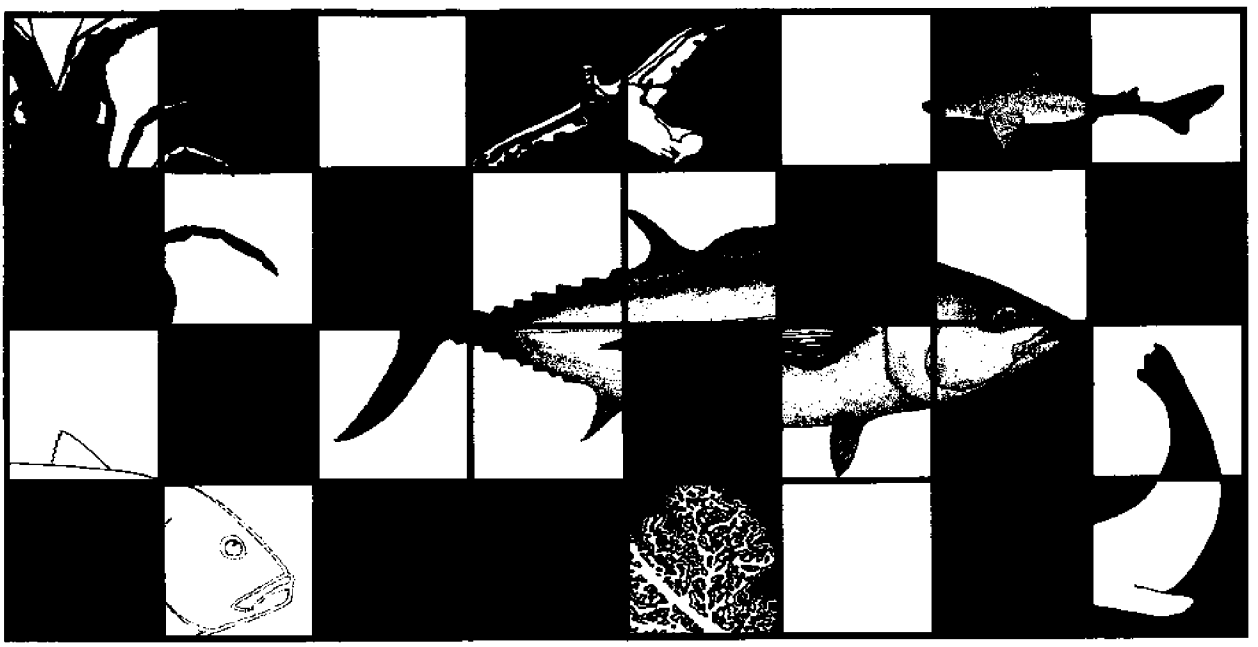
Welcoming Address and Introduction



WELCOMING ADDRESS

Governor George R. Ariyoshi*

State of Hawaii, State Capitol, Honolulu, Hawaii 96813

The Governor, as of last night, had full intention of being here to discuss the conference, the contents, and the objectives of the symposium and of participating in this morning's session. Unfortunately, something serious came up this morning. He called about a half hour ago indicating that he would not be able to participate and asked me to deliver his message. Before I deliver the Governor's message, I would like to express my appreciation on behalf of the Board of Land and Natural Resources and the staff of the Department of Land and Natural Resources in being permitted to participate in the tripartite-Sea Grant study on resources in the Northwestern Hawaiian Islands. This study is one of the most satisfying accomplishments that we have been involved in. Professionally our staff has been able to participate and benefit from this particular project, and the results that you are getting through this joint effort will help us tremendously as we move towards the next phase. The next phase is not going to be any easier than what we've gone through, but what has resulted from 5 years of research will give us a sensible direction so vitally needed in solving the management problems of conserving wildlife while allowing some opportunities for fishery development.

It is a pleasure to be here this morning to welcome you to this symposium on Resource Investigations in the Northwestern Hawaiian Islands. When we mention Hawaii we often tend to focus on only the eight major Hawaiian islands that comprise our state. This is understandable because almost all of us live within this short stretch (450 miles) of prominent islands. And because of the great distance that separates our main islands from those to the northwest, we sometimes forget that the Northwestern Hawaiian Islands are a very important part of Hawaii. Although they amount to little more than 3 square miles of dry land stretching as they do for over 1,000 miles beyond Kauai, they greatly expand the territorial limits of the state and vastly extend the jurisdiction of our nation to the northern and western Pacific. The Northwestern Hawaiian Islands are the home and breeding grounds for some of our most precious forms of native wildlife -- green sea turtles, monk seals, unique birds, and other terrestrial species. The nearshore waters of these islands hold stocks of

---

*Delivered by Mr. Susumu Ono, Chairman of the Board of Land and Natural Resources, State of Hawaii

fish and possess scenic resources of tremendous potential value to our people and offer a possible basis from which the use of these resources can be expanded. The existence of these resources has been known for some time; however, the development of a strategy for their use has been precluded by a lack of detailed information. We also have lacked information on how the various components of the Northwestern Hawaiian Islands ecosystem can be expected to interact. Without this data it is impossible to formulate a plan to manage the resources and develop a strategy which could conserve and nurture them while also opening them up to careful use by the public sector. Thus, we agreed in 1978 to be a principal in the tripartite agreement between our Department of Land and Natural Resources and two federal agencies -- the National Marine Fisheries Service and the U.S. Fish and Wildlife Service. We noted with considerable satisfaction at the 1980 symposium that this original core of participants had widened and that the much-needed information I alluded to earlier was indeed being obtained. I am particularly pleased with the concept of and the participation in this well-coordinated Northwestern Hawaiian Islands research program. Cooperation between the federal and state governments is a result of a common desire to ensure that the full spectrum of environmental, resource, and economic concerns is addressed. The additional support from the University of Hawaii Sea Grant College Program and from our Office of the Marine Affairs Coordinator has contributed significantly to the scientific merit and socioeconomic value of the results and has added prominence to this endeavor. And so with great pride and appreciation I address you today as you assemble here to present your findings. I look forward to the proceedings -- fruits of many years of labor. I also await with great interest the results of your deliberations on how we may best proceed with plans for the Northwestern Hawaiian Islands. The knowledge you have gained and the recommendations you will make are certain to be of inestimable value to the people of Hawaii and the Pacific. I wish you well in this endeavor.

INTRODUCTION

Richard S. Shomura

Director of Southwest Fisheries Center Honolulu Laboratory
National Marine Fisheries Service, NOAA
P.O. Box 3830, Honolulu, Hawaii 96812

Distinguished guests, ladies and gentlemen, it gives me great pleasure this morning to welcome you to the opening of the Northwestern Hawaiian Islands Symposium. I have been asked to say a few words as an introduction for the beginning of the formal presentation of this symposium. Since a number of you were present at the first symposium held here in April 1980 I will try not to repeat what I said in my opening remarks at that time. In that talk I focused primarily on the background that led to the tripartite-Sea Grant cooperative study of the Northwestern Hawaiian Islands.

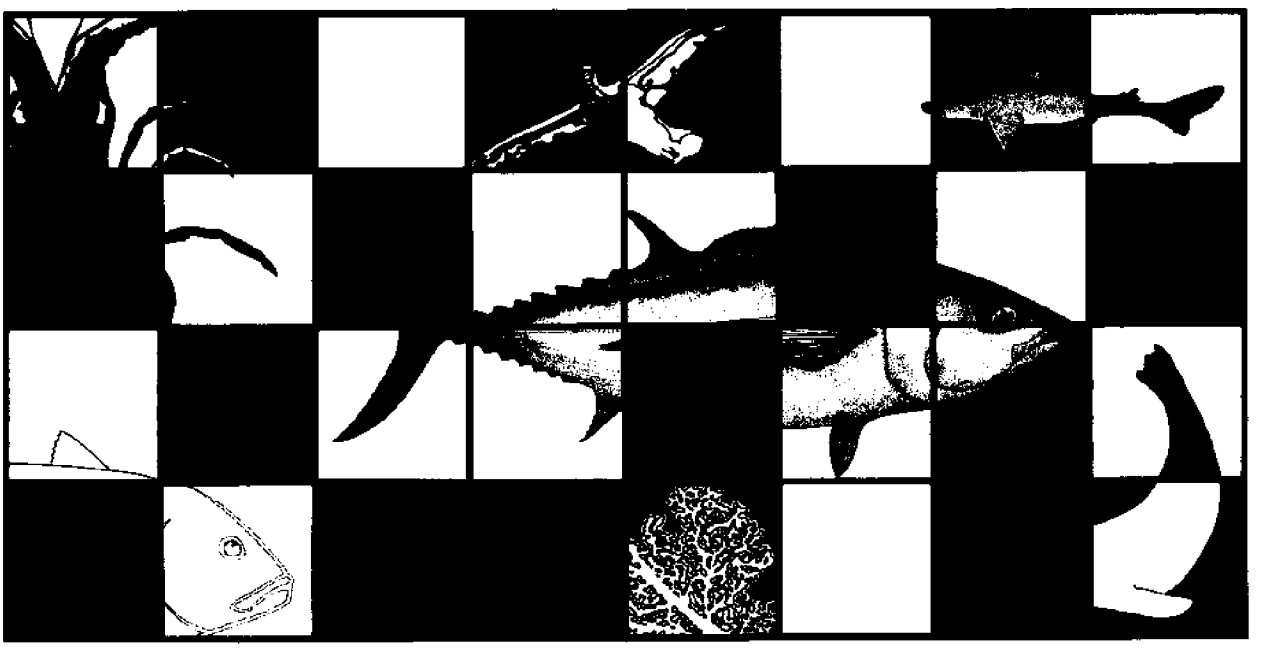
I will make my comments very brief since I would prefer that you be wide awake for the presentations by the scientists who are involved in this multi-agency undertaking. Furthermore, the film that you will see shortly will more effectively touch on the points that I wish to make. During a preview of the film shown last week, I was very impressed by its quality and content.

In reflecting upon the results of the 5-year program, I thought it might be useful to review some of the highlights. First, the study is indeed unique in that it was initiated before a crisis occurred. Although I refer to this study as a 5-year field program, much of the planning was done several years before then. Even before the formal planning of the program some early discussions were held with University of Hawaii personnel in 1973 and 1974. Even the formal planning took place well before the passage of the Magnuson Fishery Conservation and Management Act of 1976. In the early 1970s, there were very few preliminary questions being raised about the resources or the status of the monk seals and the green sea turtles. The fact that support was obtained for this cooperative undertaking before a crisis occurred is indeed remarkable. I'm sure all of you will agree that this type of research is what is needed; that is, anticipating future needs, developing the ground work, and providing the necessary information for future decisionmaking. If nothing else, the process of conducting research based on this rationale is cost effective.

Another highlight of the study is that attempts were made to look at problems in a context of an ecosystem, in this particular case, the Northwestern Hawaiian Islands ecosystem. By this I mean we did not look at resources in isolation, but rather looked at potential impacts and the interactions of these resources among themselves.

A third aspect of this study which I believe deserves mention is that it was a cooperative undertaking by several agencies. Administrators often extoll the virtues and advantages of cooperative research which unfortunately does not happen too frequently. An example of cooperation during the Northwestern Hawaiian Islands study is the use of the NOAA research vessel Townsend Cromwell as the platform vehicle by the Honolulu Laboratory as well as the other participating agencies, including the U.S. Fish and Wildlife Service, the Hawaii Division of Aquatic Resources, and the UH Sea Grant College Program. Other examples of cooperation include the study of the food habits of seabirds as well as the studies of the monk seals that were carried out between the Fish and Wildlife Service and the Honolulu Laboratory. I'm sure that all of you, after hearing the talks on the Northwestern Hawaiian Islands investigations over the next several days, will be pleased with the study results. I certainly am. Having said this, and while I am generally pleased with the program, there is no question there are some gaps in the research. One of the more obvious is that we lack a full understanding of the physical and chemical environment of the waters surrounding the Northwestern Hawaiian Islands, especially as they relate to living resources. At this time I can only partially respond to this shortcoming by saying that we could not cover all of the areas of needed research. Some research, as Mr. Ono mentioned, will have to await attention in the future. I feel confident however that most of the important resource problems were addressed by the study. We leave for other researchers the responsibility of addressing the many questions that have surfaced from this investigation. Since I may not have another opportunity during the symposium this week I would like to thank the heads of all the agencies involved in this study for their support and encouragement while the work was going on. Perhaps, more importantly, and I say this sincerely, I would like to extend my personal thanks and congratulations to all of the researchers for a job well done.

Onshore Research



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SYNOPSIS OF RESULTS OF RECENT SEABIRD RESEARCH CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS

Stewart I. Fefer, Craig S. Harrison,
Maura B. Naughton, and Robert J. Shallenberger

U.S. Fish and Wildlife Service, Refuges and Wildlife Resources,
P.O. Box 50167, Honolulu, Hawaii 96850

ABSTRACT

The Northwestern Hawaiian Islands (NWHI) are among the most important seabird colonies in the world. They harbor approximately 5.4 million breeding birds of 18 species. The composition and number of breeding birds vary throughout the year. The breeding cycle of a species may vary seasonally, annually, and geographically. Resident seabirds feed on a wide variety of shoaling fish and squid and apparently take any prey of appropriate size that occurs in surface waters. Much of the variation in diet occurs in the relative proportions of several common prey items including flyingfishes (Exocoetidae), squids (Ommastrephidae), opelu (Decapterus spp.), goatfishes (Mullidae), mesopelagic fishes, and crustaceans. Most NWHI seabirds forage within the first half meter of the ocean's surface. Boobies, tropicbirds, and possibly shearwaters can forage deeper. Seabirds exploit prey by using different foraging methods and locations. Among the current threats to seabirds in the NWHI are those associated with the proposed increase in commercial fishing. The number of seabirds killed directly in interactions with fishing gear is not expected to be significant. However, seabirds in the NWHI consume about 410,000 metric tons (900 million lb) of prey items annually. Thus, seabird predation is quantitatively important and may compete with certain fisheries. Most fisheries proposed for the NWHI, including those for bottomfishes, lobsters, shrimps, kona crabs, billfishes, sharks, and seamount species are not likely to have significant effects on seabird populations through the food chain. Significant fisheries for skipjack and yellowfin tuna, tuna baitfishes, ommastrephid squids, and opelu in the

vicinity of the NWHI may adversely affect specific seabird populations. Those seabirds with the most diverse diets are least likely to be affected by fisheries development. However, if fisheries development leads to the depletion of several prey resources, seabird populations will surely decline. The potential indirect effects of a commercial fishery that threaten NWHI seabird populations include the introduction and spread of exotic predators, insects, and vegetation; habitat alteration; disturbance and environmental contamination from heavy metals; and organochlorine compounds. At present, these affect seabirds to varying degrees on certain islands. However, indirect impacts have the potential for catastrophic effects on seabird populations. Baseline data on population, reproductive success, chick growth rate, egg size, and adult weight measurements can be compared with data collected in future years to detect changes due to food shortages or other factors. Early detection of potential problems can avert significant seabird population declines. Such a monitoring program may warn resource managers of changes in the environment which might require management actions. This could benefit seabirds and fishermen, since both depend on a healthy ocean environment for their livelihood.

seabirds	food habits
impacts	populations
fisheries	monitoring
phenology	consumption
NWHI	refuge

INTRODUCTION

This report is a summary of the research conducted to determine the status and biology of marine birds in the Northwestern Hawaiian Islands and the potential effects the expansion of commercial fisheries there would have on these species. The objectives of the U.S. Fish and Wildlife Service (FWS) and related University of Hawaii Sea Grant College Program studies were to provide information on (1) the baseline magnitude of the marine birds using the NWHI; (2) foods utilized by the marine birds; (3) at-sea distribution and foraging habits of seabirds; (4) the consumptive rate of each species; (5) the potential effects of commercial and recreational fishing upon seabird populations; and (6) the feasibility of using baseline seabird data to monitor population trends and food availability. Herein is presented a summary of the results of studies conducted to fulfill the first three objectives. Utilizing the population energetics model reported in a separate paper (see report in this proceedings by Pettit et al.), the amount of each major food item consumed by each species of seabird is estimated (objective 4). All of these data are incorporated into the assessment of the effects of an

increased fishery (objective 5). Finally, in order to monitor seabird populations and determine potential competition between fisheries and birds, techniques were developed that may be used to indicate the "health" of the seabird population in the future (objective 6).

Given the summary nature of this paper, and its necessary emphasis on assessment of fishery/seabird interactions, detail on the scope, methods, and results of the many individual research projects summarized herein is lacking. The reader is referred to the "Abstracts" section for references to publications on some of these studies. Other accounts of studies of seabirds conducted during the 5-year period of the tripartite agreement will be forthcoming, including an atlas of Hawaiian seabird colonies and a monitoring manual for NWHI seabird colonies. Both are being prepared by the U.S. Fish and Wildlife Service. The reader is also referred to the paper by Harrison and Hida (1980) in the 1980 NWHI symposium proceedings for further information.

BASELINE MAGNITUDE OF SEABIRDS

The Hawaiian Archipelago (Figure 1) is a breeding ground for millions of seabirds. Millions more of these species come ashore on islands to roost, establish territories, and select mates with which to breed in future years. To effectively manage this resource, it is essential to know how many birds use the islands and the surrounding waters. Parameters such as the numbers of birds breeding each year, the size of the resident non-breeding population, seasonal attendance patterns of breeders and non-breeders, and the frequency and timing of breeding are essential to understand the requirements of seabirds. In addition, millions of migratory seabirds that breed elsewhere occur seasonally in the waters surrounding the NWHI. These migratory species were not included in this study and data on their distribution and abundance are lacking.

Data on seabird populations of the NWHI have been collected during the past two decades by various workers, including personnel from FWS, Hawaii Department of Land and Natural Resources (DLNR), National Marine Fisheries Service (NMFS), and Smithsonian Pacific Ocean Biological Survey Program (POBSP). Unfortunately, inconsistency in reporting which population was estimated (i.e., breeding birds or total birds), inadequacy of methods description, lack of standardized and objective census methods, and inconsistency in the timing and duration of most visits make interpretation of this information difficult. Consequently, FWS conducted studies of breeding populations from 1978 to 1982 on several islands in the NWHI. Extended field studies were undertaken on Nihoa, French Frigate Shoals, Laysan Island, and Lisianski Island. Field studies varied in length from 5 weeks (at Lisianski Island) to 6 months (at Laysan Island) to year-round (at Tern Island, French Frigate Shoals). In addition, FWS participated in short visits of 1 to 3 days to most of the islands, but these allowed little chance for detailed population

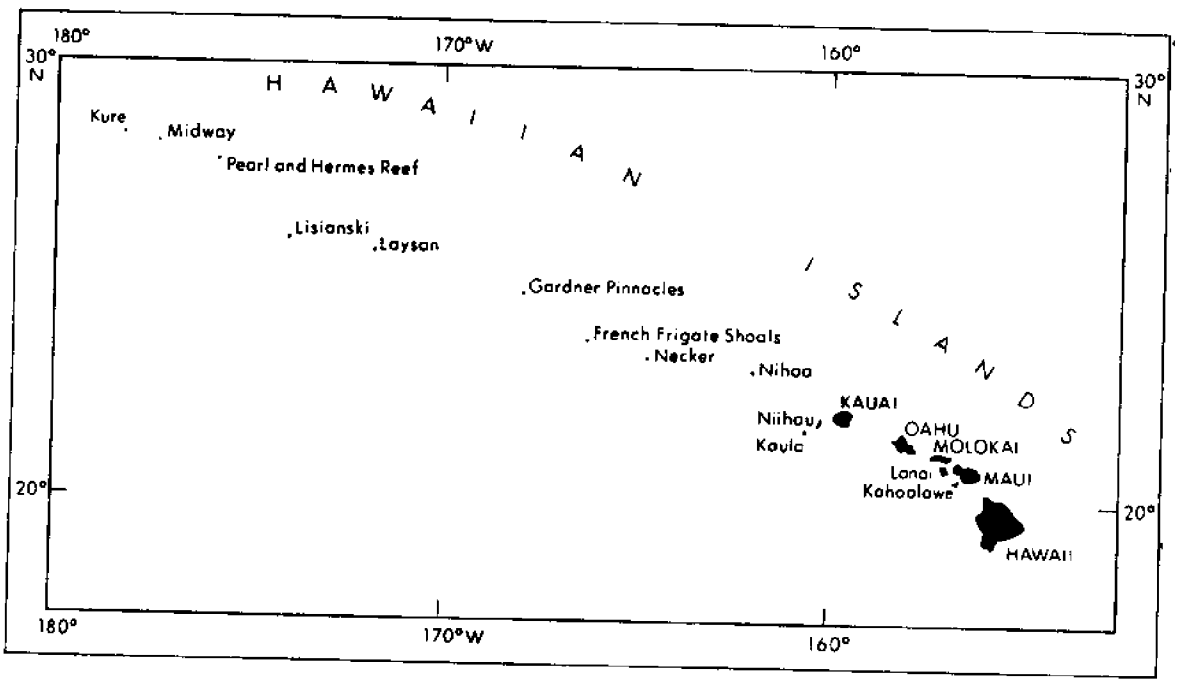


Figure 1. The Hawaiian Archipelago

studies. Nests were estimated using several methods including direct counts, strip transects, and sample plots. Our estimates for islands not visited during this study were based on data collected by POBSP personnel in the 1960s. POBSP data were also used for many winter and fall breeding species that could not be estimated adequately during the recent spring and summer visits. Numbers for Kure Atoll are almost exclusively POBSP data (Woodward, 1972) because their studies were year-round and therefore more reliable than ours. Detailed methods used to collect data on populations presented here are included in the forthcoming atlas of Hawaiian seabird colonies (FWS, in preparation).

Some of our population estimates are imprecise. The following factors account for this imprecision:

1. Seabirds breed year-round in the NWHI and visits could not always be made to count nests of all species at the optimal time(s).
2. Most breeding population estimates are based on nest counts which were adjusted for breeding success and phenology. However, breeding success and phenology vary annually and geographically.
3. It was assumed that a pair breeds only once in each year unless it was known that birds were renesting.

This is probably true in the NWHI but needs to be documented, especially for asynchronous species such as the noddies.

4. Several species of NWHI seabirds are extremely difficult to accurately census, especially the cliff and burrow nesting species.
5. The number of breeding seabirds fluctuates annually due to natural causes such as oceanographic, weather, and habitat conditions. Population estimates based on one year's data may not accurately reflect the actual population in other years. The stability of a population is determined by comparing several years' data.

Breeding Populations

Twenty-two seabird species breed in the Hawaiian Archipelago. Newell's shearwaters (Puffinus puffinus newelli), Hawaiian dark-rumped petrels (Pterodroma phaeopygia sandwichensis), and Harcourt's storm-petrels (Oceanodroma castro) are restricted to the main Hawaiian islands. These subspecies are in danger of extinction from introduced predators and increasing urbanization. The white-tailed tropicbird (Phaethon lepturus) nests almost exclusively in the main Hawaiian islands. In the NWHI, only one nesting pair was documented on Sand Island, Midway. The above-mentioned four species will not be included in the following discussion of seabird populations in the NWHI.

The NWHI harbor seabird colonies that contain about 2.7 million breeding pairs (5.4 million birds) of 18 species. Among these are albatrosses (2), petrels (2), shearwaters (2), storm-petrels (1), tropicbirds (1), boobies (3), frigatebirds (1), and terns (6). An estimate of the current numbers of breeding pairs and their distribution in the NWHI is presented in Table 1. The NWHI colonies harbor at least 60 percent of the Hawaiian population of each species and more than 90 percent of the total Hawaiian Archipelago seabird population. The amount and diversity of seabird populations result in the NWHI being among the most important breeding colonies in the world. The NWHI support a substantial portion of the worldwide population of four species including the black-footed albatross (Diomedea nigripes), Laysan albatross (Diomedea immutabilis), Bonin petrel (Pterodroma hypoleuca), and sooty storm-petrel (Oceanodroma tristrami) (Table 2). For some species it is difficult to assess the relative importance of the NWHI to Pacific and/or worldwide populations because estimates of populations elsewhere are unavailable. However, the NWHI populations of Christmas shearwater (Puffinus nativitatis), gray-backed tern (Sterna lunata), and blue-gray noddy (Procelsterna cerulea) are sizable and may be the most important populations worldwide. The sooty tern (Sterna fuscata), the most abundant breeding species of seabird in the Central Pacific, is the most numerous species nesting in the NWHI. Almost 50 percent of the breeding birds found in the NWHI are sooty terns. The sooty storm-petrel breeds on only four islands in the NWHI and is considered to be a "sensitive species" by the FWS.

TABLE 1. ESTIMATE OF BREEDING PAIRS OF SEABIRDS, NORTHWESTERN HAWAIIAN ISLANDS

	Location				
	Nihoa	Necker Island	French Frigate Shoals	Gardner Pinnacles	Laysan Island
Black-footed albatross	40 to 60	200 to 250	4,000 to 4,500	0	14,000 to 21,000
Laysan albatross	1 to 5	450 to 550	900 to 1,000	10 to 15	105,000 to 132,000
Bonin petrel	0	0	30 to 50	0	50,000 to 75,000
Bulwer's petrel	75,000 to 100,000	250 to 500	200 to 500	10 to 15	1,000 to 2,000
Wedge-tailed shearwater	30,000 to 40,000	1,500 to 2,500	1,500 to 1,750	25 to 50	125,000 to 175,000
Christmas shearwater	200 to 250	0	15 to 20	0	1,500 to 2,000
Sooty storm-petrel	2,000 to 3,000	+	+	0	500 to 2,500
Red-tailed tropicbird	250 to 300	100 to 150	550 to 600	20 to 25	1,500 to 2,500
Masked booby	250 to 300	250 to 300	500 to 600	125 to 150	400 to 425
Brown booby	150 to 200	20 to 25	40 to 60	5 to 10	34
Red-footed booby	1,500 to 2,000	650 to 750	550 to 600	0	250 to 300
Great frigatebird	3,500 to 4,500	700 to 900	350 to 375	0	2,000 to 2,500
Sooty tern	10,000 to 25,000	12,500 to 25,000	60,000 to 78,000	250 to 500	375,000 to 500,000
Gray-backed tern	9,000 to 12,000	3,500 to 4,500	750 to 1,000	1,500 to 2,500	5,000 to 10,000
Blue-gray noddy	2,000 to 2,500	1,000 to 1,500	+	+	0
Brown noddy	25,000 to 35,000	10,000 to 15,000	5,000 to 7,500	1,000 to 1,500	10,000 to 15,000
Black noddy	1,000 to 5,000	300 to 500	750 to 850	200 to 300	1,500 to 2,500
White tern	1,000 to 5,000	100 to 300	500 to 750	150 to 250	600 to 1,000
TOTAL	235,115	52,725	98,155	5,315	943,760

NOTE: + indicates breeding occurs but there was not significant data to make a quantitative statement;
? indicates breeding is suspected but no nests were found.

TABLE 1. ESTIMATE OF BREEDING PAIRS OF SEABIRDS, NORTHWESTERN HAWAIIAN ISLANDS (continued)

	Location				
	Lisianski Island	Pearl and Hermes Reef	Midway Islands	Kure Atoll	Total
Black-footed albatross	2,800 to 3,800	8,000 to 11,000	6,500 to 7,500	700 to 1,300	49,410
Laysan albatross	23,000 to 30,000	9,000 to 12,000	150,000 to 200,000	3,000 to 4,000	379,570
Bonin petrel	150,000 to 250,000	400 to 600	2,500 to 5,000	400 to 600	331,250
Bulwer's petrel	50 to 100	10	0	0	103,125
Wedge-tailed shearwater	10,000 to 30,000	5,000 to 10,000	500 to 1,000	900 to 1,100	261,400
Christmas shearwater	400 to 600	10	25 to 50	20 to 30	2,960
Sooty storm-petrel	?	1,000 to 2,000	0	?	7,500
Red-tailed tropicbird	900 to 1,300	40 to 60	4,000 to 5,000	1,000 to 1,300	11,235
Masked booby	300 to 350	140 to 160	5 to 10	65 to 75	2,370
Brown booby	15 to 25	50 to 60	0	50 to 60	474
Red-footed booby	350 to 450	40 to 60	450 to 500	400 to 450	5,110
Great frigatebird	750 to 850	300 to 400	60 to 75	200 to 250	9,850
Sooty tern	400,000 to 600,000	35,000 to 45,000	30,000 to 45,000	8,000 to 12,000	1,330,500
Gray-backed tern	15,000 to 20,000	650 to 750	100 to 200	30 to 50	51,000
Blue-gray noddy	0	0	0	0	4,000
Brown noddy	7,500 to 15,000	1,700 to 2,000	500 to 1,000	700 to 800	92,800
Black noddy	500 to 1,000	75 to 125	2,000 to 6,000	0	16,275
White tern	50 to 100	10 to 20	5,000 to 7,500	5 to 10	14,930
TOTAL	953,575	84,255	278,835	22,025	3,673,759

TABLE 2. WORLDWIDE BREEDING DISTRIBUTION OF NORTHWESTERN HAWAIIAN ISLAND SEABIRDS

Limited[1] Tropical and Subtropical North Pacific Ocean	Tropical and Subtropical Pacific Ocean	Tropical and Subtropical Pacific and Indian Oceans	Tropical and Subtropical Oceans of the World
Black-footed albatross	Christmas shearwater	Wedge-tailed shearwater	Bulwer's petrel
Laysan albatross	Gray-backed tern	Red-tailed tropicbird	Masked booby
Bonin petrel	Blue-gray noddy		Brown booby
Sooty storm-petrel			Red-footed booby
			Great frigatebird
			Sooty tern
			Brown noddy
			Black noddy
			White tern

[1]Limited to the Hawaiian, Volcano, Bonin, and Izu Islands

Distribution and Nesting Habitats

Each seabird species has specific nesting habitat requirements. Seabird populations are distributed on the islands in relation to the availability of these nesting habitats (Figure 2). The relationship between habitat availability and distribution of seabirds in the NWHI is illustrated by contrasting the numbers and composition of the seabird population on the islands. A brief description of the habitat, historical trends and present populations of resident seabirds on each of the islands follows. The NWHI include Nihoa, Necker Island, French Frigate Shoals, Gardner Pinnacles, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, Midway Islands, and Kure Atoll (Figure 1).

Nearly half a million seabirds of 17 species breed on Nihoa each year (Figures 3 and 4). This high rocky island (Figure 5) provides abundant nest sites for the crevice- and cavity-nesting petrels and noddies. Over 95 percent of the Bulwer's petrels (Bulweria bulwerii) and approximately 50 percent of the blue-gray noddies nesting in the NWHI occur on this island. The island is well-vegetated with low shrubs. The seabird populations there are especially important when viewed from the perspective of individual species. Nihoa is the largest colony in the NWHI for six seabird species: Bulwer's petrel, sooty storm- petrel, brown booby (Sula leucogaster), red-footed booby (Sula sula), great frigatebird (Fregata minor), blue-gray noddy, and brown noddy (Anous stolidus). Populations apparently are relatively stable. Due to difficulty in landing on this island, populations were probably spared the depredations of feather hunters earlier in this century.

Necker Island is smaller than Nihoa and has slightly more than 100,000 breeding seabirds of 16 species (Figures 3 and 4).

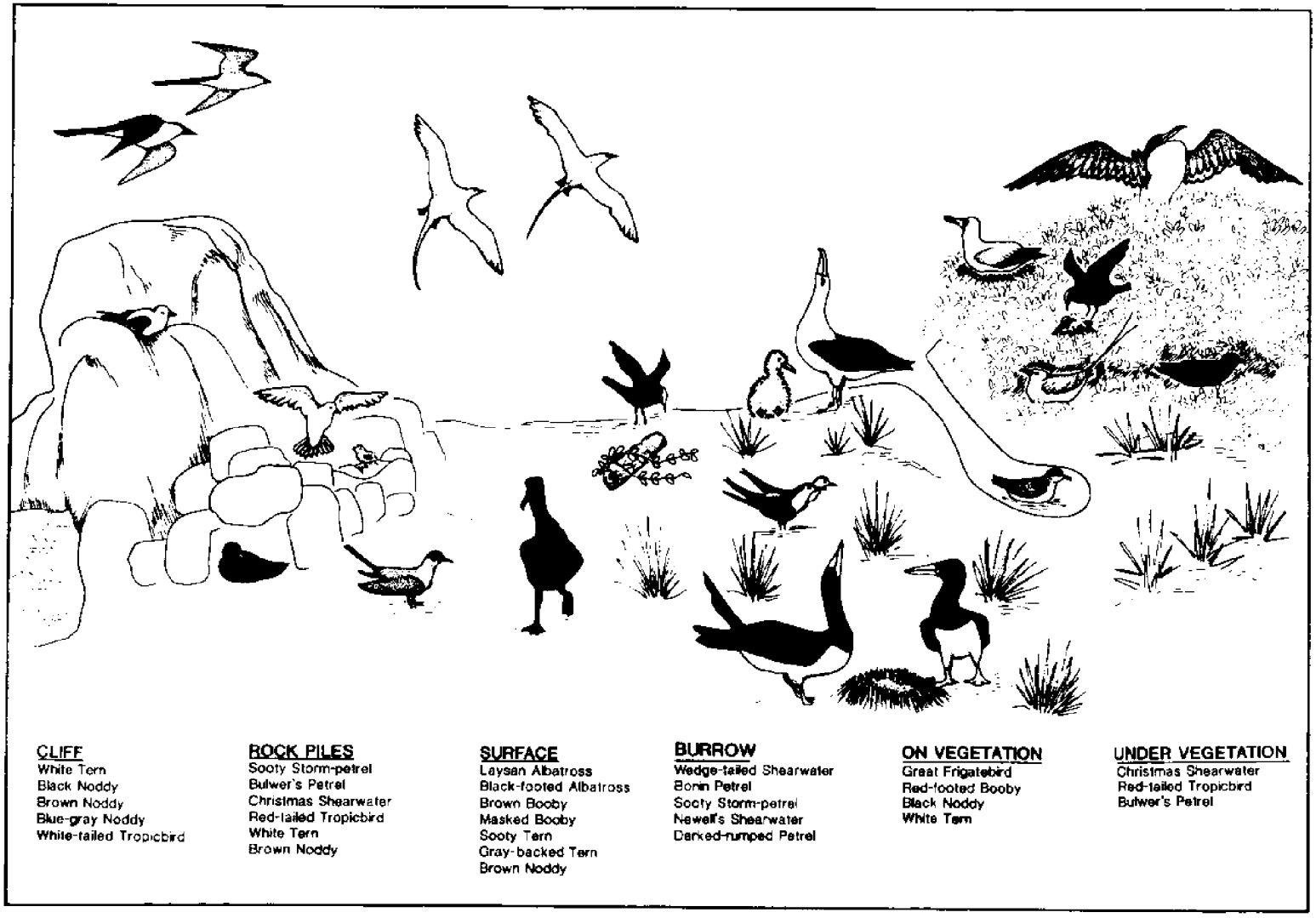


Figure 2. Nesting habitats of NWHI seabirds

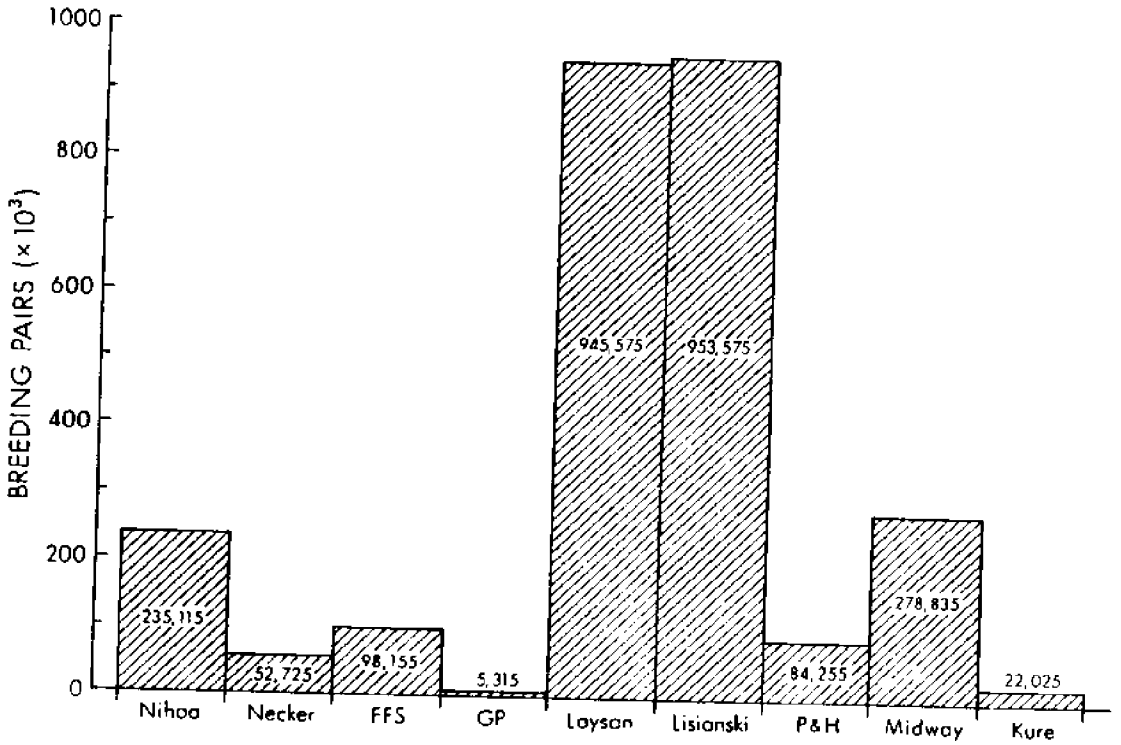


Figure 3. Number of seabird pairs nesting in the NWHI

Except for Gardner Pinnacles, Necker Island is the smallest of the island groups in the NWHI. The island has steep slopes and shallow valleys (Figure 6). Little or no vegetation is present on the steep slopes.

French Frigate Shoals provides a wide diversity of habitat types for nesting seabirds. At present, there are 13 islands in the lagoon (Figure 7). All are small sand islets except for La Perouse Pinnacles, a volcanic rock of less than one acre in size. The four largest islets in the atoll (Tern, Trig, East, and Whale-Skate Islands) have well-established vegetation. Little Gin is sparsely vegetated and the remaining islets are unvegetated. French Frigate Shoals provides rocky habitats for cavity-nesting seabirds and sandy habitats for burrowing seabirds. It is the only island group in the NWHI on which all 18 species of seabirds found in the NWHI nest. About 200,000 seabirds nest on French Frigate Shoals each year (Figure 3), including the largest colony of masked boobies (Sula dactylatra) in the NWHI.

Based on available information, population trends seem to be fairly stable over the past 20 years with few exceptions. Albatross appear to be increasing, although substantive data are lacking due to the intermittent nature of past surveys. Recently, the number of species breeding on Tern Island has increased. Military and Coast Guard forces inhabited Tern Island sporadically from 1943 to 1979. Since July 1979, FWS personnel have inhabited the island. Sooty tern, red-footed booby, and

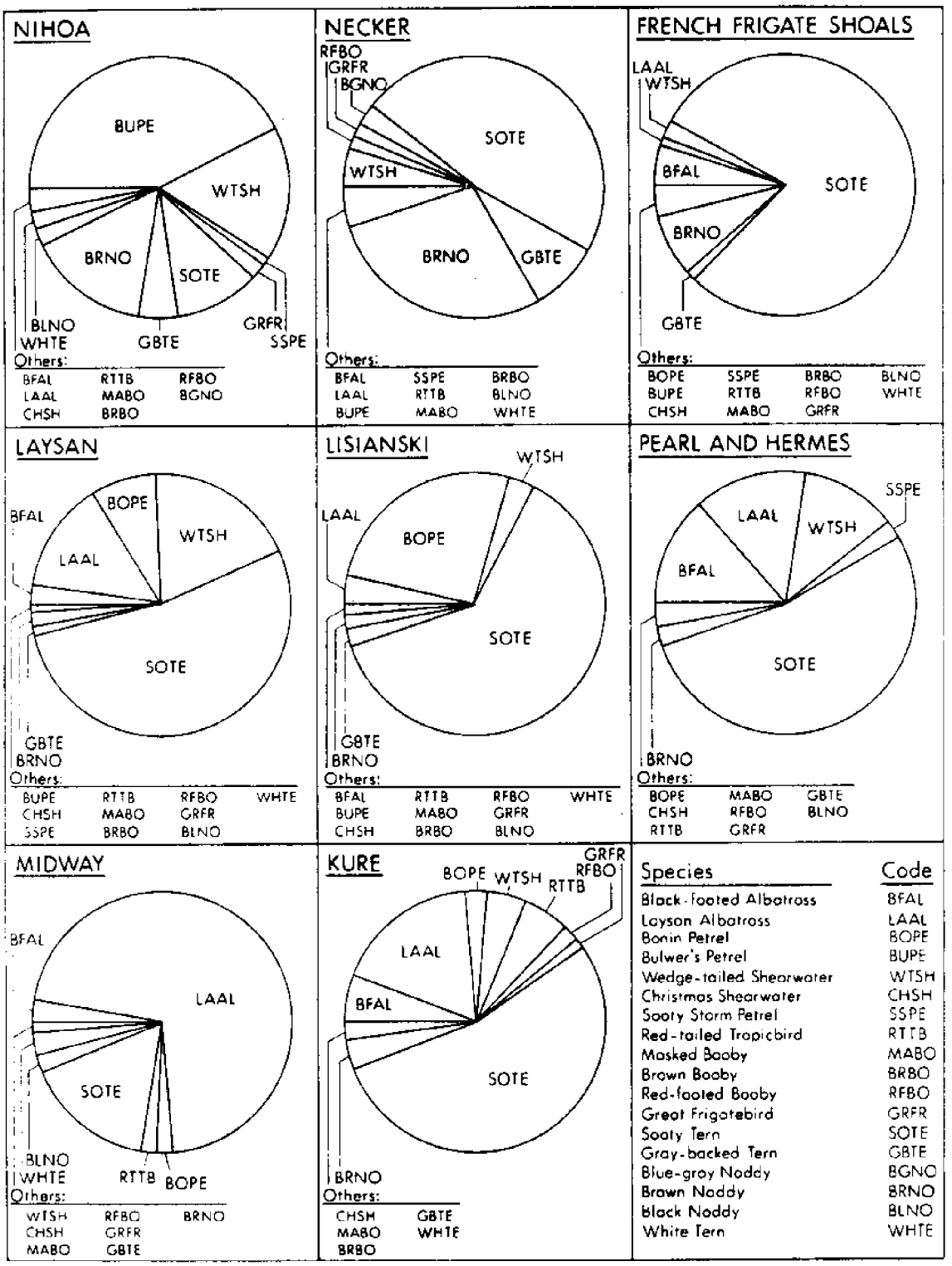


Figure 4. Species composition of NWHI seabirds

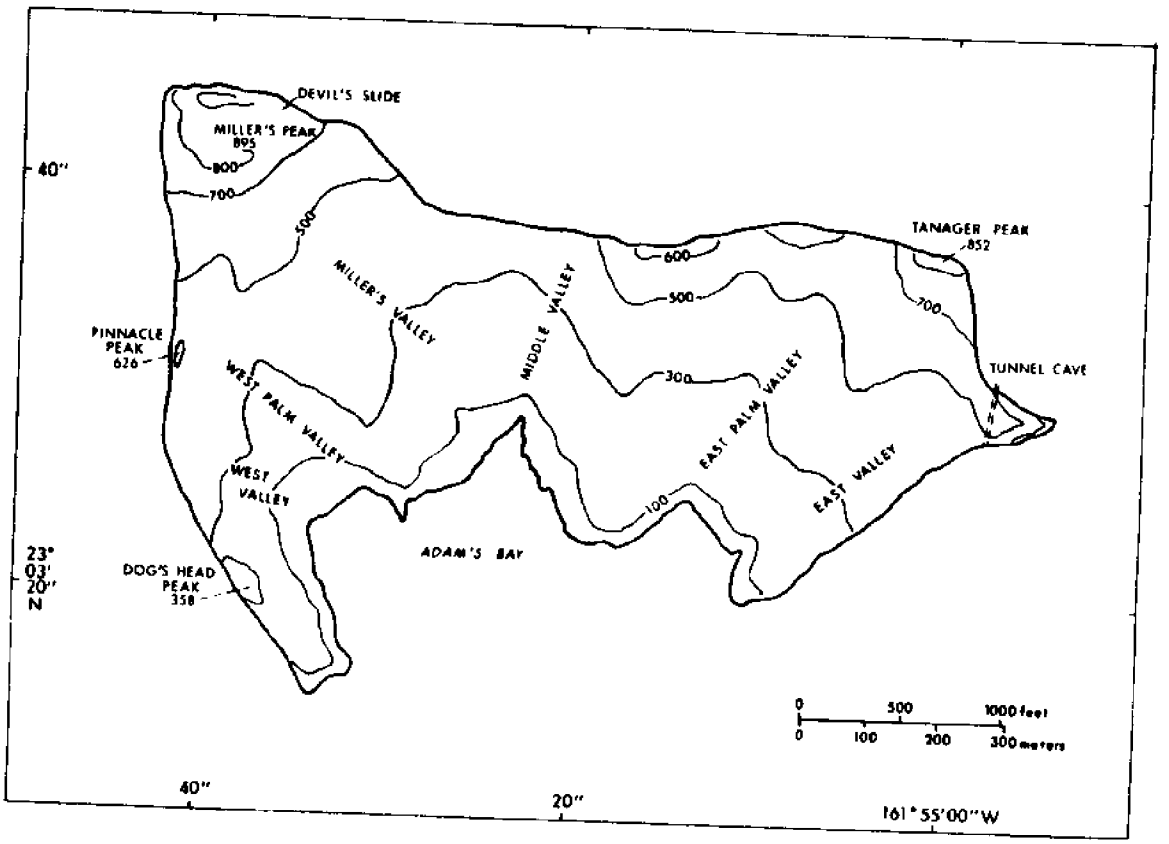


Figure 5. Nihoa

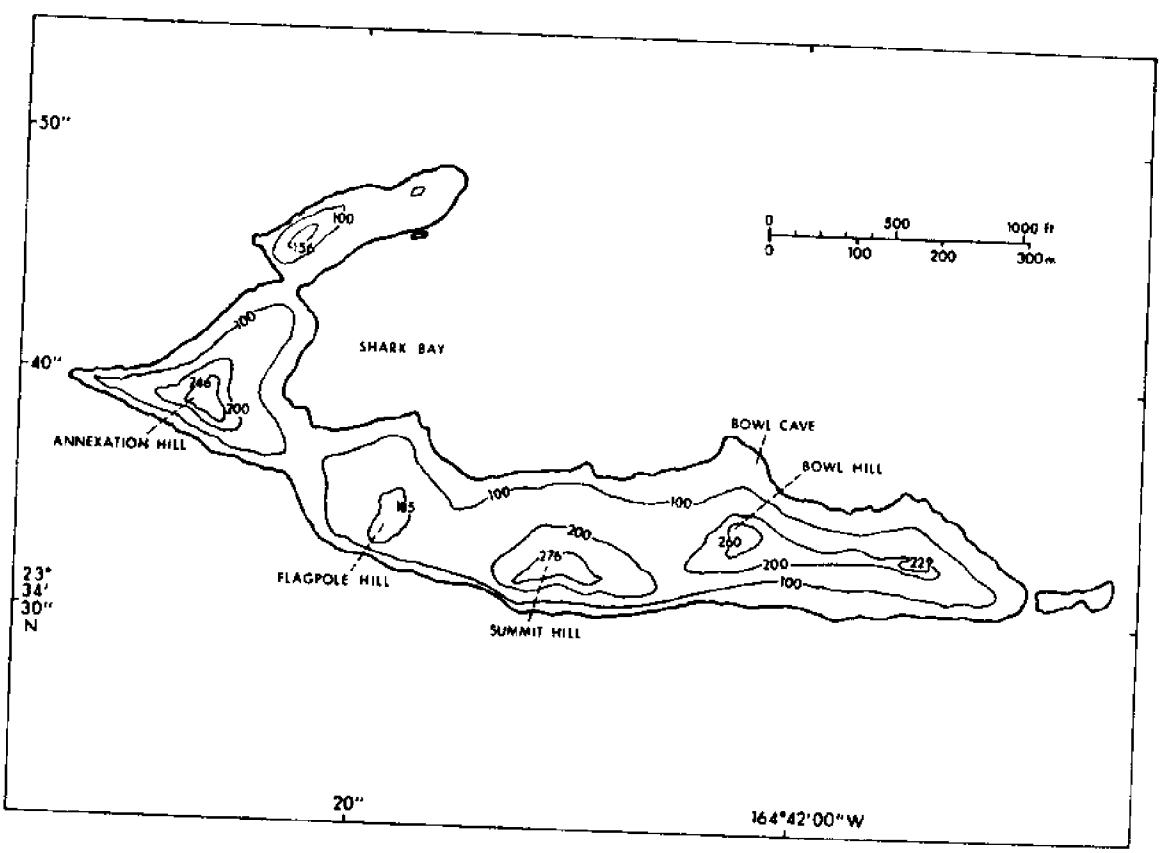


Figure 6. Necker Island

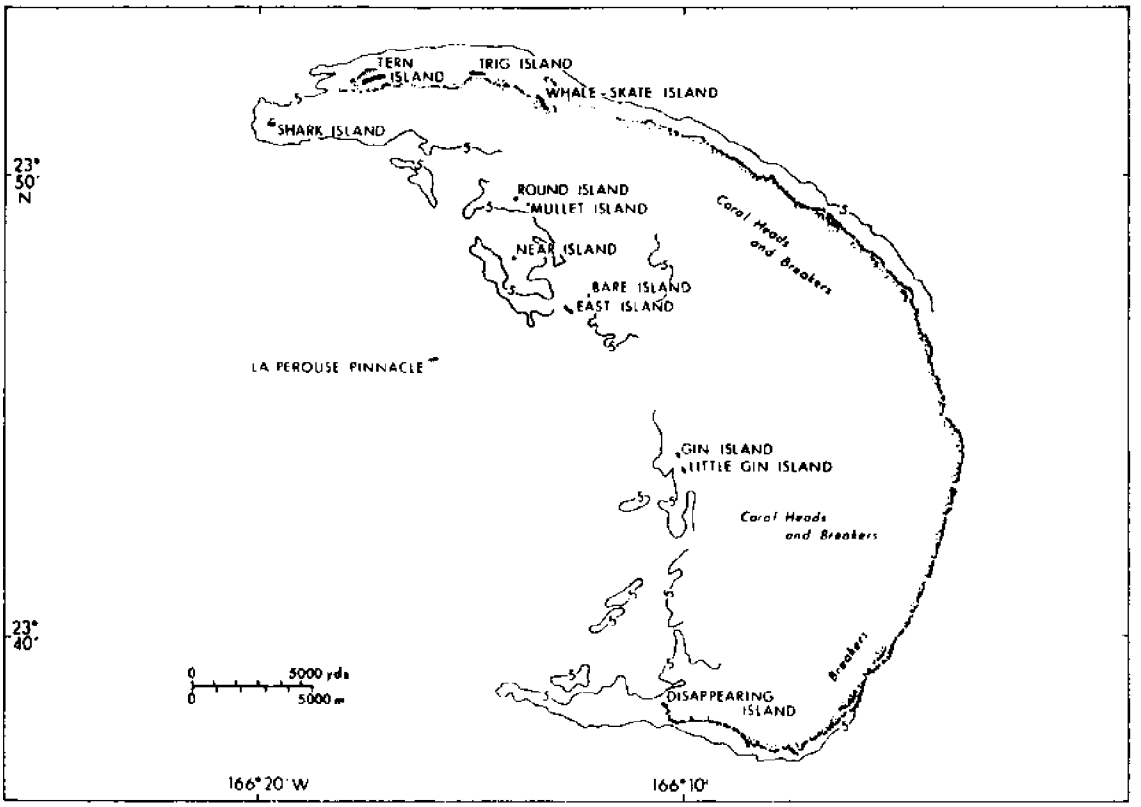


Figure 7. French Frigate Shoals

black noddy (Anous minutus) populations have been increasing steadily on Tern Island, perhaps due to a decrease in human disturbance and/or vegetation changes. More research is needed to determine whether the population increases reflect an increase in the atoll population or merely a shifting of colony location within the atoll.

Gardner Pinnacles is the smallest island group in the NWHI. Comprised of largely unvegetated islands Gardner Pinnacles supports the smallest populations and the lowest diversity of seabird species in the NWHI (Figure 3). Approximately 11,000 seabirds of 12 species nest there. Too few accurate data are available to assess population trends.

Laysan is a low coral island with a hypersaline lagoon covering approximately 20 percent of the island's interior (Figure 8). Laysan is well-vegetated with shrubs and grass over much of the interior and with low-lying succulents around the lagoon edges. Close to two million seabirds of 17 species breed there annually (Figures 3 and 4). Only the crevice-nesting blue-gray noddy is absent. The island supports the largest black-footed albatross colony in the world and the largest wedge-tailed shearwater (Puffinus pacificus) and Christmas shearwater colonies in the NWHI.

Historically, Laysan had the most diverse biota of any island in the NWHI. The numbers and diversity of birds and substantial guano deposits attracted people to Laysan late in the nineteenth century. Although guano mining in the early 1900s probably did not have much direct effect on the birds, the release of rabbits during this period was devastating. The island was almost completely devegetated by 1923, and three endemic landbirds became extinct. Also, during this period feather hunters raided Laysan Island several times, killing hundreds of thousands of seabirds. After several decades of recovery, most seabird populations have probably returned to levels comparable with those before the decline. However, the Laysan albatross and Christmas shearwater populations apparently have not completely recovered.

Lisianski, like Laysan, is a large, flat, sand and coral island (Figure 9), but it has no interior lagoon. Most of the island is covered with grasses and shrubs. When compared with Laysan Island, Lisianski Island supports a similar total seabird population (Figure 3), but with a different species composition (Figure 4). Close to two million seabirds breed each year on the island. The most abundant bird is the sooty tern, with approximately one million birds breeding each year. The Bonin petrel is the next most numerous breeding seabird there. Approximately 75 percent of the Bonin petrels nesting in Hawaii reside on this island which also has the largest colony of gray-backed terns in Hawaii.

Like Laysan Island, Lisianski Island suffered complete devegetation by rabbits in the early 1900s and a subsequent decline in seabird populations. The vegetation and most seabird species have since recovered. A notable exception is the Christmas shearwater. Present estimates indicate that populations of this species have declined considerably on this island. The decline in this species population on both Laysan and Lisianski may be related to the types of vegetation that recolonized the islands. Unfortunately, vegetation changes are difficult to assess because early accounts do not indicate distribution and abundance.

Pearl and Hermes is a low coral atoll. At present, eight islands occur inside the lagoon (Figure 10). Grass Island, Little North Island, North Island, Seal-Kittery Island, and Southeast Island are vegetated. Bird Island, Planetree Island, and Sand Island are barren sand bars. About 165,000 birds of 17 species breed there (Figures 3 and 4). Over 20 percent of the world population of black-footed albatross nest on this island, the second largest nesting colony of this species in the world. This atoll is also an important nesting area for the sooty storm-petrel. Feather hunting occurred there in the early 1900s but most populations seem to have recovered.

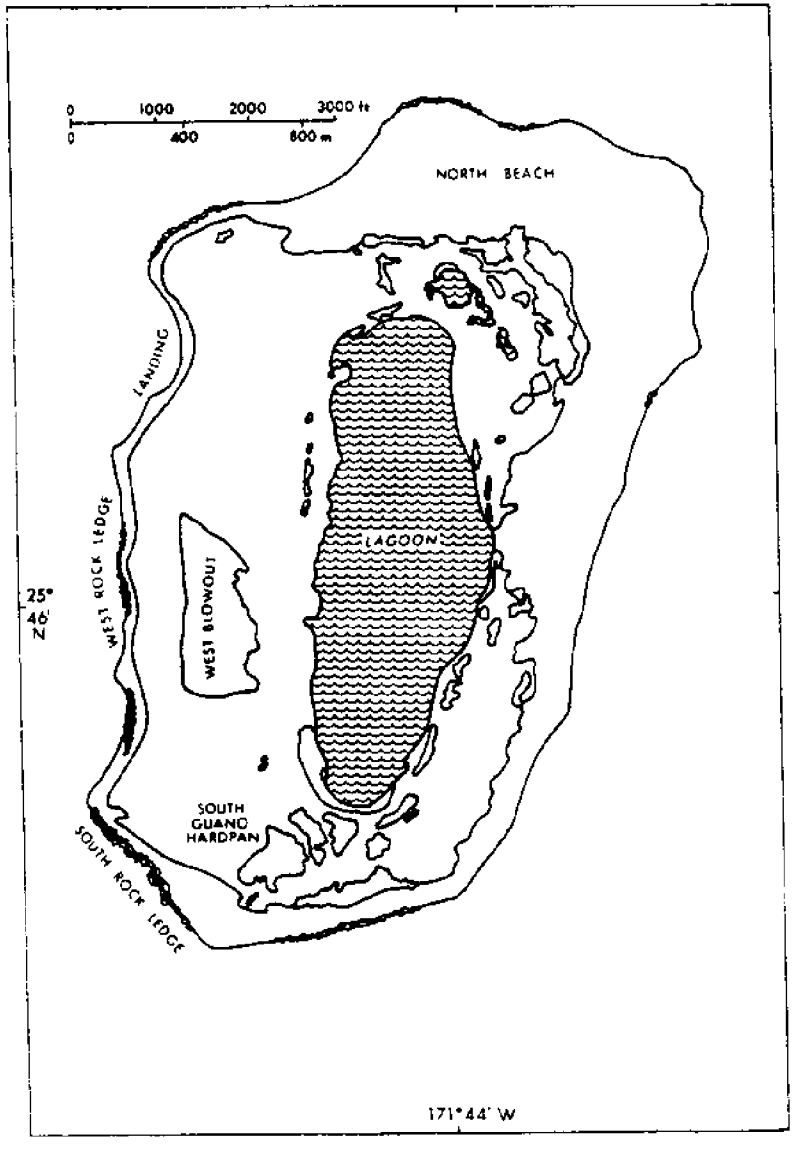


Figure 8. Laysan Island

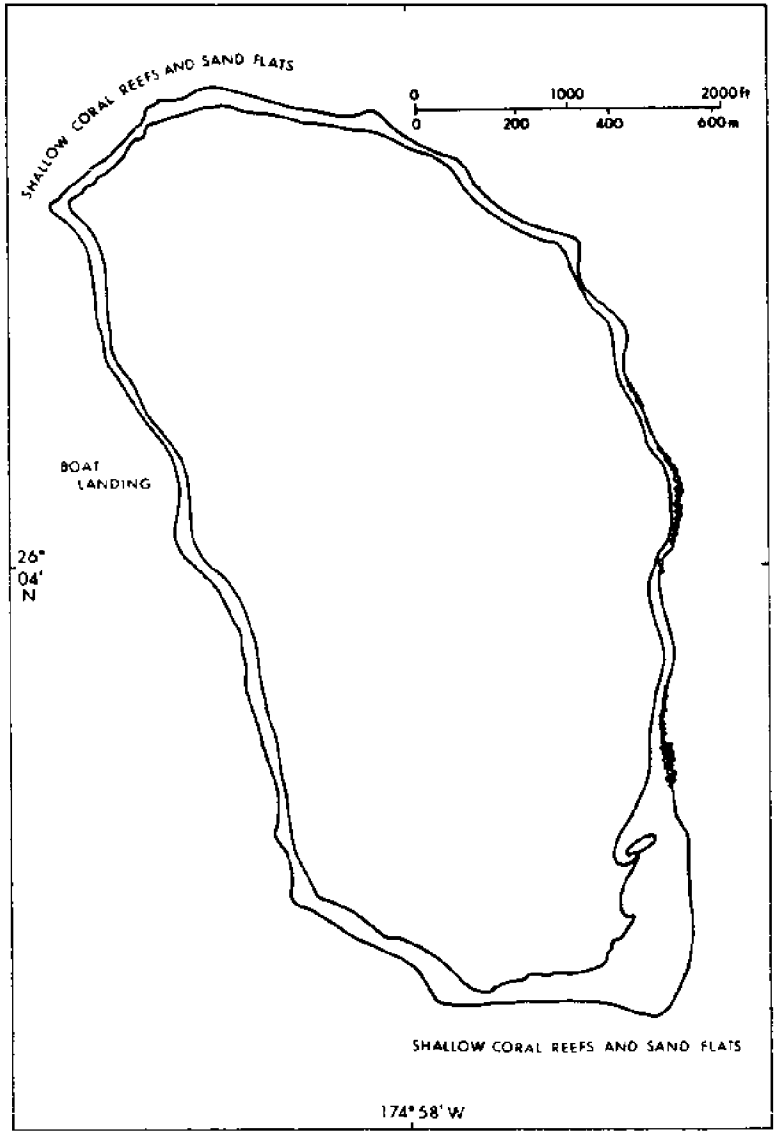


Figure 9. Lisianski Island

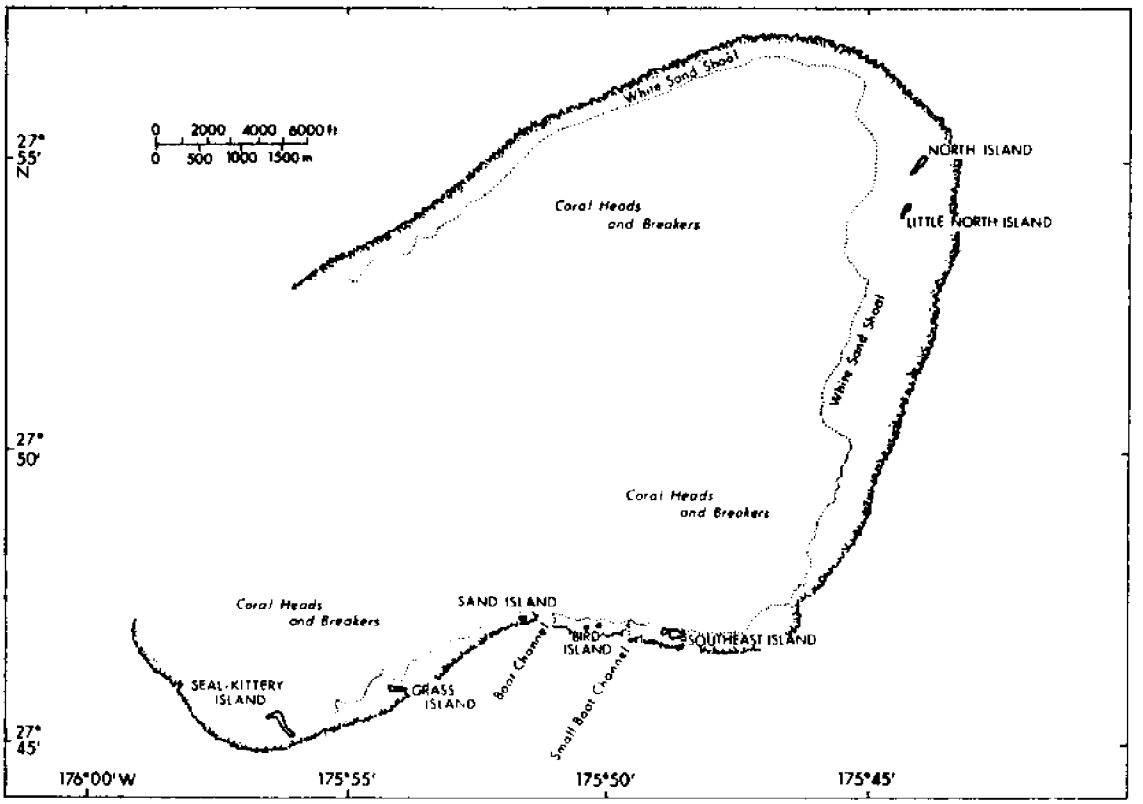


Figure 10. Pearl and Hermes Atoll

Midway, part of a low sand and coral atoll, is comprised of four islands: Sand Island, Eastern Island, and two Spit Islands (Figure 11). Midway Islands are the most altered group in the NWHI. The islands are heavily vegetated, primarily with introduced species. A significant portion of the acreages is covered with buildings, runways, or roads. Midway Islands support the largest colonies of red-tailed tropicbirds (Phaethon rubricauda), black noddies, and white terns (Gygis alba) in the NWHI and the largest Laysan albatross colony in the world. Over 550,000 seabirds of 14 species nest there (Figures 3 and 4). An individual short-tailed albatross (Diomedea albatrus), an endangered species, has occurred on Sand Island each year since 1968.

The islands of Midway and the seabird populations associated with them have changed significantly in historic times. In 1913, a few small colonies of black-footed albatross and a few nesting pairs of Laysan albatross were found (Bailey, 1956). Today, 15,000 black-footed and 400,000 Laysan albatross are estimated to breed there annually. In the late 1930s, Bonin petrels comprised the most numerous population there with an estimated 500,000 birds (Hadden, 1941). Today, the Bonin petrel population is only about 5,000 to 10,000 birds. The roof rat (Rattus rattus), introduced in 1943, is probably the main cause of this decline. Similarly, wedge-tailed shearwaters were numerous on Eastern Island in 1902 (Bryan, 1906). In 1945, 62,000 wedge-tailed shearwaters were nesting on both Sand and Eastern Islands (Fisher

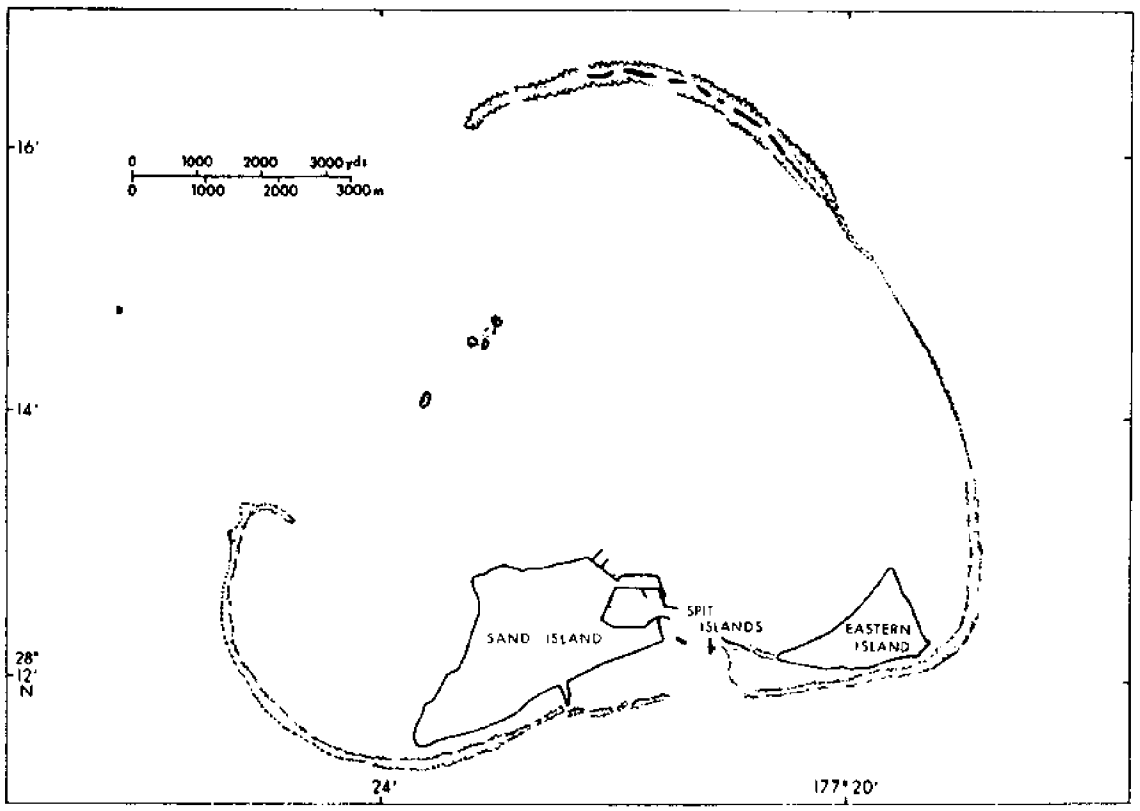


Figure 11. Midway Islands

and Baldwin, 1946). Today, approximately 2,000 birds remain. Brown boobies have declined from the most common booby in the late 1930s (Hadden, 1941) to a rare non-breeding visitor at present. In addition to the albatross, the species which have increased the most include the black noddies and white terns. These species now nest in the exotic ironwood trees (Casuarina litorea) where predation by rats may be reduced as a result.

Kure is the northernmost coral atoll in the world. It consists of Green Island, a stable island which is heavily vegetated with the beach naupaka (Scaevola taccada), and Sand Island, a barren sand islet (Figure 12). A 4,000-foot runway and a Coast Guard LORAN station are located on Green Island where approximately 44,000 birds of 14 species nest (Figures 3 and 4). Polynesian rats (Rattus exulans) were discovered on Green Island prior to 1912, and it is possible that they are responsible for the low populations of several seabird species. Seabird populations here seem to have been fairly stable since the early part of this century but data are sparse. Recent trends are difficult to determine since visits to this island were infrequent and of short duration. However, there has been an apparent increase in the population of the two albatross species.

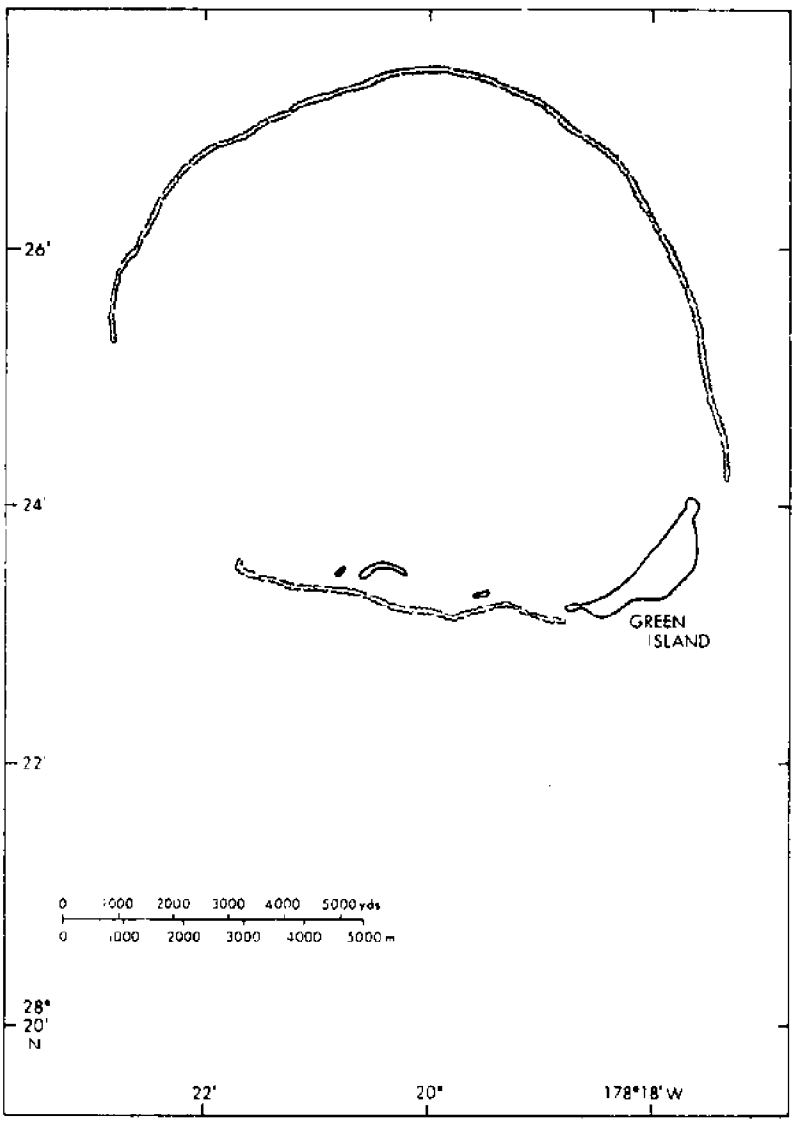


Figure 12. Kure Atoll

Non-breeding Populations

Non-breeders are defined here to be the total number of birds that visit an island at least once during the year but do not breed. Non-breeding birds constitute a significant proportion of a seabird's total population. Non-breeders include young birds that have never bred before and adults that may have bred in previous years but not that year. It is very difficult to enumerate the non-breeding proportion of the population. Intensive longterm studies with banded individuals are needed to determine numbers and attendance periods. Such long-term banding studies have rarely been conducted and hence little is known about the magnitude of non-breeders. The non-breeding component is included in our total estimate of seabird populations for the NWHI (Table 3). Proportions used to calculate non-breeding populations in the NWHI are

TABLE 3. ESTIMATED NUMBERS OF BREEDING AND NON-BREEDING SEABIRDS IN THE NORTHWESTERN HAWAIIAN ISLANDS[1]

	Estimated % of Non-breeders[2]	Estimated Number of Breeders[3]	Estimated Number of Non-breeders	Estimated Number of Birds[4]
Black-footed albatross	50[a]	98,820	98,820	197,640
Laysan albatross	70[a, b]	759,140	1,771,330	2,530,470
Bonin petrel	50[c]	662,500	662,500	1,325,000
Bulwer's petrel	50[c]	206,250	206,250	412,500
Wedge-tailed shearwater	66[a, d]	522,800	1,014,850	1,537,650
Christmas shearwater	56[a, d]	5,920	7,530	13,450
Sooty storm-petrel	31[e]	15,000	6,740	21,740
Red-tailed tropicbird	50[c]	22,470	22,470	44,940
Masked booby	27[a]	4,740	1,750	6,490
Brown booby	30[a]	950	410	1,360
Red-footed booby	45[c]	10,220	8,360	18,580
Great frigatebird	69[a, d]	19,700	43,850	63,550
Sooty tern	63[a, d]	2,661,000	4,530,890	7,191,890
Gray-backed tern	50[c]	102,000	102,000	204,000
Blue-gray noddy	50[c]	8,000	8,000	16,000
Brown noddy	45[d]	185,600	151,850	337,450
Black noddy	63[c]	32,550	55,420	87,970
White tern	63[a, c]	29,860	50,840	80,700
TOTAL		5,347,520	8,743,860	14,091,380

[1] These numbers were used to calculate consumptive rates for seabirds in the Northwestern Hawaiian Islands.
[2] Estimated percent of the total birds (i.e., breeders and non-breeders). Percentages were calculated from data presented in: [a]Woodward (1972), [b]Fisher and Fisher (1969), [c]U.S. Fish and Wildlife Service (in preparation), [d]Amerson and Shelton (1976), and [e]Allan (1962).
[3] Maximum breeding pairs from Table 1 are multiplied by two to account for both adults of the pair.
[4] Includes breeders and non-breeders

based primarily on POBSP banding studies conducted on Kure Atoll (Woodward, 1972) and Johnston Atoll (Amerson and Shelton, 1976). The estimated numbers of birds (total of breeders and non-breeders) were used to calculate consumptive rates for seabirds in the NWHI.

Phenology

Knowledge of the timing of the breeding season is essential for understanding when seabirds are present on nesting colonies. Figure 13 presents the breeding cycles of seabirds generalized

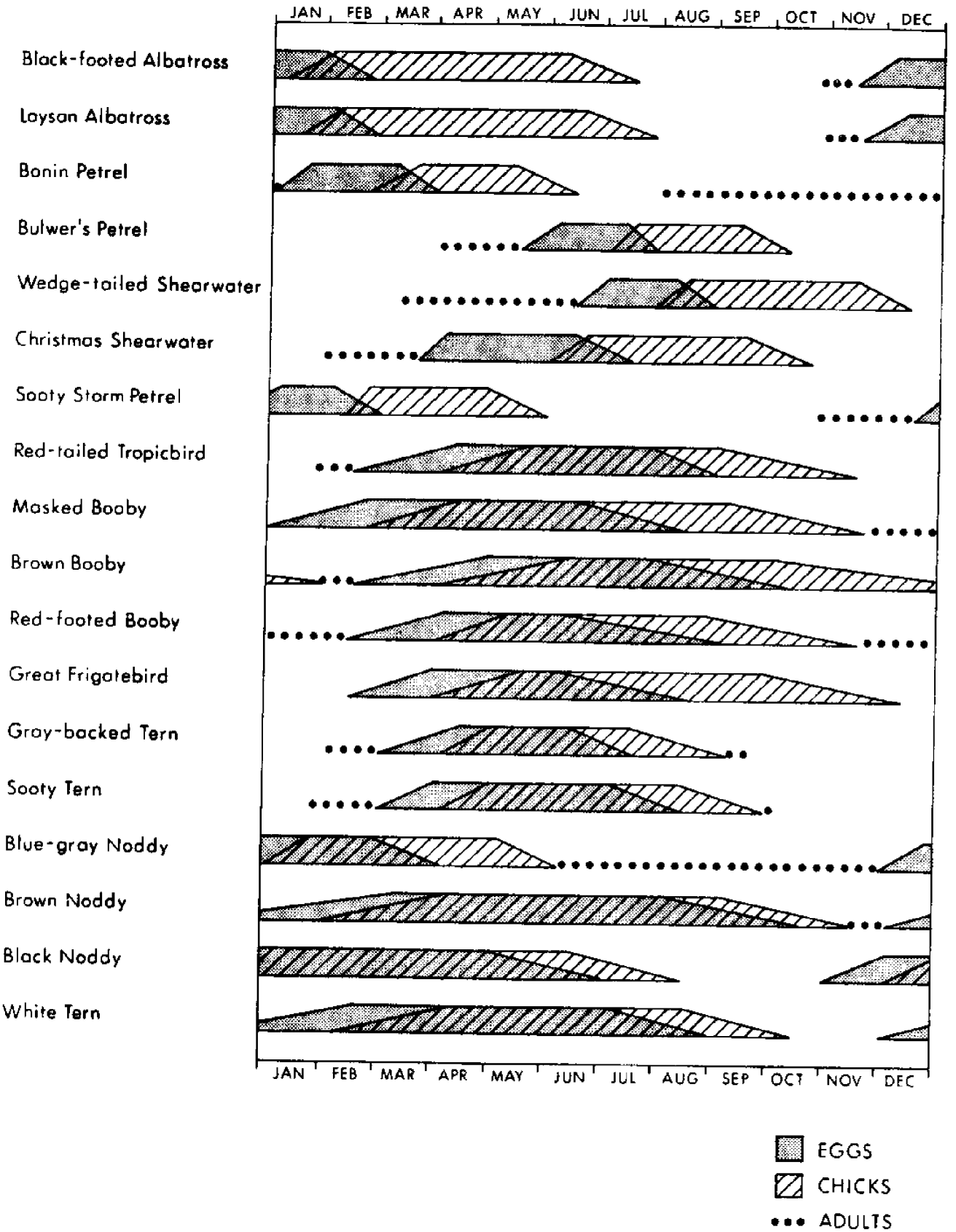


Figure 13. Generalized phenology of NWHI seabirds

for the entire NWHI chain. The species composition and the number of breeding birds vary throughout the year. During the winter months, black-footed albatross, Laysan albatross, Bonin petrels, sooty storm-petrels, masked boobies, blue-gray noddies, brown noddies, black noddies, and white terns begin breeding. Christmas shearwaters, red-tailed tropicbirds, brown boobies, red-footed boobies, great frigatebirds, gray-backed terns, and sooty terns breed in spring, and Bulwer's petrels and wedge-tailed shearwaters breed in summer. Brown noddies generally begin a second period of breeding in the summer.

The cycles for certain species may vary by as much as three months from one end of the archipelago to the other. For example, the phenology of egg laying of the sooty tern varies with location (Figure 14). Sooty terns generally initiate breeding on Nihoa in early February, on Laysan Island in early April, and on Midway Islands in early May. In addition, the timing of breeding of a species may be delayed or protracted from year to year depending on weather and/or oceanographic conditions. Thus, geographic, seasonal, and annual variations in phenology exist for the seabird population of the NWHI.

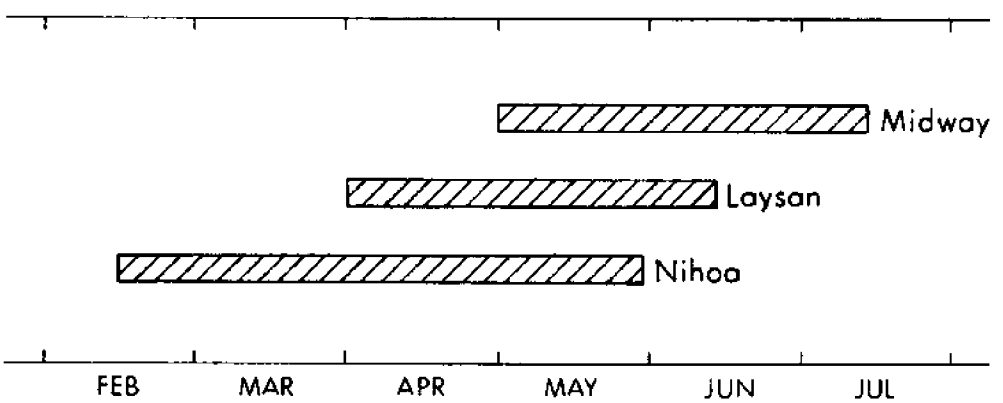


Figure 14. Phenology of sooty tern egg laying on Nihoa, Laysan, and Midway Islands

The type of breeding cycle, whether synchronous or asynchronous, is also an important factor relating to the magnitude of populations over time. Species that breed synchronously have a period of concentrated high energy demand because all birds build egg reserves and feed chicks simultaneously. Asynchronous species have a more extended breeding period and a lower peak energy demand. The shearwaters, petrels, albatrosses, and frigatebirds are the most synchronous NWHI species, whereas the noddies and terns are generally asynchronous. The boobies and tropicbirds are somewhere in between these two extremes. The degree of synchrony also varies annually.

When phenology and populations data are considered together, the magnitude of the populations of individual species, groups of species, and/or the entire seabird population can be determined for specific time periods. This is illustrated by the phenology of the population of seabirds on French Frigate Shoals throughout the annual cycle (Figure 15).

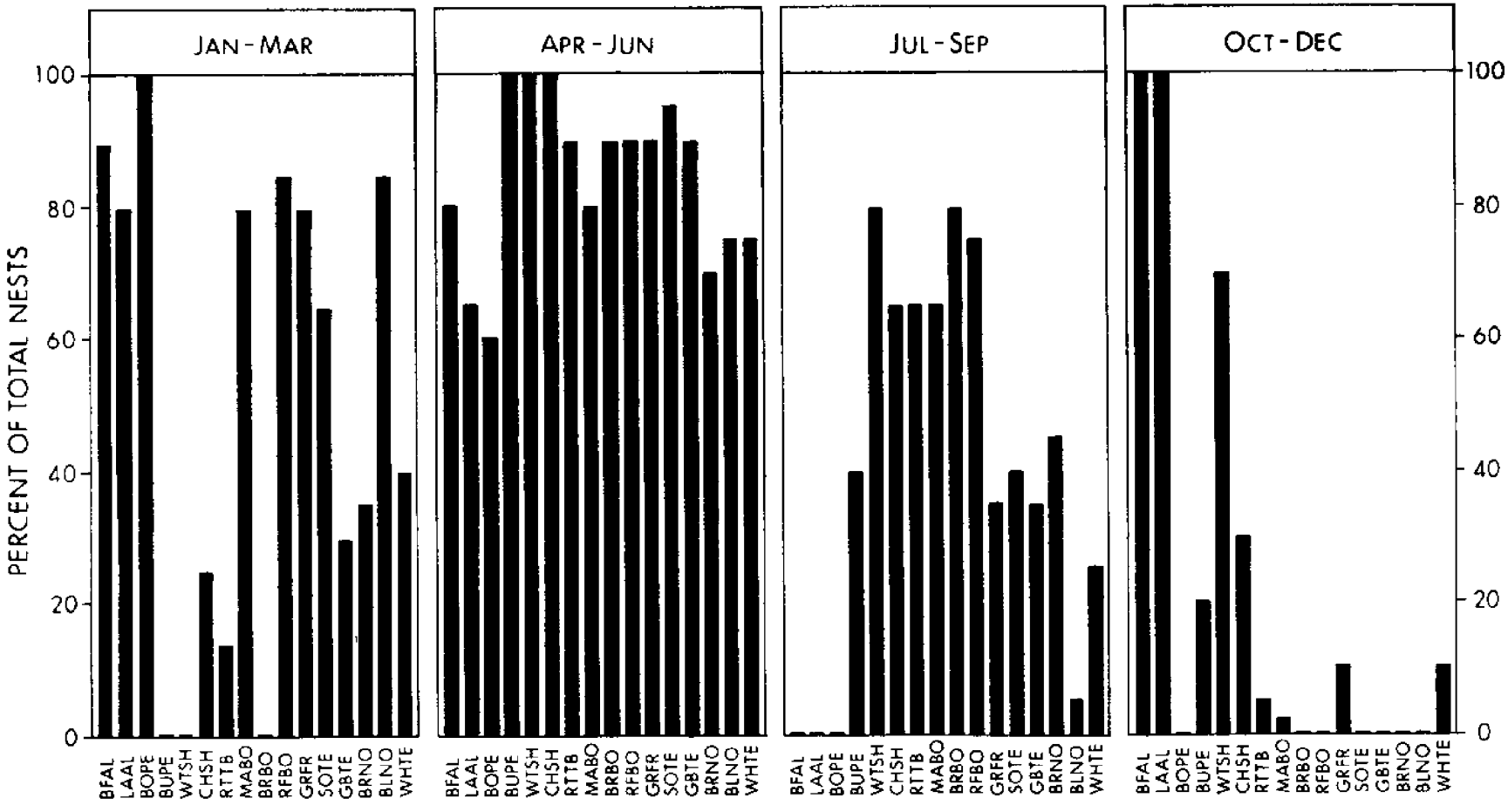
FEEDING ECOLOGY OF SEABIRDS

An understanding of the food requirements of any wildlife species is basic to its management. Given the potential for increased fishery development and competition with seabirds for prey, future management must be based on knowledge of each species' food requirements. What does each species eat? How do diets change seasonally, annually, or geographically? How adaptable is each species to changes in food supply? Answers to such questions provide guidelines for resource management. To answer these questions, FWS and NMFS initiated a study of food habits of NWHI seabirds in 1978. Results of the analysis of 4,315 food samples collected between 1978 and 1981 on an irregular series of visits to various islands in the NWHI are reviewed here briefly. The study is described in detail in a publication by C. Harrison, T. Hida, and M. Seki, (1983). Several factors concerning food sampling and analysis must be considered before interpreting the results. These are discussed below.

Methods

Practical considerations rather than statistical requirements dictated sample sizes in this study. Thus, sample sizes for species varied as a result of several factors including (1) the inaccessibility of many islands, especially during the winter; (2) the seasonal occurrence of many species on the islands; (3) the limited distribution of several species within the study area; (4) the inaccessibility of certain species on certain islands; and (5) the inability to locate birds with full stomachs during certain months. Sample sizes for each species were not distributed equally among the islands (Figure 16) or throughout the study period (Table 4). Thus, in the analysis it was necessary to pool data from various seasons and locations. It is possible that this procedure masked some local or temporal food preferences or requirements.

Food samples were obtained from bird regurgitate. Variability occurred in the behavior of the birds in relation to their willingness to regurgitate food. For example, all boobies and terns regurgitated readily if they contained food. The shearwaters, petrels, and albatrosses presented the greatest sampling problems. Adult albatrosses rarely regurgitated but chicks did if recently fed. Christmas shearwaters and wedge-tailed shearwaters were induced to regurgitate with some difficulty. Samples from sooty storm-petrels, Bulwer's petrels, and Bonin petrels consisted of food so digested that frequently only gross



Black-footed Albatross	BFAL	Sooty Storm-Petrel	SSPE	Sooty Tern	SOTE
Laysan Albatross	LAAL	Red-tailed Tropicbird	RTTB	Gray-backed Tern	GBTE
Bonin Petrel	BOPE	Masked Booby	MABO	Blue-gray Noddy	BGNO
Bulwer's Petrel	BUPE	Brown Booby	BRBO	Brown Noddy	BRNO
Wedge-tailed Shearwater	WTSH	Red-footed Booby	RFBO	Black Noddy	BLNO
Christmas Shearwater	CHSH	Great Frigatebird	GRFR	White Tern	WHTE

Figure 15. Seasonal precentage of total nests of seabirds on French Frigate Shoals

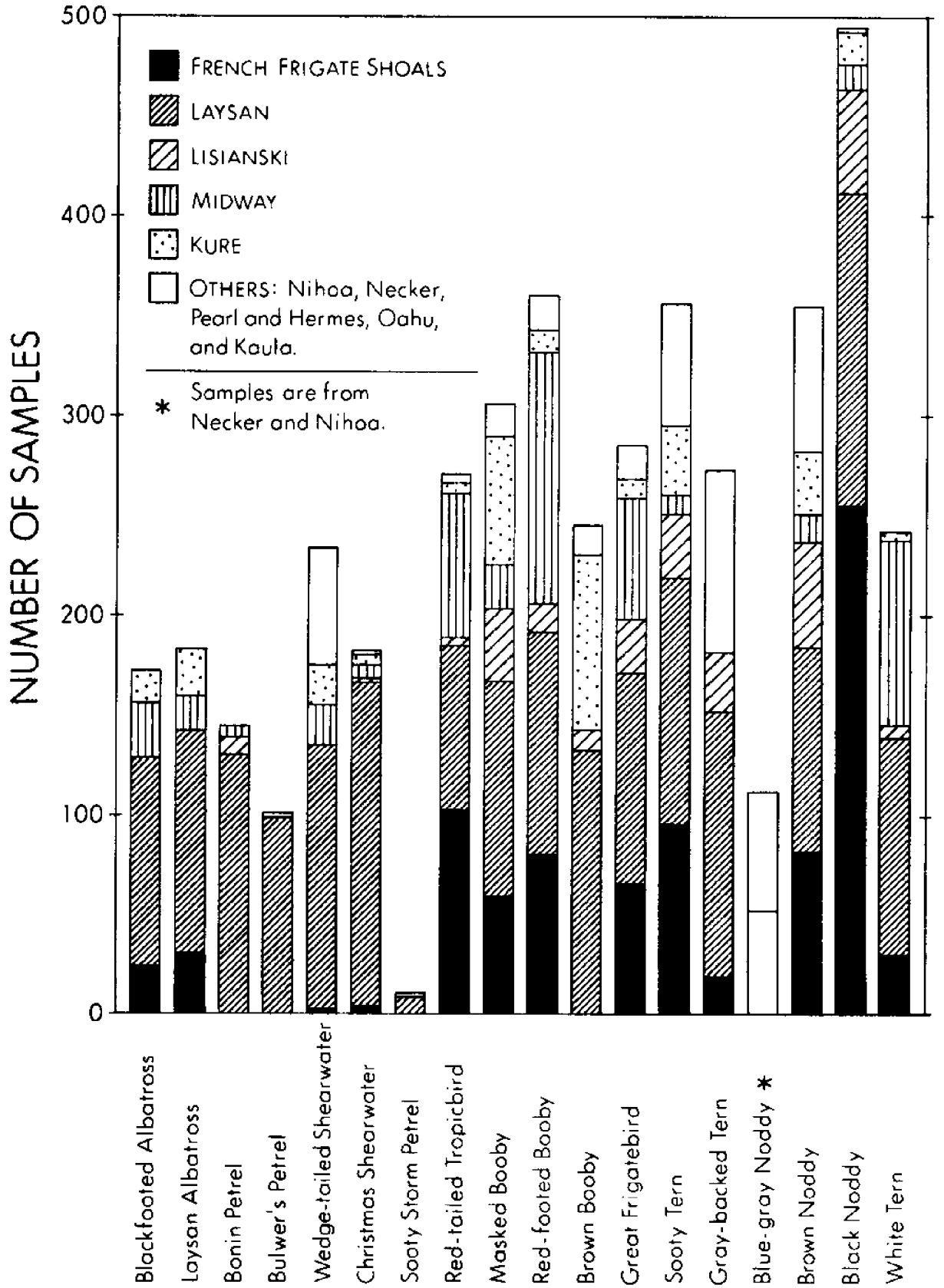


Figure 16. Number of food samples analyzed for each species of NWHI seabird

TABLE 4. THE NUMBER AND SEASONAL DISTRIBUTION OF FOOD SAMPLES COLLECTED

Species	1978				1979			
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Black-footed albatross	14	7	0	0	35	67	0	0
Laysan albatross	12	17	0	0	22	65	1	0
Bonin petrel	0	0	0	0	5	79	0	1
Bulwer's petrel	0	0	1	0	0	17	30	0
Wedge-tailed shearwater	0	1	1	1	0	37	42	30
Christmas shearwater	0	0	22	0	4	34	52	0
Sooty storm-petrel	0	0	0	0	0	5	0	0
Red-tailed tropicbird	0	4	41	0	3	47	91	18
Masked booby	0	1	33	2	11	63	13	27
Brown booby	2	0	35	0	4	43	10	21
Red-footed booby	0	11	26	26	52	66	38	11
Great frigatebird	0	1	9	6	10	74	30	26
Sooty tern	0	22	94	0	7	123	22	0
Gray-backed tern	0	14	34	0	7	110	4	0
Blue-gray noddy	0	0	1	0	0	43	0	0
Brown noddy	0	11	118	10	13	84	18	0
Black noddy	5	26	102	0	19	106	36	78
White tern	0	4	36	7	11	54	66	9
TOTAL	33	119	553	52	203	1,117	453	221

Species	1980				1981			
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Black-footed albatross	28	21	0	0	0	0	0	0
Laysan albatross	45	20	1	0	0	0	0	0
Bonin petrel	18	41	0	0	0	0	0	0
Bulwer's petrel	0	0	52	0	0	0	0	0
Wedge-tailed shearwater	0	74	36	11	0	0	0	0
Christmas shearwater	20	36	14	0	0	0	0	0
Sooty storm-petrel	1	1	0	0	3	0	0	0
Red-tailed tropicbird	10	28	15	13	0	0	0	0
Masked booby	41	61	30	23	0	0	0	0
Brown booby	6	57	51	15	0	0	0	0
Red-footed booby	49	40	25	16	0	0	0	0
Great frigatebird	33	51	37	7	0	0	0	0
Sooty tern	26	50	12	0	0	0	0	0
Gray-backed tern	17	59	27	0	0	0	0	0
Blue-gray noddy	0	52	0	0	15	0	0	0
Brown noddy	27	56	12	5	0	0	0	0
Black noddy	52	46	11	13	0	0	0	0
White tern	5	31	17	1	0	0	0	0
TOTAL	378	724	340	104	18	0	0	0

identification of prey items was possible. Stomach oils found in the samples from the laboratory analysis were excluded.

To insure the highest possible proportion of usable specimens and to minimize the problems of differential digestion rates, food samples should be collected from feeding birds. This was not always possible, however. Differences in digestibility of different prey items may have occurred and, if so, would have biased results. Variability in digestion may affect the ability to identify and to determine the volume and length of prey items. For boobies and terns, less than 1 percent of the volume of the samples was classified as unidentified remains. Unidentified remains were common in other species ranging from less than 2 percent of the sample volume in Christmas shearwaters to 24 percent in Bonin petrels. Only the best specimens were used to determine mean length and volume for common prey species. Prey length data from albatrosses, which shred prey items, must be viewed with caution. For all the samples collected from each species, the average percentage of volume is presented for major groupings of prey items, including fish, squid, and crustaceans (Figure 17). These data are also presented for the major fish families found in the samples (Figure 18). Lengths and volume of important prey items of each species are discussed in C. Harrison, T. Hida, and M. Seki, (1983).

Prey Diversity

Seabirds in Hawaii feed on a wide variety of shoaling fish and squid and apparently take any prey of appropriate size that occurs in surface waters. This diversity is reflected in the fact that no bird ate any one prey species to an extent that it comprised 50 percent or more of the volume of the diet. The analysis is confounded by prey material that could not be identified to species, but even the highest ranking undifferentiated prey family for many birds was relatively low by volume: brown booby (15 percent), wedge-tailed shearwater (18 percent), white tern (20 percent), brown noddy (28 percent), and black noddy (31 percent). Diets that contain 20 to 40 prey families are very diverse when compared with those of northern latitudes (Pearson, 1968). This may reflect the patchy distribution of prey items in tropical waters. The most specialized diets were those of gray-backed terns (42 percent cowfish, Lactoria fornasini) and black-footed albatrosses (44 percent flyingfish, Exocoetidae, eggs), but the latter included more than one species (C. Harrison, T. Hida, and M. Seki, 1983).

The opportunistic character of the feeding strategies of Hawaiian seabirds is evidenced by the many prey items that were taken during a single season or at a single location. Many prey taxa were eaten only in certain months, probably reflecting seasonal occurrence in surface waters. The difference between relative and absolute prey abundance could not be distinguished. Much of the variation in diet occurs in the relative proportions of several common prey items such as flyingfishes, squids

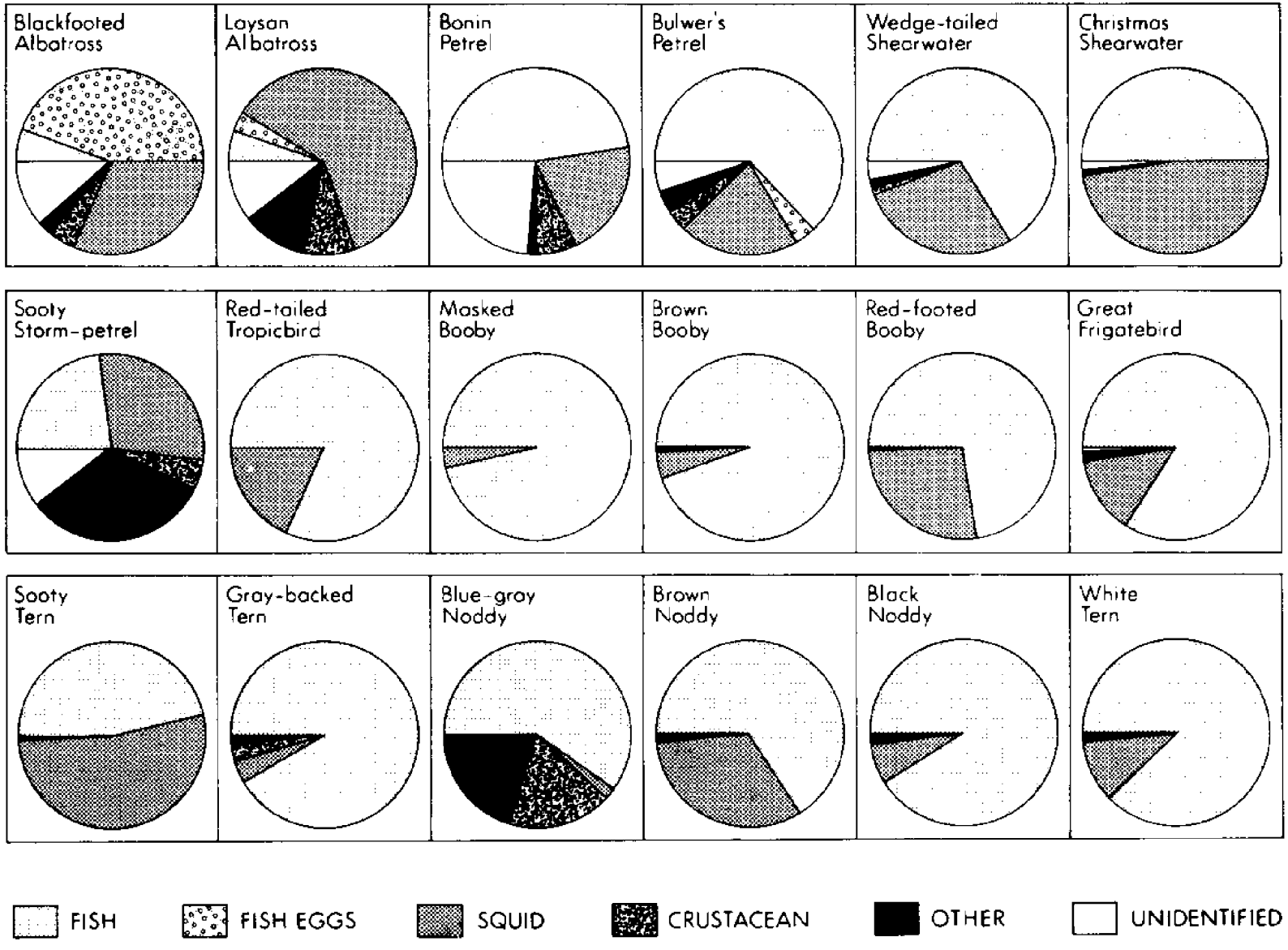


Figure 17. Average percentage of volume of major prey groups consumed by NWHI seabirds

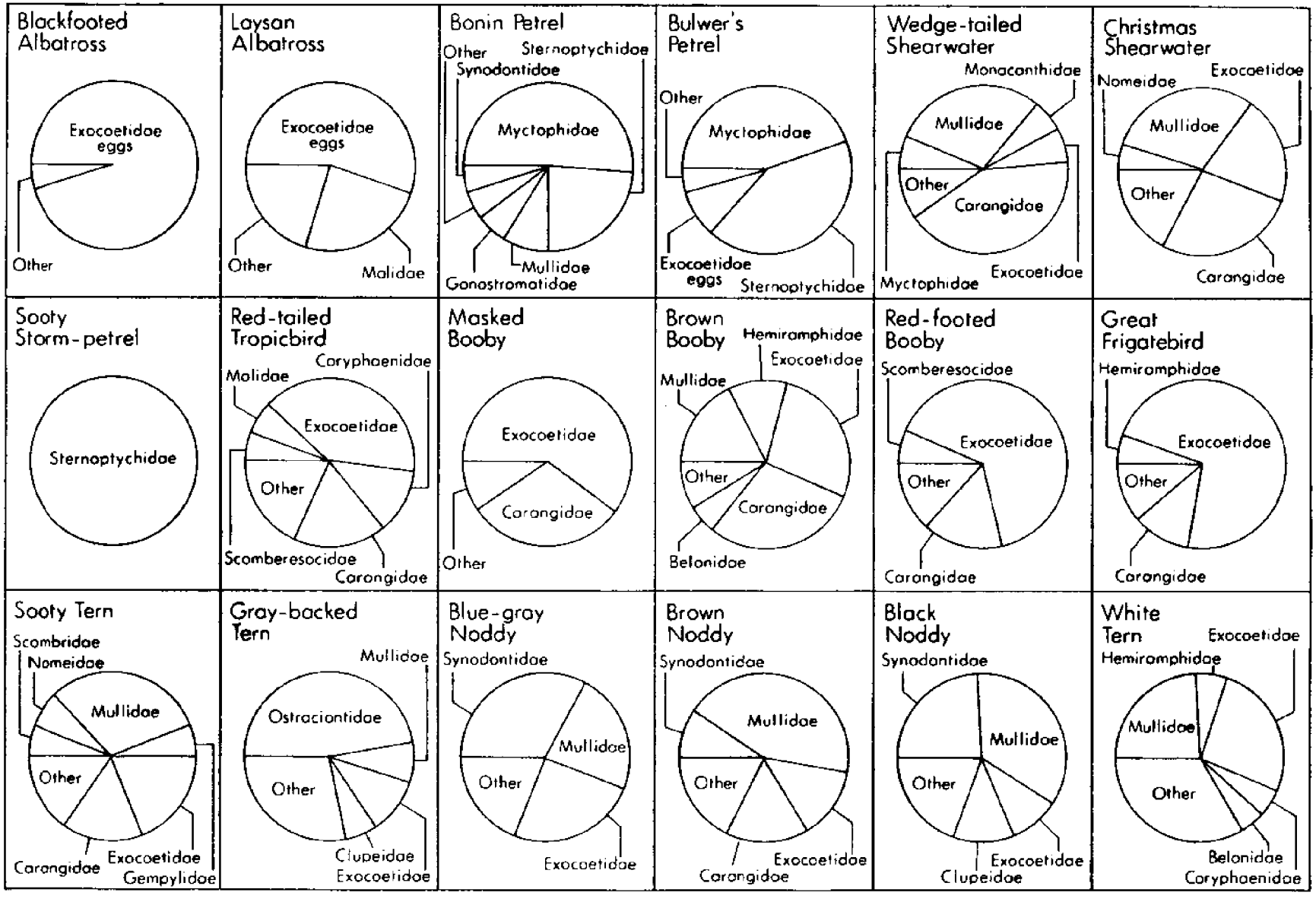


Figure 18. Percentage of composition, by family, of the fish consumed by each NWHI seabird species

(particularly Ommastrephidae), opelu (Decapterus spp.), juvenile goatfishes (Mullidae), juvenile lizardfishes (Synodontidae), and mesopelagic fishes. Birds apparently supplement this diet whenever another prey resource is available. Goatfishes, lizardfishes, opelu, and mesopelagic fishes rarely occur in the diets of tropical seabirds elsewhere, but flyingfishes and squids are commonly eaten at all tropical colonies.

Prey Size

The size of the prey species taken by each seabird species is an important factor in the assessment of food requirements. For example, both masked boobies and brown noddies feed on opelu. However, noddies feed on juvenile fish (90 mm) and boobies feed on adult fish (200 mm). A reproductive failure of opelu, which would diminish the availability of juvenile fish, would affect terns immediately but would not affect boobies until subsequent years, if at all. Both seabird species could be affected by a reproductive failure of an important prey species but not at the same time.

Relationship of Food Habits to Phenology

The amount of food eaten by each species of seabird near the NWHI varies seasonally and depends on seabird breeding phenology. For many species, non-breeding birds scatter across the ocean to feed in areas distant from the NWHI. Many birds (e.g., wedge-tailed shearwater, great frigatebird, Laysan albatross) apparently fast when courting or establishing breeding territories and live off fat reserves. During the incubation period, food demands become more localized around the islands than during non-breeding periods. The ability of several species to be away from the colonies for several days at a time implies that they may not feed near the islands. The maximum food demands in the vicinity of the colonies occurs during the chick-rearing periods, which for most species occurs in spring or summer (Figure 13). The need to provide food for adults and growing chicks plus the fact that birds seem to feed much closer to the colony indicate that food consumption near the islands will be at a maximum. During these various stages, food preferences may change, and it is possible that some prey items which are not present in abundance in our generalized analysis could be critical at certain stages of the life cycle.

Within the NWHI, variation in diet is more correlated with season than location. However, during certain months at Midway Islands, prey species that are absent elsewhere are taken (C. Harrison, T. Hida, and M. Seki, 1983). More samples are needed to refine our assessment of geographic variation in the diet.

Availability of Prey

The availability of prey is an indirect factor which may affect the ability of seabirds to obtain food. All NWHI seabirds

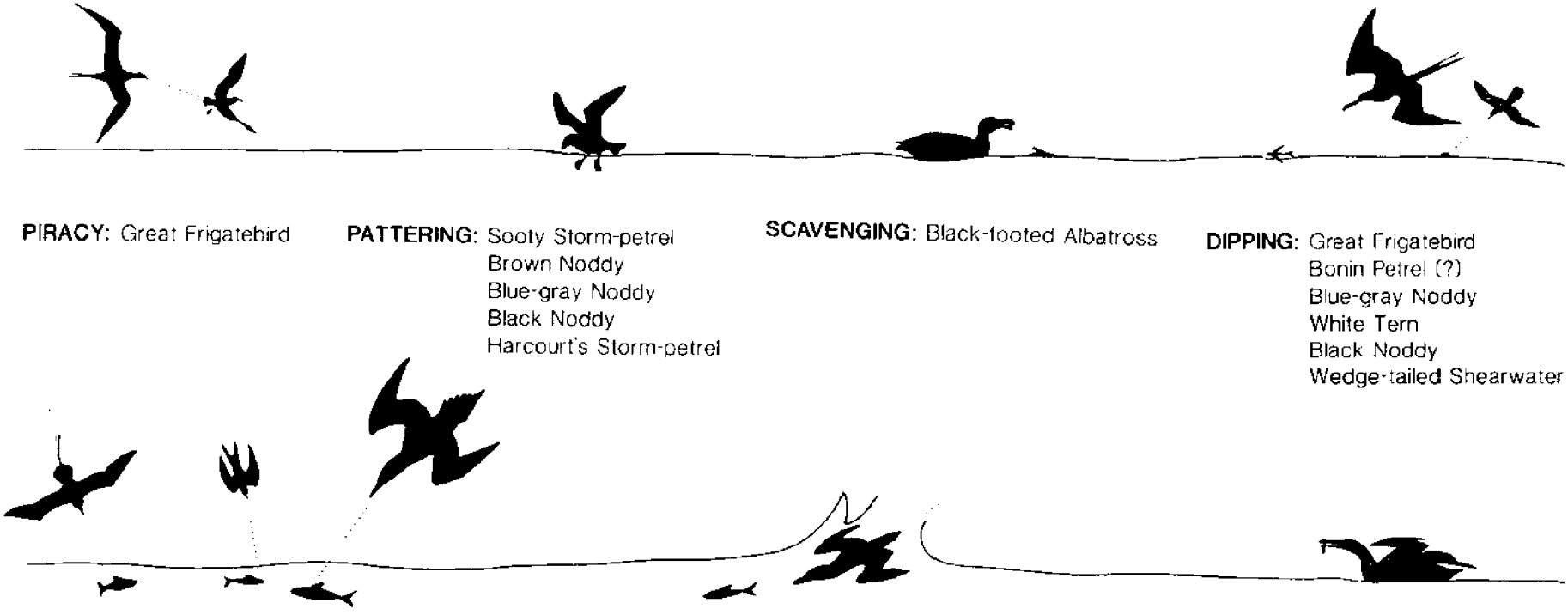
feed in surface waters. Variations in the extent of subsurface feeding exist, but the 5 m maximum diving depth of the masked booby is the deepest. Fish, squid, or other prey which are in the water column but not at the surface are not available to species whose feeding is confined to the top several meters. Large predatory fishes drive prey to the surface for many terns, boobies, and shearwaters. Yellowfin (Thunnus albacares) and skipjack (Katsuwonus pelamis) tunas are the most important predatory fishes in relation to seabird feeding in the NWHI, but uluas (Caranx spp.) are apparently important to inshore-feeding black noddies. Breeding birds must be able to locate prey within a reasonable distance from the colony, which varies with species. Prey resources distant from colonies are essentially unavailable to breeding seabirds.

FORAGING HABITS AND AT-SEA DISTRIBUTION OF SEABIRDS

The knowledge of methods and locations of areas used by seabirds for feeding is important in assessing the potential effects of fishery development. The location of feeding areas is an indication of which areas may be most vulnerable to seabird/fishery competition. Generally, feeding areas for breeding seabirds are localized around banks and shoals within specific distances from the breeding colonies. Non-breeding seabirds are also associated with these areas but they are not restricted to areas in the vicinity of breeding colonies. Several detailed studies have been conducted concerning the at-sea distribution of tropical seabirds of the Pacific Ocean as part of the POBSP research (King, 1970, 1974; Gould, 1971). However, these studies were not limited to the NWHI and thus specific data on this area are scarce. During this study, FWS personnel conducted at-sea observations of seabirds on ships of opportunity and NMFS personnel reported on seabird observations on cruises of the Townsend Cromwell. Additionally, Harrison and Stoneburner (1981) tested the feasibility of using radiotelemetry to locate seabird feeding areas. In order to accurately locate feeding areas, radial transect surveys were proposed for this study. However, due to logistical and funding constraints, transect surveys were not conducted. Seabirds have evolved to exploit prey by using different foraging methods and by foraging in different locations (Figure 19, Table 5). Many rely on feeding associations, often finding prey by visual cues from other birds. For ease of discussion, the 18 breeding species of the NWHI have been grouped into five feeding guilds: (1) albatrosses, (2) Pelecaniformes, (3) terns and shearwaters associated with predatory fishes, (4) nocturnal petrels, and (5) neuston-feeding terns.

Albatrosses

Both Laysan and black-footed albatrosses feed by sitting on the surface of the water and seizing prey (Figure 19). In addition, black-footed albatrosses regularly and Laysan albatrosses occasionally scavenge naturally occurring carrion or human refuse from ships. These birds often feed in intraspecific flocks, but



PIRACY: Great Frigatebird

PATTERING: Sooty Storm-petrel
Brown Noddy
Blue-gray Noddy
Black Noddy
Harcourt's Storm-petrel

SCAVENGING: Black-footed Albatross

DIPPING: Great Frigatebird
Bonin Petrel (?)
Blue-gray Noddy
White Tern
Black Noddy
Wedge-tailed Shearwater

PLUNGING: White Tern
Sooty Tern
Gray-backed Tern
Brown Noddy
Red-tailed Tropicbird
Red-footed Booby
Brown Booby
Masked Booby
White-tailed Tropicbird

PURSUIT PLUNGING: Christmas Shearwater
Wedge-tailed Shearwater
Newell's Shearwater

SURFACE SEIZING: Black-footed Albatross
Laysan Albatross
Bonin Petrel (?)
Bulwer's Petrel
Dark-rumped Petrel (?)

Figure 19. Feeding methods of NWHI seabirds (adapted from Ashmole, 1971)

TABLE 5. FORAGING HABITS OF NORTHWESTERN HAWAIIAN ISLANDS SEABIRDS

Bird	Feeding Location[1, 2]	Interspecific[3] Associations	Intraspecific[3] Associations
Black-footed albatross	Well offshore	None	Common
Laysan albatross	Well offshore	None	Rare
Bonin petrel	Offshore	Rare: W-t shearwater Sooty tern Gr frigatebird	None
Bulwer's petrel	Offshore	Rare: W-t shearwater Sooty tern Gr frigatebird	Rare
Wedge-tailed shearwater	Offshore	Common: Sooty tern White tern Brown noddy Gr frigatebird	Occasional
Christmas shearwater	Offshore	Occasional: Gr frigatebird W-t shearwater Sooty tern White tern	Occasional
Sooty storm-petrel	Offshore	None	None
Red-tailed tropicbird	Offshore	None	None
Masked booby	Offshore	Common: Sooty tern Brown noddy W-t shearwater	None
Red-footed booby	Offshore	Occasional: Sooty tern W-t shearwater White tern Brown noddy	None
Brown bobby	Inshore	None	None
Great frigatebird	Offshore	Occasional: Sooty tern W-t shearwater	Rare
Sooty tern	Well offshore	Common: W-t shearwater White tern Gr frigatebird	Common
Gray-backed tern	Inshore	Occasional: Sooty tern White tern W-t shearwater	Occasional
Blue-gray noddy	Inshore	Occasional: Black noddy	Common
Brown noddy	Inshore/Offshore	Common: Sooty tern W-t shearwater White tern Red-footed booby	Common
Black noddy	Inshore	Common: Sooty tern W-t shearwater Brown noddy Christmas shearwater	Common
White tern	Inshore/Offshore	Common: Sotty tern W-t shearwater Gr frigatebird	Rare

[1]Inshore = waters subject to effects of emergent lands, shoals and banks; Offshore = deep waters
[2]Data from King (1970), Diamond (1978), U.S. Fish and Wildlife Service observations
[3]Data from Gould (1971)

not in association with other species (Gould, 1971). The length of incubation bouts and times between feeds of growing young imply that each species is capable of feeding very far away from the colony. During a homing experiment with Laysan albatrosses, Kenyon and Rice (1958) reported that this species can fly over 300 miles per day, allowing very long foraging flights even for birds which must return to the colony to feed their young every other day. A comparison of rhodopsin in the eyes of these species indicated that Laysan albatross are much better adapted for nocturnal vision than black-footed albatross (A.J. Sillman, personal communication). Feeding at different times of the day may account for many of the differences in the diets of these species.

Pelecaniformes

The five species of this order form a convenient ecological unit for discussion apart from any taxonomic considerations. The three boobies and the red-tailed tropicbird plunge-dive and pursue fish and squid under water (Figure 19) to depths of several meters. Great frigatebirds are restricted to snatching prey from surface waters, probably no more than about 15 cm deep, because of their structural inability to take off from the water. At sea, the great frigatebird rarely associates with its own species (Gould, 1971), but occurs fairly regularly with sooty terns and wedge-tailed shearwaters. Both brown boobies and red-tailed tropicbirds feed entirely in a solitary fashion. Masked and red-footed boobies rarely associate at sea with other boobies, but each commonly feeds with flocks of sooty terns, brown noddies and wedge-tailed shearwaters. Red-footed boobies also frequently occur with white terns (Gould, 1971). Among this group of birds, only brown boobies feed inshore; the others forage far out at sea (King, 1970; Diamond, 1978). Red-footed boobies are particularly pelagic and can be found 100 to 150 km from the breeding colony and more than 70 km from land (Nelson, 1978), but many of the far-ranging birds are immature (King, 1970). Diamond (1978) recorded them feeding as close as 1 km from the reef at Aldabra Atoll and suggested that this species might better be termed a "deep-water" rather than offshore feeder since water 1 km from the reef can be over 500 m deep. The prevalence of opelu and goatfishes in the diets of this guild in Hawaii underscores the influence that local availability of surface-schooling fishes has on the diets of seabirds in a given location.

Terns and Shearwaters Associated with Predatory Fishes

The six species treated here are of fairly similar size' ranging from the wedge-tailed shearwater (x = 388 g) to the black noddy (x = 108 g). Other species include Christmas shearwaters, brown noddies, sooty terns, and white terns. All species feed on similar prey items of similar size and feed largely in association with predatory fishes, especially tunas (Ashmole and Ashmole, 1967). Several of these species occur in flocks (Table 6) ranging from 97 percent of the sightings for black noddies

(King, 1970) to about 50 percent of the sightings (Gould, 1971) for Christmas shearwaters. There are some differences among these birds in their ability to exploit food far away from the islands. Sooty terns and shearwaters apparently have the greatest capacity to forage far offshore, whereas the capacity of brown noddies are intermediate. Both black noddies and white terns are regarded as inshore-feeding species (Diamond, 1978), yet white terns can regularly be seen far out at sea (King, 1970). Black noddies often feed within a few meters of shore, sometimes in association with ulua (Johannes, 1981; FWS observations).

TABLE 6. FLOCKING TENDENCY OF SEABIRDS

Type of Seabird	Total No. of Birds	Birds in Flocks	Percentage in Flocks
Sooty tern	30,802	28,625	92.9
Wedge-tailed shearwater	8,733	5,941	68.0
Brown noddy	3,937	3,344	84.9
Boobies	1,209	817	67.6
Bulwer's petrel	624	58	9.3
Black noddy	435	420	96.6
Tropicbirds	413	19	4.6
Great frigatebird	304	124	40.8
White tern	227	152	67.0

Source: King, 1970

The mixed feeding flocks associated with yellowfin and skipjack tunas have been described by King (1974). When fish are not surfacing, wedge-tailed shearwaters and noddies fly lowest, usually no higher than 10 m above the water. Masked and red-footed boobies fly between 10 and 30 m, whereas sooty and white terns fly between 20 and 60 m above the water level. Great frigate birds occur substantially higher, at least at 120 m. The longer the periods between surfacing, the higher the sooty terns fly and the more dispersed the flock becomes. They act as the "eyes" of the flock, and by spotting the flash of white from long distances as they bank from a horizontal flight, exposing their white underparts against the sky in a dive toward surfacing fish, fishermen can locate schools of fish. Generally, all species in this guild flock with their own species as well as with others, but this is less pronounced with white terns and Christmas shearwaters which often occur as the solitary individual of its species in a mixed species feeding flock. Interspecific feeding associations in this guild vary to some extent (Table 5).

Nocturnal Petrels

Considered here are Bonin petrels, Bulwer's petrels, and sooty storm-petrels. Each apparently feeds primarily at night or under reduced light conditions. Feeding techniques are somewhat uncertain for these birds. Bonin petrels probably feed by dipping or surface seizing (Figure 19), but definitive observations are lacking. Bulwer's petrels feed sitting on the water with wings spread and head dipped below the surface (Gould, 1971). All storm-petrels feed strictly at the surface (Figure 19) and do not submerge the body beneath the surface (Crossin, 1974). Each of these feeds offshore, rarely associating with its own species. Bulwer's and Bonin petrels occasionally associate with feeding wedge-tailed shearwaters, sooty terns, and great frigatebirds (Table 5).

Neuston-Feeding Terns

Gray-backed terns and blue-gray noddies are considered together here because their unique feeding habits do not conveniently fit elsewhere and because there are some similarities in their diets. Both apparently feed inshore (Diamond, 1978), eating minute prey. Gould (1971) contended that gray-backed terns are gregarious, feeding by plunging (Figure 19) with other species. Blue-gray noddies feed by dipping and pattering at the surface and are not dependent on schools of predatory fishes to drive prey to the surface. This is probably also true for gray-backed terns, but convincing data are lacking. Blue-gray noddies commonly feed in intraspecific flocks, but rarely in association with other species. Gray-backed terns occasionally feed with other gray-backs, sooty terns, white terns, or wedge-tailed shearwaters (Table 5).

CONSUMPTIVE RATES OF SEABIRDS

It is necessary to know the relationship between the food requirements of seabirds and the total resource available in order to understand the seabirds' potential competition with commercial fisheries. As top predators in the marine ecosystem, seabirds have a very significant effect on prey resources, especially during the breeding season when foraging ranges are restricted and energetic demands are highest.

Since the amount of food consumed by seabirds cannot be measured directly, a model was used to estimate the energy requirements of seabirds and then the amount of food necessary to supply that amount of energy was determined. Models based on bioenergetic equations result in relatively accurate estimates of consumption. Complete methods are presented in the model for French Frigate Shoals (see report in this proceedings by Pettit et al.). For the NWHI model, the population variables were changed to include the entire seabird population (Table 3).

Briefly, the model includes the energy required by adults for daily existence multiplied by the total number of days the birds are associated with the islands and by the total number of seabirds (breeders and non-breeders) associated with the island. Added to this are the energy needed to produce an egg (multiplied by the number of eggs laid) and the energy required to raise a chick from hatching to fledging (multiplied by the total number of chicks). Energy requirements were calculated for each species individually. Egg energy was determined directly by bomb calorimetry of egg contents and estimates of the cost of synthesis. Chick daily energy requirements were obtained from growth equations resulting from chick weight data. Using data on diet composition (C. Harrison, T. Hida, and M. Seki, 1983) as well as caloric content of specific prey items (see report in this proceedings by Pettit et al.), the energy requirements were converted into grams (metric tons) of food consumed. The results of this analysis are presented in Table 7 and discussed below.

Consumptive estimates of seabird communities should be interpreted with caution. Seabird species with high body weights and/or large populations are responsible for a large proportion of the total food consumed. In the NWHI, Laysan albatross consume an estimated 250,000 metric tons or 60 percent of the estimated annual consumption of the entire NWHI seabird population. Five species including Laysan and black-footed albatrosses, Bonin petrels, wedge-tailed shearwaters, and sooty terns account for 94 percent of the total consumption in the NWHI. The remaining 13 species have relatively low body weights and/or small populations and thus account for a relatively small amount of the total prey consumption. Thus, it is important to consider the composition of the prey consumed by each species because of the emphasis in the summarized data (Table 7) on species which consume the most.

Prey consumption figures are approximations. Variables of the model including diet composition and population magnitude vary annually. Approximations of consumption provide an indication of the important role seabirds have in the marine ecosystem.

POTENTIAL EFFECTS OF FISHERY-RELATED ACTIVITIES ON SEABIRDS

Until the latter half of the nineteenth century, the remoteness and inaccessibility of the NWHI served to isolate the islands as sanctuaries for plants and animals. During the last 100 years, human activities have had both positive and negative effects on seabird populations. Prior to the NWHI being placed in a protected status in 1909, guano mining and large-scale feather hunting radically altered the habitat and decimated certain species of seabirds. Most populations of seabirds have since recovered but some, such as Christmas shearwaters, have not. Due to the continued protected status of the NWHI and the protection

TABLE 7. CONSUMPTION (METRIC TONS) OF MAJOR[1] PREY ITEMS BY NORTHWESTERN HAWAIIAN ISLANDS SEABIRDS

Species	Total Population Estimates[2]	Carangidae	Coryphaenidae	Clupeidae	Exocoetidae	Hemiramphidae	Molidae	Mullidae
Black-footed albatross	197,640				5,730[c]			
Laysan albatross	2,530,470				(9,050)[c]		(7,000)	
Bonin petrel	1,325,000							(630)
Bulwer's petrel	412,500				(90)[c]			
Wedge-tailed shearwater	1,537,647	9,780			(1,490)			6,830
Christmas shearwater	13,450	40			30			50
Sooty storm-petrel	21,740							
Red-tailed tropicbird	44,940	180	120		430	(30)	60	
Masked booby	6,490	230	(20)		470	(20)		
Brown booby	1,358	40			40	10		20
Red-footed booby	20,400	160			700	(30)	(30)	(30)
Great frigatebird	63,550	510	(100)		3,420	(260)		
Sooty tern	7,191,890	4,960			6,290		(720)	10,410
Gray-backed tern	204,000	(20)	(50)	60	110			80
Blue-gray noddy	16,000				20			20
Brown noddy	337,450	800			720			2,300
Black noddy	87,970	(20)		130	100			400
White tern	86,110	(40)	(60)	(20)	310	(60)		260
TOTAL		16,780	350	210	14,870 eggs 14,130	410	7,810	21,030

[1]Major fish families include those which comprise at least 5 percent of any one seabird's diet. Values in parentheses are less than 5 percent of that seabird's diet.
[2]From Table 3.
[c]Exocoetidae eggs

TABLE 7. CONSUMPTION (METRIC TONS) OF MAJOR[1] PREY ITEMS BY NORTHWESTERN HAWAIIAN ISLANDS SEABIRDS (continued)

Species	Myctophidae	Ostraciontidae	Sternoptychidae	Synodontidae	Other Fish	Squid	Crustacean	Others
Black-footed albatross					700	4,130	560	310
Laysan albatross					6,070	162,260	21,660	17,650
Bonin petrel	3,640		1,720	(340)	820	3,140	1,030	150
Bulwer's petrel	890		860		100	200	120	110
Wedge-tailed shearwater	(1,510)				3,770	10,000	400	530
Christmas shearwater					40	150		<10
Sooty storm-petrel			30			40	10	40
Red-tailed tropicbird					220	230		10
Masked booby					40	20		<10
Brown booby					20	10		<10
Red-footed booby					150	410		<10
Great frigatebird					420	640		30
Sooty tern					10,670	38,400		390
Gray-backed tern		480			220	40	40	20
Blue-gray noddy				20	20	<10	20	20
Brown noddy				480	920	2,610		90
Black noddy				260	200	80		20
White tern	(40)			(20)	370	160		10
TOTAL	6,080	480	2,610	1,120	24,750	222,520	23,840	19,380

TABLE 7. CONSUMPTION (METRIC TONS) OF MAJOR[1] PREY ITEMS BY NORTHWESTERN HAWAIIAN ISLANDS SEABIRDS (continued)

Species	Unidentified Remains	Total
Black-footed albatross	1,560	12,990
Laysan albatross	27,070	250,760
Bonin petrel	3,530	15,000
Bulwer's petrel	150	2,520
Wedge-tailed shearwater	1,130	35,440
Christmas shearwater	10	310
Sooty storm-petrel	10	130
Red-tailed tropicbird		1,280
Masked booby		800
Brown bobby		140
Red-footed booby		1,510
Great frigatebird		5,380
Sooty tern		71,840
Gray-backed tern		1,120
Blue-gray noddy		120
Brown noddy		7,920
Black noddy		1,210
White tern		1,350
TOTAL	33,450	409,820

of seabirds by treaty, these activities are not a problem at present. The specific impacts of these activities are described elsewhere (Ely and Clapp, 1973; Clapp and Wirtz, 1975).

Currently, among the threats to seabirds in the NWHI are those associated with increased commercial fishing. Direct effects include mortality from fishing gear and competition for fishery resources. Indirect effects from fishery-related activities may include the introduction of exotic predators, insects, and vegetation; human disturbance on breeding colonies; loss of habitat; and environmental contamination by oil, heavy metals, and organochlorine compounds.

Fishery-related activities could have some positive effects on seabirds, but these would be minimal. Such effects could include the provision of food via fish offal, potential removal of fish competitors for seabird prey items, and a reduction of sharks that prey on seabirds.

Direct Effects

Fishing activities in the NWHI directly impact seabird populations through interactions with fishing gear or through changes in the food web, increasing or decreasing prey availability.

MORTALITY FROM FISHING GEAR

The magnitude of seabird mortality due to interactions with fishing gear in the vicinity of the NWHI is not expected to be significant but could result in substantial mortality if gill-net fisheries for squid or other resources become widespread. The Japanese gill-net fisheries for salmon (Oncorhynchus spp.), which have operated since 1952 in the North Pacific, have been very destructive to seabirds. Annual mortality is estimated to be between 200,000 and 700,000 birds (King et al., 1979; Ainley et al., 1981). Lost nets cause significant additional mortality of North Pacific seabirds which become entangled in such nets and drown (DeGange and Newby, 1980). Although net fragments regularly wash up on NWHI beaches and are implicated in seal and turtle entanglement, there is currently no evidence that these fragments are adversely affecting NWHI seabird populations. Mortality of both Laysan and black-footed albatrosses occurs when birds are caught on longline tuna fishhooks (Robbins and Rice, 1974). Seabirds, particularly masked boobies, are frequently hooked during trolling operations in Hawaiian waters. However, mortality is rare and most birds are released uninjured.

DIRECT COMPETITION FOR FISHERY RESOURCES

Seabird population changes resulting from changes in the food web are known throughout the world. It has long been accepted that seabird reproductive success is sensitive to food availability (Ashmole, 1971), but this relationship has been difficult to demonstrate directly due to a lack of long-term

observations and difficulties in the measurement of food availability. Seabirds are generally top-level predators in marine ecosystems and as such are potential competitors with commercial fisheries. There have been demonstrable changes in ecosystem structure in many areas of the world due to overfishing as well as natural climatic and oceanographic fluctuations. It is inevitable that these will influence seabird populations through alterations in the availability, quantity, or quality of their food supplies. In order to make management decisions or to predict the effects of such changes, it is important to anticipate what effects changing fishing practices are likely to have on seabird populations.

Seabirds are an important component of marine ecosystems because they consume a relatively large quantity of the production of lower trophic levels. Population/energetics models of seabird communities substantiate this fact. Wiens and Scott (1975) estimated that the seabirds of coastal Oregon consume 22 percent of the annual fish production there. Furness (1978) estimated that the seabirds of Foula, Shetland consume the equivalent of 29 percent of the fish production within a 45-km radius of the colony.

Seabirds in the NWHI consume approximately 410,000 metric tons (900 million lb) of fish, squid, crustacea, and other prey (Table 7). The amount of prey of each of the major fish families consumed by the total NWHI seabird population is presented in Figure 20. Until biomass estimates for these prey items in the vicinity of the NWHI are available, the percentage of biomass consumed by seabirds cannot be determined. However, it is clear that seabird predation is quantitatively important. It is also certain that direct competition with fisheries for their prey would have a direct effect on seabird populations.

The actual effects of natural food shortages and fishery competition on seabird populations have been documented in many parts of the world. The food shortages that result from El Nino in the Peruvian current are well known (Idyll, 1973). These effects occur much farther west than was previously thought (Schreiber and Schreiber, 1983). Harris (1969) recorded the effects of food shortages on shearwaters (Puffinus lherminieri) in the Galapagos Islands. Size of feeds decreased as adults returned to the colony to feed their young, even when they found little food. Then the frequency of feeds was reduced and incubating birds had their bouts prolonged. As the situation worsened, adults abandoned their young immediately after hatching. Eggs were found abandoned and no new eggs were laid. Ultimately, all adult birds abandoned the colony, leaving any unfledged young unattended to die.

Similar periodic mortality of chicks from starvation has been reported from other tropical seabird colonies. Young of black noddies (Ashmole, 1962), sooty terns (Ashmole, 1963), and brown boobies (Dorward, 1962) have starved on Ascension Island.

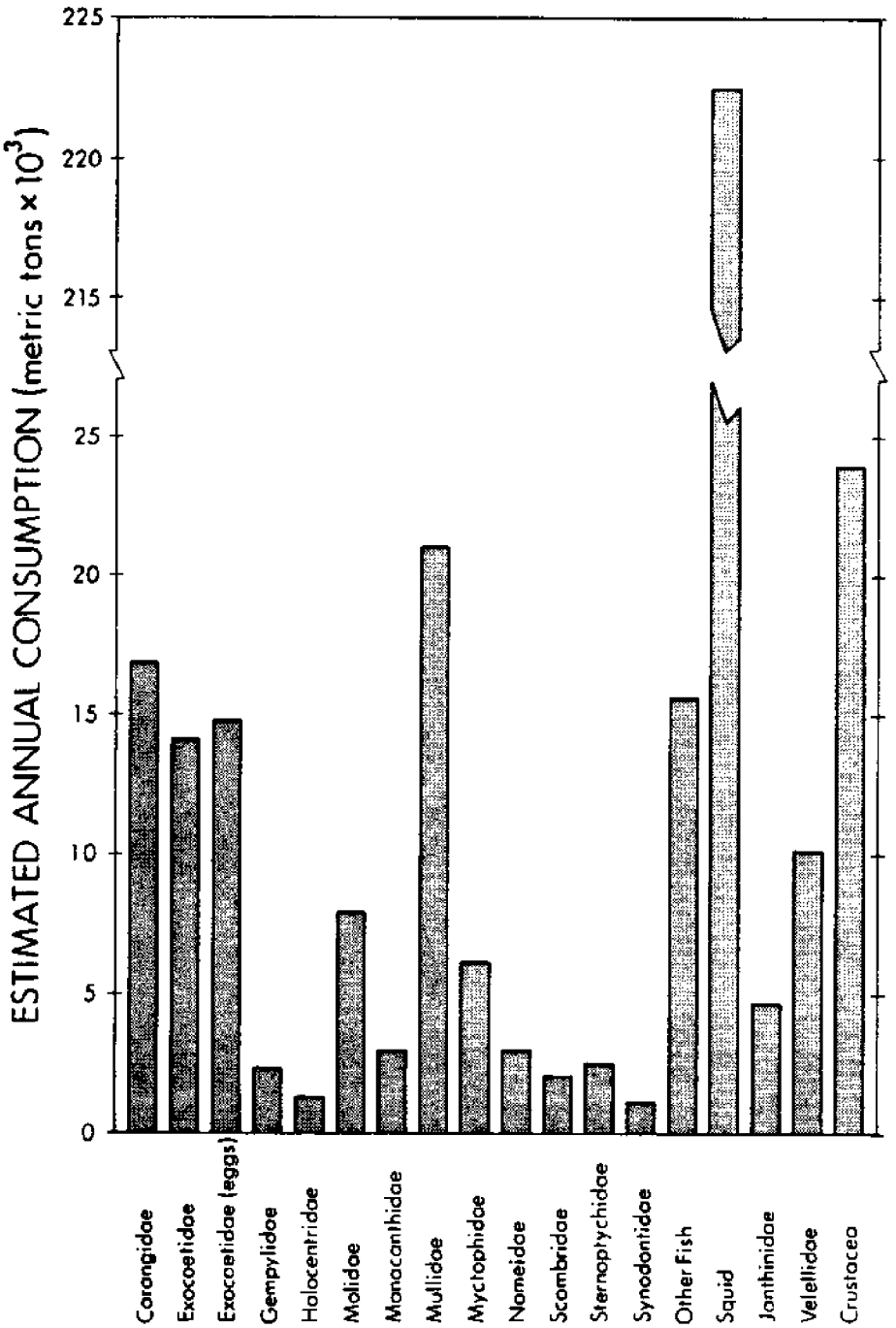


Figure 20. Estimated annual consumption of major prey items by NWHI seabirds

Sooty tern chicks have also starved on Christmas Island (Gallagher, 1960) and in the Kermadec Islands (Guthrie-Smith, 1936). Lesser frigatebirds have starved on Christmas Island and apparently many species of seabirds recently delayed breeding there due to a lack of food (Schreiber and Schreiber, 1983). In the Hawaiian Archipelago, mass starvation of young has been reported for sooty terns on Midway Islands (Bartsch, 1922), for brown noddies on Manana Island, Oahu (Richardson and Fisher, 1950), and for Laysan albatrosses on Pearl and Hermes Atoll (Galtsoff, 1933).

Seabirds of the NWHI are most vulnerable to food shortage during the breeding season. At other times of the year, many species forage far out to sea and have no biological obligation to relieve a mate incubating an egg or feed a chick which will starve if food is not forthcoming. Consequently, the effects of decreased food availability on seabirds are likely to be most profound during periods of incubation or chick-feeding.

The most critical areas for feeding seabirds during the breeding months are those banks and shoals most closely associated with the breeding islands. Certain breeding species and non-breeding birds of many species range farther out and feed at distant banks where fishery resources appear concentrated. Shoals and banks in the vicinity of Nihoa, Laysan, and Lisianski Islands are probably the most important because of the large populations of sensitive bird species there, but banks surrounding all colonies (with the possible exception of Gardner Pinnacles) are also very important.

Several fisheries have potential for growth in the NWHI, including tuna, baitfish, bottomfish, shellfish, billfish, sharks, and seamount fish species (DLNR, 1979). Most of these fisheries will probably not have a significant effect on NWHI seabird populations through the food chain, including fisheries for bottomfishes, lobsters, shrimps, kona crabs, billfishes, sharks, and seamount species. However, significant fisheries for skipjack and yellowfin tunas, tuna baitfishes, squids, and adult opelu in the vicinity of the NWHI are likely to adversely affect specific seabird populations, especially on large colonies during sensitive stages of the breeding cycle. Each fishery will be described below to detail its potential effects on the seabirds of the NWHI.

Tuna Fisheries

Fisheries for several tuna species including skipjack (aku), yellowfin (ahi), bigeye (T. obesus), albacore (T. alalunga), and kawakawa (Euthynnus affinis) are proposed for the NWHI (Table 8). Several species of seabirds associate with surface schools of skipjack and yellowfin tuna in the NWHI. The most important relationship between tuna and seabirds is the ability of the former to drive prey to the surface.

TABLE 8. CHARACTERISTICS AND POTENTIAL EFFECTS ON SEABIRDS OF PROPOSED TUNA FISHERIES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Species	Method	Depth	Effect on Availability of Food for Seabirds	Seabird Species Potentially Affected
Skipjack (aku) (*Katsuwonus pelamis*)	Trolling	Surface	Yes	Wedge-tailed shearwater
	Pole and line	Surface	Yes	Christmas shearwater
				Masked booby
				Red-footed booby
				Great frigatebird
				Sooty tern
				Brown noddy
				Black noddy
				White tern
Yellowfin (ahi) (*Thunnus albacares*)	Trolling	Surface	Yes	Wedge-tailed shearwater
	Pole and line	Surface	Yes	Christmas shearwater
	Handline (ika-shibi)	15 to 25 fa	Yes	Masked booby
	Handline (palu-ahi)	50 to 60 fa	--	Red-footed booby
	Longline	to 150 fa	--	Great frigatebird
				Sooty tern
				Brown noddy
				Black noddy
				White tern
Bigeye (ahi) (*Thunnus obesus*)	Handline (ika-shibi)	15 to 25 fa	--	--
	Longline	to 150 fa	--	--
Albacore (ahi) (*Thunnus alalunga*)	Trolling	Surface	Yes	Wedge-tailed shearwater
	Pole and line	Surface	Yes	Christmas shearwater
	Handline (ika-shibi)	15 to 25 fa	Yes	Masked booby
	Longline	to 150 fa	--	Red-footed booby
				Great frigatebird
				Sooty tern
				Brown noddy
				Black noddy
				White tern
Black skipjack (kawakawa) (*Euthynnus affinis*)	Trolling	Surface	Yes	Wedge-tailed shearwater
	Pole and line	Surface	Yes	Christmas shearwater
				Masked booby
				Red-footed booby
				Great frigatebird
				Sooty tern
				Brown noddy
				Black noddy
				White tern

Many species of seabirds can catch prey only when the latter is very close to the surface, and this happens mainly when the prey is pursued from below by surface schools of skipjack and yellowfin tunas (Ashmole and Ashmole, 1967). Consequently, if too many surface-feeding tunas were removed from the NWHI ecosystem, the carrying capacity of the area for seabirds would be diminished. Seabird associations rarely occur with bigeye and albacore tunas because they occur in fairly deep water and are unlikely to drive prey to the surface. King's (1970) at-sea observations in the vicinity of the main Hawaiian islands revealed that several species occurred regularly in flocks (defined as five or more birds) (Table 6). Our observations and those of Gould (1971) in waters south of Hawaii parallel King's findings of flocking species associated with tuna schools. From these studies, it is clear that the birds associated with tuna schools include wedge-tailed shearwaters, Christmas shearwaters, masked boobies, red-footed boobies, great frigatebirds, sooty terns, brown noddies, black noddies, and white terns. The primary species to be affected by a decrease in surface tuna schools, would be those feeding in flocks associated with these schools, especially sooty terns, wedge-tailed shearwaters, and brown noddies. Other species would probably be affected if the situation worsened, but alternative prey resources could be exploited. Black noddies often associate with schools of other predatory fishes in inshore waters, especially ulua (Johannes, 1981; FWS, unpublished data), and therefore have an alternative method of acquiring food that could minimize the consequences of food stress due to diminished tuna populations.

Our information on phenologies indicates that reproductive periods from March to September are critical for most species that may be affected by surface tuna fisheries (Figure 13). Additionally, wedge-tailed shearwaters feed their young through November, and black noddies commence breeding as early as November on Midway Islands. The least sensitive months for most species would be those occurring in late fall and winter.

Seabirds and surface schools of tuna feed near the ocean's surface. Ashmole and Ashmole (1967) compared diets of seabirds with those of surface-caught yellowfin tuna in the Central Pacific Ocean. They found that each of the most important fish families in the diet of the tuna was not found in the food of seabirds or was found only in very small numbers. They concluded that there was little overlap between the diets of seabirds and surface-caught yellowfin tuna.

A comparison of seabird diets with those of yellowfin (Reintjes and King, 1953) and skipjack (Waldron and King, 1963) tunas caught at various depths indicates that tuna fisheries could marginally enhance the numbers of prey species such as squid and certain fishes. However, subsurface prey would be largely unavailable to diurnal surface-feeding birds in the absence of sufficient populations of surface-schooling tunas.

Tuna fisheries and seabirds coexist in the vicinity of the main Hawaiian islands. Until the first part of this century, seabird colonies were decimated by native egg collecting and meat and feather hunting. Seabirds, which depend upon an association with tunas to feed, recovered from this decimation during a 70-year period when a substantial skipjack tuna fishery prospered in the main Hawaiian islands, especially in nearshore waters. Since the beginning of the twentieth century, the populations of brown noddies and sooty terns have increased on Manana Island (Oahu) after a long period of extensive human harvest. In addition, the wedge-tailed shearwater breeding population on Manana Island is estimated to be 10 to 20 thousand. These three species feed in association with tuna schools. Populations of terns are compared with the average skipjack tuna catch per year for each decade of the twentieth century (Figure 21). It is possible that the

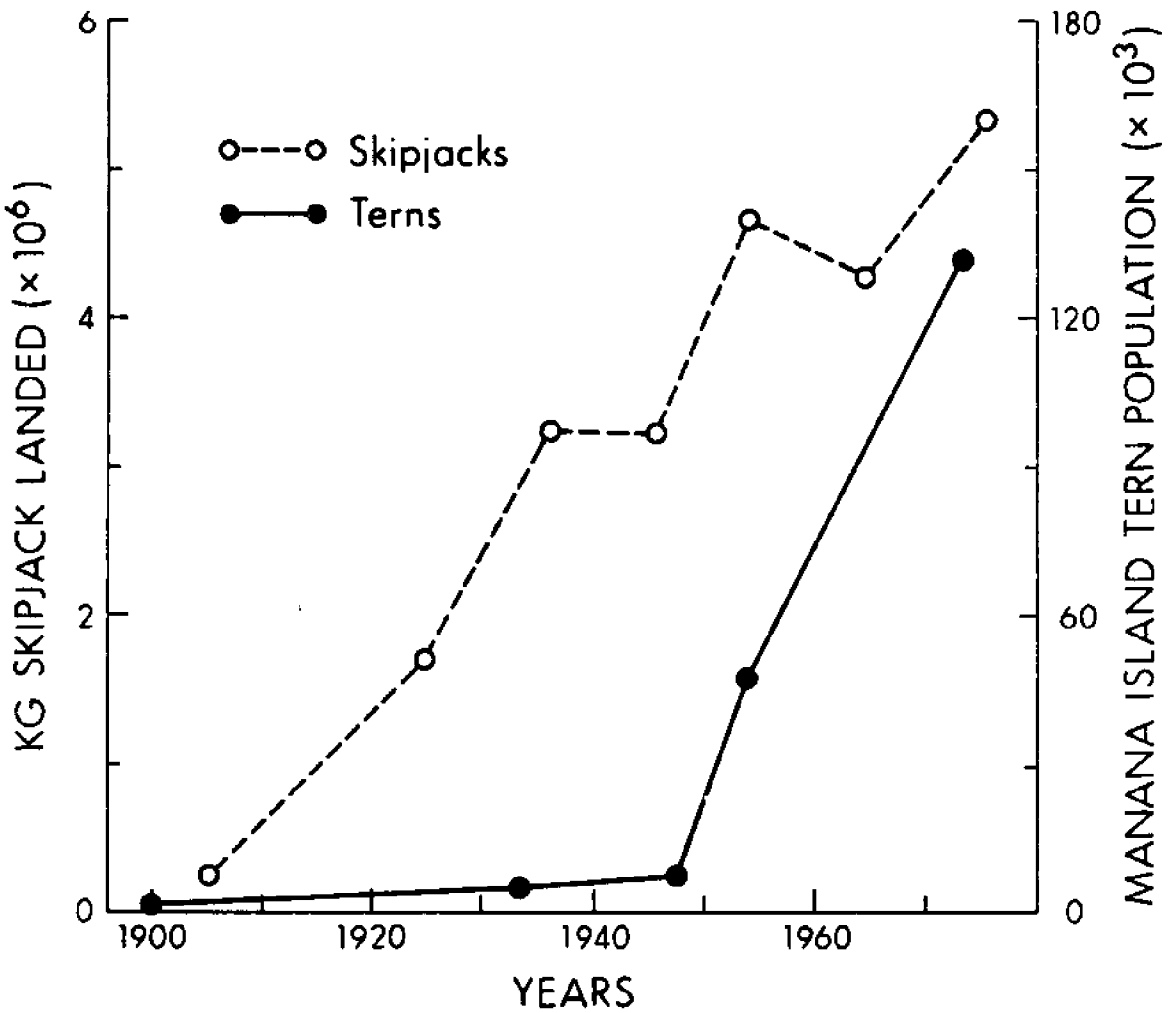


Figure 21. Relationship between Hawaiian skipjack tuna catch and recovery of Manana Island tern population (tuna catch data from Uchida, 1975)

recovery of the bird populations on Manana Island would have occurred much faster in the absence of the tuna fishery, or that the present carrying capacity would be much larger if tunas were more numerous. It is also possible that the tuna population has not declined below a level necessary to provide feeding opportunities for the present number of seabirds and, therefore, the removal of tuna has not measurably harmed the populations of sooty terns, brown noddies, or wedge-tailed shearwaters.

Bait Fishing to Support Skipjack Tuna Fishing

A pole-and-line fishery for skipjack tuna in the NWHI is dependent upon a reliable supply of good baitfishes. It has been suggested that shoaling schools of baitfish such as the oceanic nehu (Stolepherous buccaneeri), juvenile opelu (Decapterus spp.), or akule (Selar crumenopthalmus) be harvested from the waters adjacent to the NWHI for this purpose (DLNR, 1979). Piha (Spratelloides delicatulus) and juvenile goatfishes, which are potential baitfishes, and adult opelu and akule, which may be harvested for human consumption, are also included in this discussion. These fishes are important foods for most species of NWHI seabirds. Approximately 39,000 metric tons (85 million lb) of these baitfish species are consumed annually by NWHI seabirds (Table 9). The value of each of these fish species to NWHI seabirds are reviewed below.

Nehu (Stolepherous spp.). Nehu (S. purpureus) is the most commonly used baitfish in the main Hawaiian islands. The oceanic species (S. buccaneeri) is taken by five species of seabirds (Table 9), but this prey item is incidental for each in terms of year-round overall importance. S. buccaneeri is very important to wedge-tailed shearwaters and red-footed boobies during the fall at Pearl and Hermes Atoll, Midway Islands, and Kure Atoll. Approximately 390 metric tons (860,000 lb) of nehu are taken by NWHI seabirds annually (Table 9). The length of fishes eaten is about 70 mm. At present, there is no practical means for fishermen to locate and harvest oceanic nehu, but if a means were developed, wedge-tailed shearwater young in the northern portion of the archipelago could be adversely impacted during the fall.

Goatfish (Mullidae). Juvenile goatfish are extremely important as forage items to many seabirds in the NWHI (Table 9). If a large fishery for goatfish is developed, it would affect the availability of this important forage item to seabirds. Approximately 21,000 metric tons (46 million lb) of goatfish are consumed annually by NWHI seabirds (Table 9).

Akule (Selar crumenopthalmus). Juvenile akule are eaten by wedge-tailed shearwaters and brown noddies (Table 9). Adult akule occur irregularly in the diets of brown boobies and great frigatebirds. Relatively few akule are taken by seabirds when compared with other baitfish prey items. Only about 135 metric tons (300,000 lb) of akule are consumed by NWHI seabirds annually.

TABLE 9. CHARACTERISTICS AND POTENTIAL EFFECTS ON SEABIRDS OF PROPOSED BAITFISH, ADULT OPELU, AND ADULT AKULE FISHERIES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Species	Method	Depth	Estimate of Seabird Consumption	Direct Competition with Fisheries for Food	Seabird Species Potentially Affected
Nehu (Hawaiian anchovy) (Stolepherous buccaneeri)	Nets	Surface	390 metric tons (859,802 lb)	Yes	Wedge-tailed shearwater Red-footed booby Brown noddy Black noddy White tern
Goatfish (Mullidae)	Nets	1 to 25 fa	21,059 metric tons (46,427,093 lb)	Yes	Bonin petrel Christmas shearwater Red-tailed tropicbird Masked booby Red-footed booby Great frigatebird Sooty tern Gray-backed tern Blue-gray noddy Brown noddy Black noddy White tern
Akule (bigeye scad) [Selar (= trachurops) crumenopthalmus]	Surround nets Handline	10 fa 1 to 25 fa	135 metric tons (297,624 lb)	Yes	Wedge-tailed shearwater Brown noddy
Piha (small round herring) (Spratelloides delicatulus)	Surround nets	Surface	491 metric tons (1,082,468 lb)	Yes	Sooty tern Gray-backed tern Brown noddy Black noddy White tern
Opelu (mackerel scad) (Decapterus spp.)	Nets Handline	10 fa 1 to 25 fa	16,460 metric tons (36,288,045 lb)	Yes	Baitfish Bonin petrel Bulwers petrel Wedge-tailed shearwater Christmas shearwater Sooty tern Gray-backed tern Blue-gray noddy Brown noddy Black noddy White tern Adult Black-footed albatross Red-tailed tropicbird Masked bobby Brown bobby Red-footed booby Great frigatebird
TOTAL			38,535 metric tons (84,955,032 lb)		

Piha (Spratelloides delicatulus). Piha in the 30 to 40-mm size range are taken by five seabird species (Table 9). They are particularly important to gray-backed terns and black noddies. Piha are also important to white terns on Laysan and Lisianski Islands during the summer months when this tern is raising young and therefore sensitive to depletion of this resource. Gray-backed terns at Pearl and Hermes Atoll may be sensitive to the abundance of piha during the summer, and black noddies may be sensitive throughout the NWHI year-round. Approximately 490 metric tons (1.1 million lb) of piha are consumed by seabirds in the vicinity of the NWHI each year.

Opelu (Decapterus spp.). A bait fishery for opelu may have serious conflicts with seabird populations. Opelu occur in the diets of 16 seabird species. Baitfish-sized opelu occur in the diets of 10 species (Table 9). Opelu are among the top ten prey items for five species, and among the top four prey items for wedge-tailed shearwaters, Christmas shearwaters, and brown noddies. The baitfish-sized classes of this species probably become available to birds when tunas drive them to the surface. Wedge-tailed shearwaters would be most sensitive to depletion of opelu during the summer months at Laysan and Lisianski Islands. Christmas shearwaters would be most sensitive during spring and summer on Laysan and Lisianski Islands. Brown noddies would be sensitive throughout the NWHI, especially during spring and summer. NWHI seabirds consume about 16,000 metric tons (35 million lb) of opelu annually. A depletion of young opelu near breeding colonies would be manifested by any of the symptoms of food shortages mentioned for seabirds. Adult opelu, also an important prey item, are especially important for each of the pelecaniform species (Table 9). The birds, most of whose diets consist largely of adult opelu, breed in spring and summer. Consequently, the months between April and September would be most sensitive to an intensive fishery of adult opelu.

Bottomfishes. DLNR (1979) lists numerous species of bottomfishes which could be exploited in the NWHI, including opakapaka (Pristipomoides filamentosus), kalekale (P. sieboldi), onaga (Etelis carbunculus), ehu (E. marshi), hapuupuu (Epinephelus quernus), and several uluas (Caranx spp., Carangoides spp.). A fishery for bottomfishes could have some secondary effects through the food chain which could enhance the populations of some seabird prey species. However, these bottomfish prey are largely unavailable to the diurnal surface-feeding seabirds.

Uluas (Caranx spp.) are important to seabirds in shallow water areas. Black noddies, and presumably other species, feed on prey driven to the surface by uluas in fairly shallow waters (FWS, unpublished data; Johannes, 1981). Depletion of nearshore uluas in the vicinity of seabird colonies during the first 6 months of each year could affect the breeding of black noddies.

Squid. Squids were found in food samples of each of the 18 seabirds which breed in the NWHI. An estimated 222,000 metric

tons (490 million lb) of squid are consumed by seabirds annually in the vicinity of the NWHI. They are an important food item to all seabirds, except gray-backed terns and blue-gray noddies. Of outstanding importance is the surface-dwelling family Ommastrephidae, especially Symplectoteuthis oualaniensis. Most squids had mantle lengths between 50 and 100 mm, the largest intact length being 208 mm (red-footed booby). S. oualaniensis occurs as large as 460 mm (Okutani and Ih-Hsiu, 1978). However, many of the squids taken by the albatrosses may have exceeded 300 mm, but since their feeding methods involve shredding their prey. the larger squid mantles were not available intact in the regurgitations and hence could not be measured. Although at the present time there is no serious fishery proposal for squid in the NWHI (DLNR, 1979), we consider it here because of the large potential impacts such a fishery would have on seabird populations. Techniques to harvest this squid have been successfully developed in Japan (Okutani and Ih-Hsiu, 1978), and it is conceivable that a squid fishery will occur in the NWHI.

Most of the unidentified squids were probably S. oualaniensis. Although this species undoubtedly becomes available to birds when pursued to the surface by tunas, it is probable that some occur in surface waters in the absence of predatory fishes. For example, albatrosses, red-tailed tropicbirds, and Bulwer's petrels generally feed in a solitary fashion (Gould, 1971) and yet consume many squids.

There are no published accounts of seabirds being affected by squid fisheries, yet a fishery for the ommastrephid Nototodarus spp. near sooty shearwater (P. griseus) colonies in New Zealand is currently being monitored to determine if fishing should be restricted near the colonies since the squid is an important component of the shearwater diet (Imber, personal communication). The overall importance of S. oualaniensis for most NWHI seabirds implies that any harvesting of this resource near breeding colonies must take place with great caution. Numerous species raise their young during the spring and summer months, making those months sensitive throughout the archipelago. A fall (September-November) fishery would primarily impact wedge-tailed shearwater young, and the major colonies affected would include those on Laysan and Lisianski Islands. A winter (December-February) fishery could affect the black-footed albatross, Laysan albatross, and Bonin petrels. The most sensitive areas to the winter fishery would include Laysan and Lisianski Islands, Pearl and Hermes Atoll, and Midway Islands.

Other. The relationship between the remaining fisheries that have been proposed for the NWHI (DLNR, 1979) and seabirds is discussed here. Fisheries for spiny lobsters (Panulirus marginatus), penaeid and caridean deepsea shrimps (Heterocarpus ensifer and H. laevigatus), and kona crabs (Ranina ranina) will probably have little effect through the food web on seabirds since these species were not found to be important prey items. Any precious coral fishing would occur below 40 fathoms and

should have no food chain effects on seabirds. Seamount fisheries for armorhead (Pentoceros richardsoni) and alfonsin (Beryx splendens) occur below 100 fathoms and far from seabird colonies; hence, they also should have no direct effects on seabird populations.

At least 14 shark species which could be fished are known to occur in Hawaiian waters (DLNR, 1979). Fishing for these species could enhance the populations of Laysan and black-footed albatrosses, since young birds are taken adjacent to the colonies in June and July by sharks, especially tiger sharks (Galeocerdo cuvieri). Other incidental effects of shark fishing could be an increase in smaller predatory fish species including smaller sharks which may increase competition with birds for forage fishes and may also increase predation on seabirds. Troll fisheries for billfishes, mahimahi (Coryphaena hippurus), and ono (Acanthocybium solandri) could affect seabird species that rely on predatory fishes to drive smaller prey to the surface, but data are very limited on the incidence of bird flocks appearing in association with these fishes. The populations of these fishes appear small relative to those of yellowfin and skipjack tuna; consequently, they probably do not have a major influence on NWHI seabird populations.

Synergistic effects of fishery competition: While the effects of one fishery may be predicted with some certainty, the effects of two or more fisheries pursued simultaneously can have more severe impacts on seabird populations than simply the summation of the expected effects from each individual fishery. This phenomenon has been clearly demonstrated in the Southwest African declines in seabird populations. There, birds adjusted somewhat to the exploitation of one prey species but could not adapt to deteriorations in both horse mackerel and pilchard stocks (Crawford and Shelton, 1978). NWHI seabirds may withstand depletions of a single prey resource because they are able to opportunistically exploit an alternative species, but if simultaneous fisheries are developed leading to the depletion of several important prey resources, population declines will follow. If seabird colonies are reduced below a certain threshold population, the existence of the colony could be threatened. The problem for birds is not only whether there is enough prey near the colony, but also whether it can be located in an energetically economical manner. This notion was well-stated by King (1974) "the ephemeral nature of the food supply suggests that, to a point, more, rather than fewer, birds help to make the food supply more readily available" (p. 66).

Indirect Effects

Potential landings, groundings, human activities and commercial development on the islands, and environmental pollution from chemicals accumulated in the marine ecosystem threaten NWHI seabird populations. The potential indirect effects on seabirds resulting from these threats include: (1) the introduction

and/or spread of exotic predators, insects, and vegetation; (2) habitat alteration; (3) disturbance; and (4) environmental contamination by oil, heavy metals, and organochlorine compounds. Indirect impacts have the potential for catastrophic effects on seabird populations in the NWHI. In the recent past, human activities in the NWHI have affected seabird populations and productivity. Each effect must be seriously considered in an evaluation of fishery proposals.

Proposed commercial fishing in the vicinity of the NWHI will result in an increased likelihood of adverse human-related impacts on seabird colonies. The historical record is replete with documentation of numerous vessel groundings in the NWHI. Four fishing vessels that regularly fish in the NWHI grounded in Hawaiian waters (two in the NWHI) during the 5-year tripartite-Sea Grant study period. In addition, a large freighter went aground on French Frigate Shoals. No serious impacts were recorded as a result of these incidents. However, they illustrate that even experienced boat operators familiar with the area and possessing the required equipment may be involved in groundings. The probability of such accidents occurring increases with additional vessel use of the area, particularly if operators are not familiar with NWHI waters. Disturbances may result from accidental landings on uninhabited islands. Disturbance and habitat destruction may occur as a result of proposed fishery support station developments on certain islands. Fishery operations will increase the amount of refuse introduced into the marine environment. Ships introduce surface pollutants including tar and plastic (Wong et al., 1974) which contain organochlorines and heavy metals. The development of fishery support stations could result in localized point source discharges laden with organic matter. Potential indirect effects on seabirds resulting from the proposed commercial fishery are reviewed below.

INTRODUCTION OF PREDATORS

One of the most important potential threats to breeding colonies of seabirds in the NWHI is the introduction of predators. Polynesian rats (Rattus exulans), roof rats (R. rattus), and Norway rats (R. norvegicus) are predators that have been introduced by man on certain islands. Since rats occur on some fishing vessels, the potential for their introduction exists. Polynesian rats and seabirds have been associated with Kure Atoll for over 100 years. The breeding success of several seabird species has undoubtedly been reduced in certain years. Ten species of seabirds have been recorded as victims of rat predation on Kure Atoll (Table 10). Rats probably caused complete breeding failure in Bonin petrels on Kure Atoll from 1964 to 1968 (Woodward, 1972).

Not all species are equally susceptible to predation by Polynesian rats. Adult red-footed boobies and sooty terns either are aggresive towards intruders or fly away quickly when disturbed and thus are predation-free in the adult stage. Masked

boobies, whose adults defend their young, are free from nestling predators. Since Polynesian rats cannot break through shells of albatross and booby eggs, these are not eaten.

TABLE 10. AVIAN SPECIES PREYED UPON BY POLYNESIAN RATS ON GREEN ISLAND, KURE ATOLL, 1963-69

Species	Stage Preyed Upon		
	Eggs	Young	Adults
Black-footed albatross		x	
Laysan albatross		x	x
Bonin petrel	x	x	
Wedge-tailed shearwater	x	?	
Red-tailed tropicbird	x	x	
Great frigatebird			x
Sooty tern	x	x	
Gray-backed tern	x	x	
Brown noddy	x	x	
White tern		?	

Source: Woodward, 1972

The introduction of roof rats on Midway Islands occurred in 1943 as a consequence of military development. Norway rats currently occur on Midway Islands, the only islands in this area with populations of these rats. Burrowing seabirds have suffered most directly, but no species has escaped the impact of predation. Further, the presence of black rats has apparently affected the distribution of nesting birds on Sand Island, Midway. Brown noddies on Midway Islands nest as high as 10 m in ironwood trees, whereas on other NWHI this species nests on the ground. Rats depressed the populations of Bonin petrels, Bulwer's petrels, black noddies, and white terns shortly after they were introduced. They have apparently extirpated the population of Bulwer's petrels.

The most detailed information of rat predation on Midway Islands concerns the Bonin petrel which was considered to be the most abundant nesting species there in the late 1930s (Hadden, 1941). A significant decline in the numbers of this species on Sand Island, and the total decimation of this species on Eastern Island between the mid-1960s and February 1979, has occurred due to the effects of rat predation. Intense predation of the eggs of Bonin petrels on Sand Island has been noted (Grant et al., 1981). Rats also consume chicks. Additionally, they compete with birds for nesting burrows, taking them over and converting them to rat burrows by modifying the entry-ways.

Red-footed boobies, red-tailed tropicbirds, and albatross have also been preyed upon by rats on Eastern Island, Midway (Ludwig et al., 1979). An abandoned black-footed albatross egg was consumed by a rat on Sand Island (Grant et al., 1981). Shrub-nesting species, such as the red-footed booby, great frigatebird, and red-tailed tropicbird, have also been indirectly affected by the loss of natural nesting habitats. Black rats feed on native beach naupaka (Scaevola taccada), resulting in less habitat availability for shrub-nesting species.

The probability of rats and feral pets being introduced to the NWHI will increase if the proposed expansion of commercial fishery activities in this area takes place. The increased probability of shipwrecks or landings occurring on the remote islands, resulting in the introduction of stowaway predators, is an important consequence associated with the proposed fishery.

INTRODUCTION OF EXOTIC INSECTS

Insect introduction in the NWHI is likely to occur simultaneously with landings and human activities. Mosquitoes are a significant management concern on Midway Islands, since their introduction has resulted in problems associated with avian diseases. The mosquito (Culex quinquifasciatus), an exotic species on Sand Island, has been implicated in the transmission of avian pox, a viral disease causing extensive facial lesions and, in some cases, death in young albatrosses and red-tailed tropicbirds. Exotic birds including the canary (Serinus canaria), common myna (Acridotheres tristis), and rock dove (Columba livia) may be carriers of avian pox virus on Sand Island. Outbreaks of avian pox occur on Midway Islands every year in varying numbers of birds. The large number of birds present in the NWHI, and the potential for spread of avian disease to other islands by migratory birds, dictates that diseases be prevented or controlled.

Exotic insects may also indirectly affect several species of seabirds by influencing the availability of their nesting habitat. Naupaka on Lisianski Island is infested with scales (Saissetia nigra and Hemiberlisia lataniae) (Beardsley, personal communication). Such scale-weakened plants would have a poorer survival rate than normal during stress periods such as winter storms or summer drought. Naupaka dieback has occurred on Laysan Island. The dieback on Laysan Island could lead to movement of sand which would affect the habitat of burrowing, ground-nesting, and shrub-nesting seabirds, endangered land birds, and the endangered Laysan duck.

INTRODUCTION OF EXOTIC VEGETATION

Considerable changes in the composition of vegetation have occurred in the NWHI since humans began to visit the area in the late nineteenth century. Changes in the composition of vegetation on an island may have drastic effects on the breeding

seabird population. The largest change occurred when rabbits overgrazed vegetation on Laysan and Lisianski Islands, resulting in the near denudation of these islands. Less drastic, although significant, changes have been attributed to the introduction of exotic plants. A review was made of the status of plant species on each of the islands. Approximately 113 species are noncultivated exotic, i.e., plants of accidental or deliberate introduction that have become naturalized on the islands (some of which may have since died out). Certain exotic plant species compete with endemic island vegetation and may result in the extinction of endemic plant species. Further, the introduction of certain exotic plant species may result in the loss of habitat used by breeding seabirds, although direct evidence of this type of competition is lacking.

Not surprisingly, islands with the most human contact have the largest numbers of exotic plant species (99 for Midway Islands, 38 for Kure Atoll, and 28 for French Frigate Shoals). Among the exotic species with documented effects on seabird nesting are the ironwood (Casuarina litorea), golden crown-beard (Verbesina enceloides), a composite plant (Bidens alba), and wild mustard (Brassica campestris). Ironwood trees were introduced and are still present on French Frigate Shoals, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, Midway Islands, and Kure Atoll. On Midway Islands and French Frigate Shoals, wild plants have seeded from the introduced planted specimens. The ecology of ironwoods has been investigated on Midway Islands where the trees have spread widely on both major islands of the atoll since their introduction. Some ironwoods now exceed 25 m in height. They form thick canopies and drop considerable litter which reduces or eliminates other species of plants in the understory. The loss of beach-binding plants, such as naupaka and tree heliotrope (Tournefortia argentea), can lead to severe beach erosion problems. Ironwood trees are wind-disseminated and are able to colonize on virtually any habitat.

Golden crown-beard was accidentally introduced on Midway Islands from where it spread to Kure Atoll. This plant is a hardy, tall (up to 2 m) annual that poses a threat to the nesting seabirds of the central plain at Kure Atoll, especially the masked booby and Laysan albatross. Since its introduction it has spread over thousands of square meters of the plain, growing so thickly that native vegetation is completely crowded out. Birds nesting in the open will not be able to breed if this species continues to take over suitable nesting habitats. Bidens alba, a composite plant with white flowers, was introduced on Midway Islands where it currently occurs in tall, dense stands in disturbed areas of Sand Island. This plant is a preferred habitat for mosquitoes and flies. Laysan albatross which nest in areas with dense stands of this species have a high rate of infection of avian pox virus. Mosquitoes and flies which inhabit these areas serve as vectors of the pox virus.

The wild mustard has become a problem on Pearl and Hermes Atoll where it was accidentally introduced. Wirtz in 1965 noted that this species was expanding its coverage on Southeast Island (Amerson et al., 1974). This species may continue to encroach native habitats, replacing native vegetation and destroying seabird nesting habitats.

HABITAT ALTERATION

Alterations of the island habitats are not expected to be a significant consequence of commercial fishery activities. Habitat alterations have occurred in the recent past and have affected and continue to affect seabird populations. Significant areas of Midway Islands, Kure Atoll, and French Frigate Shoals have been altered by construction activities. The enlargement of Tern Island at French Frigate Shoals and Sand Island at Midway has created nesting habitats for certain species of seabirds. On the other hand, construction of roads, housing, and runway areas on islands has removed seabird nesting habitats. Additionally, antennas, towers, buildings, and aircraft interfere with seabirds on the breeding colonies. On Eastern Island at Midway, Fisher (1966) reported that about 3,000 Laysan albatross were killed in collisions with antenna wires during a 6-month period. These wires have been partially removed. Sooty terns, red-tailed tropicbirds, and albatross also collide with antenna wires during the breeding season on Midway Islands and Kure Atoll. Several thousand sooty terns died after colliding with antenna wires on Eastern Island (Fisher, 1966). Lights near towers and buildings may attract nocturnal shearwaters and petrels resulting in night blindness and collisions. On Sand Island, bright lights associated with the aircraft hangar disorient Bonin petrels and Laysan albatross. Several individuals of these species are found dead and/or stunned and injured each morning below these lights during the breeding season. The presence of active aircraft in the NWHI inevitably results in seabird collisions. Bird-aircraft collisions are not anticipated to have major impacts on the seabird populations. However, bird control programs are necessary when hazards of aircraft collisions exist. In extreme situations, the attempt at controlling the numbers of birds involved in collisions may result in loss of habitat and/or reduced populations. During control programs on Sand Island between 1954 and 1964, several thousand Laysan albatross were killed and significant portions of nesting habitats were destroyed around the runway. The U.S. Coast Guard crushed sooty tern eggs on Tern Island as recently as 1977 in an attempt to drive them away from the runway.

HUMAN DISTURBANCE

Disturbance of seabird nesting colonies during the breeding season could have significant effects on the productivity of the colony. Seabirds are extremely vulnerable to human disturbance. Surface and shrub-nesting species are especially susceptible to visits by humans. Eggs and nestlings become exposed to the sun

or predators when the adult birds are flushed from the nest. Human disturbance of burrow-nesting species such as petrels and shearwaters is usually less widespread, but burrows crushed underfoot trap and kill the inhabitants. In the NWHI, the sandy, dry soil of the nesting colonies makes burrows extremely fragile. Thus, human intrusion in shearwater and petrel colonies, especially the dense colonies of Laysan and Lisianski Islands, could cause widespread destruction of nesting burrows and have serious impacts on the population of the seabird species.

OIL POLLUTION

In the NWHI, oil may enter coastal waters as a result of spillage during transfer operations, shipwrecks, or bilge discharge. Discharges from inhabited areas (e.g., street runoff, sewage discharge) on Midway Islands also contribute to localized oil pollution. In 1977, the Irenes Challenge broke apart 50 miles north of Lisianski Island and spilled over 5 million gallons of crude oil. It was a matter of chance that this oil did not come ashore. The history of shipwrecks that mark the beaches and reefs of the NWHI, including a Japanese fishing boat aground on Laysan Island in 1969, and the recent groundings of fishing boats and a merchant vessel at French Frigate Shoals in 1980 and 1981, indicates that the threat of an accidental spill is genuine.

Although large spills have not been documented to affect refuge resources, oil, in the form of tar balls, is frequently found on beaches throughout the archipelago. Wong et al. (1974) studied the quantitative tar distribution in the Pacific Ocean from Tokyo proceeding along latitude 35°N to California. They found tar present as black or brownish lumps up to 3 cm in diameter. Its concentration was higher in the western Pacific, including the waters north of the Hawaiian islands. Concentrations of tar were the same order of magnitude as the weight of organisms. Incorporation of small lumps of tar into the food chain from surface-feeding fish may be a hazard (Conover, 1971). The persistent tar distribution may result from marine oil transport, augmented by accidental spills, prevailing wind transport, and surface circulation.

Whatever the actual source, repeated sightings of seabirds covered with oil make it clear that oil is present near the NWHI. Among the species of seabirds observed covered with oil during recent field studies in the NWHI were sooty terns, white terns, black noddies, masked boobies, red-footed boobies, and Laysan albatross. An increase in fishing vessels would likely result in increased groundings and spills. Likewise, the use of an island as a fuel storage area with increased fuel transfer operations in the nearshore waters would create an increased potential for spillage and bilge discharge in the area. The potential for a catastrophic spill was recently reduced as a result of a rule adopted by the Maritime Safety Committee of the Inter-Governmental Maritime Consultative Organization specifying that

areas in the region of the NWHI be avoided by commercial ships carrying cargoes of oil or hazardous chemicals. The "Area to be Avoided" is described as a radius of 50 nautical miles around the individual islands of the Hawaiian Islands National Wildlife Refuge (HINWR). This routing measure, which became effective on May 1, 1981, should minimize the likelihood of catastrophic spills. Unfortunately, this is only an advisory and carries no sanctions.

Detailed information on the effects of oiling on marine birds in the NWHI is very limited. Problems must be judged from observations in other geographic areas. Several excellent reviews of the effects of oil on waterbirds have been published (Ohlendorf et al., 1978; Farrington, 1977; Albers, 1977, 1978; Clapp et al., 1982). The most serious effect of oil spills on seabirds is feather oiling. In general, seabirds that spend much of their time on the water (e.g., albatross) are more susceptible to feather oiling than species that feed on the wing (e.g., shearwaters, petrels, terns, and, to a lesser extent, boobies). However, in the tropical and subtropical ocean environment, oil slicks may indirectly attract birds. Oil on the water's surface attracts fish to the water column below. Feeding seabirds are attracted to the aggregating fish and may come in contact with the oil while feeding. Oil disrupts the structure of feathers, destroying their insulating properties and buoyancy. Moderately or heavily oiled birds drown or die of exposure. Birds oiled in warm weather and warm waters (conditions found in the NWHI) would be expected to have a much higher survival rate than those oiled in a colder area, although this has not been demonstrated quantitatively. Further, warm water apparently causes the spilled liquid oil to form tar balls that may be less hazardous to birds (Bourne and Bibby, 1975).

Many oil or petroleum products are toxic to birds. Birds ingest oil while preening oil-coated feathers, drinking, or eating oil-covered food. They may also ingest petroleum products contained in tissues of fish or marine invertebrates. As a result of oil ingestion, seabirds my die or suffer physiological or behavioral changes, including reproductive failure (Crocker et al., 1974; Grau et al., 1977; Miller et al., 1977; Szaro et al., 1978b; Wooten et al., 1979).

Breeding populations are particularly susceptible to oil. The loss of one member of a pair may mean complete loss of their reproductive potential for that year. Depending on the number of offspring usually produced, this could mean that every breeding bird killed by oil represents a theoretical loss to the population of two birds. Although this loss may be recouped in the future, marine birds have a relatively low productivity rate and their populations may take many years to recover from one severe oiling incident (Clapp et al., 1982). Oil in the vicinity of breeding colonies may also diminish reproductive success in other ways, such as nesting birds transferring oil from their feathers or feet to eggs while incubating. Small amounts of oil (equal to

a few drops) can kill embryos inside the eggs (Albers, 1977; Szaro and Albers, 1977; Albers and Szaro, 1978; Szaro et al., 1978a; and others). Oiling of gull eggs has also resulted in deformed chicks (Stickel and Dieter, 1979). Bird embryos are most sensitive during the first 10 days of incubation. Chicks may also be more susceptible to oil ingestion than adults. Following the large 1974 oil spill in the Strait of Magellan, a high percentage of South American tern chicks on an island nearby died (Smithsonian Institution, 1974). In addition, reproductive success in a colony may be diminished by disturbance to the colony resulting from attempts to control oil pollution (Bourne, 1976). Oil pollution also damages the marine environment where birds feed and roost. Seabirds often abandon areas after an oil spill because habitat quality is poor and prey populations are reduced (Buck and Harrison, 1967; Abraham, 1975; Hope-Jones et al., 1978).

CHLORINATED HYDROCARBONS AND HEAVY METALS

At present, levels of chlorinated hydrocarbons and heavy metals are not threats to seabird populations in the NWHI. Seabirds are top-level carnivores and consequently accumulate concentrations of organochlorines far in excess of levels in the ocean. Because controlled dumping of refuse and bilge water by fishing vessels in the NWHl may slightly increase the levels of organochlorines and heavy metals in seabirds, the area should be monitored.

Prior to this study, there had been little work conducted on levels of pollutants in NWHI seabirds. Fisher (1973) found that the visceral fat from Laysan and black-footed albatrosses from Midway Islands contained mean DDE (a derivative of DDT) levels of 8 and 22 ppm, and mean PCB (polychlorinated biphenyls) levels of 2 and 14 ppm. Comparing these data with those reported for cormorants on a worldwide basis (Ohlendorf et al., 1978), the DDE levels are not near the levels reported for areas exposed to industrial pollution. For example, double-crested cormorants were found to have egg lipid levels of 87 ppm PCB and 754 ppm DDE (Gress et al., 1973). Fisher (1973) also reported that visceral fat from black-footed albatross and Laysan albatross on Midway Islands ranged from 0.075 ppm and 0.104 ppm mercury respectively. However, it has been acknowledged that visceral fat was not the best material for mercury analysis.

In order to provide baseline levels of chlorinated hydrocarbons and heavy metals for future comparisons, in 1980 eggs of wedge-tailed shearwaters, red-footed boobies, and sooty terns were collected from Oahu, French Frigate Shoals, Laysan Island, and Midway Islands. Mercury was found in all eggs, sometimes at moderately high levels. The highest mean concentration (0.36 ppm, wet weight) was in booby eggs from Midway Islands. In booby eggs there was a distinct trend toward higher concentrations from east to west. There were no apparent differences among sites for the shearwater and tern eggs, except for somewhat higher mercury

concentrations in shearwater eggs from Oahu. Selenium also occurred in all eggs; mean concentrations in shearwaters and terns at each location were slightly above 1 ppm (1.09 to 1.38 ppm) and in boobies they were slightly lower (0.76 to 0.92 ppm). Cadmium was not found above the limit of detection (0.1 ppm). DDE was found at low levels in all eggs of all species, and other organochlorines occurred in some. Shearwater eggs contained the highest concentrations of DDE (up to 1.5 ppm) and the broadest array of organochlorines. In general, the seabird samples further document the widespread occurrence of mercury and organochlorines in the marine environment. Further results of this study are forthcoming in a publication by H.M. Ohlendorf. In May 1979, FWS personnel collected 467 feather samples from 17 seabird species throughout the Hawaiian Archipelago which were analyzed for Al, Ba, Cd, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, Pb, Sr, and Zn. These baseline data do not indicate hazardous levels (FWS, unpublished data).

Synergistic Effects of Fishery-Related Activities

While natural fluctuations in populations and productivity occur, it is generally true that seabird populations in their natural habitat rebound and vary around the habitat's carrying capacity. Certain short-term natural variations in oceanic habitat conditions may result in changes in the availability of prey and thus temporary decreases in seabird populations and productivity. If availability of prey items is reduced due to natural conditions and commercial fishery competition, and if indirect effects of pollutants, exotic pests, and/or diseases are manifested, severe long-term declines in seabird populations could result. These declines may not occur given any one of the factors mentioned independently, but may occur due to the synergistic effects of combinations of these factors. Further, because of the inherent low reproductive potential of seabirds, population recovery requires several years under natural conditions. Given further constraints on the habitat's carrying capacity due to the effects of human activities, recovery would be further delayed, if it occurs at all. Therefore, careful monitoring of seabird population/productivity trends is necessary to inform resource managers about the status or health of the population in order to effect management programs to mitigate natural or human-induced effects on seabird populations.

MONITORING SEABIRD POPULATIONS

Anticipated increases in human activities in the vicinity of NWHI seabird colonies resulted in the need for methods to assess seabird population trends and to determine causative factors for the observed trends. From 1979 to 1983, a major thrust of the FWS seabird research effort involved collecting data on the food habits, pollutant levels, and aspects of the breeding biology of NWHI seabirds, which might prove useful to detect trends in seabird populations. Population magnitude, reproductive success, chick growth rate, egg size, and adult weight measurements may be

useful as monitoring techniques. Baseline data on these parameters serve to document the natural variability in seabird populations. Changes due to food shortages or other factors may be detected when comparing baseline data with data to be collected in future years. Early detection of potential problems could avert significant seabird population declines. Brief descriptions of the various parameters investigated as possible monitoring indices are included below. A report on the results of the monitoring studies is being prepared by the Honolulu office of the U.S. Fish and Wildlife Service.

1. Breeding population estimate. The number of birds nesting each year is a good indicator of population stability if examined over many years. However, interpretation of such numbers is complicated by the effects of phenology and reproductive success. Furthermore, radical fluctuations in consecutive years are common. These factors reduce the suitability of using breeding population estimates as monitoring indicators, especially for detecting population changes over a short period of time.

2. Phenology. Knowledge of the timing of a species' breeding cycle is required to interpret all other breeding biology measures and to plan research trips for maximum effectiveness. The onset, synchrony, and rate of progress of seabird breeding cycles can be influenced by many environmental factors.

3. Reproductive success. Reproductive success is an important indicator of annual colony productivity (number of fledglings produced) and ultimately of population stability. In conjunction with good breeding population estimates, success rates are the most meaningful measure of a colony's condition.

4. Adult weight. The relationship between body weight and food availability is intuitive. Baseline studies documented "normal" adult weights and variability. Studies explored seasonal trends and/or effects of breeding status on adult weights.

5. Chick growth rate. Chick growth rates depend on the quantity and quality of food and attention provided by adults. Parental behavior, in turn, is influenced greatly by food availability and forage conditions. Chick growth rates correlate strongly with fledging success. Growth rate data have been analyzed for a number of species. Short-visit and long visit monitoring methods are being examined.

6. Egg size. Egg size can be estimated from measurements easily taken in the field. Larger egg volumes correlate with greater reproductive success in some seabird

species. In addition, egg volumes may reflect food availability for female birds prior to egg laying. Our data document egg volumes for most species throughout the NWHI and examine correlations with hatching success whenever possible.

7. Diet. Seabirds appear to feed opportunistically. Thus, consistent changes in their diet are probably due to changes in the composition or abundance of available fish stocks.

8. Toxic chemicals. The effect of chlorinated hydrocarbons and heavy metals on the health and reproductive success of some seabirds is well documented. Our data establish baseline levels for NWHI seabirds which can be used for future comparisons.

An ideal monitoring system should include a combination of short-term and long-term indicators selected for responsiveness to the anticipated impacts on the ecosystem and animals being studied. While it is sometimes possible to determine the most probable cause of change in a species behavior, most indices do not reflect "threat-specific" factors, but rather an integrated picture of success of a species in its environment. Thus, monitoring programs serve best to warn managers of unspecified changes in the environment that might require additional study or management changes. Steps can then be taken to protect the seabirds while the cause(s) of the warning signal is explored. In the NWHI, such a system could benefit both seabirds and fishermen, since both depend on a healthy ocean environment for their livelihood.

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THE UNIQUE TERRESTRIAL BIOTA OF THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

The endemic terrestrial biota of the Northwestern Hawaiian Islands (NWHI) contains at least 8 land snails, 12 plants, 4 land birds, and an incompletely known arthropod fauna in excess of 50 species. The distributions of all of these organisms are restricted to the NWHI. Nihoa, followed by Laysan and Necker Islands, support the most diverse native biotas. The NWHI land biotas are unique because in total they represent the only Hawaiian high island remnant and atoll biotas and because certain of their components have been largely extirpated from the main Hawaiian islands. An unknown number of plants and invertebrates and three land birds became extinct in the early 1900s due to the effects of human disturbance to some islands. Undoubtedly, the most serious threat to the land biotas of all of the islands is the accidental introduction of exotic species. Predators such as rats and carnivorous ants can destroy populations of endangered birds and native invertebrates, and exotic weeds can seriously alter the habitats of these animals while displacing rare native plants. Although the terrestrial ecosystems of the NWHI are not pristine, their biotas are among the least modified in Hawaii and populations of endangered and other vulnerable species appear vigorous, "endangered" status being the result of limited distributions, small populations, and vulnerability to ecological perturbations. Effective protection, monitoring, and enforcement measures can help ensure that these ecosystems remain largely

undisturbed. A wisely managed commercial fishing industry need not negatively impact the terrestrial ecosystems of the NWHI if authorized and accidental landings are minimized and illegal landings eliminated. At the same time, active protection of these ecosystems is unlikely to have negative impacts on the fishing industry.

arthropods
land snails
plants
land birds
terrestrial
endangered

INTRODUCTION

The terrestrial biota of the Northwestern Hawaiian Islands is comprised of a complex and poorly known assemblage of plants, molluscs, arthropods, and birds. Although there are substantial numbers of exotic species in the NWHI, particularly on Midway Islands and Kure Atoll, most islands support a number of endemic and indigenous species, especially those of plants and arthropods. This paper presents an overview of the biogeographic status, distribution, and present state of knowledge for plants, land snails, arthropods, and land birds of the NWHI.

Four biogeographic terms should be clearly defined at the outset. A "native" species is one whose occurrence on a particular island is not due to deliberate or accidental human influence. An "endemic" species, as used in this paper, is a native species whose distribution is limited to the NWHI, although it may occur on more than one island. An "indigenous" species is a native species that occurs in the NWHI and elsewhere in Hawaii and/or the world. Finally, an "exotic" species is one that has been deliberately or accidentally introduced to the NWHI by human actions.

Studies of the terrestrial biota of the NWHI outlined in the tripartite agreement focused almost entirely on seabirds, undoubtedly because of their obvious and important relationship to the fisheries. With the exception of some routine monitoring efforts, a study of seabird energetics, and a study of the Laysan duck that was logistically facilitated by seabird studies, there were originally no specific surveys or ecological studies planned for land-based flora and fauna. However, when we initiated research on terrestrial organisms in 1980, participating agencies immediately responded with funding and logistic support. Nevertheless, it can be said that the terrestrial biota of the NWHI, particularly the arthropods, is still poorly known. For this reason, we have assembled the material presented here to emphasize the necessity for including consideration of essential protective measures for entire terrestrial ecosystems as a priority item in any plans for expansion of commercial fisheries in the NWHI.

It should also be mentioned that Nihoa and Necker Islands harbor significant cultural, archaeological, and anthropological resources in their terrestrial environments (Emory, 1928).

METHODS

The data presented here have been gleaned both from the literature and from unpublished data and collections made on various expeditions to the NWHI. Recent (March through May 1983) collections of arthropods, algae, and lichens from Midway and Nihoa have resulted in large numbers of new island records, including those of species new to science and many species whose identifications will require careful study by a number of experts and, hence, cannot be reported in this paper. It is clear that additional surveys will be required to complete basic faunal and floral lists for each island. Virtually nothing is known of the ecology of terrestrial invertebrates in the NWHI, and ecological studies of plants and land birds have only recently begun.

RESULTS AND DISCUSSION

Here the composition of several components of the NWHI terrestrial biota is reviewed: plants, molluscs, arthropods, and land birds. Following the summary for each element of the biota, a brief discussion of the significance of that element as a unique natural resource of the NWHI is given.

Plants

In 1981, D. Herbst compiled a list of all vascular plant species that have been reported from the NWHI. Magnusson (1942) listed the lichens from Necker and Nihoa, and recent collections from Nihoa are expected to add some algal and lichen species to this list. Herbst's list includes a total of 312 plant species from the NWHI of which 151 are exotic cultivars and ornamentals that have apparently not established naturally sustaining populations. Of the remaining, self-sustaining plants, 112 species are exotic, 37 indigenous, and 12 endemic (Table 1). Among the endemics, some species are limited in distribution to a single island. For example, all four endemic plants on Nihoa are restricted to that island, although the Nihoa lo'ulu (Pritchardia remota) may once have occurred on Laysan.

TABLE 1. ENDEMIC, INDIGENOUS, AND EXOTIC PLANTS ESTABLISHED IN THE NORTHWESTERN HAWAIIAN ISLANDS

Island Group	Endemic Species	Indigenous Species	Total Native Species	Exotic Species
Nihoa	4	17	21	5
Necker Island	--	5	5	--
French Frigate Shoals	1	11	13	28
Gardner Pinnacles	--	1	1	--
Laysan Island	6	23	29	11
Lisianski Island	1	13	14	3
Pearl and Hermes Atoll	3	12	15	8
Midway Islands	4	21	25	99
Kure Atoll	6	14	20	38
TOTAL	12	37	49	112

Note: List compiled by Derral Herbst, July 1981. It does not include non-naturalized ornamentals and garden cultivars. In calculating the totals each species was counted only once even though many species occur on more than one island.

A number of the exotic plants found in the NWHI pose serious problems as aggressive weeds. For example, Portulaca oleracea, which is thought to have been introduced to Nihoa during military operations in 1961 (Herbst in Clapp et al., 1977), has become considerably more abundant than the indigenous Portulaca lutea in recent years. Six of Nihoa's seven land snails are endemic to the island and all seven are virtually restricted to Eragrostis variabilis clumps. Accidental introduction of any weed, disease, or other perturbation that would decrease Eragrostis abundance would seriously affect native snail populations. Clearly, prevention of new plant introductions to any of the islands should be a high management priority, and control or elimination of currently existing weeds may be warranted. Accumulation of weeds locally on Midway Islands may facilitate breeding of mosquitos that are vectors of avian pox. Weed control coupled with elimination of standing water may be of great help in controlling the serious outbreak of pox now occurring on Midway.

The flora of the NWHI contains important endemic and indigenous elements. Some species are important because of their uniqueness. For example, Amaranthus brownii is the only Hawaiian endemic in this large genus which contains many economically and nutritionally important species. Several of the indigenous species found in relatively large numbers in the NWHI (e.g.,

Sesbania tomentosa and Solanum nelsoni) have very restricted distributions in the main Hawaiian islands and are candidate endangered species (Fosberg and Herbst, 1975). Both the endemic and indigenous plants can be found in associations now rare in the main islands (e.g., coastal strand vegetation) and are certainly important as host plants for the NWHI's numerous native invertebrates.

Terrestrial Molluscs

The land snail fauna of the NWHI is not large in numbers of species, but it is of scientific interest and is certainly unique. Table 2 lists the taxa that have been reported from the various islands. The first observations of terrestrial molluscs in the NWHI were by W.A. Bryan, who in 1911 collected Lamellidea gracilis and the species later named Tornatellides bryani on Laysan (Pilsbry and Cooke, 1914-16). In 1923, C.M. Cooke, Jr. and other Bishop Museum staff members with the Tanager Expedition made major collections of land molluscs throughout the NWHI; the 25,000+ specimens obtained are the principal basis for current knowledge of the fauna of these islands. Nihoa was found to have a diverse fauna of seven species, six of them (1 Endodonta, 1 Cookeconcha, 3 Tornatellides, and the monotypic genus Philopoa) endemic to the island. More than 96 percent of the specimens collected were obtained from Eragrostis clumps, indicating the importance of this native bunch grass in the ecology of these snails. The single species found on Necker was found to represent a monotypic subgenus of Tornatellides (Aedituans) restricted to that island. Species of Tornatellides, Tornatellinops, and Lamellidea were found to inhabit Kure, Midway, Pearl and Hermes Atoll, and Lisianski. Despite careful search, no land molluscs were found on Laysan, Gardner Pinnacles, or French Frigate Shoals. Cooke attributed the absence of land snails on Laysan, where two species had been reported a decade earlier, to destruction of the island's vegetation by rabbits. Much of the Tanager Expedition material remains undescribed, although Philopoa singularis and Tornatellides (Aedituans) neckeri were described in a 1960 monograph of the family Achatinellidae by Cooke and Kondo; these authors also provided a brief summary of the land snail fauna of Nihoa and listed records of Lamellidea gracilis for Ocean (Kure), Lisianski, and Nihoa. In 1959 and 1961, G.D. Butler, Jr. made small collections on Kure and Laysan incidental to studies of terrestrial arthropods; his material added a second species of Tornatellides to the Kure list and provided the first NWHI report for Succinea, from Laysan. In 1980, D. Herbst and W. Takeuchi of the U.S. Fish and Wildlife Service obtained samples of leaf litter from Pearl and Hermes Atoll, Lisianski, Laysan, and Nihoa; minute snails recovered from this material were proof of the continued existence of previously collected species on Pearl and Hermes Atoll and Lisianski, as well as one of the endemic Tornatellides of Nihoa. This material also demonstrated the recovery of the Laysan fauna after its devastation 60 years earlier. On Pearl and Hermes Atoll and Laysan they found populations of Gastrocopta servilis, the first

TABLE 2. TERRESTRIAL MOLLUSCS OF THE NORTHWESTERN HAWAIIAN ISLANDS

Genus/Status	Species Numbers								
	Kure Atoll	Midway Islands	Pearl and Hermes Atoll	Lisianski Island	Laysan Island	Gardner Pinnacles	French Frigate Shoals	Necker Island	Nihoa
Endemic/Indigenous									
Lamellidea	1	—	1	1	1	—	—	—	1
Tornatellinops	1	—	—	1	—	—	—	—	—
Tornatellides	2	1	2	2	2	—	—	1	3
Philopoa	—	—	—	—	—	—	—	—	1
Succinea	—	—	—	—	1	—	—	—	—
Cookeconcha	—	—	—	—	—	—	—	—	1
Endodonta	—	—	—	—	—	—	—	—	1
Exotic									
Laevicaulis	—	1	—	—	—	—	—	—	—
Gastrocopta	—	1	1	—	1	—	—	—	—
Hawaiia	—	1	—	—	—	—	—	—	—
Subulina	—	1	—	—	—	—	—	—	—
Bradybaena	—	1	—	—	—	—	—	—	—
TOTAL	4	6	4	4	5	0	0	1	7

Note: Data based on collections by W.A. Bryan in 1911, the Tanager Expedition in 1923, G.D. Butler, Jr. in 1959 and 1961, D. Herbst and W. Takeuchi in 1980, C. Christensen in 1980, S. Conant and W.C. Gagné in 1983.

exotic land mollusc recorded from the NWHI. Also, in 1980 C. Christensen visited Nihoa with the aim of ascertaining the status of endemic species not observed since the 1923 Tanager Expedition. Despite a limited time on the island, he was successful in demonstrating the survival of six of the seven species previously encountered (the seventh, an undescribed Tornatellides, was found to be rare and localized in 1923; undoubtedly a more thorough survey would reveal it to be extant). In July 1983 S. Conant and W. Gagné collected five exotic species on Midway (Laevicaulis alte, G. servilis, Hawaiia minuscula, Subulina octona, and Bradybaena similaris) as well as an indigenous Tornatellides.

The NWHI, particularly the island of Nihoa, serve as a unique relictual example of the native land mollusc communities that once occurred throughout the arid lowlands of the main Hawaiian islands (their former presence there is documented by extensive fossil deposits in areas where exotic species are now dominant). For example, some 200 species of the family Endodontidae formerly inhabited the Hawaiian islands. Of these, only a very few living individuals of Cookeconcha have been observed in the main islands in recent years; to our knowledge, no living Endodonta have been found there in some 40 years. Nihoa, with thriving populations of both Cookeconcha and Endodonta, serves as a last refuge for these snails. The Endodontidae are thought by some to be the most primitive of the higher land snails (order Sigmurethra), and as these snails have been extirpated virtually everywhere else in the Pacific, the Nihoa populations provide a unique opportunity for research regarding the biology of these animals. Lowland Achatinellidae in the main islands have also been subject to massive extinctions, and NWHI populations again provide a last haven for relictual populations of endemic species.

Terrestrial Arthropods

The arthropod fauna of the NWHI includes a larger and more ecologically diverse species assemblage than any other terrestrial biota group. As such, its potential as a sensitive monitoring instrument is highly significant, and the potential for studies of arthropods to contribute to our knowledge of evolutionary biology and ecology of island ecosystems is of global significance.

In this paper the terrestrial arthropods are divided into two groups: the acarine or mite fauna and the non-acarine fauna. The class Acari includes mites and ticks. Spiders, myriapods (centipedes and millipedes), crustaceans (amphipods and isopods), and insects are discussed as a group.

Information on the Acari in Hawaii is, at best, fragmentary and in the case of the NWHI, almost completely nonexistent. The most recent attempt at a listing of Hawaiian acarines was made by

Garrett and Haramoto (1967), who listed 210 species in 67 families and 138 genera. When compared with the estimated total of 75,000 species in the 400 families and 5,000 genera of this group (Krantz, 1978), the Hawaiian fauna, at first glance, appears depauperate. By contrast they are represented in the NWHI by only 21 families and 32 species. Of these, 12 families and 22 species are in the order Oribatida, a large group of soil-dwelling mites frequently mistaken for beetles. The suborder Actinidida are represented by four families containing five species, three of which are widely distributed pests of agriculture. The suborder Gamasida list includes only two species, one of which has been identified only to the generic level. The Ixodid ticks are well represented at the family level with both major families, Ixodidae and Argassidae, listed. Ixodidae has only one species, Ixodes laysanensis, recorded from Laysan Island. The Argassidae have one identified species, Ornithodoros capensis, with the remaining argassids relegated to the taxonomically confused "Ornithodoros capensis group." No species in the minor suborders, Opilioacarida and Holothyrida, are listed for the islands. Neither are species recorded for the major suborder, Acaridida.

Distribution records for Acari in the NWHI reflect collecting efforts rather than actual distributions and are closely associated with human activities. For example, Laysan has 18 species recorded, Midway 9 species, and Kure 8 species (Garrett and Haramoto, 1967). The other islands are less well represented, with two species each reported from French Frigate Shoals. Nihoa, Necker, Pearl and Hermes Atoll, and Lisianski each have a single species recorded. These records by no means accurately reflect the acarine fauna of these islands. More recent collections have greatly increased knowledge of these islands and their acarine fauna, but the picture is still far from complete. Goff (1971) recorded three species of trombiculid mites from soil samples and marine birds collected on Laysan and Pearl and Hermes Atoll, and Brennan and Amerson (1971) described Schoengastia pobsa from specimens collected from the endemic Laysan finch (Telespyza cantans). Subsequently Goff (1975) described a species of Neotrombicula from rats on Midway, and recorded the families Laelapidae, Macronyssidae, Listrophoridae, Myobiidae, and Myocoptidae for the first time in the NWHI. Recent collections of soil samples and birds by A. Gettman and S. Conant on Midway and Nihoa, respectively, have provided specimens of four additional species of trombiculids from the NWHI, three of which are new, and the first record of a speleognathine Ereynetidae from an endemic Hawaiian bird, the Nihoa finch, Telespyza ultima. Additional collecting by W. Gagne on Nihoa has produced the first record of the ixodid tick, Ixodes laysanensis, from Nihoa. Although Garrett and Haramoto (1967) do not list any feather mites (Analgoidea) from birds in the NWHI, recent collections of the Nihoa finch and the Nihoa millerbird, Acrocephalus familiaris kingi, have yielded records of seven species in five families of the feather mite complex (unpublished data). Additionally, an unidentified ixodid tick larva was taken from a

specimen of the Nihoa finch. Aside from bird-infesting acarines, Furman and Dailey (1980) described a species of halarachnid mite from the Hawaiian monk seal, Monachus schauinslandi, on Laysan.

As evidenced by the above discussion, the primary emphasis in acarine studies in the NWHI in recent years has been on the parasitic species. There are two basic reasons for this emphasis. The parasitic species are frequently vectors of diseases of potential concern to both veterinary and human medicine. For example, the Trombiculidae are of significance in the transmission of chigger-borne rickettsiosis, or scrub typhus fever, and as causative agents for chigger-caused dermatitis. While none of the vector species for chigger-borne rickettsiosis has been recovered from the NWHI, to date, Goff (1971) reported Leptotrombidium (L.) intermedium, a suspect vector according to Traub and Wissemann (1974), from Pearl and Hermes Atoll. Species of the genera Neoschoengastia, Neotrombicula, and Schoengastia and Eutrombicula are frequently involved in chigger-caused dermatitis and are represented in the NWHI. In addition to the Trombiculidae, Ixodidae and Argassidae are major vectors of a large number of viruses. Recently a new virus, Midway virus, has been characterized from ticks collected on Midway, Kure, and Manana (Takahashi et al., 1982).

The second reason for the apparent emphasis on the parasitic acarines is the ease of collection. Parasitic forms are frequently collected along with birds and mammals as an incidental "bonus." But, collection of free-living Acari requires a distinct effort. Due to size, these acarines are not generally noticed, even by entomologists, and require specialized collecting techniques. Recent collections of soil and litter on Nihoa and Midway revealed a large number of taxa from these islands which had not been previously reported, including new island records for the families Cryptognathidae, Camerobeidae, Tydeidae, Paratydeidae, Sejidae, Uropodidae, Tetranychidae, and Cheyletidae, as well as the superfamily Eupodoidea. Strandtmann and Goff (1978) reviewed the Eupodoidea in the Hawaiian islands and listed 12 species in 3 families, including the descriptions of 4 new species and 2 new genera, none of which were from the NWHI. Zacharda (1980) added several more species from the family Rhagidiidae to the list of Hawaiian fauna, but none to the list for the NWHI. However, examination of the Berlese samples from Nihoa and Midway shows a rich Eupodid fauna that does not appear to be closely related to that of the main islands, which is comprised mainly of boreal forms having essentially holarctic distributions. In addition to these works, there have been some incidental descriptions of new species from the NWHI. For example, Goff (1982) described a new species of cheyletid from Kure Atoll.

The significance of the acarine fauna as a resource is difficult to describe because it is so poorly known. At the very least there is a possibility for a large number of endemic species to be discovered, although the actual status of "endemic" vs

"exotic" may be difficult to determine due to lack of knowledge of acarine fauna on a worldwide basis and human disturbance to ecosystems in the main islands. Due to the limited size of the individual islands involved, the NWHI represents excellent possibilities for distributional and ecological work, as well as the study of host-parasite interactions. Finally, due to the possibility of disease vectors being accidentally introduced, monitoring of parasites is essential from a public health and veterinary health standpoint. The status of knowledge of this faunal element strongly indicates that further research is needed.

Regarding the non-acarine arthropods, available data (Beardsley, 1966; Brindle, 1980; Butler, 1961; Butler and Usinger, 1963a, 1963b; Hardy, 1960-81; Suehiro, 1960; Suman, 1964, 1970; Zimmermann, 1948-78) indicate that at least 451 terrestrial, mostly free-living species occur in the NWHI (Table 3). Of these, 288 have been introduced, 99 are indigenous, and 64 are endemic. Similar to the molluscs, the largest numbers of endemic arthropods occur on the two high islands of Necker and Nihoa and on Laysan atoll. Nihoa, which rises to almost 275 m and which supports a diversity of microhabitats, has more than 50 percent (at least 35) of the known endemic arthropods in the NWHI. Biogeographical similarities between the plants and arthropods emerge when the distribution of exotic species is examined; that is, those islands that have histories of heavy human use, particularly Midway, Laysan, and Kure, have the largest numbers of exotic species.

In reviewing the data presented in Table 3, it is essential to point out that all the arthropods, not just acarines, are still very poorly known. Ten days of collecting effort on Nihoa in April and May of 1983 yielded over 50 new island records of arthropods, including at least 6 new species that are probably endemic to Nihoa only. These results underscore the need for further baseline surveys of terrestrial arthropods, although we do not expect results from the ecologically less diverse islands to be as spectacular as those from Nihoa. Surveys are also needed to document possible recent extinctions or rediscoveries, as well as possible recent introductions, especially if very harmful species are involved.

So far we know of no non-acarine arthropod group having endemic taxa in higher systematic categories, i.e., genus or higher, but this situation is likely to change when specialists examine recently collected samples. Thus, it would appear that most non-acarine arthropods have successfully colonized the NWHI from the main Hawaiian islands, or vice versa. The means and frequency by which they did so are of great scientific interest.

Just as certain biota represented by some of the terrestrial molluscs, plants, and land birds contain species that have been eliminated from the main Hawaiian islands, so also does the arthropod fauna of the NWHI contain an even more remarkably

TABLE 3. APPROXIMATE NUMBERS OF ENDEMIC, INDIGENOUS, AND EXOTIC TERRESTRIAL ARTHROPODS OTHER THAN MITES REPORTED FROM THE NORTHWESTERN HAWAIIAN ISLANDS

Island Group	Species Type				
	Endemic	Indigenous	Total Native	Exotic	Total[1]
Nihoa	35	26	61	59	132
Necker Island	15	12	27	37	71
French Frigate Shoals	3	10	27	39	52
Gardner Pinnacles			(Unknown)		
Laysan Island	17	59	76	96	195
Lisianski Island	4	7	11	24	35
Pearl and Hermes Atoll	4	9	13	34	51
Midway Islands	8	36	44	157	221
Kure Atoll	5	19	24	81	105
TOTAL	64	99	163	288	451

Note: List compiled by W.C. Gagné, S. Conant, and P. Conant. Numerous species are recently recorded or new to science, and many species will probably be discovered if research is continued. Each species was counted only once even though many species occur on more than one island.

[1]Includes some species for which biogeographic status cannot yet be determined.

intact assemblage of species no longer found in the main islands. It is postulated that there is a whole assemblage or ecological "guild" of crickets, earwigs, mites and their dependent predators, such as spiders, among others, which are directly dependent upon large concentrations of breeding seabirds. Only fragments of this postulated guild still survive on the main islands, for most of these species have likely disappeared with the seabird colonies formerly there (S. Olson and H. James, 1982). These NWHI species and their ecologies can also elucidate the biogeographic status and evolutionary biology of invertebrates in the main islands. The opportunities for studies of speciation and survival on high island remnants remain largely untapped.

Arthropod ecology in the NWHI may help provide keys to understanding anthropogenic changes in the main islands, as well as natural changes in geological (long-term) and ecological (short-term) time scales. Each of the islands has a differing

complement of introduced ants, a group considered to have high actual and potential ecological impact. Thus, we have in place an accidental association of different ants and native species with which to compare their impacts.

The entire terrestrial arthropod fauna of the NWHI has the potential to serve as the most sensitive measure of perturbation in the NWHI. There are more species of arthropods in all biogeographic classes (endemic, etc.) than in any other organism group against which to measure changes due to extinction, colonization, species turnover, seasonality and species interactions, and interdependence (e.g., food for insectivorous birds, plant pollinators). Other aspects of this interdependence are discussed below.

Land Birds

In the late 1800s the NWHI had seven endemic land birds, five of which were endemic to Laysan: the Laysan duck (Anas laysanensis), the Laysan rail (Porzana palmeri), the Laysan millerbird (Acrocephalus familiaris familiaris), the Laysan finch (Telespyza cantans), and the Laysan honeycreeper (Himatione sanguinea freethi). The effects of guano mining, and in particular the impacts of devegetation by introduced rabbits, were severe, resulting in the extinction of the rail, the millerbird, and the honeycreeper. We know the special interdependence of the land birds upon certain of the arthropods. When Laysan was devegetated by rabbits, a biological chain reaction ensued. The rabbits destroyed the plants upon which the larvae of miller moths fed. The Laysan millerbird, so named because of its apparent reliance on miller moths for food, followed these insects into extinction (Gagne and Howarth, in press).

Routine monitoring efforts by the U.S. Fish and Wildlife Service indicate that Laysan finch numbers are stable and the population vigorous. However, this species' life history and ecology are virtually unknown, and no studies have been initiated to fill this obvious gap in our knowledge of this endangered bird. In contrast, Laysan duck numbers have been observed to fluctuate markedly, causing concern for this rare species of waterfowl. However, recent studies by D. Moulton and M. Weller (in review) have raised a serious question as to whether many of these fluctuations are real or at least in part an artifact of census techniques used to study this secretive bird. These researchers concluded that intensive management of this species is not called for at this point, but that monitoring is essential to ensure that appropriate action can be taken if the species begins to decline. Part of this monitoring effort will require assessment of brine fly (Neoscatella sexmaculata) populations found in the island's lagoon, because they are known to form an important part of the duck's diet (see abstract by D. Moulton and M. Weller).

Recent studies (Conant et al., 1981) of the Nihoa finch (Telespyza ultima) and the Nihoa millerbird (Acrocephalus familiaris kingi) have resulted in the development and evaluation of suitable census techniques and provide population estimates of about 1,500 for the finch and about 300 for the millerbird. S. Conant is continuing to study the life history and ecology of these species and to date has found that the populations appear vigorous, and are probably saturating available habitat on the island.

It seems reasonable to say that the populations of the four endangered birds in the NWHI appear to be vigorous and relatively stable, their endangered status being primarily a reflection of their extremely limited distributions and their vulnerability to the potential effects of accidentally introduced weeds that could replace plant species essential to suitable habitat, predators that could eliminate their populations, or insects that could be a serious source of competition (e.g., ants predacious on the insects essential to the millerbird diet) or that might cause deleterious habitat changes (e.g., by affecting certain key plant species). Clearly, the major threat to the endangered birds of the NWHI is identical to that of the plants and other animals: the accidental or intentional introduction of exotic species to the island.

Because of their legally recognized endangered status, the land birds of the NWHI are a highly visible, internationally significant resource. Aside from this consideration, the finches are considered by ornithologists to be uniquely important members of the endemic land bird group called Hawaiian honeycreepers (Fringillidae: Drepanidinae). They are scientifically important because they are thought to be more similar to the hypothetical ancestral type that gave rise to the honeycreeper line than any other living species in this group. As such, studies of their behavior and ecology could shed considerable light on the poorly understood evolutionary history of the Drepanidines, whose diversity is recognized as the most spectacular example of adaptive radiation among birds. The finches and the millerbird are the only surviving endemic land birds inhabiting lowland dry ecosystems. As such they are a unique surviving element of the largely extinct Hawaiian avifauna. Studies of Laysan finches have already helped shed some light on the importance of avian diseases for native Hawaiian land birds (van Riper et al., 1982).

MANAGEMENT AND PROTECTION OF TERRESTRIAL ECOSYSTEMS

In this section, we would like to offer recommendations on how the unique terrestrial ecosystems in the NWHI can be better protected and further studied to provide new knowledge of both scientific and management significance. We propose what we believe to be essential and desirable protection measures, monitoring efforts, and the significance of these ecosystems for enhancing scientific management and cultural information bases.

Three measures are regarded as essential to help provide basic protection for land-based ecosystems in the NWHI:

1. Authorized and accidental landings must be minimized and illegal landings eliminated via careful planning and a more comprehensive enforcement and contingency response system than exists at present.

2. There must be regular, timely, and thorough monitoring of ecosystem components, including all elements of terrestrial ecosystems, rather than merely of seabirds and the officially recognized endangered species.

3. There should be an established, adequately funded and equipped infrastructure to allow immediate emergency reactions to accidental or illegal ecosystem disturbances, including measures to eliminate disruptive exotic organisms.

Among protection measures that are desirable we would like to particularly mention the following two:

1. Future management planning should include design and implementation of programs to eliminate or control exotic species with high potential as ecological hazards (e.g., ants, mosquitoes, rats, weeds).

2. Some effort should be made to solicit the assistance of appropriate agencies (e.g., U.S. Coast Guard) to aid in aerial monitoring efforts aimed at precluding accidents and enhancing enforcement capacity.

Several areas of scientific research on terrestrial ecosystems in the Northwestern Hawaiian Islands could make major contributions to our knowledge of the ecosystems themselves and could enhance our understanding of island biology on a global basis. Clearly, the terrestrial ecosystems of the NWHI are a neglected resource from the standpoint of basic information and understanding. These islands contain some of the last remnants of dry lowland ecosystems in the Hawaiian Archipelago, many supporting species in groups long extinct in the main islands. The great diversity of the biota renders it a potentially highly sensitive monitoring device, provided we can reach a basic understanding of its dynamics and constitution. Development of monitoring techniques could be of benefit to managers of island ecosystems worldwide. This biota offers ample opportunities for in-depth studies of speciation and survival on high island remnants, an aspect of Hawaiian natural history that is very poorly understood. Such studies could elucidate the biogeographic status and evolutionary biology of invertebrates in the main islands and greatly enhance our present knowledge of the role of pelagic seabird colonies in the distribution, evolution, and ecology of terrestrial biota of these and other Pacific oceanic islands. Finally, the terrestrial biota of the NWHI

provides a baseline for studying, for example, the role of ants and mosquitoes in the extinction and reduction (via predation and disease transmission) of invertebrates and birds in the main islands.

If our recommendations regarding adequate monitoring are to be implemented, we should provide some idea of the nature of the effort that would be required. Ideally each refuge island, and preferably all the islands, should have their plant and invertebrate populations surveyed twice per year -- at the end of the "wet season" and at the height of the "dry season." If yearly monitoring proves unfeasible, an every-other-year schedule might be acceptable. The amount of time required on each island will vary, depending on island size, logistics, and, as always, weather. Monitoring teams should include an invertebrate zoologist, a botanist, and, on Laysan and Nihoa, a land bird specialist. It is estimated that on the two most diverse islands, Laysan and Nihoa, about 6 or 7 days per visit would be required if all types of land biota sampling are to be accomplished. Other islands would take less time to survey. These surveys could become routine only after all islands have been adequately studied to establish basic faunal lists for the incompletely known groups. Such a schedule will be difficult to establish and maintain. However, there are researchers anxious to conduct surveys on an opportunistic basis. In some cases, such as for surveys of molluscs and the free-living acarines, non-expert research workers could perform the required sampling. Without adequate knowledge of the size and complexity of the ecosystems, it is difficult to provide more specific guidelines. However, we are optimistic that the cooperative spirit that has prevailed among members of agencies and industry can facilitate an adequate monitoring program.

CONCLUSIONS

Although the terrestrial ecosystems of the NWHI are not pristine, their biota are among the least modified by disturbance in Hawaii, and most endemic populations that have not become extinct appear relatively stable.

Provided essential protection and enforcement measures are effective (e.g., no new introductions occur and monitoring programs enable quick and effective reactions to ecological perturbations), there is a good chance that the terrestrial biota of the NWHI can remain relatively undisturbed.

Because Nihoa has by far the most diverse native biota, it is especially deserving of strict protection. Similarly, Laysan and Necker Islands should receive high management and protection priorities.

Implementation of essential protection measures for NWHI terrestrial ecosystems is unlikely to have a negative impact on a carefully managed commercial fishing industry.

A judiciously managed commercial fishing industry need not jeopardize terrestrial ecosystems if authorized and accidental landings are minimized and illegal landings prevented.

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THE HAWAIIAN MONK SEAL: A SYNOPSIS OF RESEARCH

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EXPANDED ABSTRACT

The Hawaiian monk seal, Monachus schauinslandi, was listed as an endangered species under provisions of the Endangered Species Act in 1976, following a decline in beach counts of seals by about 50 percent in the Northwestern Hawaiian Islands. To reverse the declining population trend, a research and observational program was initiated. Survival of monk seal pups has been greatly enhanced at Kure Atoll by maintaining weaned pups in a large enclosure during their first summer. At all of the islands west of French Frigate Shoals the adult sex ratio is highly skewed toward males, but at French Frigate Shoals it may be nearly equal. A weaned pup flipper-tagging program has been initiated following a study which showed no significant disturbance was caused to the pups by the tagging technique. Temporal haul-out patterns and depth-of-dive records suggest that young seals dive deeper and forage for longer duration than do adults. Attacks on females by adult males and the first observation of sharks killing a monk seal have been documented at Laysan Island. Reduced human use of beaches at Tern Island, French Frigate Shoals during the last 3 years has coincided with a marked increase in seal counts from a few animals to over 100. The incidence of the entanglement of pups in lost or discarded fishing nets and other flotsam indicates that this may be a potentially serious problem. There appears to be a difference in the preference of food among seal populations on the various islands.

A recovery plan has been approved for the Hawaiian monk seal and will serve as a guide for the National Marine Fisheries Service research on this endangered species.

Note: A full-length conference paper was delivered at the symposium; however, only an expanded abstract appears here to avoid duplication with other published work. Reference to the paper(s) can be found in the "Abstracts of Published Papers" and "Abstracts of Unpublished Papers" sections in Volume 2 of this proceedings.

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POPULATION STATUS AND ECOLOGY OF THE GREEN TURTLE IN THE NORTHWESTERN HAWAIIAN ISLANDS

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EXPANDED ABSTRACT

A history of underprotection and overexploitation has resulted in a reduction in the range and numbers of the Hawaiian green turtle (Chelonia mydas). In an effort to reverse this trend, the state of Hawaii closed down the commercial turtle fishery in 1974. In 1978 the population was granted full legal protection when it was listed as "threatened" under the U.S. Endangered Species Act. State wildlife rules were later revised to afford equivalent protection. At present there are some encouraging signs that the population has started to recover. However, full recovery is likely to be a protracted process due to slow growth rates found for turtles living in the wild and the impacts of natural and human predation.

Between 1977 and 1980 the University of Hawaii Sea Grant College Program and the state of Hawaii funded a study of the green turtle. Since 1980, research responsibilities of Hawaiian and certain other Pacific sea turtles have been assumed by the Southwest Fisheries Center Honolulu Laboratory of the National Marine Fisheries Service.

Hawaiian green turtles migrate to breed in the Northwestern Hawaiian Islands where at least 90 percent of all nesting occurs at French Frigate Shoals. An

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estimated 300 adult females were present at this key location during each of the past two breeding seasons. The important aspects of reproductive ecology at French Frigate Shoals, as determined by tagging, have been identified. The study has also yielded significant published results relevant to migrations, food sources, growth rates, predation, and the unique land-basking behavior that takes place at undisturbed sites in the Northwestern Hawaiian Islands.

Note: A full-length conference paper was delivered at the symposium; however, only an expanded abstract appears here to avoid duplication with other published work. Reference to the paper(s) can be found in the "Abstracts of Published Papers" section in Volume 2 of this proceedings.

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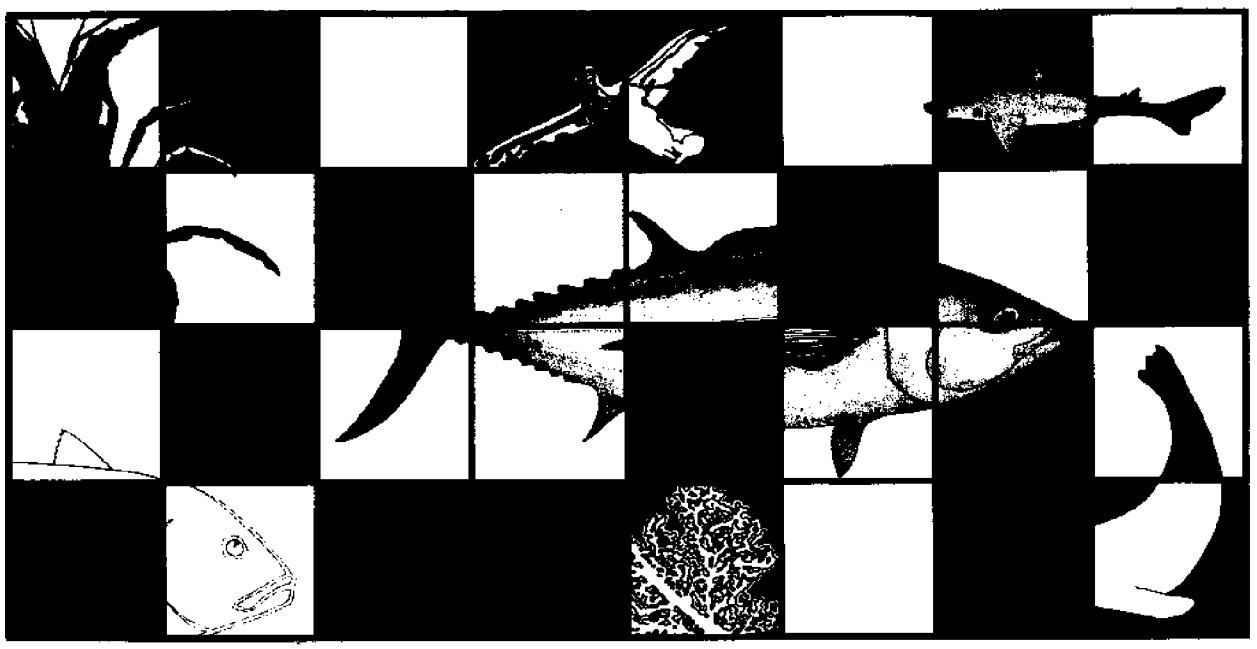
Nearshore Research



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THE STRUCTURE OF REEF FISH COMMUNITIES IN THE HAWAIIAN ARCHIPELAGO

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ABSTRACT

The great variety of reef habitats in the Hawaiian Archipelago has a profound influence on how the species of reef fishes are distributed. For some species, however, the pattern has been strongly modified by fishing pressures. The fauna is basically derived from the tropical western Pacific, a relationship that is generally most evident in communities at the southeastern end of the archipelago, but is also particularly evident at French Frigate Shoals which is located at the center of the archipelago. Although communities at the northwestern end of the archipelago similarly show close ties to the tropical Pacific, they also include species from more temperate regions of the western Pacific. These more temperate derivatives decrease in numbers and/or occur in deeper water southeastward. Conversely, some deep-water tropical forms that exist only on deeper reefs in the southeast occur on shallow reefs in the northwest. The predominant members of the northwestern communities, as a group, are better tuned to the overall Hawaiian environment than are the predominant members of the southeastern communities. They show this by being more evenly distributed over the archipelago and by including proportionally more endemics. The southeastward distributions of species in the northwestern communities are limited by both environmental and fishing pressures, but the northwestward distributions of species in the southeastern communities are limited only by environmental factors.

fishes
Hawaii
fish communities
zoogeography

INTRODUCTION

The distribution of reef fish species in Hawaii is strongly influenced by the great diversity of reef habitats over the archipelago. Because each species' occurrence is defined by a combination of characteristics adapted to specific environmental conditions, its greatest numbers should occur where these conditions are best approximated. But patterns of occurrence no doubt have been distorted by fishing pressures, which have been species and area specific. These opinions remain largely conjectural because the actual patterns of distribution for the various species remain poorly known. This study was undertaken to improve and expand our knowledge of these relationships for the purpose of developing more effective management guidelines.

REEF HABITATS

Reef habitats in the Hawaiian Archipelago range from those that fringe the massive volcanic island of Hawaii, to those located more than 1,500 km northwestward that are the major structure of Kure Atoll. Each of the major high islands offers many distinct habitats, but it is a mix that tends to recur because these islands have similar topographies. Being in essence one or more large volcanic peaks that block the prevailing wind and seas, the high islands support distinctive windward and leeward reefs. Furthermore, so abrupt is their rise from great ocean depths that room for nearshore reefs is limited.

In contrast, highly dissimilar underwater settings exist from one end of the Northwestern Hawaiian Islands to the other. In part, this is because they cover almost three times the distance and more than twice the latitude of the high islands. Probably more important, however, is the fact that their topographies are more varied. Nihoa and Necker are most like the high islands, being small volcanic peaks that rise abruptly from the sea. But they offer no appreciable lee, and both rest on broad submerged platforms that provide more suitable depths for shallow habitats than do the comparatively narrow shelves that surround the high islands. Northwestward from Necker, conditions progressively become even more different. At French Frigate Shoals exposed volcanic rock is limited to La Perouse Pinnacle, a basaltic structure that juts from amid expansive shallows and low sandy islets. This and Gardner Pinnacles -- two precipitous volcanic rocks surrounded by a broad submerged platform -- are the last bits of exposed basalt to the northwest. Farther on, Maro Reef is the almost totally submerged crest of an oval-shaped seamount, whereas Laysan and Lisianski are low sandy islands surrounded by wide shallows. Finally, Pearl and Hermes, Midway, and Kure are coral atolls, even though they lie at high latitudes.

METHODS

Between 1977 and 1982, reef fish communities between shore and depths of 20 to 35 m were assessed throughout the archipelago (Table 1). Because the various stations were sampled at different times during different seasons, often 1 or more years apart, it was important to know how much the species composition of the fish communities could be expected to vary over time. For this reason, assessments were repeated over 2 or more years in selected locations at each end of the archipelago. A site off the island of Hawaii was sampled throughout the 5 years of the study, including all seasons, and a site off Midway was sampled over 2 years, including two seasons. Repeated counts and observations also were made at several other sites during the study, but because the results relevant to this question were the same as for the stations off Hawaii and Midway, they are not presented in this paper. In general, however, the limited number of opportunities available to sample this vast area, with so many habitats, precluded replicate assessments at specific stations.

TABLE 1. ASSESSMENT OF REEF FISH COMMUNITIES AT VARIOUS STATIONS IN THE HAWAIIAN ARCHIPELAGO, JULY 1977 TO OCTOBER 1982

Station	No. of Habitats	No. of Transects	Transect Depths (m)
Hawaii	6	54	2-12
Oahu	6	17	5-12
Niihau	2	4	7-10
Nihoa	2	5	8-10
Necker Island	2	3	10-15
French Frigate Shoals	8	11	9-15
Gardner Pinnacles	3	3	10-12
Maro Reef	3	4	2-12
Laysan Island	4	4	3-16
Lisianski Island[1]	5	5	7-10
Pearl and Hermes Atoll	2	2	7-12
Midway Islands	8	16	2-12
Kure Atoll	8	14	2-12

[1]Including Neva Shoal

A standard procedure was used at all the islands in order to obtain comparable data. First, a general reconnaissance was made to obtain provide familiarity with the area and fauna, identify

representative habitats, and provide a list of the species present. Then in each representative habitat the community was characterized upon conducting two consecutive visual counts of the fishes in 4 m x 25 m transects. The intent was to determine which species frequented the sampled habitat and not to measure the existing biomass. Forty minutes were spent tabulating species on each transect. The final tally included many more individuals than were present in the sampled area at any one moment. Other details of the procedures used in making the counts are reported in Hobson (1980).

Counts were limited to individuals that appeared and behaved as adults because the occurrences of many juveniles varied greatly with season and from year to year for reasons unrelated to conditions on the reef. Inclusion of juveniles would have, in fact, obscured rather than clarified the zoogeographic questions considered in this paper.

Owing to limitations in the visual sampling method, highly cryptic forms such as muraenid eels are greatly underrepresented. Also, in some habitats the same is true of certain nocturnal species, such as holocentrids, that spend the daytime under cover. However, because this bias was constant throughout the study, the counts should illustrate any major differences in numbers of individuals of these species between sites.

Non-reef species that occurred near the reefs were excluded from the counts. These include certain small forms, such as atherinids and engraulids, that occurred just under the water's surface and also small benthic forms, such as gobiids, that often were abundant on the sand adjacent to the reef.

Following each count the surrounding area was inspected for other species, noting their relative numbers and any indications that the transect counts might have produced a misleading assessment of the community. These supplemental observations contributed to the interpretations drawn from the transect data and are especially important as added support when a species was noted as absent. The comparisons are limited to observations made during this study in order to reduce the bias that otherwise would stem from including the many observations made during other studies in previous years in the high islands, especially around Oahu and Hawaii.

RESULTS

Temporal Patterns

The major components of the reef fish communities remained relatively unchanged at the sites on Hawaii and Midway (Table 2). The 10 most numerous species at the time of the first counts at each site continued (with a few exceptions among the lower-ranked forms) to maintain similar proportions in the same communities in later years.

TABLE 2. TEMPORAL VARIATIONS IN FISH COMMUNITIES ON TWO HAWAIIAN REEFS

LEEWARD HAWAII	Jul 1977	Oct 1978	Sep 1979	Apr 1980	Oct 1982
Number of Transects	4	4	4	2	2
$\bar{x}$ Species	34	33	35	31	34
$\bar{x}$ Individuals	185	159	191	158	188
1977 Species Ranking	Relative Abundance Index[1]				
Chromis agilis	19.1	18.0	18.5	18.0	13.9
Ctenochaetus strigosus	12.7	15.8	15.4	13.2	17.6
Zebrasoma flavescens	12.1	16.6	13.8	17.2	23.2
Chaetodon multicinctus	8.4	10.1	8.3	9.4	6.4
Chromis vanderbilti	6.3	0.9	4.7	4.1	0
Thalassoma duperrey	6.1	4.4	3.4	4.1	1.9
Acanthurus nigrofuscus	4.4	1.7	1.0	0	0.8
Plectroglyphidodon johnstonianus	3.3	3.0	1.8	2.5	2.5
Centropyge potteri	3.1	3.3	3.8	3.5	3.5
Chromis hanui	2.4	2.8	1.8	1.9	0.8

WINDWARD MIDWAY	Aug 1977	Sep 1979
Number of Transects	2	2
$\bar{x}$ Species	33	35
$\bar{x}$ Individuals	316	223
1977 Species Ranking	Relative Abundance Index[1]	
Acanthurus triostegus	16.3	11.7
Chromis ovalis	14.2	13.9
Acanthurus leucopareius	12.3	12.8
Myripristis amaenus	7.0	6.1
Stegastes fasciolatus	6.3	8.5
Kyphosus bigibbus	5.4	4.9
Thalassoma duperrey	4.9	8.5
Acanthurus nigroris	4.7	0.4
Abudefduf abdominalis	2.7	7.6
Thalassoma ballieui	1.9	2.9

[1]Relative Abundance Index is the percentage of all individuals counted that were of this species.

Spatial Patterns

The species constituting the reef fish communities varied greatly from one reef habitat to another, but there were broad similarities in certain basic features. Although there were 30 to 40 species in most of the communities, just three or four of them included over 50 percent of the individuals present. Typically, one species included 15 to 20 percent of all individuals, whereas the other two or three species included 10 to 15 percent each. These major species, which differed from one habitat to another, presumably are those best attuned to the prevailing environment and thus probably can be considered characteristic of that particular habitat. It is instructive, therefore, to consider the distribution throughout the archipelago of species that were major forms in any one of the many distinctive communities examined (Table 3). Species included in this list are those that comprised at least 10 percent of the individuals counted in two or more transects in any one habitat.

These major species generally were most prominent at one or the other end of the archipelago. Significantly, those that predominated in the northwestern communities tended to be more evenly distributed over the archipelago than those that predominated in the southeastern communities. Thus, although the northern dominants -- Myripristis amaenus, Kyphosus bigibbus, Chromis ovalis, Stegastes fasciolatus, Thalassoma duperrey, T. ballieui, Acanthurus leucopareius, A. nigroris, and A. triostegus -- declined somewhat in numbers southeastward, the trend was uneven, and all were relatively numerous, if not dominant, throughout the archipelago. In comparison, the southern dominants -- Chaetodon multicinctus, Chromis agilis, C. vanderbilti, Acanthurus nigrofuscus, Ctenochaetus strigosus, and Zebrasoma flavescens -- lost dominance at some point northwestward and hence were few or absent at Midway and Kure.

The numbers of some prominent members of the northwestern communities declined sharply southeastward until at some point they were absent from the shallow reefs. Consider those species that occurred in two or more transects in any one habitat at Kure or Midway, but which were not seen off the island of Hawaii (Table 4). Three -- Pristilepis oligolepis, Epinephelus quernus (Figure 1), and Oplegnathus fasciatus -- were seen nowhere else, while two others -- Oplegnathus punctuatus and Carangoides othogrammus -- occurred southward only in sharply reduced numbers -- the former to Maro Reef, the latter to Nihoa. Two -- Cheilodactylus vittatus and Epibulus insidiator -- were relatively numerous at French Frigate Shoals, but were not seen farther south, and the other two -- Carcharhinus amblyrhynchos, and Caranx ignobilis (Figure 2) -- were numerous all the way to Nihoa, but were not seen in the major high islands during this study period. Two other species seen repeatedly on reefs as shallow as 20 m at Midway and Kure, but not in the transects,

TABLE 3. DISTRIBUTION OF MAJOR REEF FISHES THROUGHOUT THE HAWAIIAN ARCHIPELAGO

Species	Location[1]													
	Hl	Hw	Ol	Ow	NI	NE	FFS	GP	MR	LA	LI	PH	MKl	MKo
Myripristis amaenus	<0.1	•[2]	0[2]	0	•	0	0.1	0.2	0.1	<0.1	0	0.3	0	2.3
Kyphosus bigibbus	<0.1	•	•	0.1	4.4	0.2	0.6	6.0	0.8	4.6	0.2	3.1	2.2	5.9
Chaetodon multicinctus	4.7	3.2	5.0	0.2	0.8	0.6	0.8	0	0	1.3	0	0.1	0	<0.1
Stegastes fasciolatus	1.2	5.9	4.6	6.5	3.1	4.5	2.2	9.4	13.8	4.2	5.0	1.5	18.0	7.2
Plectroglyphidodon imparipennis	0.8	<0.1	•	1.7	1.7	0.7	0.4	1.0	0	0	0	0	0	0
Dascyllus albisella	•	0	•	•	0	•	2.8	0	<0.1	0	0.4	•	0.3	0
Chromis agilis	3.8	0.2	0.1	0	0	0	<0.1	0	0	0	0	0	0	0
C. ovalis	•	0.2	7.1	4.2	2.4	7.5	6.8	3.4	16.2	26.2	•	39.7	0.1	18.3
C. vanderbilti	5.7	4.0	<0.1	6.8	23.6	6.6	3.7	22.3	0	0.6	0	2.4	0	0.1
Thalassoma ballieui	<0.1	<0.1	0.4	0.2	<0.1	1.6	1.5	2.0	2.1	2.5	2.4	1.0	6.3	2.3
T. duperrey	4.8	4.0	6.0	10.6	4.8	13.9	7.0	6.2	8.8	4.8	9.9	1.2	18.9	10.4
Acanthurus leucopareius	0.3	<0.1	0	0.6	0.6	0.3	<0.1	•	•	0.4	•	0.1	0	5.4
A. nigrofuscus	8.6	9.3	11.2	9.8	5.6	0.7	1.4[3]	0.7	•	<0.1	0	0	0	0
A. nigroris	0.4	0.8	0.4	0	2.3	2.0	1.8	5.5	6.0	4.3	9.1	0.9	0.7	8.6
A. triostegus	0.2	0.1	0.6	0.5	0.1	2.0	0.5	4.7	7.4	<0.1	4.9	0.5	2.0	4.7
Ctenochaetus strigosus	13.1	13.5	9.3	1.7	3.4	0	7.0	0.2	2.2	1.4	7.5	1.2	1.4	0.4
Zebrasoma flavescens	16.6	0.7	1.5	0	<0.1	0	0.8	0	•	<0.1	<0.1	0.4	•	0
Melichthys niger	0.1	0.1	<0.1	0	0.2	0.3	8.1	3.0	<0.1	3.0	•	5.8	0	0.9
Pervagor spilosoma	<0.1	0	1.3	1.0	0	0.2	0.4	<0.1	0	1.1	8.8	0.1	<0.1	0

Note: Values given are occurrence indices, which are the product of the mean relative abundance index and frequency of occurrence for all transects at each location.

[1]Hl = Hawaii: leeward; Hw = Hawaii: windward; Ol = Oahu: leeward; Ow = Oahu: windward; NI = Nihoa; NE = Necker Island; FFS = French Frigate Shoals; GP = Gardner Pinnacles; MR = Maro Reef; LA = Laysan Island; LI = Lisianski Island; PH = Pearl and Hermes Atoll; MKl = Midway Islands - Kure Atoll: lagoons; MKo = Midway Islands - Kure Atoll: outside barrier reefs

[2]• = seen but not on transect; 0 = not seen

[3]Virtually all A. nigrofuscus at La Perouse Pinnacle; occurrence index there: 8.0 (4 transects)

TABLE 4. OCCURRENCES OF SPECIES COUNTED IN TWO OR MORE TRANSECTS IN ANY ONE HABITAT MOVING SOUTHEASTWARD IN THE HAWAIIAN ARCHIPELAGO

Species	Location[1]												
	KA	MI	PH	LI	LA	MR	GP	FFS	NE	NI	NU	OA	HI
Carcharhinus amblyrhynchos	*	*	*	*	●	●	●	*	*	x			
Pristilepis oligolepis	*	●											
Epinephelus quernus	*	*											
Oplegnathus fasciatus	●	*											
O. punctatus	x	*			●	●							
Cheilodactylus vittatus	*	*	●			●	x	x					
Caranx ignobilis	*	*	*	*	x	*	*	*	●	●			
Pseudocarnx dentex	●	*											
Carangoides othogrammus	*							*		●			
Epibulus insidiator	*	*	*	x		x		*					

Note: * = occurring in two or more transects; x = occurring in one transect; ● = seen. None were seen off Niihau, Oahu, and Hawaii.

[1]KA = Kure Atoll; MI = Midway Islands; PH = Pearl and Hermes Atoll; LI = Lisianski Island; LA = Laysan Island; MR = Maro Reef; GP = Gardner Pinnacles; FFS = French Frigate Shoals; NE = Necker Island; NI = Nihoa; NU = Niihau; OA = Oahu; HI = Hawaii

Figure 1. Epinephelus quernus on a reef 10 m deep at Midway

Figure 2. Caranx ignobilis at Maro Reef

were the pentacerotid Hystiopterus acutirostris and the pomacanthid Genicanthus personatus, neither of which were seen elsewhere during this study period.

In comparison, consider the many more species that occurred in two or more transects in any one habitat in the lee of the island of Hawaii, but were not seen at Kure or Midway (Table 5). Three -- Chromis agilis, Plectroglyphidodon imparipennis, and Acanthurus nigrofuscus -- were among the major species noted above. Five -- Chaetodon reticuluatus, C. lineolatus, Hemitaurichthys thompsoni, Forcipiger longirostris, and Ostracion whitelyi -- were seen nowhere else, while four -- Epinephelus argus, Chaetodon ephippium, Plectroglyphidodon sindonis, and Pervagor melanocephalus -- occurred northward only in sharply reduced numbers. Two -- Thalassoma quinquevittata and Ctenochaetus hawaiiensis -- occurred only in the lee of Hawaii and at French Frigate Shoals. The remaining 11 species in this group -- Aphareus furcatus, Monotaxis grandoculis, Coris gaimard, Thalassoma fuscus, Scarus rubroviolaceus, Naso lituratus, N. breviorstris, Plagiotremus goslinei, Rhinecanthus rectangulus, Cantherines sandwichiensis, and Canthigaster amboinensis -- were relatively numerous as far as French Frigate Shoals, or Gardner Pinnacles, but declined sharply in numbers northward from there.

Perhaps the most striking departure from the general patterns of distribution outlined above was the almost total absence of small planktivorous fishes at Lisianski and adjoining Neva Shoal (data from the two locations are combined in Table 3). Not only were there no planktivores in the transects at these locations, but the only ones seen in all the widespread observations there were just a few scattered Chromis ovalis. At these same locations, on the other hand, the monacanthid Pervagor spilosoma was unusually abundant. It may be significant that most of the P. spilosoma were found above the reefs in small aggregations, much like those formed by the planktivorous Chromis spp. elsewhere, rather than scattered close to the reef as members of this species usually are. These same circumstances were paired at Kahe, on leeward Oahu, where in two transects conducted 4 months apart planktivores were absent, and P. spilosoma represented 4.6 and 5.6 percent of the fishes counted (compared with a mean of 0.5 percent; range 0 to 0.9 percent in transects elsewhere off leeward Oahu). Interestingly, the transects at Lisianski (and Neva Shoal) and at Kahe were the only ones during the entire study (in water more than 2 m deep) in which planktivores were absent (where in fact at least one planktivorous species was not a major form) and in which P. spilosoma represented more than 1 percent of the fishes present.

In all of the widespread locations visited during this study, only three species were seen that did not also occur either off the island of Hawaii or at Midway-Kure. Two of these -- the chaetodontids Chaetodon trifasciatus and C. citrinellus -- occurred only at French Frigate Shoals, whereas the monacanthid Cantherines verecundes occurred only at Laysan and Lisianski.

TABLE 5. OCCURRENCES OF SPECIES COUNTED IN TWO OR MORE TRANSECTS IN ANY ONE HABITAT MOVING NORTHWESTWARD IN THE HAWAIIAN ARCHIPELAGO

Species	Location[1]														
	Hl	Hw	Ol	Ow	NU	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Epinephelus argus	*				*										
Aphareus furcatus	*	*	*		*	●		x	●	x					
Monotaxis grandoculis	*	x	●		x	x	●	x			●				
Chaetodon ephippium	*				●	x									
C. reticulatus	*														
C. lineolatus	*														
Forcipiger longirostris	*														
Hemitaurichthys thompsoni	*														
Chromis agilis	*	x	x					x							
Plectroglyphidodon imparipennis	*	x	●	*	●	*	x	*	*						
P. sindonis	*	●						●	x						
Coris gaimard	*	x	x	●		●	*	x							
Thalassoma fuscus[2]	*	●	●	●	●	●	●	x	●	●					
T. quinquevittata	*							x							
Scarus rubroviolaceus	*	*	x	●	x	●	●	x							
Acanthurus nigrofuscus	*	*	*	*	*	*	x	*	x	x	●				
Ctenochaetus hawaiiensis	*							●							
Naso lituratus	*	*	*	*		*	x	*	x	●		●	●		
N. brevirostris	*				●		x	*	●						
Plagiotremus goslinei	*	*		x	x	x	x		x						
Rhinecanthus rectangulus	*	●	*	x		*	●	●	●		●				
Cantherines sandwichiensis	*	x	*	*	x	*	●	x	x						
Pervagor melanocephalus	*		*	x											
Ostracion whitelyi	*														
Canthigaster amboinensis	*	*	*	*		x		●							

Note: * = occurring in two or more transects; x = occurring in one transect; ● = seen.

[1]Hl = Hawaii: leeward; Hw = Hawaii: windward; Ol = Oahu: leeward; Ow = Ohau: windward; NU = Niihau; NI = Nihoa; NE = Necker Island; FFS = French Frigate Shoals; GP = Gardner Pinnacles; MR = Maro Reef; LA = Laysan Island; LI = Lisianski Island; PH = Pearl and Hermes Atoll; MI = Midway Islands; KA = Kure Atoll

[2]The nominal T. umbrostigma, which is considered the female of this species based on observations of spawning (Hobson, 1974), was numerous throughout the archipelago.

Chaetodon trifasciatus invariably occurred with coral of the genus Acropora, which dominated some reefs at French Frigate Shoals, but was not abundant elsewhere (see paper in this proceedings by Grigg). It was present on all four transect reefs rich in Acropora, where it represented a mean of 2.1 percent (range of 1.6 to 3.4 percent) of the fishes counted. Chaetodon cintrinellus was relatively abundant in the shallow waters behind the windward reef flat, but no transects were established in that habitat. Cantherines verecundes was seen in just one transect at Laysan that was set on a large patch reef at a depth of 20 m, but it represented 3.1 percent of the individuals there. At Lisianski, C. verecundes was in all the habitats sampled and represented a mean of 2.7 percent (range of 2.3 to 3.6 percent) of the fishes in the five transects conducted there.

An additional feature of fish communities in the Northwestern Hawaiian Islands was the relatively high incidence in shallow water of the large terminal male phase of many labrid species. Most prominent were: Bodianus bilunulatus, Coris flavovittata, Anampses cuvier, Thalassoma purpureum, and T. ballieui. These were especially numerous at Midway and Kure.

DISCUSSION

Temporal Stability

The question of whether reef fish communities are stable or unstable over time has evoked much interest in recent years (e.g., Sale, 1980b). Probably it is significant that proponents of the instability concept have based most of their arguments on short-term studies of small isolated reefs. Most have been experimental colonizations of isolated coral heads (e.g., Sale and Dybdahl, 1975) or artificial reefs (e.g., Talbot et al., 1978; Bohnsack and Talbot, 1980) over periods of less than 3 years. The proponents of the stability concept, on the other hand, have drawn most of their evidence from long-term studies of larger reefs. These have included studies of both natural (Brock et al., 1979) and artificial (Ogden and Ebersole, 1981) reefs that were examined more than 10 years after being defaunated and recolonized. A persistent uncertainty in these studies stems from not knowing how long it takes reef communities to fully recover from defaunation. The uncertainty is increased when artificial reefs are involved because no one knows whether these will in fact ever support truly natural communities. Significantly, however, Sale (1980a) found that the structure of fish communities on undisturbed natural, but small (20 m x 1 m x 1 m), patch reefs (which were controls for his defaunation experiments) changed continuously over time.

The major components of the Hawaiian fish communities described in this paper were stable over the duration of the study, and probably it is significant that these communities were established on extensive, natural reefs that had not been disturbed. Based on these circumstances and the variable results

noted above, the stability-instability controversy may stem from (1) differences in the size and complexity of the reef systems studied by the various investigators; (2) time passed since the communities had been disturbed; and (3) the extent to which the physical conditions of the reefs approximate those of natural, undisturbed reefs in the area. Also, it is important that the stability reported here refers to the adult populations. As mentioned in the "Methods" section, the numbers of juveniles varied with season and from year-to-year for reasons that seemed unrelated to circumstances on the reef, but this variability had no observable impact on the established adults during this study.

Spatial Distribution: General

Most Hawaiian reef fishes are widely distributed on the islands of the Pacific plate, which occupies most of the Pacific basin, and has been defined by Springer (1982) as a distinct biogeographic unit. Apparently these species are adapted to certain features held in common by the variety of high islands, low islands, atolls, and submerged sea mounts, that characterize this, the largest of the earth's lithospheric plates. It is not surprising, therefore, that so many of them occur in diverse habitats throughout the Hawaiian Archipelago. Despite these widespread occurrences, however, the major species differ greatly in their relative numbers from one habitat to another.

Because most of these major forms were most numerous at one end of the archipelago or the other, it is convenient to focus on the northwestward distribution of the southeastern dominants and the southeastward distribution of the northwestern dominants. Significantly, those species which dominated in the southeast were more restricted in their distribution over the archipelago than were those which dominated in the northwest. Apparently the southeastern dominants -- Chaetodon multicinctus, Plectroglyphidodon imparipennis, Chromis agilis, C. vanderbilti, Acanthurus nigrofuscus, Chaetodon strigosus, and Zebrasoma flavescens -- are less attuned to the overall Hawaiian environment than are their northwestern counterparts -- Myripristis amaenus, Kyphosus bigibbus, Chromis ovalis, Dascyllus albisella, Stegastes fasciolatus, Thalassoma duperrey, T. ballieui, Acanthurus leucopareius, A. nigroris, and A. triostegus (Table 3). Not only are the southeastern dominants less numerous in more places throughout the archipelago, but they also include fewer endemics -- just one (C. multicinctus) compared with four (C. ovalis, D. albisella, T. duperrey, and T. ballieui) among the northern groups. It is recognized that some of the most abundant Hawaiian species are endemics (Gosline and Brock, 1960), but not all of the endemics are abundant (e.g., the pomacentrid Plectroglyphidodon sindonis, Table 5).

Patterns of distribution northwestward are basically different from patterns of distribution southeastward presumably because of different selection pressures. In the discussion below several of these selection pressures are distinguished.

Environmental Selection Pressures That Influence Distribution Northwestward

The species in nearshore communities at the southeastern end of the archipelago show close relationships with the fishes of the more tropical regions of the Pacific. Even the one endemic species among the major forms -- Chaetodon multicinctus -- has a western Pacific analog in C. punctatofasciatus, and a South Pacific analog in C. pelewensis (Burgess, 1978). The several species that occurred in transects in the lee of the island of Hawaii, but were not seen elsewhere (Table 5) -- Chaetodon reticulatus, C. lineolatus, Hemitaurichthys thompsoni, Forcipiger longirostris, and Ostracion whitelyi -- are widespread Pacific species that apparently find conditions more suitable here than elsewhere in Hawaii. Gosline and Brock (1960) reported that C. reticulatus has been "reported only twice in Hawaii," that C. lineolatus inhabits "relatively deep water," and that H. thompsoni is "quite rare." They included O. whitelyi (as O. solorensis) in their account of the Hawaiian fauna based only on a small specimen from Johnston Island, but Randall (1972) subsequently noted its occurrence in the lee of Hawaii. F. longirostris was long confused with the common F. flavissimus, but now is recognized as a distinct species rare in the Hawaiian Archipelago except on the leeward reefs of the island of Hawaii (Randall and Caldwell, 1970). Chromis agilis is common and widespread in the tropical western Pacific (Allen, 1975) but has a limited distribution in Hawaii. Although it is the major species on certain reefs in the lee of Hawaii where the coral Porites compressa is abundant, its occurrence northwestward is limited to small aggregations off windward Hawaii and leeward Oahu (on a reef in Hanauma Bay which is rich in Porites compressa). One individual was seen at French Frigate Shoals.

One might assume that distribution of tropical Pacific fishes northwestward in the Hawaiian Archipelago would be limited by lower water temperature. This is probably true for some species, but certain other forces are more limiting for other species.

Reduced protection from prevailing wind and seas northwestward probably limits distribution for some species. Zebrasoma flavescens, for example, seemed to require some feature associated with leeward reefs. This species is the major component of communities on various reefs in the lee of Hawaii, the largest island, but is much less prominent in the lee of the smaller island of Oahu. On the windward side of Hawaii, adults were seen in numbers only south of Cape Kumukahi, where there is in essence a lee shore. North of the cape along the Hamakua Coast just one adult occurred in the transects, whereas juveniles were the most numerous fish on a reef rich in the coral Porites compressa in a sheltered bay near Hilo. Conditions suitable for adults were clearly lacking along the Hamakua Coast, however, as only a few were seen.

Zebrasoma flavescens was found to be sparse off windward Oahu, except in Kaneohe Bay. This pattern is consistent with the work of Brock (1954), who found this fish to be prominent only in certain leeward habitats around Oahu and Hawaii. Zebrasoma flavescens was sparsely distributed in the Northwestern Hawaiian Islands during this study, generally as a few individuals on the more protected reefs. The only sightings at Midway, for example, were a few scattered individuals on patch reefs in the lagoon where the coral Porites compressa also was most abundant. Apparently this coral, which grows as closely spaced finger-like branchings, is important to the juveniles of Z. flavescens, just as it appears to be for adult Chromis agilis.

The decreased occurrence of exposed basalt northwestward appeared to influence the distribution of several species, most notably Acanthurus nigrofuscus, which Randall (1960) described as "...probably second only to the manini (Acanthurus triostegus) in abundance among surgeonfishes in Hawaii." This species was numerous only where the reefs were largely exposed basalt, a widespread habitat in the high islands. The dependence of A. nigrofuscus on some factor related to exposed basalt was especially evident at French Frigate Shoals, where its prominence was confined to La Perouse Pinnacle, the only basaltic structure there. At Gardner Pinnacles, the last exposed basalt occurrence northwestward, A. nigrofuscus was numerous on the basaltic face of the pinnacles, but was not seen elsewhere. Only one individual was seen at Maro Reef and another at Laysan, the latter in a transect. None were seen northwestward from there. Despite the apparent dependence of Hawaiian A. nigrofuscus on habitats that include exposed basalt, the occurrences of this species, on Pacific atolls (Randall, 1956), which lack such habitats, indicates that conspecifics elsewhere may have different requirements. The same is true of the pomacentrid Plectroglyphidodon imparipennis, which was found only among surge-swept basaltic reefs during this study (it was not seen northwest of Gardner Pinnacles), but is widespread elsewhere in the Pacific on reefs that lack exposed basalt (Allen, 1975). Three other species with distributions that coincided with exposed basalt were Hawaiian endemics: the pomacentrid Plectroglyphidodon sindonis (which frequented surge-swept boulders), the blenniid Plagiotremus goslinei, and the monacanthid Cantherines sandwichiensis.

Certain species which are widespread in the central Pacific seem to find conditions more suitable at French Frigate Shoals than elsewhere in the Hawaiian Archipelago. Probably the most striking example is the common occurrence of the chaetodontid Chaetodon trifasciatus, a species that lives in close association with corals of the genus Acropora (Burgess, 1978). Both the fish and corals are common throughout most of the tropical Indo-Pacific, but are rare or absent in the Hawaiian Archipelago except at French Frigate Shoals. In noting the abundance of Acropora at French Frigate Shoals and its sharp decline both southward (to Kauai) and northward (to Laysan), Grigg et al. (1981) suggested that French Frigate Shoals is the site of active

colonization of some Indo-Pacific forms from the west (by way of the subtropical countercurrent), and that this location is the center of distribution of such forms to the other islands. This pattern is consistent with the distribution of some Indo-Pacific fishes in Hawaii. Another widespread Indo-Pacific species that was abundant at French Frigate Shoals, but which went unseen elsewhere during this study, was the chaetodontid Chaetodon citrinellus. This species, considered rare in Hawaii by Gosline and Brock (1960), was among the species that colonized a newly created harbor on the lee shore of Hawaii (Brock, 1981).

These two widely separated and very different settings -- French Frigate Shoals and leeward Hawaii -- may have characteristics that make them more suitable than other Hawaiian habitats for certain Indo-Pacific species. Leeward Hawaii is noted for its warm, sediment-free water and rich coral growth -- all of which are likely to be associated with environments favored by fishes adapted to more tropical Pacific habitats. French Frigate Shoals may be favorable to some because it is in essence a barrier reef that encloses expansive shallows -- a setting which is widespread in the more tropical areas of the central and western Pacific, but limited in those islands to the southeast of French Frigate Shoals.

Barrier reefs that enclose expansive shallows are prominent to the northwest of French Frigate Shoals, especially at Pearl and Hermes, Midway, and Kure -- which are atolls. But during the winter water temperatures fall below 18 C at these locations (Mauck, 1975) which presumably would be a problem for many Indo-Pacific species. Water temperature, however, has not limited Epibulus insidiator, a widespread Indo-Pacific labrid that is common from French Frigate Shoals northwestward to Kure, but which has not been reported southeastward to Hawaii.

Environmental Selection Pressures that Influence Distribution Southeastward

Although the major species in the northwestern communities are more distinctively Hawaiian than their southeastern counterparts, they too are closely related to fishes of the tropical western Pacific. But some of the less prominent species in the northwest are closely related to, or conspecific with, fishes of the more temperate regions in the western Pacific. Furthermore, in contrast with the major species in these communities, which are widely distributed in shallow water, these more temperate species have limited distributions on shallow reefs southeastward. Both Opelgnathus fasciatus and O. punctatus are prominent in coastal waters of Japan, where they are popular game fishes (Masuda et al., 1975). But despite the common occurrences of both species at Kure and Midway, they are uncommon elsewhere in the Hawaiian Archipelago. O. punctatus had not been recorded from Hawaii prior to this study (Hobson, 1980), and O. fasciatus was recognized from just one specimen taken almost a century ago (Gosline and Brock, 1960).

Similar relationships to fishes of more temperate regions in the western Pacific exist for Pristolepis oligolepis, Pseudocaranx dentex, Cheilodactylus vittatus, and Histiopterus acutirostris, all of which also occur in Japanese waters (Masuda et al., 1975; Springer 1982). But here another dimension of distribution must be considered -- variations in depth of occurrence with latitude. All four species are common inhabitants of shallow reefs at Kure and Midway, but occur at greater depths southeastward. Gosline and Brock (1960) noted that although H. acutirostris appears to be rare there, P. oligolepis and C. vittatus are not uncommon in deeper water. P. dentex (as Caranx cheilio), according to Gosline and Brock, is "not now common around the high islands, but is abundant from French Frigate Shoals to Midway," and Moffitt (1980) reported it to be a major target of offshore bottom fishermen in the Northwestern Hawaiian Islands.

Many fishes which have wide latitude distribution inhabit deeper water toward the equator (Hubbs, 1948). The distribution of such fishes often relates to water temperatures, as shown by studies along the western coast of North America where the pattern reverses at points of local upwelling (Hubbs 1948). Thus, at least some of the fishes that inhabit progressively deeper habitats southeastward in Hawaii may be responding to features related to water temperature. In addition to the species mentioned above, an affinity to lower water temperatures may account for the distribution of Genicanthus personatus, which is relatively common on reefs 20 to 30 m deep at Midway and Kure, but which has been reported only from deeper water around the high islands (Randall, 1975). The same pattern may hold true for the grouper Epinephelus quernus, which is common on shallow reefs at Midway and Kure, but is only found in deeper water southeastward. This species constitutes a large part of the catch of the offshore hand-line fishery at depths below 60 m around the high islands (Ralston, 1980). The same pattern may hold true for the large terminal male phase of the labrid Bodianus bilunulatus, which is another form that commonly frequents reefs as shallow as 1 m at the northwestern end of the archipelago, but rarely occurs shallower than 20 m at the southeastern end.

Pristolepis oligolepis, P. dentex, C. vittatus, and H. acutirostris, as well as certain congeners of G. personatus, B. bilunulatus, and the two oplegnathids, have antitropical distributions that are thought to have been established when surface waters were cooler than at present (Randall, 1981). Springer (1982), however, cited evidence that equatorial sea-surface temperatures have been relatively stable since these antitropical distributions are thought to have been established. He suggested that these distributions have an ecological basis related to the antitropical distribution of the high islands, but this possibility is inconsistent with the fact that most of the species involved are more numerous around the Hawaiian atolls than around the high islands.

The Planktivore-*Pervagor spilosoma* Anomaly

The possibility of a connection between an absence of planktivores and an abundance of *Pervagor spilosoma*, is strengthened by the fact that at the only locations where either circumstance occurred -- Lisianski (and Neva Shoal) and Kahe, Oahu -- they occurred together. The basis for the apparent relationship between these species, or between these species and the two locations, remains unclear. Perhaps it is significant that the water at Lisianski was noted to have a milky quality and that a fine sediment coated much of the seafloor, especially at Neva Shoal. This condition can mean that the water is not circulating, which would in turn mean a reduced supply of zooplankton. On the other hand, it is conceivable that certain materials in suspension could adversely affect small planktivores. There is no measure of the zooplankton at these locations, but it was striking that in the absence of planktivores at Lisianski, the normally bottom-dwelling *P. spilosoma* aggregated above the reef, just as the planktivores did elsewhere. These *S. spilosoma* were not seen feeding, however, and a diet of zooplankters certainly would have been a radical departure from the usual diet of this species. Under more typical circumstances at the island of Hawaii, *P. spilosoma* fed primarily on scleractinian coral polyps (Hobson, 1974). On the other hand, it is conceivable that under appropriate circumstances, features adapted to pluck coral polyps could also be effective in feeding on zooplankters.

Fishing Pressures

Because fishing pressures have been concentrated on just certain places, they seem likely to have distorted patterns of distribution for at least some species. Fishing pressures seem to account for the reduced numbers in the southeast of certain of the species prominent in the northwest (Tables 3 and 4). Perhaps this was predictable, because fishing pressures should have been expected to increase toward the fishing ports on the major high islands. Nevertheless, it is difficult to hold fishing pressures accountable for the southeastward decline of some species. Although *Epinephelus quernus* and *Pseudocaranx dentex* are major targets of fishermen in the area southeast of Midway, the fishing effort is in deeper water offshore. There has been virtually no fishing on the shallow reefs of the Northwestern Hawaiian Islands from Pearl and Hermes Atoll southeastward; hence, the absence of *E. quernes* and *P. dentex* from these reefs cannot be attributed to fishing pressures. Probably both species are simply better adapted to deeper water in southeastern areas.

Population shifts into deeper water cannot account for the southeastward decline in numbers of some shallow-water potential target species. This is because they inhabit shallow reef areas throughout the archipelago. Some of those which are abundant throughout the Northwestern Hawaiian Islands, but generally sparse throughout the major high islands, such as the shark

Carcharhinus amblyrhynchos, may find certain environmental features of major high island reefs unfavorable. On the other hand, shark populations are known to be particularly vulnerable to fishing pressures, and there have been concerted and apparently successful efforts to reduce the populations of these fishes around the high islands.

The most likely victims of fishing pressures are those species known to be well adapted to shallow-water reef areas in the high islands, but which were found only in low numbers during this study. Examples among the species listed in the tables are the holocentrid Myripristis amaenus and the carangid Caranx ignobilis. M. amaenus and its congeners M. murdjan and M. kuntee, are prime targets of fishermen and are especially vulnerable owing to their habit of concentrating in reef caves during the day. [M. kuntee was considered a major species in the preliminary report on this study (Hobson, 1980) based on its numbers in one transect in the lagoon at Kure atoll.] C. ignobilis is coveted by both spearfishermen and shore fishermen and is especially vulnerable to the former owing to its boldness. Fishing would seem to have had a major influence on the observed distribution of C. ignobilis. In contrast to its extreme prominence from Nihoa northwestward to Kure, it was never observed in the major high islands during this study. On other occasions in the high islands, sightings have been infrequent and usually involved solitary individuals.

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PRELIMINARY REPORT ON THE NEARSHORE FISHERY RESOURCE ASSESSMENT OF THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82

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ABSTRACT

The Division of Aquatic Resources of the Hawaii Department of Land and Natural Resources has gathered data from the Northwestern Hawaiian Islands (NWHI) for the past 6 years to assess the nearshore fishery resources. In addition to surveys of the splash zones that are exposed to wave action and shallow-water habitat around the emerged lands, 574 underwater fish count transects were conducted in depths ranging from 3 to 70 feet to record the fish species composition and to estimate their densities in an area roughly representing 400,000 acres. Fish specimens were collected for food studies and for ciguatera fish toxicity analysis by the University of Hawaii. Trapping was conducted to determine the presence of spiny lobsters and to derive some measure of their densities. Ulua (jack crevally) were tagged and released in an effort to gather information on their growth rate, movement, and relative densities.

Surveys of the splash zones revealed an estimated 12,000 pounds of opihi (limpet) on the high basalt islands. Surveys conducted in the shallow waters around the emerged lands revealed the presence of large concentrations of shoaling fishes. Approximately 240 different fish species and numerous invertebrates and limu (seaweed) species were identified in the nearshore environment. The species composition of fishes was found to be basically similar to that of the main Hawaiian islands. However, several species rare or unknown to the main islands were found in NWHI waters, and some species common to the main islands were not found or were observed in diminished numbers to the northwest, suggesting a geographical basis for species distribution. The densely populated nearshore waters

are indicative of the lack of fishing pressure on these resources. Most nearshore fishes were of the non-migratory type. Preliminary evaluation of the fish counts revealed densities ranging from 0 to 24,000 pounds per acre, with an average of nearly 400 pounds per acre. Calculations suggest a conservative 150 million pounds of finfish present in the nearshore waters of the NWHI. Analysis of the gut contents of the more common species suggest that approximately 60 percent of the biomass are herbivores and 40 percent carnivores. Fish tissue assays indicate that many species contain ciguatoxin with toxicity levels varying among species and locations. Spiny lobster trapping results from several islands corresponded with diving observations, except at Pearl and Hermes Atoll where trap catches were lower than expected. To date, tagged ulua have been sighted during surveys, but no recoveries have been reported by commercial fishermen.

INTRODUCTION

The nearshore waters of the Northwestern Hawaiian Islands are reputed to have excellent fishing potential that could enormously benefit the fishermen of Hawaii. In recent years, increasing attention given to the marine and terrestrial resources of this remote area has resulted in the need for developing a plan to rationally manage these resources.

In May 1978, the Hawaii Department of Land and Natural Resources (DLNR) formally entered into a 5-year cooperative agreement with the National Marine Fisheries Service (NMFS) of the U.S. Department of Commerce, and the Fish and Wildlife Service (FWS) of the U.S. Department of the Interior to intensively survey and assess the terrestrial and marine resources of the NWHI. The DLNR's Division of Aquatic Resources (formerly Division of Fish and Game) was made responsible for the collection of baseline data on the nearshore living resources from the fast land areas exposed to spray and wave action seaward to about 10 fathoms in depth. In total, the nearshore study area comprises nearly 400,000 acres. FWS and NMFS were respectively made responsible for the terrestrial and offshore resources assessment studies. The survey data gathering efforts and results will form the basis for future federal-state management decisions on long-range uses and preservation of the living resources in the NWHI. Since the initiation of field work under this study actually preceded the formal execution of the agreement by about a year, an additional year of field research was involved under this agreement; therefore, this report includes 6 years of research. The nearshore surveys were accomplished through funding provided by the Dingell-Johnson Federal Aid in Fish Restoration Project, "Fishery Resource Assessment of the Northwestern Hawaiian Islands" (Project No. F-17-R, Study No. III, Job No. 3).

The primary objectives of the nearshore fishery resource assessment study were to determine fish species composition and diversity and to obtain estimates of their densities. In addition, the size ranges, distribution, annual and seasonal variation of abundances, diet, spawning periods, growth, migration, behavioral characteristics, and ciguatoxin level of certain species were to be investigated. Moreover, habitat description, identification of seaweed and macro-invertebrates, density estimates of certain shellfish, and behavioral characteristics of certain wildlife were to be recorded.

METHODS

During 1977-80, the National Oceanic and Atmospheric Administration's research vessel Townsend Cromwell was utilized as the primary platform from which smaller boats were launched to carry field research parties to the nearshore areas for the NWHI study. During subsequent surveys in 1981-82, the commercial fishing vessels Easy Rider (1981) and Wicked Wahine (1982) were chartered to function as support vessels. The U.S. Coast Guard provided logistic support to survey Kure Atoll in December 1979 and again in August 1980. In addition, the U.S. Navy provided land-based support during the survey of Midway Islands in September 1980.

Due to the different types of topographical features in the nearshore area, the study area was divided into three zones: (1) splash zone which is defined as exposed land under the influence of wave and spray action; (2) inner nearshore zone which is defined as a narrow band of shallow water adjacent to land and usually less than 2 feet in depth; and (3) outer nearshore zone which is defined as the nearshore shallow reefs and submerged lands to the 10-fathom depth.

Resource information obtained from the splash zone included species observed and their densities (characterized as sparse, moderate, or dense). However, since these semi-quantitative values are arbitrary interpretations of densities, more precise estimates were made by direct sampling at selected splash-zone sites for species of special recreational/commercial interest, such as opihi or limpets (Patellidae). Sampling involved the removal of opihi from randomly selected 1-yard squares. Individuals sampled were then measured to determine size and weight ranges.

The study data for the inner nearshore zone included only records of shoaling species observed adjacent to land in 1 to 2 feet of water. Use of the underwater fish count method was not feasible due to the shallowness of this zone. The information recorded included the species name and their approximate individual sizes (weight) and the estimated total biomass of fish schools.

In the outer nearshore zone, data on fish species composition, density, and size distribution were primarily obtained

through underwater fish transecting techniques modified to allow quantitative and qualitative inventory of the biota and habitat. Generally, this involved the laying down of a pre-measured transect line extending up to 250 yards along which fish species on both sides of the line were counted and their sizes estimated. Tabulation of fish species and documentation of their sizes were also accomplished within 100-foot diameter underwater areas to diminish the risks of encounters with sharks and to enable the surface support skiff to anchor in close proximity to the divers. Diving activities were conducted at depths ranging from 3 to 70 feet using either snorkel or scuba gear, depending on the depth.

Since underwater fish counts were conducted at sites where ocean conditions such as underwater visibility, current, wave action, and shark numbers were considered safe for diving, selection of survey sites tended to be biased. Also, there was a tendency to conduct surveys at sites where fish were more abundant. It was anticipated that these sampling biases would need to be adjusted.

In adjusting the fish count data, the outer nearshore zone for each island was first divided into smooth, moderate, and rough bottom habitat areas. Each fish count site was then categorized according to one of these habitat areas. Fish counts for each habitat area were then pooled to provide average estimates of fish for each respective type of bottom habitat.

In addition to underwater fish counts, other methods to determine species composition and sizes were used, including recording of surface observations and collection of samples with hook-and-line, throw-net, and spear. The collections provided specimens for determining identification, length-weight relationships, stomach contents, sex, and gonad development. Fish samples were also provided to other researchers to study age through otolith examination and ciguatoxicity through tissue analysis. Additionally, certain macro-algae and macro-invertebrates were hand collected and brought back for identification and other scientific purposes. Trapping was also conducted to determine the presence of spiny lobsters and to derive some measure of their density.

For tagging, specimens of ulua (Carangidae) were obtained by handline fishing. The tags, numbered plastic discs strung on a 100-pound break-strength monofilament line, were passed through and tied below the dorsal fin of the fish while length measurements were taken. The tag was slightly modified in 1979 when the monofilament line was replaced with a lock-knot line to expedite the procedure.

RESULTS AND DISCUSSION

The following are preliminary findings based on conservative calculations of data collected during the 6 years of research.

Survey Period

Nearshore fishery resource assessment surveys were conducted during the summer and fall months, except for a December survey conducted at Kure Atoll in 1979. Limiting nearshore surveys to the summer and fall months was due primarily to weather and sea conditions being unfavorable during other times of the year. During the December trip to Kure Atoll in 1979, winds of 30 to 60 knots, high surf, and strong ocean current conditions made it necessary to cancel field activities during 7 of 16 scheduled days of surveys. In comparison, field activities during the summer and fall months were cancelled less than 10 percent of the time.

A preliminary survey conducted in May-June 1976 to inspect the nearshore waters of the NWHI suggested seasonal abundance of sharks in the nearshore waters during that period. To minimize shark hazard to divers, survey periods were usually scheduled during the latter part of summer.

The modes of transportation to the NWHI were by ship or aircraft, with the latter used to survey Kure Atoll in 1979 and 1980 and Midway Islands in 1980. Annual ship cruises to the NWHI ranged from 24 to 45 days each. Land-based surveys at Kure Atoll and Midway Islands were conducted in 14 to 16-day periods.

Splash Zone Survey

Splash zone surveys were conducted on all of the islands in the NWHI, except at Maro Reef where no emerged land was observed. Splash zone substrate types were composed of lava rocks, limestone, or sand. Lava substrate dominated the splash zone habitat at Nihoa, Necker Island, La Perouse Pinnacles in French Frigate Shoals, and Gardner Pinnacles. Limestone beach was common to Laysan Island, Lisianski Island, and Pearl and Hermes Atoll. Although limestone habitat was also found at Midway Islands and Kure Atoll, it was restricted to outcroppings along the periphery of the fringing reef and was not part of the islands proper. Permanent sand beaches occurred at all islands except Nihoa, Necker Island, and Gardner Pinnacles.

The ohiki or ghost crab (Ocypode spp.) was found on all the permanent sand beaches. Based on the number of sand burrows, density estimates suggest that their abundance is sparse to moderate in comparison with the higher densities on Oahu beaches.

In contrast with sand beach habitat, a variety of macroinvertebrates and seaweed species was recorded from the lava rock and limestone habitats. Shellfish that were common to lava rock areas included the opihi, haukeuke or sea urchin (Colobocentrotus atratus), pipipi or sea snail (Neritidae), periwinkle (Littorinidae), and aama or rock crab (Grapsus grapsus). Shellfish on limestone substrate included the periwinkle and aama crab. Both were generally less abundant on limestone substrate than on lava

substrate. Exceptions occured at Laysan Island and Kure Atoll where large quantities of periwinkle and aama crabs, respectively were found. However, the aama crab noticed on exposed reefs at Kure Atoll appeared to be a different variety from the common darker aama crab found on rocky shores from Nihoa to Pearl and Hermes Atoll. Seaweed species common to rocky limestone and lava substrates in the splash zone were the green algae, Caulerpa racemosa, and the red algae, Galidiella sp.

Because of recreational and commercial interest in the opihi resources, more detailed information was collected on these resources than any other splash zone organisms. At least two species, Cellana melanostoma and C. sandwicensis, were abundant at Nihoa and Necker Islands. However, C. sandwicensis was not present at La Perouse Pinnacles or at Gardner Pinnacles.

Samples or counts taken from various parts of the lava splash zone habitat at different islands showed that opihi densities ranged from an average of about one per square yard (La Perouse Pinnacles) to about 50 per square yard (Nihoa). Although tabulation of all data related to opihi has not been completed, preliminary calculations suggest a total density of approximately 12,000 pounds for all four islands.

Inner Nearshore Zone Survey

Surveys conducted in the inner nearshore zone revealed large concentrations of aholehole or flagtail (Kuhlia sandvicensis), moi or threadfin (Polydactylus sexfilis), amaama or mullet (Mugil cephalus), and iao or silverside (Pranesus insularum) throughout most of the island areas in the NWHI.

The largest concentration of shoaling fishes in the inner nearshore zone was observed in 1977 at Pearl and Hermes Atoll, where an estimated 16,000 pounds of one-half pound size aholehole, 12,000 pounds of 1 to 5 pound size moi, 1,000 pounds of 3 to 5 pound size amaama, and 100 pounds of 1 pound size akule or big-eye scad (Selar crumenophthalmus) were recorded from Southeast, Grass, and Seal-Kittery Islands. These same locations, when resurveyed in 1978, provided an estimated 15,000 pounds of aholehole, 5,000 pounds of moi, 4,000 pounds of amaama, and 30 pounds of akule, all of similar sizes as that of the previous year. In addition, North Island was surveyed in 1978 when an estimated 10,000 pounds of 3 to 5 pound size amaama were observed.

The above density estimates of shoaling shallow-water species recorded from Pearl and Hermes Atoll represented only partial densities of larger populations. The exact population magnitudes of each species are not known. However, it is speculated that the density could be three times greater for amaama (14,000 x 3 = 42,000 pounds) and moi (12,000 x 3 = 36,000 pounds) and possibly 20 times larger for aholehole (16,000 x 20 = 360,000 pounds).

The iao, a baitfish which reaches approximately 5 inches in length, was not abundant at Pearl and Hermes Atoll. Rather, the largest concentration of iao occured at Lisianski Island in 1981 when an estimated 200 buckets (one bucket equals approximately 11 pounds) were recorded. The iao was also observed in significant quantities at Tern Island in French Frigate Shoals when a 1977 survey revealed a school estimated to contain 30 to 40 buckets. The piha (Spratelloides delicatulus), a dussumerid, another baitfish species that attains a maximum of about 2.5 inches in length, was observed in fairly large quantities along the shoreline throughout the NWHI. Since this species also occurred in the outer nearshore zone, no special effort was made to record its abundance during inner nearshore surveys.

Quantities of shoaling species varied from island to island. Generally aholehole was very abundant throughout the NWHI chain, especially at coral atolls. Although moi and amaama were abundant at Pearl and Hermes Atoll, they were not nearly as numerous at the other islands. Analysis of habitat types suggests that the disparity in densities may be due to availability of habitats for recruitment.

Evaluation of data also suggests that shoaling species were generally transitory in behavior. Moi was recorded in greater abundance along the shoreline during early rather than late summer. Variation in the densities of aholehole was also noted; the fish was more abundant during summer than fall.

Outer Nearshore Zone Survey

In all, 574 underwater fish counts were conducted at the various island areas in the NWHI. The transects conducted at each island area are summarized in Table 1. The underwater counts included 58 resurveys at select stations for monitoring annual variation. A winter survey was also conducted at Kure Atoll to determine seasonal variation in species composition and abundance.

Seasonal and Annual Variation

Although preliminary analysis of data from resurvey counts suggest variation in species composition and densities to some degree, except for a few species, the information does not indicate significant variation in fish populations. Among the exceptions, piha abundance varied from year to year, with the greatest abundance recorded in 1977. Although the kawakawa or little tunny (Euthynnus affinis) was rarely recorded during underwater fish counts, surface observations suggested a direct relationship in the abundance of kawakawa with the abundance of piha.

TABLE 1. NUMBER AND LOCATION OF FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS FROM 1977 THROUGH 1982

Location	Number of Fish Counts		
	Initial	Resurvey	Total
Nihoa	12	4	16
Necker Island	8	5	13
French Frigate Shoals	107	19	126
Gardner Pinnacles	4	--	4
Maro Reef	59	5	64
Laysan Island	33	3	36
Lisianski Island	42	2	44
Pearl and Hermes Atoll	134	13	147
Midway Islands	51	1	52
Kure Atoll	66	6	72
TOTAL	516	58	574

The survey conducted in December at Kure Atoll also suggested a lesser number of piha in winter than summer. The gray reef shark (Carcharhinus amblyrhynchos) appeared to be more abundant in nearshore waters during the early rather than latter part of summer.

Other nearshore resources with indications of undergoing seasonal variation in abundance included the tiger shark (Galeocerdo cuvier) and the day octopus (Octopus cyanea). Although tiger sharks were recorded only during observation surveys conducted from the skiff, the data indicate that more were observed during the early rather than the latter part of summer at Laysan Island, Lisianski Island, and Pearl and Hermes Atoll. Day octopus were more abundant during fall than summer, suggesting a similar pattern of seasonal abundance with the main Hawaiian islands.

Species Composition and Densities

Fish species recorded through fish transecting, general observation, and specimen collecting activities accounted for about 240 different species from the nearshore waters of the NWHI. In Table 2, fish species recorded from the underwater fish counts are summarized for each island. Taxonomic names for the fishes are based on Gosline and Brock (1960) and Masuda et al. (1975).

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Acanthuridae										
Acanthurus achilles	x	x	x		x	x	x	x		
A. dussumieri	x	x	x		x	x	x	x	x	
A. glaucopareius		x								
A. guttatus		x					x	x		
A. leucopareius	x	x	x	x	x	x	x	x	x	x
A. mata	x	x	x		x	x	x			
A. nigrofuscus	x	x	x	x	x	x		x		
A. nigroris	x	x	x	x	x	x	x	x	x	x
A. olivaceus	x	x	x	x	x	x	x	x	x	
A. thompsoni			x							
A. triostegus	x	x	x	x	x	x	x	x	x	x
A. xanthopterus	x		x							
Ctenochaetus strigosus	x	x	x	x	x	x	x	x	x	x
Naso brevirostris	x		x	x	x			x	x	
N. hexacanthus	x		x		x					
N. lituratus	x	x	x	x	x	x	x		x	
N. unicornis	x	x	x	x	x	x	x	x	x	x
Zanclus cornutus	x	x	x	x	x	x	x	x	x	x
Zebrasoma flavescens	x		x		x	x	x	x	x	x
Z. veliferum	x		x		x	x	x	x	x	x
Unidentified acanthurid								x		
Albulidae										
Albula vulpes			x							
Apogonidae										
Apogon kallopterus			x					x	x	x
A. maculiferus			x	x				x	x	
A. menesemus			x		x			x		x
Unidentified apogonid		x	x		x	x	x	x	x	x
Atherinidae										
Pranesus insularum			x		x	x	x	x	x	x
Aulostomidae										
Aulostomus chinensis	x	x	x	x	x	x	x	x	x	x
Balistidae										
Melichthys niger	x	x	x	x	x	x	x	x	x	x
M. vidua	x	x	x	x	x			x	x	x
Rhinecanthus aculeatus	x	x	x							
R. rectangulus	x	x	x	x						

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Sufflamen bursa	x		x							
S. frenatus	x		x							
Xanthichthys mento	x							x	x	x
Belonidae										
Belone platyura								x		
Strongylura gigantea									x	
Unidentified belonid	x					x	x	x		x
Blenniidae										
Cirripectes obscurus	x		x		x	x	x	x		x
C. variolosus	x	x	x		x	x	x	x	x	x
Entomacrodus marmoratus									x	
Exallias brevis	x	x	x	x	x	x	x	x		
Istiblennius sp.						x			x	
I. zebra				x						
Plagiotremus goslinei	x	x	x			x	x	x		
P. rhinorhynchus			x	x				x		x
Unidentified blenniid						x	x	x		x
Bothidae										
Bothus mancus			x							x
Canthigasteridae										
Canthigaster amboinensis	x	x	x			x	x			
C. coronata	x	x	x					x		
C. janthinopterus	x	x	x	x	x	x	x	x	x	x
C. rivulata				x				x		
Carangidae										
Carangoides ferdau	x	x	x	x	x	x	x	x	x	x
C. hemigymnostethus		x	x		x	x	x		x	x
C. cheilio			x			x		x	x	x
C. ignobilis	x	x	x	x	x	x	x	x	x	x
C. lugubris	x									
C. melampygus	x	x	x	x	x	x	x	x	x	x
C. sexfasciatus										x
Decapterus pinnulatus	x	x	x		x	x		x		
Elagatis bipinnulatus	x							x		
Scomberoides lysan			x				x			
Seriola dumerili	x		x				x		x	x
Selar crumenopthalmus								x		

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Carcharhinidae										
Carcharhinus amblyrhynchos	x	x	x	x	x	x	x	x	x	x
C. galapagensis			x					x		
Triaenodon obesus	x	x	x	x	x			x	x	x
Chaetodontidae										
Chaetodon auriga	x		x		x	x	x	x	x	x
C. citrinellus			x					x		
C. ephippium			x			x			x	
C. fremblii	x	x	x	x	x	x	x	x	x	x
C. lunula	x		x			x	x			
C. miliaris	x	x	x	x	x	x	x	x	x	x
C. multicinctus	x	x	x	x	x	x		x		x
C. ornatissimus	x		x		x	x	x	x	x	x
C. quadrimaculatus	x	x	x	x	x		x			
C. trifascialis			x		x					
C. trifasciatus			x		x	x	x	x	x	x
C. unimaculatus	x		x		x	x	x	x	x	x
Forcipiger flavissimus	x	x	x	x	x	x		x	x	x
Hemitaurichthys thompsoni			x					x		
Heniochus acuminatus			x							
Cheilodactylidae										
Goniistius vittatus			x		x	x	x	x	x	x
Cirrhitidae										
Cirrhitops fasciatus	x	x	x			x		x	x	x
Cirrhitus pinnulatus	x	x	x	x	x	x	x	x	x	x
Paracirrhites arcatus	x	x	x	x	x	x	x	x	x	x
P. forsteri	x	x	x	x	x	x	x	x	x	x
Unidentified cirrhitid		x								x
Clupeidae										
Spratelloides delicatulus	x	x	x	x	x	x	x	x	x	x
Congridae										
Conger cinereus					x			x	x	x

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Diodontidae										
Diodon hystrix	x	x	x	x	x	x	x	x	x	x
D. holocanthus	x		x		x			x	x	x
Fistulariidae										
Fistularia commersonii	x	x	x	x	x	x	x	x	x	x
Hemiramphidae										
Unidentified halfbeak	x	x	x		x	x	x	x	x	x
Holocentridae										
Adioryx sp.			x							
A. diadema			x			x	x	x		
A. ensifer					x	x		x		
A. lacteoguttatus			x	x	x	x	x	x	x	x
A. spinifer			x		x	x	x	x	x	x
A. tiere	x									
A. xantherythrus	x		x		x	x	x	x	x	x
Flammeo sammara	x			x	x	x	x	x	x	x
Myripristis amaenus	x		x		x	x	x	x	x	x
M. chryseres								x		
M. kuntee	x		x			x		x		
M. murdjan	x		x	x	x	x	x	x	x	x
Unidentified holocentrid			x					x		
Histiopteridae										
Histiopterus typus										x
Kuhliidae										
Kuhlia sandvicensis			x			x	x	x	x	x
Kyphosidae										
Kyphosus cinerascens	x	x	x	x	x	x	x	x	x	x
Labridae										
Anampses chrysocephalus			x					x	x	x
A. cuvier	x	x	x	x	x	x	x	x	x	x
Bodianus bilunulatus	x	x	x		x	x	x	x	x	x
B. sp.		x								
Cheilinus rhodochrous	x		x		x	x	x	x	x	x
C. bimaculatus						x		x		x
Cheilio inermis			x					x		
Coris ballieui			x		x			x	x	

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
C. flavovittata	x	x	x		x	x	x	x	x	x
C. gaimard		x	x			x		x		x
C. venusta	x	x	x	x	x	x	x	x	x	x
Epibulus insidiator			x		x	x	x	x	x	
Gomphosus varius			x		x	x	x	x	x	x
Halichoeres ornatissimus	x		x			x		x		x
Hemipteronotus leclusei			x			x			x	x
H. taeniourus			x			x		x	x	x
H. sp.							x	x		
Labroides phthirophagus	x	x	x	x	x	x	x	x	x	x
Macropharyngodon geoffroy		x	x	x	x	x	x	x	x	x
Pseudocheilinus octotaenia			x					x	x	x
Stethojulis balteata	x	x	x	x	x	x	x	x	x	x
Thalassoma ballieui	x	x	x	x	x	x	x	x	x	x
T. duperrey	x	x	x	x	x	x	x	x	x	x
T. fuscum	x	x	x		x	x				
T. lutescens		x				x		x		x
T. purpureum	x	x	x	x	x	x	x	x	x	x
Unidentified labrid		x	x			x	x	x	x	x
Lethrinidae										
Monotaxis grandoculis	x	x	x		x			x		
Lutjanidae										
Aphareus furcatus	x	x	x						x	
Aprion virescens	x	x	x					x	x	
Lutjanus kasmira			x							
Malacanthidae										
Malacanthus hoedtii			x					x		x
Mobulidae										
Manta alfredi			x		x					
Monacanthidae										
Alutera scripta	x									x
Cantherhines dumerili	x	x	x	x	x	x	x	x		x
C. sandwichiensis	x	x	x				x			
Pervagor spilosoma	x	x	x	x	x	x	x	x	x	x

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Mugilidae										
Mugil cephalus							x	x		
Neomyxus leuciscus						x	x			
Mullidae										
Mulloidichthys flavolineatus	x	x	x		x	x	x	x	x	x
M. vanicolensis	x	x	x	x	x	x	x	x	x	x
M. pflugeri			x							
Parupeneus bifasciatus	x	x	x	x	x	x	x	x		
P. cyclostomus	x	x	x	x	x	x	x	x	x	x
P. multifasciatus	x	x	x	x	x	x	x	x	x	x
P. pleurostigma	x	x	x	x	x	x	x	x	x	x
P. porphyreus	x	x	x	x	x	x	x	x	x	x
Muraenidae										
Echidna nebulosa									x	
E. sp.			x							
Gymnomuraena zebra			x							
Gymnothorax eurostus			x							
G. flavimarginatus	x		x		x	x		x	x	x
G. meleagris	x	x	x	x		x		x	x	
G. undulatus			x					x	x	x
Muraena pardalis					x			x	x	
Unidentified muraenid	x		x		x		x	x	x	x
Myliobatidae										
Aetobatus narinari		x	x	x	x	x		x	x	x
Ophichthidae										
Myrichthys maculosus								x	x	x
Ophidiidae:brotulidae										
Brotula multibarbarta	x									
Oplegnathidae										
Oplegnathus fasciatus				x		x			x	x
O. punctatus		x							x	x
Ostraciontidae										
Ostracion meleagris	x	x	x	x	x	x	x	x	x	x
O. whitleyi			x							x
Lactoria fornasini			x		x		x	x	x	x

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Polynemidae										
Polydactylus sexfilis								x		
Pomacanthidae										
Centropyge loriculus			x							
C. potteri	x	x	x	x	x	x	x	x	x	x
Genicanthus personatus								x		
Holacanthus arcuatus	x		x	x				x	x	
Pomacentridae										
Abudefduf abdominalis	x	x	x	x	x	x	x	x	x	x
A. sordidus	x	x	x			x	x	x	x	x
Chromis agilis			x			x		x		
C. hanui	x	x	x	x	x	x	x	x	x	x
C. ovalis	x	x	x	x	x	x	x	x	x	x
C. vanderbilti	x	x	x	x	x	x	x	x	x	x
C. verator	x		x		x			x	x	
Dascyllus albisella			x		x	x	x	x	x	x
Plectroglyphidodon imparipennis	x	x	x	x	x	x	x	x	x	
P. johnstonianus	x	x	x		x	x	x	x	x	x
P. sindonis			x							
Stegastes fasciolatus	x	x	x	x	x	x	x	x	x	x
Priacanthidae										
Priacanthus cruentatus			x			x	x	x	x	
P. meeki	x		x	x	x	x		x	x	x
Unidentified priacanthid	x		x	x	x	x	x	x	x	x
Scaridae										
Calotomus spinidens	x	x	x							
C. zonarcha	x	x	x	x	x	x		x	x	x
C. sp.			x		x	x		x	x	x
Scarus dubius	x	x	x		x	x	x	x	x	x
S. perspicillatus	x	x	x	x	x	x	x	x	x	x
S. rubroviolaceus	x	x	x		x					x
S. sordidus	x	x	x		x	x	x	x	x	x
Unidentified scarid	x	x	x	x	x		x	x	x	x
Scombridae										
Euthynnus yaito	x	x	x		x					

TABLE 2. FISH SPECIES RECORDED DURING UNDERWATER FISH COUNTS CONDUCTED IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1977-82 (continued)

Species	Location									
	NI	NE	FFS	GP	MR	LA	LI	PH	MI	KA
Scorpaenidae										
Dendrochirus barberi			x							
Pterois sphex								x		x
Scorpaenopsis cacopsis								x	x	x
S. diabolus									x	
Unidentified scorpaenid			x					x		x
Serranidae										
Epinephelus quernus									x	x
Pseudanthias thompsoni								x		
Sphyraenidae										
Sphyraena barracuda		x								
S. helleri			x							
Synodontidae										
Unidentified synodontid		x	x		x	x	x	x	x	x
Tetraodontidae										
Arothron hispidus			x			x		x	x	
A. meleagris			x		x				x	

Notes: NI = Nihoa; NE = Necker Island; FFS = French Frigate Shoals; GP = Gardner Pinnacles; MR = Maro Reef; LA = Laysan Island; LI = Lisianski Island; PH = Pearl and Hermes Atoll; MI = Midway Islands; KA = Kure Atoll; x = species was found at the location

In addition to fish species, numerous macro-invertebrates and seaweed species were recorded. The data collected indicated that fish species in the NWHI are similar in composition to that of the main Hawaiian islands, with a few exceptions.

Generally, the number of balistid species appeared to diminish in a northwesterly direction along the NWHI chain. The triggerfishes, Sufflamen frenatus and S. bursa, both very common in the nearshore waters of the main Hawaiian islands, were not observed beyond French Frigate Shoals. Similarly, the lavender tang, Acanthurus nigrofuscus, a very abundant acanthurid in the main Hawaiian islands, became progressively scarce further up the NWHI chain and were extremely rare beyond Laysan Island. The opelu kala (Naso hexacanthus), another common surgeonfish in the main Hawaiian islands which generally occurs in deeper water than most other acanthurid species, was not recorded beyond Maro Reef. With regard to species missing in or rare to the main Hawaiian islands, the sling jaw wrasse (Epibulus insidiator) and the false parrot fishes (Oplegnathus fasciatus and O. punctatus) were observed in the NWHI.

Species known to occur mainly in the deeper waters of the main Hawaiian islands were observed in shallow depths at the upper end of the NWHI chain. The hapuupuu or grouper (Epinephelus quernus), which is known only to occur in depths ranging from about 50 to 120 fathoms in the main Hawaiian islands, were observed at shallow depths (less than 10 fathoms) at Kure Atoll and Midway Islands. The butaguchi ulua (Caranx chelio), a carangid which is somewhat rare in the main Hawaiian islands but occasionally caught at depths over 30 fathoms, was also observed at shallow depths in the NWHI. Other species known to occur in deeper waters of the main Hawaiian islands but were found in waters of less than 10 fathoms in the NWHI, were the uu or squirrelfish (Myripristis chryseres), boarfish (Histiopterus typus), angelfish (Genicanthus personatus), and grouper (Pseudanthias thompsoni).

Evaluation of survey data suggests that geographical differences rather than fishing pressure is the cause of the species distribution patterns noted. However, the presence of larger size fishes and their greater abundance in the NWHI do indicate a lack of fishing pressure.

Depending on the selection of locations for the underwater fish counts, considerable variation in fish densities were noted. Generally, fish densities were low in smooth bottom areas. Higher standing fish crops were recorded where bottom profiles were irregular.

Although a detailed analysis of fish count data has not been completed, fish density estimates obtained from surveys in smooth bottom habitats ranged from 0 to 1,300 pounds per acre and averaged about 40 pounds per acre. Fish density estimates from surveys in moderate bottom habitats ranged from 15 to 5,200 pounds

per acre and averaged about 340 pounds per acre. Estimates from surveys in rough bottom habitats ranged from about 100 to 24,000 pounds per acre and averaged about 1,000 to 2,000 pounds per acre. Rough bottom habitats comprised about 20 percent of the nearshore environment; moderate bottom habitats about 30 percent; and smooth bottom habitats the remaining 50 percent.

Based on preliminary calculations, it is estimated that the shallow waters within the 10-fathom isobath of the NWHI support approximately 400 pounds of finfish per acre and about 150 million pounds of fish for the 10 islands surveyed. In terms of numbers, the baitfish piha far outnumbered other species of fishes, but their small size (1 to 2.5 inches) did not contribute much in terms of weight. The nenue (rudderfish) appeared to contribute most significantly to the biomass of the fishes in the outer nearshore zone. Nenue reaches a size of up to 6 pounds, but those recorded were mostly between 1 and 4 pounds.

Other fishery resources contributing significantly to the estimated biomass were the parrotfishes or uhu (Scarus spp.), jacks (Caranx spp. and Carangoides spp.), gray reef shark, goatfishes or weke (Mulloidichthys vanicolensis and M. flavolineatus), surgeonfishes (Acanthurus triostegus, A. nigroris, Naso unicornis, and A. leucoparius), and squirrelfishes (Myripristis amaenus and M. murdjan).

Evaluation of fish counts shows that differences in species biomass do occur between islands. The most abundant single species (e.g., nenue) did not consistently have the highest biomass at every island. Therefore, species abundance in the nearshore waters of the NWHI needs to be characterized island by island; this information will be included in a final report.

Information Derived From Fish Samples

Approximately 3,000 fish specimens, representing about 100 species, were collected by various methods. In addition to providing length and weight data, the specimens were used by appropriate research investigators to evaluate dietary items, sex, gonad conditions, and ciguatoxin levels, as well as to conduct analysis of select fish species.

Examination of the gut contents of the more common and abundant species suggests that approximately 60 percent by weight are herbivores and 40 percent carnivores. However, it should be kept in mind that many of the fishes seem to be at least facultative omnivores. Evaluation of the stomach contents of nenue, for example, suggests that this species feeds both day and night. In addition, although primarily herbivorous, fish and crustacean remains found in nenue guts suggest there is some degree of opportunism.

Because much of the gut content data has not been processed, the information will be provided later in a final report. Other

related information on dietary items of other species, has been reported by Okamoto and Kawamoto (1980) and Parrish et al. (1980); also see paper in this proceedings by Parrish et al.

Approximately 2,500 individual fish samples from the nearshore area of the NWHI were tested for ciguatera. Tests of tissue samples were conducted by the University of Hawaii, John A. Burns School of Medicine, Department of Pathology, using RIA (Hokama et al., 1977) and EIA (Hokama et al., in press) methods. Results of the test are provided in Okamoto (1981); also see papers in this proceedings by Kimura et al. and Ito et al.

Ciguatera test results show that fishes were more toxic during 1977-78 as compared with 1979-82. This finding may have some bearing on the high monk seal (Monachus schauinslandi) mortality reported from Laysan Island during 1978 by Johnson and Johnson (1981). Among the fish species tested, the poou (Cheilinus rhodochrous), a wrasse, had the highest incidence of toxicity. Its gut contents suggest a diet comprised primarily of small reef fishes.

Lobster Trapping

Underwater fish counts also included records of spiny lobsters (Panulirus spp.). To support transect estimates, lobster trapping was also conducted in the nearshore area. Preliminary evaluation shows that their densities vary from island to island, with estimates ranging from less than one lobster per acre to six lobsters per acre. Analysis of count data and trapping effort data suggests that the trap catch rates correspond with the observed densities except at Pearl and Hermes Atoll. The observed density estimate obtained from this area was about four lobsters per acre, the second highest recorded among the ten different islands. However, the trap catch-per-unit-effort results from Pearl and Hermes Atoll was about one-fourth that of Maro Reef whereas it should have been closer to two-thirds. Type of bait, moon-phase or trapping site were discounted for the catch discrepancy. Rather, it is suspected that the higher density of predatory white ulua or jack (Caranx ignobilis) at Pearl and Hermes Atoll than at Maro Reef (with about half as much white ulua), may be responsible for the lower catch rates at Pearl and Hermes Atoll.

Ulua Tagging

Approximately 500 white ulua ranging in size from 2 to 100 pounds were caught and tagged from French Frigate Shoals, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, and Kure Atoll to determine growth, movement, and density estimates.

Most of the white ulua tagged ranged from 5 to 20 pounds. In terms of catchability and the rate at which it was possible to tag the white ulua, up to 40 fish from a school containing about

200 individuals could be caught with two handlines and tagged within the first half-hour of fishing. After that the catch rate gradually declined.

To date, only one tagged white ulua has been recovered (at Lisianski Island in 1979). Unfortunately, without the identifying numbered disc, it was not possible to extract meaningful data from this fish. In the summer of 1980, two tagged fishes were sighted at Maro Reef. Although effort was made to recapture these fishes, they were not among some 67 fishes caught from a school estimated to contain 200 individuals. However, examination of tagging records suggest that both fish were tagged in the summer of 1978 at the same location. It is estimated that these fishes doubled in weight from 8 to 16 pounds during the 2-year period.

CONCLUSIONS

The purpose of the tripartite cooperative agreement was to collect biological information of various resources for future federal/state resource management plans that could adequately address the concomitant concern for judicious utilization of renewable resources while providing protection to the unique wildlife values of the NWHI.

Insofar as information concerning the nearshore fishery resources, much of the data collected by the DAR are still in the process of being tabulated and analyzed. A final report is forthcoming.

The nearshore fishery resource assessment study identified each island in the NWHI to be unique from the others. The disparities among islands in species distribution and densities could be useful as a source of information to estimate potential impact on the ecosystem should development of a certain fishery resource be proposed.

RECOMMENDATIONS

In view of the present status of this study, and especially since resource managers have not had the opportunity to review the information collected from the nearshore waters of the NWHI, any fishery resource management proposal for this area appears premature at this time.

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CIGUATERA RESEARCH IN THE NORTHWESTERN HAWAIIAN ISLANDS: LABORATORY AND FIELD STUDIES ON CIGUATOXIGENIC DINOFLAGELLATES IN THE HAWAIIAN ARCHIPELAGO

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ABSTRACT

In coral reef ecosytems, blooms of the toxic dinoflagellate, Gambierdiscus toxicus Adachi and Fukuyo, sporadically appear as benthic analogs of toxic planktonic dinoflagellate "red tides." Gambierdiscus toxicus synthesizes toxins which are apparently accumulated through the food web into many species of tropical and subtropical fish, resulting in occasional "ciguatera fish outbreaks" harmful to humans. Little is known about the distribution, growth, and toxin synthesis of this dinoflagellate which was postulated in 1977 to be the primary source of toxin in ciguateric outbreaks. The aim of this research was to learn about the distribution and toxicity of G. toxicus in the NWHI chain. Parallel laboratory studies measured growth and toxin synthesis of the species under controlled conditions.

Results of field studies revealed the widespread yet low-level distribution of G. toxicus (found only on macroalgal substrates) throughout the NWHI: population densities ranged from 3 to 119 dinoflagellate cells per gram weight macroalgal substrate. A marked preference was indicated by the dinoflagellate for specific red and brown algal substrates (especially Dictyota acutiloba, Spyridea filamentosa, and Acanthophora spicifera). Limited "epibenthic blooms" occurred with no seasonal regularity on sites studied on Oahu and at French Frigate Shoals. No specific factors which could trigger a bloom were found; although the data indicate that temperature range and substrate availability may control blooms.

Wild cells collected on Tern Island, Oahu, and Hawaii were always highly toxic as measured by mouse intraperitoneal (i.p.) injection of extracted cells (for wild cells, the LD_{50} was 750 cells/mouse). In culture, the Kaneohe Bay, Oahu clone synthesized only one-eighth as much toxin as the "wild" parent population (LD_{50} of 6,200 cells/mouse for cultured cells from dose response studies by mouse i.p.). Both the Kaneohe Bay clone and the Tern Island clone in mass culture (in 200L of F/2-t media plus seaweed extract at 25° to 27°C and 40 microeinsteins/m^2/sec) yielded consistently large amounts of the potent water soluble toxin "maitotoxin" which appears in many edible fishes. However, little, if any, "ciguatoxin" (compared with reference moray eel ciguatoxin) was detected in these cultured cells. The reason for the reduction in total toxin and apparent absence of ciguatoxin in G. toxicus cultured cells vs collected "wild" cell populations is unknown.

Based on G. toxicus population levels, it is not currently possible to predict ciguatera outbreaks and a reliable test for the detection of ciguatera toxins in fish has not been developed yet. Therefore, a fisheries developed in the NWHI would be subject to the same risk of ciguatera fish poisoning as all other tropical and subtropical fisheries around the world. Fortunately epidemiological studies indicate lower incidence of ciguatera in the Hawaiian islands in comparison with many other Pacific and Caribbean islands.

toxic dinoflagellate
Gambierdiscus toxicus
Northwestern Hawaiian Islands

ciguatera
seaweed

INTRODUCTION

Ciguatera is a term referring to human intoxications resulting from the ingestion of a variety of tropical reef and inshore fishes which produce diverse but characteristic symptoms, infrequently causing mortality (Banner, 1976; Lewis, 1981; Withers, 1982). The term ciguatera was derived from a name used in the eighteenth century in the Spanish Antilles for intoxication brought about by ingestion of the "cigua" or turban shell Cittarium (Livona or Turbo) pica (Lawrence et al., 1980). Ciguatera was recorded (Gudger, 1930) in the West Indies by the first historian of the Americas, Peter Martyr (1457-1526), and noted in the Pacific as early as 1606 when the sailors with the Spanish explorer de Quiros suffered from ciguatera in the New Hebrides (Banner, 1976). Toxic outbreaks of ciguatera are sporadic and unpredictable, with a patchy distribution in both space and time (Halstead, 1978; Cooper, 1964). The syndrome affects both tropical and subtropical coastal regions of the world, but is largely confined to islands in the true tropics (Banner, 1976). Ciguatera fish poisoning has characteristic gastrointestinal and

neurological symptoms and it is occasionally fatal (Lawrence et al., 1980). In recent surveys (1971-77), ciguatera outranked both scombroid (fish) and paralytic shellfish poisoning as the most frequently reported foodborne disease of chemical nature in the United States, where most of the cases are from southeastern Florida and Hawaii (Hughes, 1979). In the Caribbean and the South Pacific, it is a much more widespread and serious problem, not only as a general health hazard but also because of the restrictions it imposes on the use of fish resources in these tropical island regions, many of which depend upon reef fish as an important protein source (Bagnis, 1973; Dawson, 1977; Morris, 1980). Mortality of an endangered species, Monachus schauinslandi (Hawaiian monk seal) on Laysan Island in the Northwestern Hawaiian Islands may be a result of ciguatera poisoning (Gilmartin et al., 1980).

The liver of the moray eel, Lycondontis javanicus, has been extracted for the major toxin, ciguatoxin, a lipid-soluble, compound of molecular weight 1112, which has been recently crystallized (Scheuer et al., 1967; Nukina et al., in press). Ciguatoxin and other toxins associated with ciguatera (including "ciguaterin" and maitotoxin) arrive in the fish from their diet. A new species and genus of dinoflagellate, the benthic Gambierdiscus toxicus Adachi and Fukuyo, is a suspected source of these toxins (Taylor, 1979). We report here on toxicity of the Hawaiian strain of G. toxicus and its distribution throughout the Northwestern Hawaiian Islands.

MATERIALS AND METHODS

Field Survey

The method of collecting and measuring populations of G. toxicus was a simple procedure slightly modified from that of Yasumoto et al. (1979), which takes advantage of the epiphytic nature of this species. Algae and other substances were collected from selected areas at the 0 to 15 m depth by skin or scuba diving. The algae (or coral debris) were placed in a plastic bag underwater and brought to shore where 50 to 100 g wet weight seaweed (by displacement) were measured out in a 500-ml cylinder filled with filtered seawater. After vigorous shaking 50 times, the suspended material was screened successively through 1-mm, 250-μ, and 75-μ mesh screens. The filtrate was passed through a 36-μ mesh screen, and all the material which was retained was transferred to an 8-ml screw cap tube for immediate microscopic examination, or if no microscope was available, a 3 percent formalin solution was prepared to preserve the specimen for later counting. Table 1 gives the results of G. toxicus sampling in the Hawaiian islands.

TABLE 1. *GAMBIERDISCUS TOXICUS* SURVEY

Date	Location	No. Samples Collected	No. Samples With *G. toxicus* Present	No. Cells *G. toxicus*/ 100-g Substrate	Substrate
08/78	Hawaii: Keokea Beach Spencer's Beach (Taylor, 1979)		Present in low numbers	Very low numbers	*Ceramium*, *Chondria*, *Wrangelia*, *Gelidium*, *Sargassum*, *Padina*, and *Turbinaria*
01/78	Oahu: Coconut Island	--	+	+	
08/78	Oahu: Checker Reef, Kaneohe Bay Pokai Bay (Taylor, 1979) Lualualei Beach Park Kewalo Basin		+ + + +	100 cells/algal thallus Very low numbers Very low numbers Very low numbers	Absent from *Ulva* and *Codium*
08/78	Coconut Island water tables		+		*Pseudobrvopsis* sp.
10/10/80	Checker Reef, Kaneohe Bay	--	+	500 cells	*Sargassum polyphyllum*
09/18/80	Lagoon edge of barrier reef, Kaneohe Bay	--	+	48 cells	*Acanthophora spicifera*
03/21/80	Kualoa Point (4 locations -- sand, mud, and coral substrate) 0 to 20 ft	21	0	0	*Turbinaria*, *Acanthophora* *Sargassum*, coral rubble, sand
01/29/81	Checker Reef, Kaneohe Bay 3 to 6 ft	4	2	6 cells 0 0	*Turbinaria ornata* *Acanthophora spicifera* *Dictysphaeria*
01/29/81	Coconut Island, lagoon Kaneohe Bay	1	0	1 cell 0	*Eucheuma* sp.
02/09/81	Pokai Bay	1	1	50 cells	*Sargassum polyphyllum*
11/05/80	Nihoa (west side)	6	Possibly 1	3 cells	*Ahnfeltia concinna* (red)
11/10/80	French Frigate Shoals a. Tern Island SE reef, inshore b. Whaleskate Island	8 7	4 0	3 to 12, $\bar{X}$ = 7 0	*Colpomenia sinuosa*, *Halimeda opuntia*, and *Laurencia nidifica* *Laurencia* sp., *Microdictyon* sp.
11/16/80	Laysan Island a. West reef	5	5	100 to 400, $\bar{X}$ = 200	*Laurencia* sp., *Halimeda opuntia*, *Halimeda discoidea*, *Chaetomorpha* sp., and *Dictyota* sp.
	b. SW reef	6	6	12 to 160, $\bar{X}$ = 54	*Martensia fragilis*, *Turbinaria ornata*, *Dictyota* sp., *Laurencia* sp., *Plocamium* sp., *Halymenia* sp., and *Halimeda*
11/17/80	c. Rock ledges, high wave action	2	0	0	*Sargassum echinocarpum*
11/19/80	Pearl and Hermes Atoll a. Seal Island	4	1	2	On coralline - *Porolithon*, *Jania*. none - *Microdictyon* sp., *Cladophora* sp., *Neomaris* sp.
	b. SE Island (1) inner reef	1	0	0	Red/bluegreen epiphytes
	(2) leeward patch reef - offshore	2	2	3 to 20	*Laurencia nidifica*, *Trichoglea requienii*
08/07/81	Tern Island NE beach	1	0	0	*Lyngbya* sp. (rose colored)
	S reef, 8 ft	2	1	10	*Acanthophora spicifera*
	S beach, sand	1	1	4	*Acanthophora spicifera*
	N beach	1	0	0	*Acanthophora spicifera*
08/08/81	Tern Island SE end and Open ocean	3	0	0	*Halimeda*, *Lobophora variegata* on *Pocillopora*
	Tern Island W beach, off pier	1	1	200	*Laurencia*, *Lyngbya confervoides*, *Dictyota acutiloba*
	Scuba, 15 ft				
	Scuba, 12 ft	1	1	11,200	*Dictyota acutiloba*
	Scuba, 12 ft*	1	1	10,000	*Dictyota acutiloba* + *Lyngbya* sp.

*Collected for toxicity testing, mouse intraperitoneal bioassay. Overall toxicity: less than 1,000 cells/mouse unit, Table 2. Clone in culture at HIMB (labeled "clone T-39-1").

Cultures

Single cell isolates were made directly from these samples by micropipetting and washing (with serial dilutions) single G. toxicus cells. To reduce diatom contamination, GeO_2 (80 ppm) was added. The cultures were grown in F/2-t media (Guillard, 1975) plus seaweed extract (aqueous autoclaved extract of blended fresh A. spicifera and Sargassum sp. added at 1 ml/l) at 40 micro-einsteins/m^2/sec and 25°to 27°C, without aeration, in Fernbach flasks.

Extraction

For the dose response study, the "wild cell" samples of G. toxicus (GT) cells (Kaneohe) mixed with sand and macroalgal fragments were combined and extracted with 150-ml MeOH. After filtration, the residue was re-extracted three times with 100-ml MeOH and mild heating. The methanol extracts were combined and lyophilized to yield a dry weight of 1.24 g which was redissolved in 25-ml methonol. Portions were removed for i.p. injections to estimate toxicity. The highest dose (7 mg extract, dry weight) represents 6.2×10^3 cells of GT extracted. The cultured cells were harvested by centrifugation and immediately extracted with 50-ml MeOH. The extraction procedure was repeated as for the wild cells, and a portion of the methanol extract was used for the dose response curve (maximum dose represents 4×10^4 extracted cultured GT cells).

Fractionation of Extract

The total methanol extracts remaining after the dose response test was evaporated and brought up in 125-ml ether/water, 4/1, v/v. The water phase was re-extracted with ether two times, and the ether fractions combined. The water-soluble material was lyophilized and brought up in MeOH of which portions were used for bioassay. The ether-soluble material was evaporated and brought up in ether, portions of which were tested by bioassay.

Bioassay -- Mouse i.p. Infections

Aliquots of extracts from G. toxicus were transferred in methanol to small tubes, evaporated to dryness under vacuum, weighed, and brought up in 5 percent Tween 80 in distilled water and homogenized with a vortex-mixer. Several controls were used in each experiment with no toxic extract added. The injection volume was 0.5 ml, applied intraperitoneally to ICR female mice, averaging 20 g.

Toxicity

Dose response curves with death as the endpoint were determined for two toxic extracts: the methanol extract (which contains both ether and water-soluble toxins) of GT cells collected

from the reef and GT cells in culture. The LD_{50} as expressed in equivalent cells or weight from this test was used as a quantitative measurement of toxicity.

In addition, for smaller samples, a "cell/mouse unit" value was determined as a rough estimate of toxicity. A "mouse unit" is the minimal amount of toxin required to kill a 20-g mouse within 48 hours.

RESULTS

Low-level cell counts (0 to 500 cells/100 g algal substrate) of Gambierdiscus toxicus were found in most collection sites in this survey of Oahu and the Northwestern Hawaiian Islands. G. toxicus was present in 45 percent of the samples collected, indicating a widespread, if low-level, distribution of the organism (Table 1). High levels, 400 to 500 cells/100-g substrate, were found on Laysan Island and Checker Reef, Kaneohe Bay in October and November 1980; 250 cells/100-g substrate on Tern Island. Several limited "blooms" (>1,000 cells/100-g substrate) were found around the island of Oahu: at Portlock (maximum 26,400 cells/100 g), Sand Island (11,800 cells/100 g), Kapiolani Park (24,000 cells/100 g), Kalanai Point (15,300 cells/100 g), Waimanalo (10,800 cells/100 g), and all around Kaneohe Bay (maximum 72,500 cells/100 g at Ahuolaka). There was no apparent seasonal periodicity in the appearances of the confined blooms on Oahu. On Tern Island, a confined bloom of 11,200 cells per 100 g of Dictyota acutiloba were collected by scuba. Ostreopsis sp. was also detected (at a level of about 300 cells per 100-g wet weight macroalgal substrate) (Withers, 1981).

Environmental parameters at "bloom" sites (on Tern Island) were standard: pH, 8.0 (night) to 8.25 (day); temperature, 27.5°C (range: 26.5° to 28°C); oxygen, 5.5 ppm (day) to 7.5 ppm (night); CO_2, 0.02 mM/L (calculated); alkalinity, 2.35 mM/L; PO_4, 0 to 0.1 M; and salinity, 35.5 °/oo (range: 35 to 36.5 °/oo). No large fluctuations were detected in pH, CO_2, O_2 or PO_4 levels. No specific factors which could trigger a bloom were found, although temperature and macroalgal substrate availability may control blooms.

In the Hawaiian islands, the highest levels of G. toxicus were found on the brown algae, Dictyota acutiloba and Sargassum polyphyllum, and the red algae, Spyridea filamentosa and Martensia fragilis. Next highest levels were detected on Acanthophora spicifera, Laurencia sp. (rhodophytes); Turbinaria ornata and Dictyota sp. (phaeophytes), and Halimeda opuntia, H. discoidea, and Chaetomorpha sp. (chlorophytes). No G. toxicus cells were seen in the coral rubble or and particle samples in the present study. Both large benthic dinoflagellates, Ostreopsis sp. and Coolia sp., were occasionally present in the algal samples; Coolia sp. co-occured most frequently with G. toxicus. The Hawaiian strain of G. toxicus ranges from 40 to 100 μ in diameter.

These values approximate the lowest population levels found in the South Pacific by Yasumoto et al. (1979). In that survey, a drop in numbers of G. toxicus from 76,500 to 450 cells/100 g of algae occurred on Hitiaa after a 15-month period. This was representative of population changes in the Tahiti region in general. In the Gambier Islands, much higher concentrations of G. toxicus -- 17,000 to 31,800,000 cells/100 g algae -- were found. By comparison, in the Caribbean Islands, population densities of G. toxicus ranged from 0 to 60,000 cells/100-g substrate which is lower than the South Pacific but still higher than the Hawaiian island populations reported here (F.J.R. Taylor: personal communication; Besada et al., 1982).

Toxicity

The dose response curves are shown for the "wild" and cultured G. toxicus cells, crude methanol extract (Figure 1 and Table 2). Table 3 shows that total toxin production on a per cell basis is eight times greater in the "wild" G. toxicus cells than in the cultures. The extract from the cultures gave an LD_{50} of 6200 cells per mouse in contrast with the LD_{50} of 750 cells for the "wild" GT cells (Figure 1).

Symptoms elicited by the crude extract (total toxins) from G. toxicus in "wild" cells included dyspnea, temperature depression, and apparent respiratory failure. For the cultured cells, apnea, temperature depression, and occasional viscous saliva were elicited. There was no severe diarrhea in either wild or cultured cells of G. toxicus as noted with eel ciguatoxin. In mice treated with cultured cell extract, the heart was still fibrillating 10 minutes after death. The most significant symptom common to both "wild" and cultured cell extracts upon injection in mice was the extreme depressed body temperature (detected upon touch) (Sawyer et al., in press).

Symptoms elicited by the "ether" extract (so-called ciguatoxin) of the wild cells included convulsions just prior to death, pytalism, and apnea. Symptoms from the methanol fraction (so-called maitotoxin) from the wild GT cells included diarrhea, exopthalmia, and depressed body temperature.

In the cultured cells, most if not all of the toxicity was associated with the water-soluble (a "maitotoxin" fraction) (Table 3). When the ether-soluble fraction of the mass cultured cell extract was re-chromatographed, no substantial toxicity was detected in the fraction corresponding exactly to that of authentic ciguatoxin from G. javanicus (Nukina et al., in press). However, both the G. toxicus cultured cell extracts and the eel ciguatoxin shared three unique properties in the mouse i.p. bioassay: (1) a very steep dose response curve (Figure 1), (2) heat stability, and (3) temperature depression (Sawyer et al., in press).

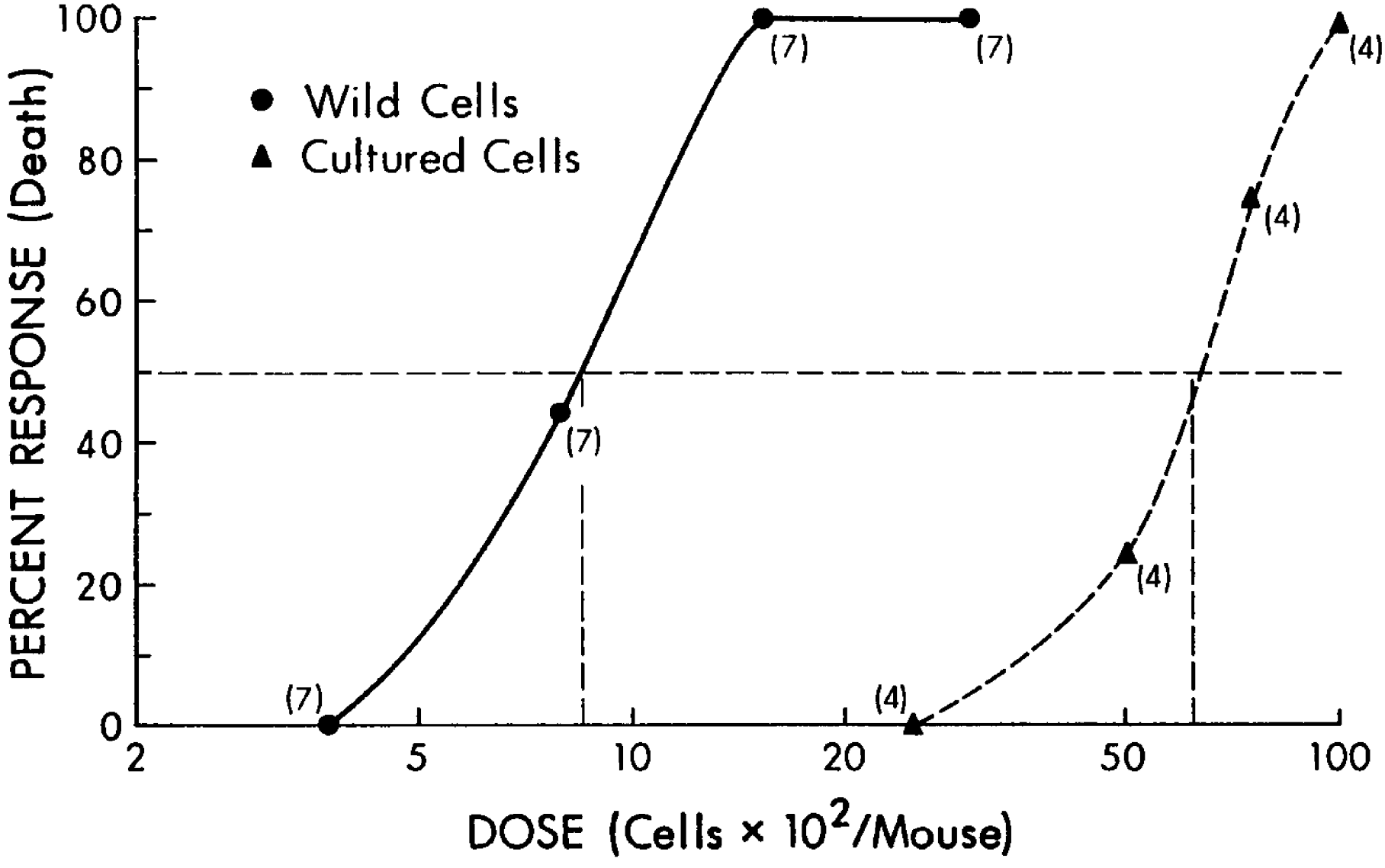

Figure 1. Dose response curves for "wild" and cultured Gambierdiscus toxicus cells (Oahu strain), crude methanol extract

TABLE 2. DOSE RESPONSE CURVE -- G. TOXICUS TOTAL TOXINS, MOUSE INTRAPERITONEAL BIOASSAY

No. of Mice Injected	Amount Crude Toxin (mg)	Equivalent Number Cells Extracted X10^4	% Response (death)	Death Time x ± SD (min)
Wild cells, Kaneohe Bay (4/81)				
4	0	0	0	0
7	7	6.2	71	156 ± 47
7	3.5	3.1	100	205 ± 79
7	1.75	1.55	100	548 ± 205
7	0.875	0.775	57	1,248 ± 151
7	0.4875	0.388	0	0
Cultured cells, Kaneohe Bay isolate (8/81) (isolated from "wild cells" above)				
4	--	40	100	150 ± 18
4	--	20	100	194 ± 26
4	--	10	100	699 ± 305
4	--	7.5	75	753 ± 37
4	--	5.0	25	1,000
4	--	2.5	0	0

TABLE 3. TOXICITY OF *GAMBIERDISCUS TOXICUS*, HAWAIIAN ISLANDS MOUSE INTRAPERITONEAL BIOASSAY

I. Crude extract, methanol

Location	Substrate	Equivalent Cell Number Tested (10^4)	Mouse Weight (g)	Death Time (min)	Approximate Cells/Mouse Unit (x)	LD_{50} (cells/mouse)
G. *toxicus*, "wild cells"						
HIMB docks	*Spyridea filamentosa*	2.5	20	720	<25,000	
HIMB docks	*Spyridea*, *Dictyota*	3.86	20	3		
Sand bar	*Spyridea*, *Dictyota*	0.62	19	159	1,500	750
Kaneohe Bay	*Spyridea*, *Dictyota*	1.8	21	80		
Tern Island pier (Table 1)	*Dictyota*	0.1	26	1,020	< 1,000	—
G. *toxicus*, cultured						
HIMB isolate		10.0	20 28	699 ± 305	10,000*	6,200*

II. Fractionated extracts, ether soluble "ciguatoxin" and water soluble "maitotoxin" of "wild" *G. toxicus* cells

Location	Equivalent Cell Number Tested (10^4)	Mouse Weight (g)	Death Time (min)	Cells/MU "Ciguatoxin" Fraction (x)	Cells/MU "Maitotoxin" Fraction (x)
Kaneohe Bay					
Ether soluble	13	18	959		
Ether soluble	11.3	23	48		
Ether soluble	11.3	21	24	~60,000	
	13.5	26	68		
	6.48	24	73		
Water soluble	6.48	20	NF		
Water soluble	11.6	22.5	2		
Water soluble	5.8	21.5	3		11,600
Water soluble	1.16	25.0	1,305		
	1.16	265	1,328		
Water soluble	2.32	25.0	301		
Water soluble	3.9	25.0	235		
Kaneohe Bay[†]					
Ether soluble				32,000 (+/-5,000)	
Water soluble					8,200 (+/-800)

*Collected for toxicity testing, mouse intraperitoneal bioassay. Overall toxicity: less than 1,000 cells/mouse unit, Table 2. Clone in culture at HIMB (labeled "clone T-39-1").

†Shimizu et al., 1982

CONCLUSIONS

A survey through the Northwestern Hawaiian Island chain revealed a widespread low-level population distribution of the epibenthic dinoflagellate Gambierdiscus toxicus. Cell counts normally ranged from 0 to 500 cells/100-g macroalgal substrate. Several epibenthic blooms (1,000 cells/100-g substrate) were found but there was no obvious environmental factor which could explain their appearance. The dinoflagellate appeared most frequently on certain preferred macroalgal "host" species, e.g., Spyridea filamentosa and Dictyota acutiloba.

The dinoflagellate, Gambierdiscus toxicus, Hawaiian strain produces potent toxins, although the cells in culture produce only one-eighth the overall toxicity of the cells collected from the field. Both an "ether-soluble" toxin which may be ciguatoxin and a "water-soluble" toxin are present in the "wild" cells. However, the cultured G. toxicus cells synthesize a "water-soluble" (apparent maitotoxin) fraction; there was little if any toxin which could be identified as ciguatoxin in these cultured cells. However, the three features which are common to both the G. toxicus toxin and eel ciguatoxin (temperature depression in mice, heat stability, and a steep dose response curve) suggest the possibility of bioconversion of the G. toxicus toxin to ciguatoxin in the coral reef food chain. The reasons for the discrepancy in toxin production by G. toxicus cells in the "wild" vs in culture are not known and will be the subject of future study.

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BIOLOGY, DISTRIBUTION, POPULATION STRUCTURE, AND PRE-EXPLOITATION ABUNDANCE OF SPINY LOBSTER, PANULIRUS MARGINATUS (QUOY AND GAIMARD 1825), IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

This overview incorporates results of studies conducted on the spiny lobster, Panulirus marginatus (Quoy and Gaimard 1825), resource in the Northwestern Hawaiian Islands by the Honolulu Laboratory from October 1976 to September 1981. Of 26 sites surveyed, only Necker Island and Maro reef appeared to have sufficiently large stocks for commercial exploitation. Included also are data on historical catches and fishery development, and results of analyses on geographic and depth distributions, pre-exploitation abundance, size composition, sex ratio, size at maturity, reproduction, behavior, and morphometry. Extrapolation of results from the assessment of the stock at Necker Island provided estimates of the maximum sustainable yield of spiny lobster for the entire Northwestern Hawaiian Islands.

Discussions on economics, fishery potential, and management guidelines are also presented.

spiny lobster	Northwestern Hawaiian Islands
biology	population structure
abundance	distribution

INTRODUCTION

Before 1976, little was known about the marine resources of the Northwestern Hawaiian Islands (NWHI) (Figure 1) and, except for a few commercial fishermen who used French Frigate Shoals as a fishing base or those who made periodic fishing trips for bottomfish, these resources were virtually untouched by humans.

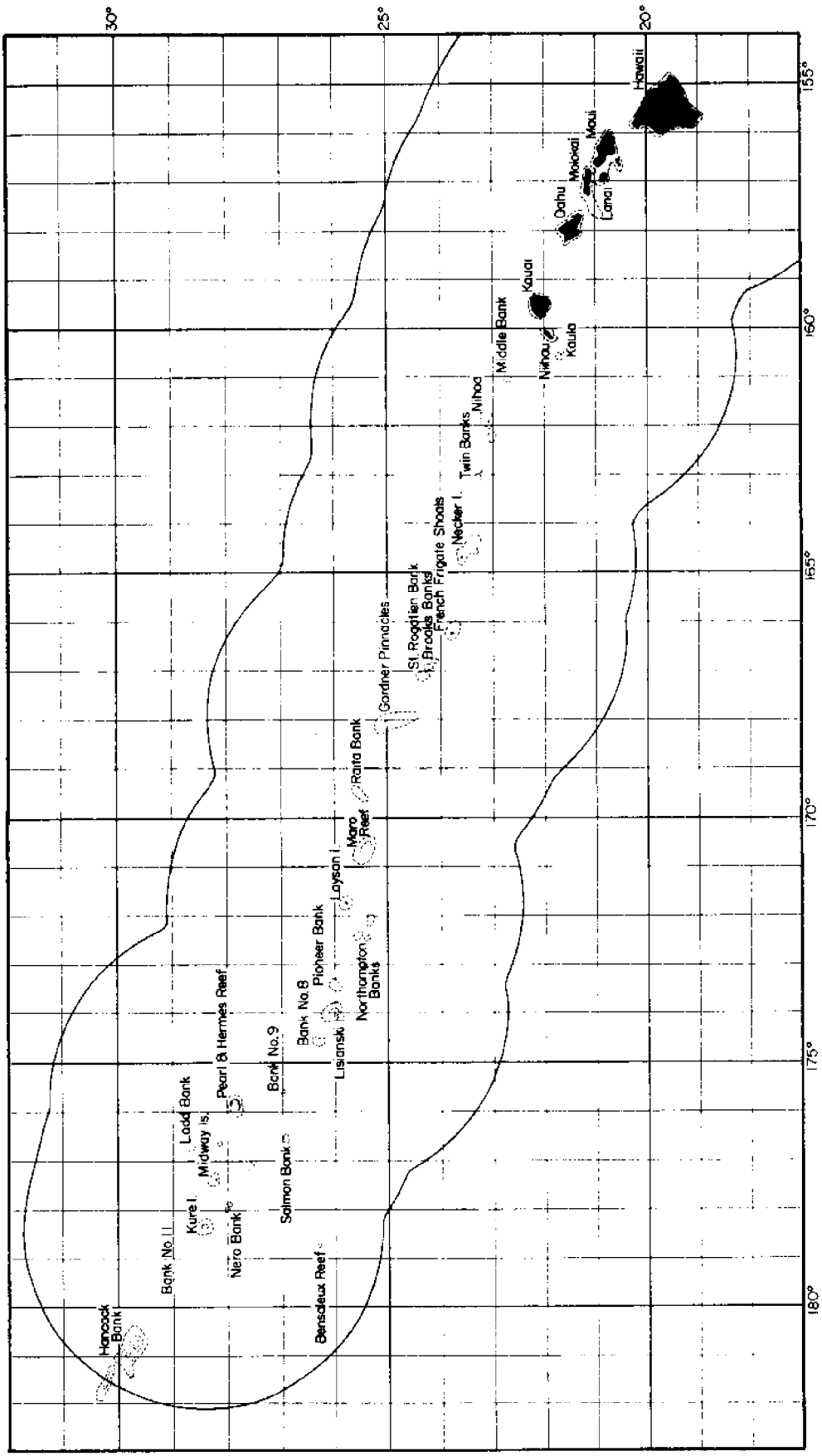

Figure 1. The Hawaiian Archipelago, including the Northwestern Hawaiian Islands

The sequence of events that led to the investigation of the marine and terrestrial resources of these islands is documented in Uchida et al. (1980) and Grigg and Pfund (1980).

From October 1976 to September 1981, the Southwest Fisheries Center Honolulu Laboratory of the National Marine Fisheries Service conducted resource surveys in the NWHI, concentrating on those species of economic significance and high development potential. The objectives of these surveys were to investigate the unfished waters of the NWHI to determine the species that were available, to define their distribution and abundance, to make a first estimate of their potential yield, and to provide preliminary estimates of the likely catch rates. Among the species that showed excellent potential for development was the spiny lobster, Panulirus marginatus.

Thus studies were undertaken to determine the geographic and depth distribution, fecundity and spawning, growth and movement, behavior, population structure, and population dynamics of the spiny lobster. Also studied were predation on spiny lobsters, gear competition, and ghost fishing. The results of these surveys form the basis of this overview report. Results of many of the experiments and individual studies are included in published and unpublished reports of the Honolulu Laboratory.

MATERIALS AND METHODS

The data for this study were obtained from trapping operations of research and charter cruises. The standard gear used was the California two-chambered lobster pot. Because fish traps were also used during the surveys, and because lobsters were also taken by these traps, data from fish trapping stations are also included. Both the pot and trap had identical entrances; however, several pots and traps with modified entrances were used for special studies. The lobster pot and fish trap are described in detail in a forthcoming fishery atlas of the NWHI by R.N. Uchida and J.H. Uchiyama.

On our first cruise (TC-76-06), lobster pots and fish traps were alternated on a string. Each lobster pot was separated from the fish trap by 5 m; each pair of trap-pot combination was spaced 18 m apart. Only two pairs of trap-pot combination were used per string with six strings making up the set at each station.

On subsequent cruises, usually eight lobster pots, spaced 35 m apart, were attached to one string and up to five strings were set at varying depths between 20 and 91 m (10 and 50 fathoms); the pots were occasionally set as shallow as 4 m (2 fathoms). For fish traps, usually four traps were placed on a string and up to five strings set at each station. Depths varied from 9 to 337 m (5 to 75 fathoms).

Occasionally, special large-entrance lobster pots were set as deep as 183 m (100 fathoms) to determine whether large lobsters (>140-mm carapace length, CL) were in deeper water and also to examine the spiny lobster's depth distribution. At some stations, fish traps were set singly to depths of 329 m (180 fathoms) to evaluate the catchability of fishes of the snapper-grouper complex; the data obtained from these stations were used to define the spiny lobster's depth limits.

Trapping stations were occupied from about 1800 to 0800 thereby allowing the pots and traps to soak for about 14 hours.

Because almost nothing was known about the distribution of spiny lobsters in time and space (various habitats), preliminary surveys were conducted to identify the most promising sites within the NWHI. A search for suitable depth and bottom conditions was required to make the most efficient use of gear and fishing time. Stations were selected by using existing navigational and bottom contour charts; where information was lacking, bathymetric profiles were first obtained with the echo sounder.

The sampling scheme was modified, after analysis of data from the preliminary surveys, to increase the efficiency of later surveys. The area around each island, bank, and atoll was subdivided into smaller grids or equal-area sampling units 0.1° of latitude and longitude, and within each grid, fishing stations were stratified, whenever possible, by depth. Although some sets were made in waters less than 18 m, sampling was usually confined to the inner shelf (18 to 36 m), outer shelf (36 to 45 m), and shelf edge (45 to 90 m). Some sets were also made in the slope zone (90 to 360 m).

Records were usually kept of the number of legal, sublegal, male, female, and ovigerous female lobsters caught. For most of the lobsters, missing appendages, carapace length, weights, and whether or not the female bore spermatophores (mated) were also recorded. When catches were large or when time was limited, only the total number and weight caught were recorded and the catch was subsampled for lenghts and weights.

For this study, effort is defined as a pot-night for the lobster pot and a trap-night for the fish trap, that is, one pot or one trap fishing overnight, usually for 14 or more hours.

RESULTS

Taxonomy

The spiny lobsters, a clearly defined group in the order Decapoda, can be distinguished from the true lobsters by the lack of claws and the presence of a subcylindrical spiny carapace. In Hawaiian waters, two species of spiny lobsters are found around the major islands -- P. marginatus and P. penicillatus. Although the species may sometimes be confused with one another, there are

distinguishing features that easily separate the two. In P. marginatus, the anterior border of the carapace is armed with a pair of strong prominent frontal horns above the eyes, whereas in P. penicillatus, there are two pairs of strong anterior spines on the antennal plate (McGinnis, 1972).

Panulirus marginatus is endemic to the Hawaiian islands (George and Holthuis, 1965) and Johnston Atoll (Brock, 1973). Panulirus penicillatus, the most widely distributed Indo-Pacific Panulirus species, is found from the Galapagos Islands in the east to the Red Sea in the west (Holthuis, 1947).

Historical Catch and Fishery Development

Before the fishery expanded to the NWHI, spiny lobsters were mostly caught around the major Hawaiian islands. The catches were small and constituted only an insignificant part of the total marine fish and shellfish landings in the state. In 1961-75, the mean annual catch reported to the Division of Aquatic Resources, Hawaii Department of Land and Natural Resources, was 3 metric tons (MT) or less than 1 percent of the state's total marine production; however, it is believed that large numbers of lobsters are also taken by recreational fishermen, who are not required to report their catches. The magnitude of the recreational catch has never been determined.

The principal gears used in the commercial fishery around the major Hawaiian islands are tangle nets which are set primarily for spiny lobster, and fish traps (lobsters caught in these traps are considered incidental). About 82 percent of the lobster catch was made in waters around Oahu (Morris, 1968).

The spiny lobster fishery in the NWHI began in November 1976 when one vessel began fishing commercially at Necker Island. In 1977, four other vessels participated in the fishery. The vessels fished primarily at Nihoa and Necker Island but effort was also expended at French Frigate Shoals and as far north as Maro Reef. The principal gear used in this fishery was the California two-chambered lobster pot, a small (0.9 m x 0.6 m x 0.4 m), easy-to-handle, rectangular pot, which occupies about a third as much space as a conventional Hawaiian fish trap.

By 1977, the spiny lobster catch in Hawaii had risen from less than 3 MT in 1976 to slightly more than 37.5 MT (Figure 2). Annual landings in subsequent years fluctuated widely as vessels entered and left the fishery. Because there was no management plan for lobsters during the early years of the fishery, many catches went unreported. Therefore, the catches shown in Figure 2 for 1977-82 were estimated from data collected by NMFS and DAR observers on vessels or from the weight of frozen tails landed (Skillman and Ito, 1981).

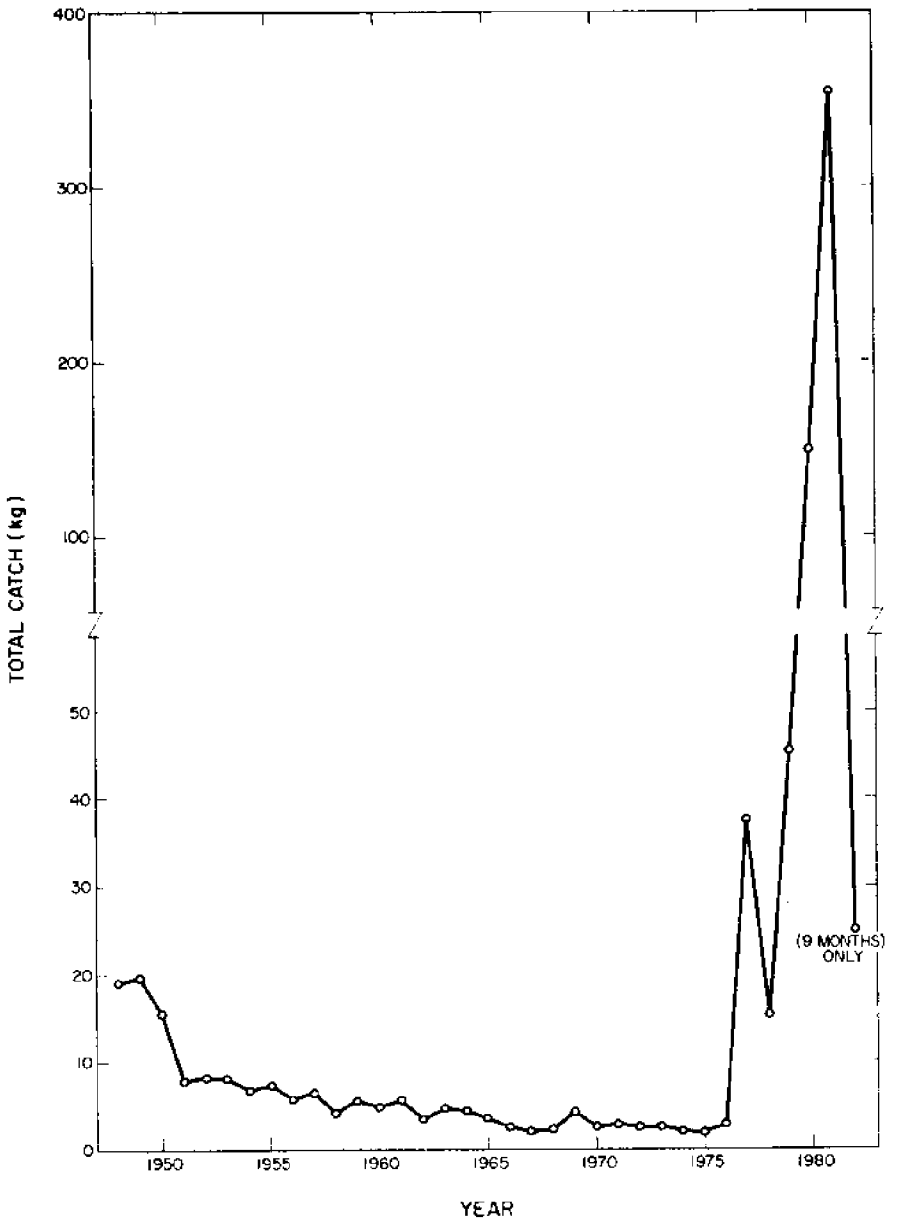

Figure 2. Catch of spiny lobsters in the Hawaiian Archipelago. Data for 1948-78 are from Skillman and Ito (1981); data for 1979-82 are from R.A. Skillman, Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, (1983: personal communication).

Geographical Distribution and Pre-exploitation Abundance

Although two species of spiny lobsters occur in waters of the NWHI, they are distinctly separated by depth, unlike their

distribution in waters of the main islands where they are found together. P. penicillatus, being a shallow-water inhabitant in the NWHI, were never caught in the area of operation, which included all offshore waters from about 18 m and deeper (except at Maro Reef and those islands northward where it was possible to occupy stations in waters less than 18 m deep).

In the NWHI, sampling for P. marginatus began at Nihoa, where lobster trapping surveys produced maximum catches of 2.7 individuals/pot-night and 1.84 individuals/trap-night along the southeastern part of the bank (grid 230617) (Table 1 and Figure 3). Nihoa, because of its close proximity to Honolulu, was one of the first lobster grounds in the early years when commercial fishing began in 1976. P. marginatus was also found on an isolated bank (henceforth referred to as Nihoa West Bank) near Nihoa, but the catches here were relatively small. Bank 3, a small bank located between Nihoa and Necker, was also visited but no evidence of lobster was found.

Moving northwestward to Necker Island, dense aggregations of P. marginatus were found over much of the northern and southern parts of the bank. Catch rates of lobsters in some of the areas reached as high as 13.25 individuals/pot-night (grid 236646) and 25.83 individuals/trap-night (grid 236647). Commercial operations in late 1976 and 1977 produced catches averaging 5-7 individuals/pot-night. The catch rate reached 6.62 individuals/pot-night in 1976 but dropped to 4.83 individuals/pot-night by 1977 and continued a downward trend to 3.32 in 1978, 1.88 in 1979, 1.70 in 1980, and 1.09 in 1981. The fish trap catch rate was 6.18 individuals/trap-night in 1976, 3.32 in 1977, 3.97 in 1978, 5.09 in 1979, 1.82 in 1980, and 5.62 in 1981. The rise in the fish trap catch rate in 1979 and 1981 was due primarily to sublegal lobsters (<77.0 mm CL), which made up 70 to 80 percent of the catch. Because commercial operations significantly reduced the abundance at Necker by the end of 1979, when total catch reached an estimated 45,372 kg, data only for 1976-78 were regarded as indicative of pre-exploitation abundance.

Northwest of Necker Island, P. marginatus was also found at French Frigate Shoals, Brooks Banks, St. Rogatien Bank, Gardner Pinnacles, and Raita Bank; however, nowhere was it as abundant as at Necker. The pre-exploitation abundance of P. marginatus was extremely low at French Frigate Shoals, Brook Banks, and St. Rogatien Bank, and the species was not caught in fish traps set at Bank 7. Abundance varied at Gardner Pinnacles; some areas (grids 245680, 246681, and 251682) along the southwest and northwest edges of the bank produced relatively good catches. Because the bank at Gardner Pinnacles is extremely large (about 50 nmi in the north-south direction and 24 nmi at the widest point in the east-west direction), about half of it remains unsurveyed. Only one grid at Raita Bank showed relatively high catches.

TABLE 1. CATCH OF LOBSTERS (LEGAL-SIZED, SUBLEGAL-SIZED, AND BERRIED) IN LOBSTER POTS AND FISH TRAPS DURING RESEARCH AND CHARTER CRUISES TO THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976 TO SEPTEMBER 1981

Location	Grid		Lobster Pot Catches						Total	Catch/ Pot Night
			1976	1977	1978	1979	1980	1981		
Middle Bank (22°42'N, 161°02'W)	227	610	--	0(40)	--	--	--	--	0(40)	0.00
Nihoa (23°03'N, 161°55'W)	230	617	--	--	108(40)	--	--	--	108(40)	2.70
	230	619	--	40(40)	--	--	--	--	40(40)	1.00
	231	619	--	107(98)	--	--	--	--	107(98)	1.09
	232	618	--	--	--	--	--	0(32)	0(32)	0.00
		Total	--	147(138)	108(40)	--	--	0(32)	255(210)	1.21
Nihoa West Bank (22°58'N, 162°14'W)	229	621	--	--	15(40)	--	--	--	15(40)	0.38
	229	622	--	48(80)	--	--	--	--	48(80)	0.60
	229	623	--	--	--	--	--	0(26)	0(26)	0.00
	230	621	--	98(98)	--	--	--	--	98(98)	1.00
		Total	--	146(178)	15(40)	--	--	0(26)	161(244)	0.66
Bank 3 (23°13'N, 163°09'W)	231	631	--	--	--	--	--	0(7)	0(7)	0.00
	232	631	--	--	--	--	--	0(24)	0(24)	0.00
		Total	--	--	--	--	--	0(31)	0(31)	0.00
Necker Island (23°34'N, 164°42'W)	232	642	--	--	308(80)	--	--	--	308(80)	3.85
	232	643	--	246(40)	--	--	--	27(28)	273(68)	4.01
	233	644	--	21(40)	--	--	--	--	21(40)	0.52
	233	645	--	4(40)	--	--	--	--	4(40)	0.10
	233	646	--	142(100)	--	--	--	--	142(100)	1.42
	234	643	--	--	--	--	--	--	--	--
	234	644	--	--	--	--	34(24)	--	34(24)	1.42
	234	645	--	220(101)	--	--	--	9(8)	229(109)	2.10
	234	646	--	319(102)	--	--	--	--	319(102)	3.13
	235	645	--	--	186(48)	--	--	--	186(48)	3.88
	235	646	--	395(100)	--	--	15(30)	--	410(130)	3.15
	235	647	1(12)	1,892(337)	--	0(1)	--	--	1,893(350)	5.41
	235	648	96(20)	593(70)	--	--	--	34(23)	723(113)	6.40
	236	645	157(22)	796(98)	--	--	--	151(135)	1,104(255)	4.33
	236	646	160(8)	687(133)	183(40)	301(143)	518(279)	17(25)	1,812(628)	2.88
	236	647	93(6)	710(138)	13(40)	--	--	--	816(184)	4.43
	236	648	24(4)	738(101)	--	86(62)	--	--	848(167)	5.08
		Total	477(72)	6,763(1,400)	690(208)	387(206)	567(333)	238(219)	9,122(2,438)	3.74
French Frigate Shoals (23°46'N, 166°18'W)	236	660	--	12(40)	--	--	--	--	12(40)	0.30
	236	662	--	1(40)	--	--	--	--	1(40)	0.02
	236	663	--	--	--	--	--	--	--	--
	237	662	--	7(60)	--	--	--	--	7(60)	0.12
	237	663	--	--	97(80)	0(22)	--	--	97(102)	0.95
	238	662	--	--	--	--	--	8(48)	8(48)	0.17
	238	663	--	16(99)	7(40)	3(23)	--	--	26(162)	0.16
	238	664	--	--	--	--	--	--	--	--
	239	662	--	--	--	--	--	--	--	--
	239	663	--	--	--	--	--	--	--	--
		Total	--	36(239)	104(120)	3(45)	--	8(48)	151(452)	0.33
Brooks Banks (24°05'N, 166°50'W)	240	668	--	--	--	3(8)	13(48)	--	16(56)	0.28
	241	667	--	--	--	--	--	--	--	--
	241	668	--	--	--	6(32)	3(32)	--	9(64)	0.14
	241	669	--	--	--	25(32)	--	--	25(32)	0.78
	242	669	--	--	--	5(8)	2(40)	--	7(48)	0.14
		Total	--	--	--	39(80)	18(120)	--	57(200)	0.28
St. Rogatien Bank (24°25'N, 167°15'W)	242	670	--	--	--	--	--	--	--	--
	242	671	--	41(59)	--	--	--	--	41(59)	0.70
	243	670	--	--	--	--	5(24)	--	5(24)	0.21
	243	671	--	--	--	--	10(55)	--	10(55)	0.18
	244	671	--	--	--	--	7(39)	--	7(39)	0.18
		Total	--	41(59)	--	--	22(118)	--	63(177)	0.36
Bank 7 (24°36'N, 167°18'W)	246	672	--	--	--	--	--	--	--	--
Gardner Pinnacles (25°01'N,167°59'W)	244	679	--	--	26(16)	--	--	--	26(16)	1.62
	245	680	--	--	--	--	--	74(32)	74(32)	2.31
	246	681	--	--	37(16)	--	--	--	37(16)	2.31
	247	681	--	--	--	--	--	--	--	--
	248	681	--	--	23(29)	--	--	--	23(29)	0.79
	249	682	--	--	--	--	42(24)	54(32)	96(56)	1.71
	250	679	--	28(58)	--	--	--	--	28(58)	0.48
	250	680	--	--	--	--	--	0(7)	0(7)	0.00
	250	682	--	--	--	--	53(24)	38(24)	91(48)	1.90
	250	683	--	--	--	--	--	--	--	--
	251	681	--	--	--	--	19(23)	--	19(23)	0.83
	251	682	--	--	152(30)	--	--	--	152(30)	5.07
	252	680	--	--	--	--	--	--	--	--
	252	681	--	--	--	--	12(8)	--	12(8)	1.50
		Total	--	28(58)	238(91)	--	126(79)	166(95)	558(323)	1.73

Note: (N) = trap-nights

TABLE 1. CATCH OF LOBSTERS (LEGAL-SIZED, SUBLEGAL-SIZED AND BERRIED) IN LOBSTER POTS AND FISH TRAPS DURING RESEARCH AND CHARTER CRUISES TO THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976 TO SEPTEMBER 1981 (continued)

Location	Grid		Lobster Pot Catches						Total	Catch/ Pot Night
			1976	1977	1978	1979	1980	1981		
Raita Bank	254	694	--	--	--	--	16(40)	--	16(40)	0.40
(25°35'N, 169°35'W)	254	696	--	5(22)	--	--	--	--	5(22)	0.23
	255	693	--	137(40)	--	--	--	--	137(40)	3.42
	255	694	--	--	21(24)	--	--	--	21(24)	0.88
	255	695	--	--	--	--	37(32)	--	37(32)	1.16
	256	693	--	--	--	--	40(47)	--	40(47)	0.85
	256	694	--	--	6(6)	--	17(31)	16(32)	39(69)	0.56
	256	695	--	--	--	--	35(23)	--	35(23)	1.52
		Total	--	142(62)	27(30)	--	145(173)	16(32)	330(297)	1.11
Maro Reef	252	704	--	825(151)	--	--	--	--	825(151)	5.46
(25°29'N, 170°35'W)	252	706	--	613(99)	96(48)	--	--	--	709(147)	4.82
	253	704	--	50(16)	--	--	--	--	50(16)	3.12
	253	707	--	--	--	--	--	12(24)	12(24)	0.50
	253	708	--	409(142)	--	--	--	--	409(142)	2.88
	254	706	--	69(18)	--	--	65(12)	--	134(30)	4.47
	254	707	--	166(52)	151(48)	--	--	188(64)	505(164)	3.08
	254	708	--	--	--	--	131(48)	59(23)	190(71)	2.68
	254	709	--	--	--	25(16)	--	--	25(16)	1.56
	255	705	--	--	--	--	49(26)	--	49(26)	1.88
	255	706	--	161(47)	--	--	--	--	161(47)	3.42
	255	707	--	--	--	--	145(32)	--	145(32)	4.53
	255	708	--	--	--	90(16)	123(32)	--	213(48)	4.44
	255	709	--	--	--	--	--	--	--	--
	256	706	--	--	--	--	--	--	--	--
	256	707	--	144(40)	--	--	--	--	144(40)	3.60
		Total	--	2,437(565)	247(96)	115(32)	513(150)	259(111)	3,571(954)	3.74
Northampton Seamounts (25°18'N, 172°04'W)	254	724	--	--	--	--	3(40)	--	3(40)	0.08
Laysan Island	256	717	--	40(24)	--	--	--	--	40(24)	1.67
(25°42'N, 171°44'W)	257	716	--	41(24)	--	--	--	--	41(24)	1.71
	257	717	--	91(81)	--	--	--	--	91(81)	1.12
	257	718	--	97(24)	--	--	--	--	97(24)	4.04
	258	715	--	1(10)	--	--	--	--	1(10)	0.10
	258	716	--	120(56)	--	4(40)	0(24)	--	124(120)	1.03
	258	717	--	42(24)	--	--	--	--	42(24)	1.75
	258	718	--	116(64)	27(40)	9(23)	--	--	152(127)	1.20
		Total	--	548(307)	27(40)	13(63)	0(24)	--	588(434)	1.35
Pioneer Bank (26°00'N, 173°25'W)	259	735	--	--	0(24)	--	--	--	0(24)	0.00
Lisianski Island	258	738	--	--	--	0(16)	--	--	0(16)	0.00
(26°02'N, 174°00'W)	259	737	--	--	--	0(40)	--	--	0(40)	0.00
	259	738	--	--	--	--	--	--	--	--
	259	739	--	0(24)	--	--	--	--	0(24)	0.00
	259	741	--	3(24)	--	--	--	--	3(24)	0.12
	260	738	--	4(64)	--	--	--	--	4(64)	0.06
	260	739	--	--	--	--	0(4)	--	0(4)	0.00
	260	740	--	2(4)	--	--	0(4)	--	2(8)	0.25
	261	739	--	0(23)	--	--	--	--	0(23)	0.00
	262	741	--	0(40)	--	--	--	--	0(40)	0.00
		Total	--	9(179)	--	0(56)	0(8)	--	9(243)	0.04
Bank 8	262	745	--	--	0(24)	--	--	--	0(24)	0.00
(26°17'N, 174°34'W)	263	745	--	--	--	0(32)	--	--	0(32)	0.00
		Total	--	--	0(24)	0(32)	--	--	0(56)	0.00
Salmon Bank	269	763	--	--	--	--	--	--	--	--
(26°56'N, 176°28'W)	269	764	--	2(47)	--	--	0(40)	--	2(87)	0.02
		Total	--	2(47)	--	--	0(40)	--	2(87)	0.02
Pearl and Hermes Atoll	277	757	--	25(40)	--	--	--	2(24)	27(64)	0.42
	277	758	8(12)	3(24)	--	--	--	0(24)	11(60)	0.18
(27°48'N, 175°51'W)	277	759	--	25(24)	--	--	7(64)	2(24)	34(112)	0.30
	277	760	--	--	--	--	--	0(22)	0(22)	0.00
	278	757	--	29(24)	--	9(23)	--	2(16)	40(63)	0.63
	278	759	--	16(11)	--	--	6(4)	--	22(15)	1.47
	278	760	--	120(64)	--	119(62)	2(4)	--	241(130)	1.85
	279	757	--	9(24)	--	--	--	4(32)	13(56)	0.23
	279	758	--	6(22)	--	--	--	--	6(22)	0.27
	279	759	--	--	--	8(23)	--	--	8(23)	0.35
		Total	8(12)	233(233)	--	136(108)	15(72)	10(142)	402(567)	0.71
Nero Seamount (27°57'N, 177°58'W)	279	779	--	--	--	--	0(24)	--	0(24)	0.00

TABLE 1. CATCH OF LOBSTERS (LEGAL-SIZED, SUBLEGAL-SIZED AND BERRIED) IN LOBSTER POTS AND FISH TRAPS DURING RESEARCH AND CHARTER CRUISES TO THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976 TO SEPTEMBER 1981 (continued)

Location	Grid		Lobster Pot Catches						Total	Catch/ Pot Night
			1976	1977	1978	1979	1980	1981		
Midway Islands	281	774	--	16(30)	--	--	--	--	16(30)	0.53
(28°12'N, 177°22'W)	282	772	--	1(8)	--	--	--	--	1(8)	0.12
	282	773	--	158(88)	166(40)	52(16)	--	--	376(144)	2.61
	282	774	--	111(61)	124(39)	34(23)	--	--	269(123)	2.19
	283	773	--	--	--	--	--	--	--	--
	283	774	--	0(15)	--	--	--	--	0(15)	0.00
		Total	--	286(202)	290(79)	86(39)	--	--	662(320)	2.07
Kure Atoll	283	782	--	--	--	--	0(4)	--	0(4)	0.00
(28°25'N, 178°25'W)	283	783	--	26(96)	20(40)	--	0(4)	--	46(140)	0.33
	284	782	--	101(81)	--	--	--	--	101(81)	1.25
	284	783	--	11(23)	--	--	31(8)	--	42(31)	1.35
	285	783	--	--	--	--	--	--	--	--
		Total	--	138(200)	20(40)	--	31(16)	--	189(256)	0.74
Ladd Seamount	284	766	--	--	--	--	--	--	--	--
(28°32'N, 176°40'W)	285	766	--	--	--	--	0(40)	0(48)	0(88)	0.00
		Total	--	--	--	--	0(40)	0(48)	0(88)	0.00
Bank 11	288	795	--	--	--	--	--	--	--	--
(28°53'N, 179°38'W)	289	795	--	--	--	--	--	--	--	--
		Total	--	--	--	--	--	--	--	--
SE Hancock Seamount (29°47'N, 179°04'E)	298	790	--	--	--	--	--	--	--	--
NW Hancock Seamount (30°16'N, 178°43'W)	302	787	--	--	--	--	--	--	--	--

Location	Grid		Fish Trap Catches						Total	Catch/ Trap Night
			1976	1977	1978	1979	1980	1981		
Middle Bank	227	610	--	0(16)	--	--	--	--	0(16)	0.00
(22°42'N, 161°02'W)										
Nihoa	230	617	--	--	35(19)	--	--	--	35(19)	1.84
(23°03'N, 161°55'W)	230	619	--	5(16)	--	--	--	--	5(16)	0.31
	231	619	--	--	--	--	--	--	--	--
	232	618	--	--	--	--	--	--	--	--
		Total	--	5(16)	35(19)	--	--	--	40(35)	1.14
Nihoa West Bank	229	621	--	1(16)	--	--	--	--	1(16)	0.06
(22°58'N, 162°14'W)	229	622	--	2(20)	--	--	--	--	2(20)	0.10
	229	623	--	--	--	--	--	--	--	--
	230	621	--	--	--	--	0(1)	--	0(1)	0.00
		Total	--	3(36)	--	--	0(1)	--	3(37)	0.08
Bank 3	231	631	--	--	--	--	--	0(1)	0(1)	0.00
(23°13'N, 163°09'W)	232	631	--	--	--	--	--	0(4)	0(4)	0.00
		Total	--	--	--	--	--	0(5)	0(5)	0.00
Necker Island	232	642	--	--	121(23)	--	--	--	121(23)	5.26
(23°34'N, 164°42'W)	232	643	--	168(20)	40(8)	--	--	34(4)	242(32)	7.56
	233	644	--	--	--	--	--	--	--	--
	233	645	--	39(20)	--	--	--	--	39(20)	1.95
	233	646	--	8(20)	--	--	--	--	8(20)	0.40
	234	643	--	43(20)	--	--	--	--	43(20)	2.15
	234	644	--	--	--	--	39(8)	--	39(8)	4.88
	234	645	--	--	--	--	--	--	--	--
	234	646	--	--	--	--	--	--	--	--
	235	645	--	--	72(8)	--	--	--	72(8)	9.00
	235	646	--	--	--	--	--	--	--	--
	235	647	4(12)	20(17)	--	119(27)	--	--	143(56)	2.55
	235	648	50(20)	--	--	--	--	69(12)	119(32)	3.72
	236	645	159(22)	--	--	--	1(5)	350(64)	510(91)	5.60
	236	646	74(8)	--	20(12)	512(92)	0(9)	30(6)	636(127)	5.01
	236	647	155(6)	97(16)	21(18)	33(10)	--	--	306(50)	6.12
	236	648	3(4)	--	--	99(21)	--	--	102(25)	4.08
		Total	455(72)	375(113)	274(69)	763(150)	40(22)	483(86)	2,380(512)	4.65
French Frigate	236	660	--	9(20)	--	--	0(2)	--	9(22)	0.41
Shoals	236	662	--	1(20)	--	--	--	--	1(20)	0.05
(23°46'N, 166°18'W)	236	663	--	--	--	0(11)	--	--	0(11)	0.00
	237	662	--	0(20)	--	--	--	--	0(20)	0.00
	237	663	--	--	73(35)	--	0(5)	--	73(40)	1.82
	238	662	--	--	--	--	--	2(8)	2(8)	0.25
	238	663	--	0(20)	1(10)	1(7)	--	0(8)	2(45)	0.04
	238	664	--	--	--	0(4)	--	--	0(4)	0.00
	239	662	--	--	--	--	--	0(4)	0(4)	0.00
	239	663	--	--	--	--	--	0(2)	0(2)	0.00
		Total	--	10(80)	74(45)	1(22)	0(7)	2(22)	87(176)	0.49

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Location	Grid		Fish Trap Catches						Total	Catch/ Trap Night
			1976	1977	1978	1979	1980	1981		
Brooks Banks	240	668	--	--	--	1(8)	--	--	1(8)	0.12
(24°05'N, 166°50'W)	241	667	--	--	--	--	0(2)	--	0(2)	0.00
	241	668	--	--	--	4(7)	0(3)	--	4(10)	0.40
	241	669	--	--	--	0(2)	--	--	0(2)	0.00
	242	669	--	--	--	1(4)	--	--	1(4)	0.25
		Total	--	--	--	6(21)	0(5)	--	6(26)	0.23
St. Rogatien Bank	242	670	--	--	--	1(9)	--	--	1(9)	0.11
(24°25'N, 167°15'W)	242	671	--	--	--	--	--	--	--	--
	243	670	--	--	--	--	0(3)	--	0(3)	0.00
	243	671	--	--	--	--	--	--	--	--
	244	671	--	--	--	--	--	--	--	--
		Total	--	--	--	1(9)	0(3)	--	1(12)	0.08
Bank 7	246	672	--	--	--	--	0(6)	--	0(6)	0.00
(24°36'N, 167°18'W)										
Gardner Pinnacles	244	679	--	--	--	--	--	--	--	--
(25°01'N, 167°59'W)	245	680	--	--	--	--	--	0(6)	0(6)	0.00
	246	681	--	--	--	--	--	--	--	--
	247	681	--	--	0(1)	--	--	--	0(1)	0.00
	248	681	--	--	2(9)	--	--	--	2(9)	0.22
	249	682	--	--	--	--	--	5(6)	5(6)	0.83
	250	679	--	--	--	--	--	--	--	--
	250	680	--	--	--	--	--	0(1)	0(1)	0.00
	250	682	--	--	--	--	3(2)	4(4)	7(6)	1.17
	250	683	--	--	--	--	0(3)	0(2)	0(5)	0.00
	251	681	--	--	--	--	5(8)	--	5(8)	0.62
	251	682	--	--	2(9)	--	0(6)	--	2(15)	0.13
	252	680	--	--	--	1(8)	--	--	1(8)	0.12
	252	681	--	--	--	--	17(14)	--	17(14)	1.21
		Total	--	--	4(19)	1(8)	25(33)	9(19)	39(79)	0.49
Raita Bank	254	694	--	--	--	--	--	--	--	--
(25°35'N, 169°35'W)	254	696	--	4(12)	--	--	--	--	4(12)	0.33
	255	693	--	52(20)	--	--	--	--	52(20)	2.60
	255	694	--	--	5(8)	--	--	--	5(8)	0.62
	255	695	--	--	--	--	--	--	--	--
	256	693	--	--	--	--	0(2)	--	0(2)	0.00
	256	694	--	--	0(1)	--	0(2)	0(6)	0(9)	0.00
	256	695	--	--	--	--	--	--	--	--
		Total	--	56(32)	5(9)	--	0(4)	0(6)	61(51)	1.20
Maro Reef	252	704	--	137(20)	--	--	--	--	137(20)	6.85
(25°29'N, 170°35'W)	252	706	--	--	0(6)	--	--	--	0(6)	0.00
	253	704	--	33(4)	--	--	--	--	33(4)	8.25
	253	707	--	--	--	--	--	1(8)	1(8)	0.12
	253	708	--	365(60)	0(4)	--	--	--	365(64)	5.70
	254	706	--	0(4)	--	--	--	--	0(4)	0.00
	254	707	--	170(24)	27(8)	--	--	43(12)	240(44)	5.45
	254	708	--	--	0(1)	--	17(7)	32(8)	49(16)	3.06
	254	709	--	--	--	0(11)	0(6)	--	0(17)	0.00
	255	705	--	--	--	--	--	--	--	--
	255	706	--	79(24)	--	--	--	--	79(24)	3.29
	255	707	--	--	--	--	--	--	--	--
	255	708	--	--	--	75(11)	--	--	75(11)	6.82
	255	709	--	--	--	--	0(3)	--	0(3)	0.00
	256	706	--	--	--	--	1(3)	--	1(3)	0.33
	256	707	--	82(20)	--	--	--	--	82(20)	4.10
		Total	--	866(156)	27(19)	75(22)	18(19)	76(28)	1,062(244)	4.35
Northhampton Seamounts	254	724	--	--	--	--	0(4)	--	0(4)	0.00
(25°18'N, 172°04'W)										
Laysan Island	256	717	--	12(8)	--	--	--	--	12(8)	1.50
(25°42'N, 171°44'W)	257	716	--	34(12)	--	--	--	--	34(12)	2.83
	257	717	--	31(40)	--	--	--	--	31(40)	0.78
	257	718	--	45(14)	--	--	0(1)	--	45(15)	3.00
	258	715	--	1(4)	--	--	--	--	1(4)	0.25
	258	716	--	120(28)	--	6(20)	0(6)	--	126(54)	2.33
	258	717	--	27(12)	--	--	--	--	27(12)	2.25
	258	718	--	126(32)	--	0(11)	--	--	126(43)	2.93
		Total	--	396(150)	--	6(31)	0(7)	--	402(188)	2.14
Pioneer Bank	259	735	--	--	0(24)	--	--	--	0(24)	0.00
(26°00'N, 173°25'W)										

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Location	Grid		Fish Trap Catches						Total	Catch/ Trap Night
			1976	1977	1978	1979	1980	1981		
Lisianski Island	258	738	--	--	--	0(8)	--	--	0(8)	0.00
(26°02'N, 174°00'W)	259	737	--	--	--	1(20)	--	--	1(20)	0.05
	259	738	--	--	--	0(3)	--	--	0(3)	0.00
	259	739	--	2(12)	--	--	--	--	2(12)	0.17
	259	741	--	2(12)	--	--	--	--	2(12)	0.17
	260	738	--	6(32)	--	--	--	--	6(32)	0.19
	260	739	--	--	--	--	--	--	--	--
	260	740	--	--	--	--	--	--	--	--
	261	739	--	0(12)	--	--	--	--	0(12)	0.00
	262	741	--	0(20)	--	--	--	--	0(20)	0.00
		Total	--	10(88)	--	1(31)	--	--	11(119)	0.09
Bank 8	262	745	--	--	0(8)	--	--	--	0(8)	0.00
(26°17'N, 174°34'W)	263	745	--	--	--	0(8)	--	--	0(8)	0.00
		Total	--	--	0(8)	0(8)	--	--	0(16)	0.00
Salmon Bank	269	763	--	--	--	--	0(5)	--	0(5)	0.00
(26°56'N, 176°28'W)	269	764	--	0(26)	--	--	--	--	0(26)	0.00
		Total	--	0(26)	--	--	0(5)	--	0(31)	0.00
Pearl and Hermes	277	757	--	0(20)	--	--	0(2)	1(5)	1(27)	0.04
Atoll	277	758	7(12)	13(12)	--	--	0(7)	0(4)	20(35)	0.57
(27°48'N, 175°51'W)	277	759	--	14(12)	--	--	0(7)	2(8)	16(27)	0.59
	277	760	--	--	--	--	--	0(13)	0(13)	0.00
	278	757	--	28(13)	--	0(11)	--	0(2)	28(26)	1.08
	278	759	--	--	--	--	--	--	--	--
	278	760	--	41(32)	--	40(34)	--	--	81(66)	1.23
	279	757	--	15(12)	--	--	--	0(6)	15(18)	0.83
	279	758	--	5(12)	--	--	--	--	5(12)	0.42
	279	759	--	--	--	4(11)	--	--	4(11)	0.36
		Total	7(12)	116(113)	--	44(56)	0(16)	3(38)	170(235)	0.72
Nero Seamount	279	779	--	--	--	--	0(6)	--	0(6)	0.00
(27°57'N, 177°58'W)										
Midway Islands	281	774	--	48(21)	--	--	--	--	48(21)	2.28
(28°12'N, 177°22'W)	282	772	--	--	--	--	--	--	--	--
	282	773	--	124(44)	62(20)	--	--	--	186(64)	2.91
	282	774	--	34(28)	62(20)	13(4)	--	--	109(52)	2.10
	283	773	--	0(4)	--	--	--	--	0(4)	0.00
	283	774	--	0(8)	--	--	--	--	0(8)	0.00
		Total	--	206(105)	124(40)	13(4)	--	--	343(149)	2.30
Kure Atoll	283	782	--	--	--	--	0(2)	--	0(2)	0.00
(28°25'N, 178°25'W)	283	783	--	7(48)	0(20)	--	--	--	7(68)	0.10
	284	782	--	2(37)	--	--	--	--	2(37)	0.05
	284	783	--	2(16)	--	--	--	--	2(16)	0.12
	285	783	--	--	--	--	0(2)	--	0(2)	0.00
		Total	--	11(101)	0(20)	--	0(4)	--	11(125)	0.09
Ladd Seamount	284	766	--	--	--	--	0(1)	0(6)	0(7)	0.00
(28°32'N, 176°40'W)	285	766	--	--	--	--	0(6)	0(16)	0(22)	0.00
		Total	--	--	--	--	0(7)	0(22)	0(29)	0.00
Bank 11	288	795	--	--	--	--	0(1)	--	0(1)	0.00
(28°53'N, 179°38'W)	289	795	--	--	--	--	0(4)	--	0(4)	0.00
		Total	--	--	--	--	0(5)	--	0(5)	0.00
SE Hancock Seamount	298	790	--	--	0(4)	--	0(5)	--	0(9)	0.00
(29°47'N, 179°04'E)										
NW Hancock Seamount	302	787	--	--	0(4)	0(1)	--	--	0(5)	0.00
(30°16'N, 178°43'W)										

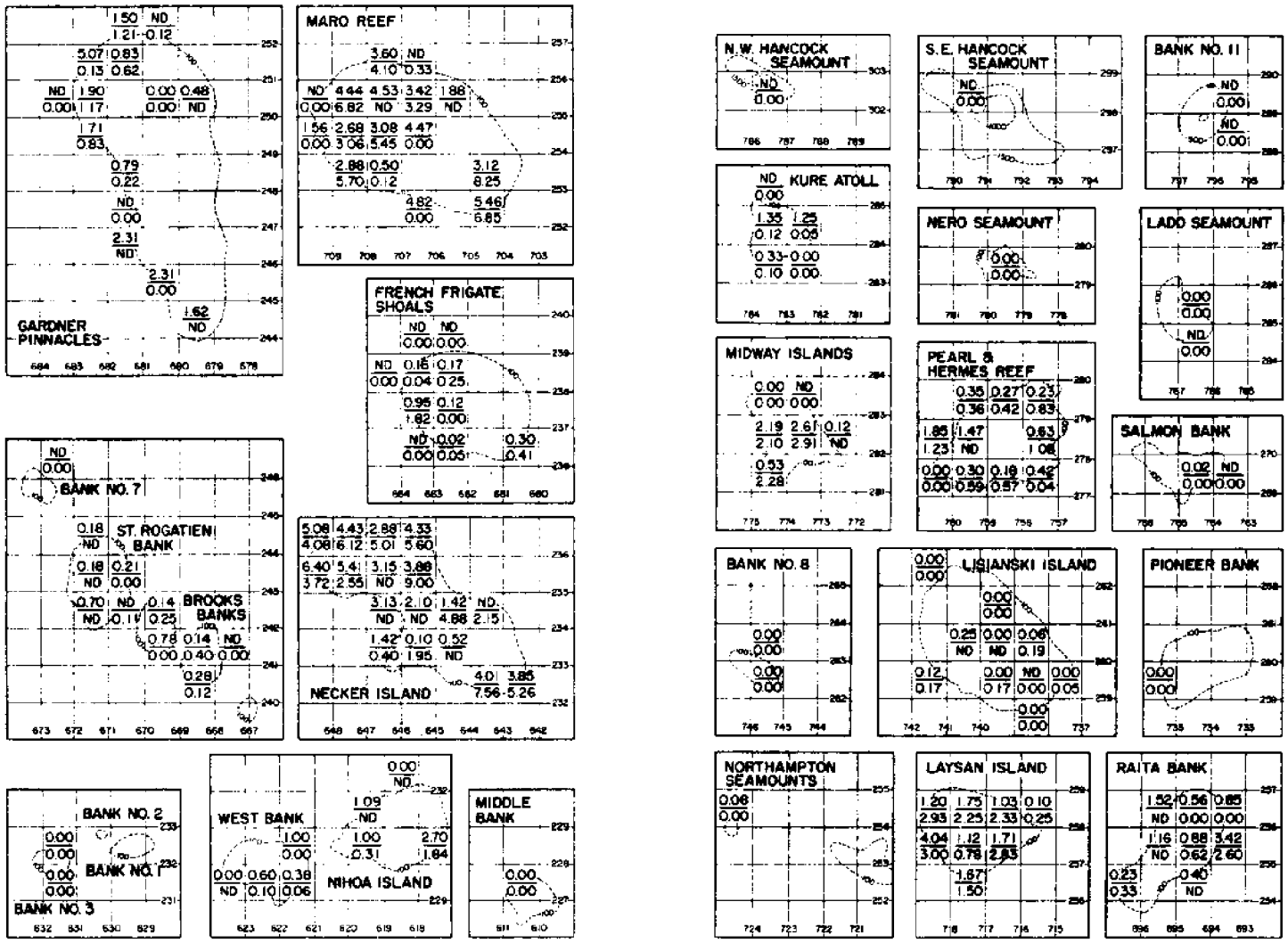

Figure 3. Distribution of spiny lobster catch rates by lobster traps (upper figure) and fish traps (lower figure) for 0.1° squares in the Northwestern Hawaiian Islands, October 1976 to September 1981. (ND = No data)

P. marginatus was also found around the islands and atolls farther up the chain. At Maro Reef, which contrasted sharply with Necker in substratum condition, high catch rates of P. marginatus were also obtained. The surveys conducted at Maro Reef in 1977 produced catch rates varying between 2.88 and 6.19 individuals/pot-night, whereas the fish traps produced catches ranging from 0.00 to 8.25 individuals/pot-night. The high abundance at Maro Reef was unexpected because subsurface observations made during a cruise in 1977 revealed a substratum of predominantly sand and sandstone just outside that coral reef; however, subsequent discussions with other investigators who dove at Maro Reef brought out the fact that many areas in the 10 to 55 m depth range have suitable lobster habitat. Due to the high catch rates, Maro Reef was established as the second important area in the spiny lobster fishery.

Beyond Maro Reef, none of the sites surveyed showed commercial concentrations of P. marginatus, although several had moderately good catch rates. Whether a commercial fishery can be developed at these sites depends to a large extent on the cost of operating at such distances from the home port. Few lobsters were found at Northampton Seamounts, but relatively good catches were made at several sites (grids 257716, 257718, 258716, 258717, 258718) at Laysan Island. Pioneer Bank near Lisianski Island produced nothing and catches at Lisianski, which has a rather large bank, were extremely low at all the sites surveyed.

Bank 8 and Salmon Bank received very little effort; the former produced nothing and only two lobsters were caught in 87 pot-nights and 31 trap-nights at the latter. At Pearl and Hermes Atoll, the entire area outside the reef was surveyed and good catches were made along the central western edge of the bank (grids 278759 and 278760); other survey sites produced relatively small catches.

At Nero Seamounts, 24 pot-nights and 6 trap-nights of effort produced no spiny lobsters, but at Midway Islands, the catch rates were over 2 individuals/pot-night and trap-night in three grids (281774, 282773, and 282774). At the extreme northwestern end of the Hawaiian Archipelago, P. marginatus was found at Kure Atoll but not in the same numbers as at Midway. Kure marks the northern limit of the distribution of P. marginatus as none were found at Ladd Seamount, which is located slightly north of Kure, nor at Bank 11 and Hancock Seamounts to the northwest.

Simpson (1976) speculated that for P. argus, areas which are conducive to high survival could be associated with bottom topography, that is, there are many suitable hiding places for the young stages to molt safely. This is believed to be a plausible explanation for the high densities of spiny lobster at Necker and Maro Reef.

Catch by Depth

Although P. marginatus has been reported at depths ranging from 110 to 183 m in Hawaiian waters (McGinnis, 1972), we believe the species is not found at depths beyond 137 m[1]. The surveys indicated that this species was usually found in water depths of 90 m or less. The relative abundance of spiny lobster taken in lobster pots and fish traps by 9-m strata was calculated for each of the islands and banks (Figure 4). Along the lower portion of the archipelago the relative abundance was highest at the 55 to 64 m depth around Nihoa and Necker and at the 65 to 73 m depth around French Frigate Shoals. Farther northward at Gardner Pinnacles, the relative abundance of spiny lobsters was higher at shallower depths of 19 to 27 m to about 46 to 54 m.

At Raita Bank, the relative abundance was highest between 28 and 36 m. Northwestward at Maro Reef, there was a dramatic shift in relative abundance: the highest values were in the shallowest area. This trend towards higher abundance at shallower depth appeared to be consistent at the remaining islands, banks, and atolls to the northwest of Maro Reef. Uchida et al. (1980b) suggest that the relatively low catch rates observed in waters deeper than 64 m in the northern part of the archipelago may be the result of differences in the temperature regime from north to south in the NWHI.

The proportion of legal-sized, sublegal-sized, and berried female lobsters were also examined by depth for Necker and Maro Reef, because of the importance of these areas for commercial trapping (Figure 5). At Necker, it was found that catches at the 19 to 27 m depth were composed predominantly of sublegal-sized lobsters, but at the 28 to 36 m depth the proportion of legal-sized and sublegal-sized lobsters was nearly 1:1. At depths deeper than 36 m, however, legal sizes predominated by a slight margin. At Maro Reef, legal-sized lobsters predominated at the shallowest depth by a small margin. At the 10 to 18 m depth sublegal-sized lobsters were predominant, comprising 60 percent of the catch. The catches at depths greater than 18 m were composed of legal-sized lobsters by a very wide margin over sublegal-sized lobsters.

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[1]McGinnis (1972) cited cruise report 35 of the Townsend Cromwell, prepared by the Bureau of Commercial Fisheries (now NMFS), and which involved shrimp, Penaeus marginatus, trawling operations. McGinnis assumed that the by-catch of spiny lobster, Panulirus marginatus, was also made at the same depths trawled for shrimp. The original catch records reveal that 22 spiny lobsters were captured on the bank north of Molokai between Kaiehu Point and Paualaia Point during four trawl hauls on April 6, 1968 in waters which averaged 110, 124, 128, and 137 m in depth.

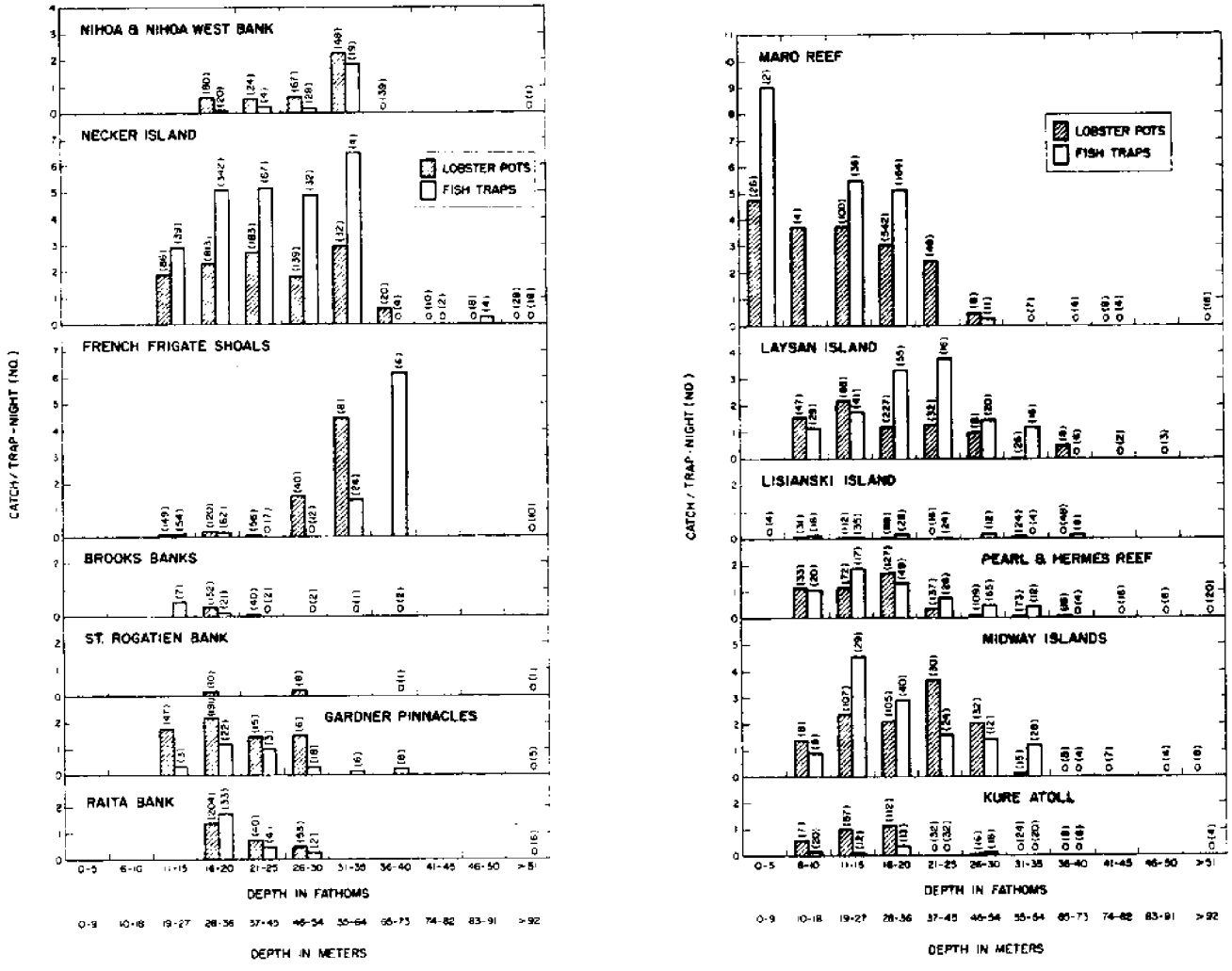

Figure 4. Distribution of spiny lobster catch rates, by depth, in the Northwestern Hawaiian Islands, October 1976 to September 1981. (No.) = effort in pot-night or trap-night

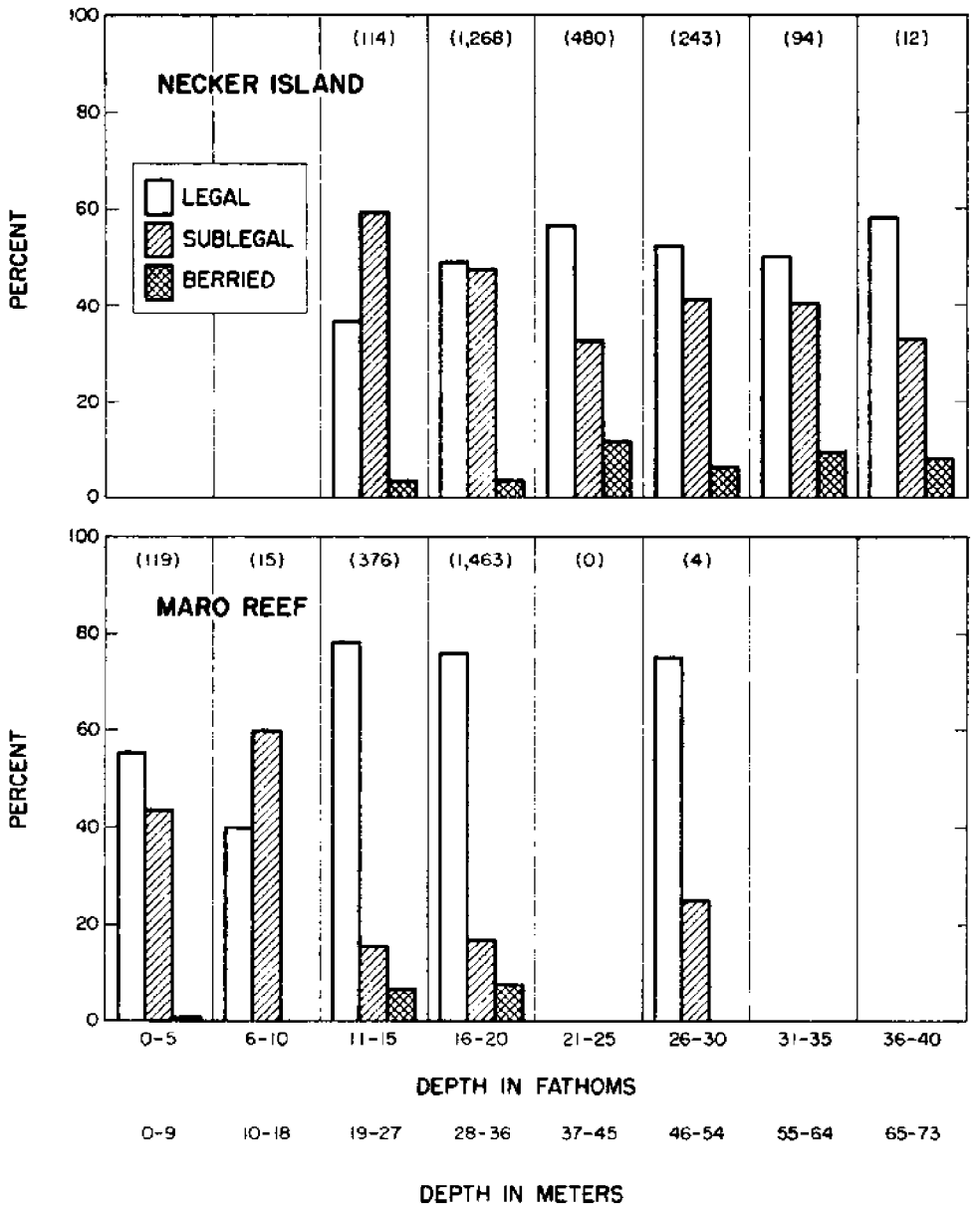

Figure 5. Percentage of legal, sublegal, and berried (ovigerous) female lobsters in catches by depth at Necker Island and Maro Reef, October 1976 to September 1981. (No.) = number of lobsters; zero indicates effort expended at that depth range but no lobsters caught.

Life History

To satisfy the data needs of the Western Pacific Regional Fishery Management Council, and also to fill gaps in the knowledge of the life history of P. marginatus in the NWHI, studies on several aspects of the life history, including fecundity and spawning (Honda, 1980, in preparation), growth and movement (Uchiyama, in preparation), size at maturity (Prescott, in preparation), behavior (reaction to offal) (Gooding, in preparation), and predators (Gooding, 1979, 1982), of P. marginatus were conducted. The results of these studies are reviewed in the following sections.

FECUNDITY AND SPAWNING

Fecundity of P. marginatus from Oahu was estimated by Morris (1968) and McGinnis (1972). Fecundity studies conducted by Honda (1980, in preparation) on NWHI P. marginatus collected between 1978 and 1981 are based on egg counts of 75 samples of egg masses from berried females at Necker and Maro Reef. The slopes of the regression of fecundity on CL for the Maro Reef and Necker samples were not significantly different. Honda also showed that fecundity increased with size. The fecundity-CL relationship (Maro Reef and Necker samples pooled) is described by the equation:

$$Y = 6.5334CL^{2.3706}$$

where

CL = carapace length in millimeters, and
Y = number of eggs carried

When compared with fecundity estimates for Oahu, Honda found that the NWHI estimates were in rather close agreement as far as the smaller females were concerned; however, the discrepancy between Oahu and NWHI estimates became greater for the larger females. For example, at 110-mm CL, an NWHI female was estimated to carry 460,000 eggs whereas an Oahu female had an estimated 575,000 eggs.

The percentage of berried females in the catch was examined by month at Necker and Maro Reef (Table 2). Using only data for reproductively mature females of 60.7-mm CL (see section on "Size at Maturity" below) it was found that between 9 and 23 percent of the female population at Necker was berried in all months of the year except January (no data available) and August, when only 19 male and 5 non-berried female lobsters were captured. Data on berried females from Maro Reef were even sparser; however, it appears evident that spawning occurs at least during the summer. Data for other months are either not available or too sparse to be meaningful.

TABLE 2. PERCENTAGE OF BERRIED FEMALE IN THE CATCH AT NECKER ISLAND AND MARO REEF, BY MONTH, BASED ON DATA COLLECTED DURING FISH AND LOBSTER TRAPPING OPERATIONS, OCTOBER 1976 TO SEPTEMBER 1981

	Necker Island			Maro Reef		
	Total Female	Berried		Total Female	Berried	
		Total	%		Total	%
January	--	--	--	--	--	--
February	44	8	18	--	--	--
March	98	9	9	--	--	--
April	65	12	18	60	10	17
May	254	51	20	165	31	19
June	163	24	15	577	103	18
July	215	42	20	266	51	19
August	5	0	0	39	10	26
September	350	80	23	--	--	--
October	185	34	18	362	23	6
November	191	20	10	--	--	--
December	22	5	23	8	2	25

Of 8,304 females caught on research and charter cruises to the NWHI, information on the presence or absence of the sperm packet or spermatophores was recorded for about a third or 2,716 individuals. The smallest mated female measured 48.3-mm CL and the largest 140.0-mm CL. The percentage of mated females was highest among those between 80.00 and 89.0-mm CL. Of 774 mated sublegal-sized (<77.0-mm CL) females collected during the surveys, 673 individuals or 87 percent were from Necker, indicating that copulation takes place in greater numbers there among sublegal-sized females than at any other site in the NWHI.

Of the 668 berried females measured, nearly 63 percent were between 80.0 and 99.0-mm CL. The smallest berried female, caught at Necker, measured 49.5-mm CL whereas the largest, from Maro Reef, was 132.5-mm CL. The Necker population of females apparently spawned at a smaller size; of 165 berried sublegal-sized females sampled throughout the NWHI, 137 individuals or 83 percent were from Necker.

GROWTH AND MOVEMENT

Lobsters were tagged to collect data on growth, movement, and abundance. Of 5,367 lobsters tagged during the early phases of the investigation, 139 were recaptured, either by commercial vessels or on research cruises. Tagged lobsters ranged from 45.3

to 145.8-mm CL; recaptures were from 68.0 to 100.3-mm CL. Considerable difficulty was experienced with tags; many of the vinyl and polyurethane tags, when recovered, were worn down to small stubs as if chewed on by other lobsters. Also 98 or 70 percent of the recoveries either were not accompanied by any CL measurements or showed no positive growth which would be useful for determing growth rates. As a result, analysis was restricted to modes in the length-frequency data collected from the northern sector of Necker Island on four cruises during 1976-78. Confining the analysis to data from the northern sector of Necker bank reduced variability attributable to differences in habitat, stock density, stages of exploitation, and population structure.

Whereas a progression of modes was evident in the male length-frequency distribution, that for the females was unimodal and the mode appeared to regress with time (Uchiyama, in preparation). Including the lobster puerulus, a von Bertalanffy growth curve was constructed based on modal progression in the length-frequency distribution of males collected at Necker Island (Figure 6).

Based on tagging data published by McGinnis (1972) the growth of male and female lobsters caught around Oahu were estimated and compared with the male growth curve from Necker. The curves are similar for the males. Data on growth rates furnished by C. MacDonald (1983: personal communication) indicated that lobsters at Kure Atoll and French Frigate Shoals grows slightly faster than those around Necker and Oahu.

Although the tag recovery data were not appropriate for calculating the growth curve, sufficient data was obtained on recapture location to determine the movement of lobsters. For tagged lobsters which were recovered by a NMFS research vessel, or by commercial vessels carrying NMFS observers, the recapture locations were determined rather precisely; however, for those recoveries made by commercial vessels with no NMFS observer aboard, reliance was made on data supplied by the captain. Of 94 recoveries with usable data, 85 (90 percent) showed movement of 5 nmi or less. Only 9 (10 percent) had traveled more than 5 nmi, the farthest being 15.6 nmi. No correlation was found between CL and distance traveled ($r = -0.102$; d.f. = 92; $P > 0.05$) or between days at liberty and distance traveled ($r = 0.226$; d.f. = 92; $P > 0.05$). Twenty-one lobsters (22 percent) were at liberty for 30 days or less, 49 (53 percent) for 31 to 60 days, and 11 (12 percent) for 61 to 90 days. The remaining 13 (14 percent) were at liberty for 322 days.

SIZE AT MATURITY

Most of the past studies on size at maturity have been based on females because males lack satisfactory indicators of sexual maturity. Studies by Heydorn (1965, 1969), Berry (1973), and Aiken and Waddy (1980) on size at maturity of male lobsters are

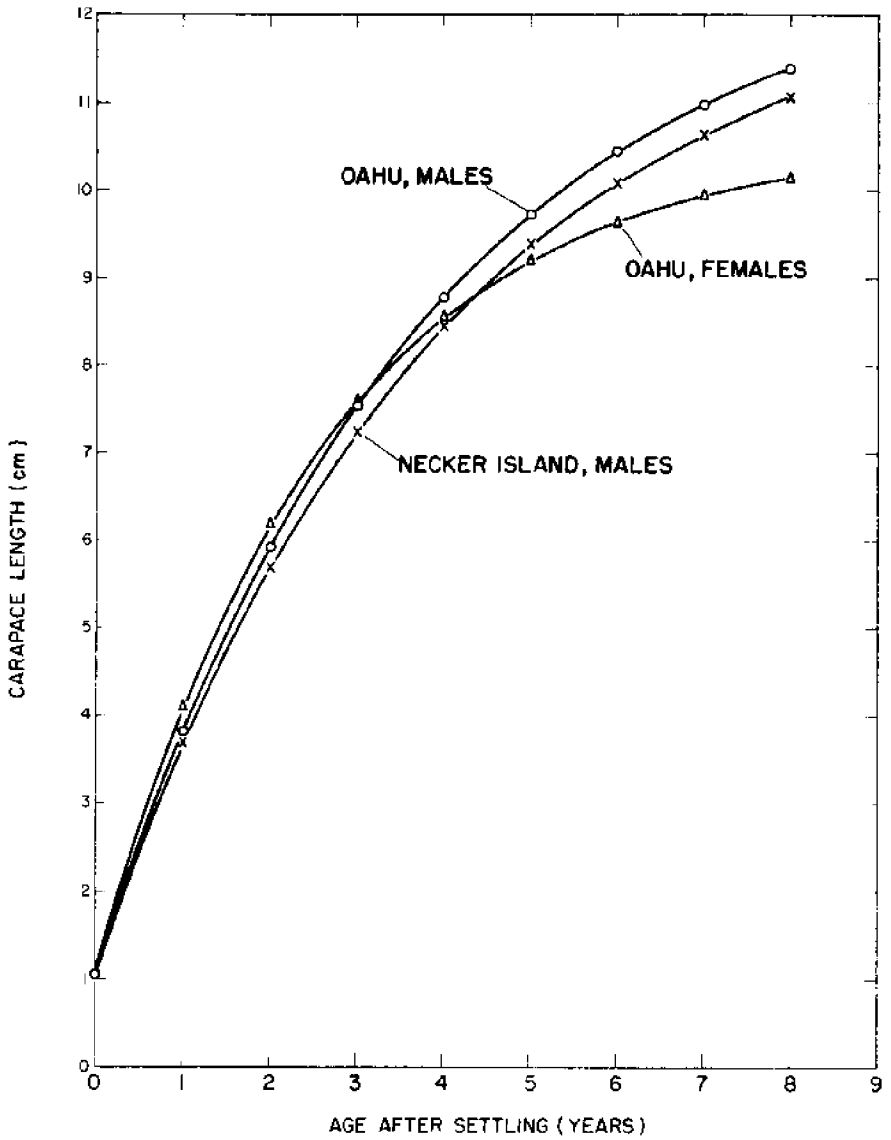

Figure 6. Growth curve of spiny lobsters from Necker Island and Oahu
Oahu male: L = 12.77 cm; K = 0.2698
Oahu female: L = 10.60 cm; K = 0.3857
Necker male: L = 12.46 cm; K = 0.2632

based on either weight or stage of development of the vas deferentia.

Among the secondary sexual characteristics in male spiny and clawed lobsters, length of the walking legs was found to increase significantly in some species as the lobster grew. George and Morgan (1979) for P. versicolor and Grey (1979) for P. cygnus estimated the size at maturity using linear growth phases of the walking legs.

Estimates of the size at maturity of P. marginatus were obtained from populations around Oahu and Necker Island (Prescott, in preparation). Using regression analysis, Prescott estimated size at maturity from changes in the allometric growth of pairs of walking legs. For the Oahu population, Prescott found that males mature at 63.6-mm CL and females at 58.6-mm CL, a difference in CL of 5.0 mm. For the Necker Island population, Prescott obtained estimates of 59.2-mm CL for males and 60.7-mm CL for females. No significant differences were found in size at maturity between sexes and between localities. The size at maturity estimated for Necker females is considerably larger than the size of the smallest mated female found there (48.3-mm CL); however, this discrepancy does not invalidate Prescott's results because the presence of spermatophores is not conclusive evidence that the female has mature ovaries (Wilson, 1948).

Population Structure

SIZE COMPOSITION

The percentage frequency distributions of carapace lengths of male and female spiny lobsters caught during our surveys are given by island and bank in Figure 7. Because there are wide temporal and spatial gaps in sampling, only a descriptive summary of size differences among areas and between sexes is provided.

It was shown earlier that the size of lobsters differed with locality (Uchida et al., 1980a). Because catches from both fish traps and lobster pots are included in the samples from almost all of the localities surveyed, differences in size reflect the population and not an artifact of the sampling gear.

Moving from Nihoa northwestward, the lobsters were smallest at Necker and only slightly larger at French Frigate Shoals. At these localities, the average size was much smaller than that from other islands and banks, even during earlier surveys (Uchida et al., 1980a). Therefore, the small sizes, particularly at Necker, do not represent a gradual reduction in size caused by increasing fishing effort and removal of the large adults. Farther north, no apparent trend or cline in the average size of the lobsters was found; the largest lobsters were found at Kure Atoll where the males averaged 116-mm CL followed by those at Brooks Banks where the males averaged 113-mm CL (Table 3).

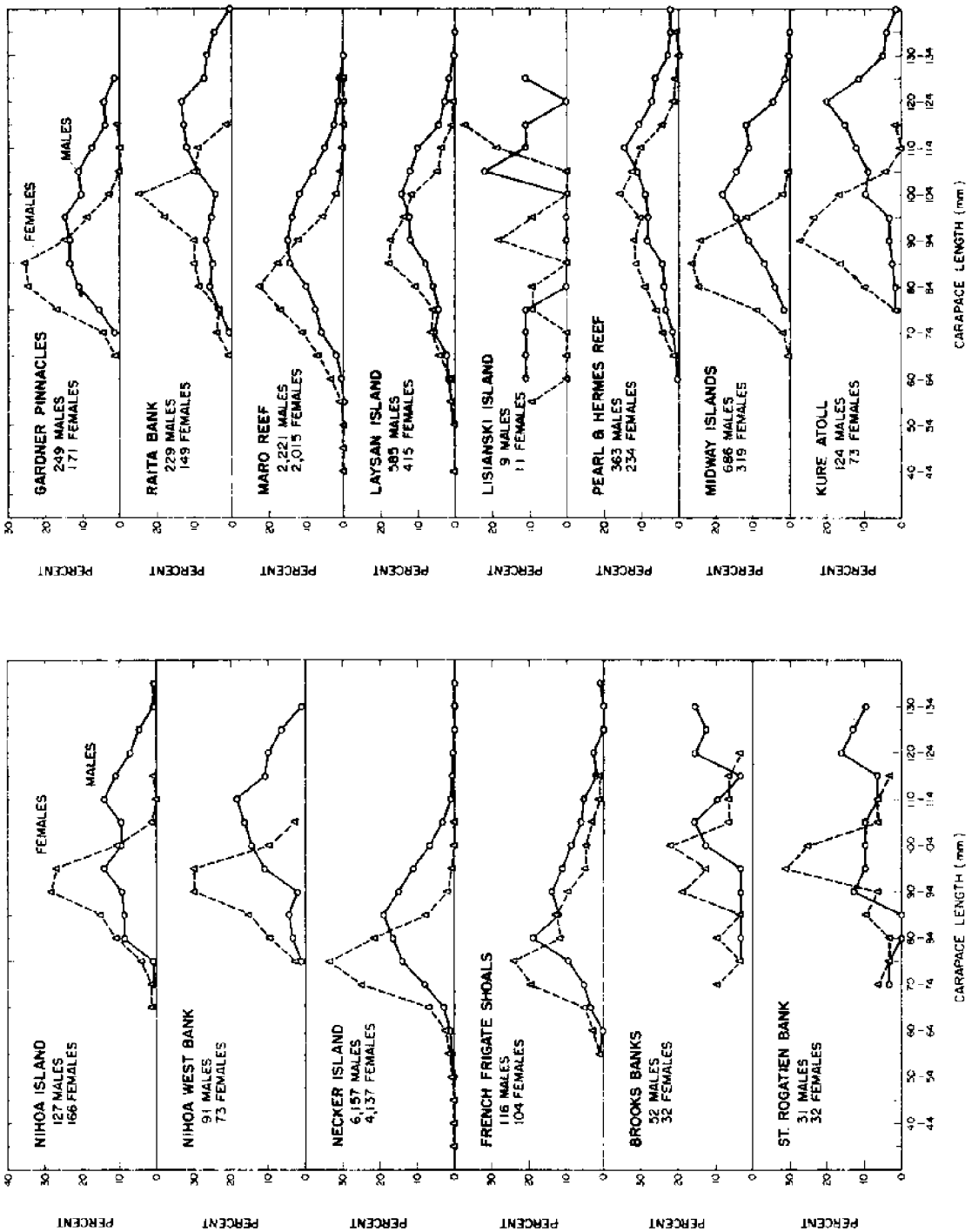

Figure 7. Percentage frequency distribution of carapace lengths of male and female spiny lobsters sampled in the Northwestern Hawaiian Islands, October 1976 to September 1981

TABLE 3. THE SIZE RANGE, MEAN CARAPACE LENGTH, STANDARD DEVIATION, AND VARIANCE OF MALE AND FEMALE SPINY LOBSTERS SAMPLED IN THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976 TO SEPTEMBER 1981

Location	Male				Female			
	Size Range (cm)	Mean Carapace Length (cm)	Standard Deviation	Variance	Size Range (cm)	Mean Carapace Length (cm)	Standard Deviation	Variance
Nihoa	7.18 to 13.56	10.41	1.3964	1.9499	6.72 to 11.70	9.21	0.7513	0.5644
Nihoa West Bank	7.66 to 13.15	10.86	1.1677	1.3636	7.60 to 10.61	9.30	0.6317	0.3990
Necker Island	4.28 to 13.70	8.70	1.0895	1.1869	3.37 to 10.52	7.71	0.6739	0.4542
French Frigate Shoals	5.96 to 13.51	9.16	1.3793	1.9024	5.62 to 11.56	8.25	1.1577	1.3402
Brooks Banks	7.59 to 13.50	11.31	1.5870	2.5186	7.36 to 12.01	9.70	1.3102	1.7165
St. Rogatien Bank	7.25 to 13.18	11.06	1.6002	2.5606	7.39 to 11.94	9.73	1.0290	1.0589
Gardner Pinnacles	7.21 to 12.79	9.75	1.2862	1.6543	6.77 to 11.70	8.58	0.7559	0.5713
Raita Bank	7.49 to 14.31	11.06	1.6722	2.7963	6.98 to 11.70	9.67	1.0685	1.1417
Maro Reef	4.74 to 13.67	9.34	1.3190	1.7397	4.38 to 13.25	8.70	0.9906	0.9813
Laysan Island	5.19 to 13.90	9.69	1.5332	2.3508	4.48 to 12.40	9.01	1.2588	1.5847
Lisianski Island	6.15 to 12.94	9.50	2.4550	6.0268	6.00 to 11.88	9.82	1.9997	3.9990
Pearl and Hermes Atoll	6.05 to 14.91	10.84	1.7121	2.9312	6.77 to 14.00	9.74	1.3509	1.8249
Salmon Bank	7.72 to 12.51	10.90	2.7569	7.6004	8.54 to 11.25	9.90	1.9162	3.6720
Midway Islands	7.53 to 13.64	10.34	1.1122	1.2369	6.73 to 10.94	8.78	0.6539	0.4275
Kure Atoll	7.71 to 14.34	11.55	1.3510	1.8253	7.91 to 11.85	9.45	0.7227	0.5223

There is no known explanation for the small size of lobsters at Necker. It has been speculated that there may be a density-dependent effect on growth rate caused by intraspecific competition (Uchida et al., 1980a). Such an effect could occur in a large population over a limited area and may account for the high catch rates at Necker. Also, if most of the food energy available to lobsters at Necker was converted into egg production, then one would expect not only small sizes associated with impaired somatic growth, but also a smaller size at maturity. Data presented earlier on percentage of ovigerous and mated females at Necker provide evidence supporting this conclusion. Chittleborough (1979) also reported that when the density of the breeding stock is high, the mean size at maturity is low and the adults are generally stunted.

The size of the sexes also differed. In every area except Lisianski, where the sample size was too small to be meaningful, males were consistently predominant among the large size classes. The differences in average size between sexes is thought to result from dimorphism related to egg bearing in females (Heydorn, 1969). Simpson (1976) cited a faster growth rate or reduced mortality among males, or both, in accounting for the predominance of males in populations of P. argus. MacDonald (in Prescott, in preparation) believes that growth rate per se does not account for the difference in size between the sexes for P. marginatus. Rather it is reduced mortality among males that is responsible for their predominance in the population.

RATIO OF LEGAL-SIZED TO SUBLEGAL-SIZED LOBSTERS

The lobster catches based on a legal size of 82.5-mm CL were analyzed in an earlier study (Uchida et al., 1980a). However, because of a new legal minimum size of 77.0-mm CL for the NWHI lobster, the ratio between legal and sublegal sizes was calculated (Table 4). Apparently, the ratios have not changed drastically from those calculated earlier.

The ratio of legal- to sublegal-sized lobster, by locality, for pot catches during October 1976 to September 1981 varied widely between 51:49 at Necker and 97:3 at Kure. For fish trap catches, where the number of sublegal-sized lobsters would be expected to be higher, the ratios varied from 39:61 at Necker to 100:0 at several banks; however, if those banks where less than 25 lobsters were taken by fish traps are not counted, then the ratio is closer to 94:6.

Except at Necker and French Frigate Shoals where the catch of sublegal-sized lobsters was as high as if not higher than legal lobsters, the proportion of sublegal-sized lobsters in the NWHI is expected to be low, because juveniles molt more frequently than adults, tend to remain secluded and, hence, are not subject to capture. They are, however, more susceptible to

TABLE 4. THE LEGAL TO SUBLEGAL SIZE RATIO AND MALE TO FEMALE SEX RATIO OF CATCHES BY LOBSTER POTS AND FISH TRAPS DURING RESEARCH CHARTER CRUISES IN THE NORTHWESTERN HAWAIIAN ISLANDS, OCTOBER 1976 TO SEPTEMBER 1981

Island/Bank	Gear	Legal Size			Male: Female Sex Ratio	Sublegal Size			Male: Female Sex Ratio	Total Male	Total Female[2]	Male: Female Sex Ratio	Legal: Sublegal Size Ratio
		Male No.	Female No.[1]	Total No.		Male No.	Female No.[1]	Total No.					
Nihoa	Lobster	110	83	193	57:43	5	9	14	36:64	115	151	43:57	93:7
	Fish	16	12	28	57:43	3	1	4	75:25	19	21	48:52	88:12
Nihoa West Bank	Lobster	80	44	124	64:36	3	2	5	60:40	83	64	56:44	96:4
	Fish	2	1	3	67:33	0	0	0	0:0	2	1	67:33	100:0
Necker Island	Lobster	3,343	516	3,859	87:13	1,531	2,110	3,641	42:58	4,874	3,307	60:40	51:49
	Fish	649	114	763	85:15	611	594	1,205	51:49	1,260	860	59:41	39:61
French Frigate Shoals	Lobster	56	30	86	65:35	20	32	52	38:62	76	64	54:46	62:38
	Fish	26	13	39	67:33	14	24	38	37:63	40	41	49:51	51:49
Gardner Pinnacles	Lobster	298	144	442	67:33	27	53	80	34:66	325	236	58:42	85:15
	Fish	20	6	26	77:23	4	5	9	44:56	24	11	68:32	76:26
Brooks Banks	Lobster	26	22	48	54:46	1	1	2	50:50	27	30	47:53	96.4
	Fish	5	2	7	71:29	0	0	0	0:0	5	2	71:29	100:0
St. Rogatien Bank	Lobster	30	26	56	54:46	1	3	4	25:75	31	32	49:51	93:7
	Fish	—	—	--	--	--	—	--	—	—	—	—	--
Raita Bank	Lobster	419	258	677	62:38	18	24	42	43:57	437	290	60:40	94:6
	Fish	35	20	55	64:36	2	4	6	33:67	37	24	61:39	90:10
Maro Reef	Lobster	1,405	980	2,385	59:41	313	331	644	49:51	1,718	1,626	51:49	79:21
	Fish	417	246	663	63:37	147	149	296	50:50	564	481	54:46	69:31
Laysan Island	Lobster	306	195	501	61:39	33	32	65	51:49	339	249	58:42	89:11
	Fish	177	92	269	66:34	66	61	127	52:48	243	168	59:41	68:32
Lisianski Island	Lobster	2	5	7	29:71	2	0	2	100:0	4	5	44:56	78:22
	Fish	3	1	4	75:25	2	3	5	40:60	5	6	45:55	44:56
Pearl and Hermes Atoll	Lobster	229	137	366	62:38	11	11	22	50:50	240	161	60:40	94:6
	Fish	92	61	153	60:40	4	5	9	44:56	96	72	57:43	94:6
Midway Islands	Lobster	440	156	596	74:26	17	34	51	33:67	457	215	68:32	92:8
	Fish	222	82	304	73:27	8	25	33	24:76	230	113	67:33	90:10
Kure Atoll	Lobster	117	60	177	66:34	2	4	6	33:67	119	69	63:37	97:3
	Fish	6	3	9	67:33	0	0	0	0:0	6	5	55:45	100.0

[1] Excludes berried females
[2] Includes berried females

predation because of their smaller size. Furthermore, the initial catches at any given locality would tend to include a large proportion of the large older individuals, particularly males, partly because of their aggressive behavior. This display of dominance for shelter and food exists in a natural environment (Chittleborough, 1974). In a fishery, however it is the baited trap that becomes an object of dominant behavior.

That large lobsters were removed from the population early in the fishery was quite evident from changes in the proportion of legal lobsters in the catches at Necker. In November 1976 when trapping operations first began, the ratio of legal- to sublegal-sized lobsters at grid 236646, located north of Necker Island, was 60:40 but dropped to 43:57 by May 1977 and declined to 34:66 by August 1977. The rapid decline in the proportion of legal-sized lobsters is attributable to heavy fishing pressure by the commercial vessels.

SEX RATIO

The study data show that for lobsters taken in the NWHI, some selectivity was evident in that the proportion of females was usually lower among the legal sizes whereas it was higher among sublegal sizes in most areas sampled. Among the areas sampled, several had small sample sizes and it is believed that the ratios calculated are unlikely to be representative of the populations at those locales. For this analysis, samples with less than 10 lobsters were ignored. For the lobster pot catches, the male and female ratio among legal-sized lobsters varied from 87:13 at Necker to 54:46 at Brooks Banks and St. Rogatien Bank. For fish trap catches, the ratios were not dissimilar, ranging from 85:15 at Necker to 57:43 at Nihoa.

Among sublegal-sized lobsters, the male to female ratio was near 50:50 at Maro Reef, Laysan, and Pearl and Hermes Atoll but considerably in favor of the females at Nihoa, Necker, French Frigate Shoals, Gardner Pinnacles, Raita Bank, Midway, and Kure. The fish trap catches reflect a somewhat similar preponderance of females. Whereas it was near 50:50 or very slightly in favor of males at Necker, Maro Reef, and Laysan, the ratios were largely in favor of females at French Frigate Shoals and Midway. Samples from other areas were too small to be representative. Therefore, although male predominance in the catch is evident at almost every bank among legal-sized lobsters, it is not reflected in the catch of sublegal-sized lobsters.

MORPHOMETRIC STUDIES

A study of the relationship between CL and total weight was completed in 1979 (Uchida et al., 1980a). Six hundred five lobster measurements and weights collected from Necker, Maro Reef, and French Frigate Shoals were used. Because there is sexual dimorphism in the growth of spiny lobsters, the exponential model, $W = aCL^b$, was fitted to data for males and females by the

least squares method after log transformation. The length-weight relationships for the 408 males and 197 females are:

Males: $W = 0.00423CL$

Females: $W = 0.00090CL$

where

W = weight (g), and
CL = carapace length (mm).

The relationships are shown in Figure 8. For lobsters having a CL of 77.0 mm, the equations predict a total weight of 378.1 g (13.3 oz) for males and 402.4 g (14.2 oz) for females.

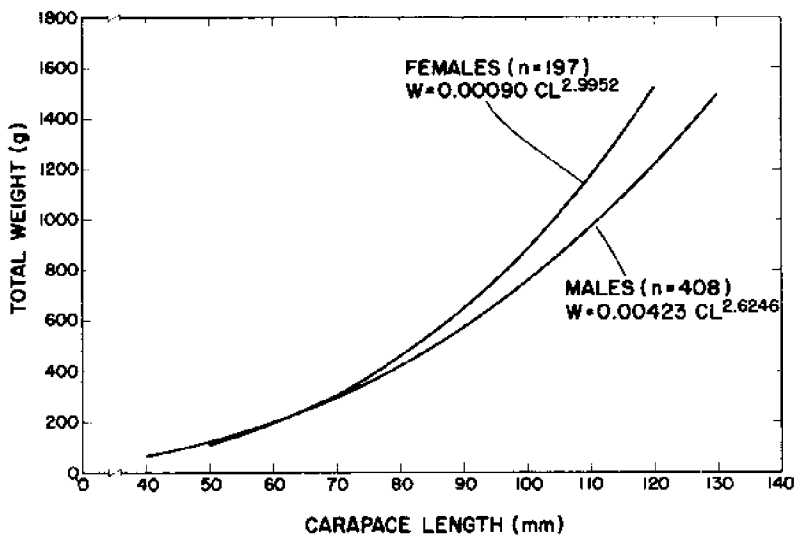

Figure 8. Length-weight relationship of male and female Panulirus marginatus determined from samples collected at Necker Island, French Frigate Shoals, and Maro Reef

For enforcement purposes in situations where a vessel lands only frozen tails, it is useful to know the relationship between tail weight or tail width, provided that either one is used as a criterion for minimum legal size. Uchida et al., (1980a) fitted exponential models to data for male and female CL and frozen tail weight and obtained:

Males: $TW = 0.00731CL$

Females: $TW = 0.00094CL$

where

TW = tail weight (g), and
CL = carapace length (mm).

The equations predict that lobsters with a CL of 77.0 mm would have a tail weight of 130.4 g (4.6 oz) for males and 156.3 g (5.5 oz) for females.

To determine whether a lobster was of legal size when captured, based on frozen tail width, a discriminant analysis procedure to classify them was performed (Polovina and Tagami, 1981). Based on the discriminant analysis, a lobster in which the width of the first tail segment equals or exceeds 49 mm can be classified as legal size.[2] The discriminant analysis correctly classified 94.8 percent of the sublegal-sized and 85.8 percent of the legal-sized lobsters. The tolerance factor adopted was that no more than 15 percent of the total number of tails may be less than the specified tail width limit.

MAXIMUM SUSTAINABLE YIELD (MSY)

In the NWHI, the fishery for spiny lobster is based on a single homogeneous stock within the archipelago (Shaklee and Samollow, 1980). A model developed to assess the fishery for P. marginatus therefore addressed the Hawaiian population as a single stock (Polovina and Tagami, 1980).

Polovina and Tagami assumed that the ratio of natural mortality to recruitment was constant and used changes in catch/pot-night at Necker during November 1976 to April 1979 to make the first preliminary assessment of the fishery. Because the fishery was relatively new and historical catch data were not available, they used data from research cruises as well as available commercial data to estimate population size and catchability. They derived an estimate of the initial population size of 132,400 legal-sized lobsters (≥82.5-mm CL) in Region I, which is the northern, most heavily fished sector of Necker bank. By April 1979, according to their analysis, this population was reduced to 68,571 legal-sized lobsters. Their study concludes that Region I had a sustainable yield of 10,000 to 21,000 legal-sized lobsters which translated to a density estimate of 13.3 to 27.5 legal-sized lobsters/km^2/year.

Considering the possibility that the legal minimum size could be lowered, Polovina and Tagami used a Beverton-Holt equilibrium yield model to estimate yield per recruit at several levels of fishing intensity and minimum CL. They determined that a minimum legal size of 67.5 mm would produce the maximum yield per recruit. A worst-case situation would result in a decrease

[2]The spiny lobster Fishery Management Plan was approved with a 50-mm requirement.

of 15 percent in yield per recruit at a minimum legal size of 67.5 mm as compared with a 82.5-mm minimum legal size. In the best case, a 167 percent increase in yield per recruit would result. This analysis, however does not consider the effects that a lowered minimum legal size would have on stock reproductive potential.

Extrapolating the region I estimates to the entire population in the NWHI provided possible MSY ranges of 210,000 to 435,000 lobsters/year. Adjusting for differences in the geographic distribution of lobsters within the NWHI and using catch rates obtained during research cruise surveys, Polovina and Tagami also calculated lower ranges of possible MSY values of 200,000 to 378,000 lobsters/year. They also determined that although the precise magnitude of the impact of lowering the legal minimum size cannot be determined conclusively, it appears that a 15 percent increase in yield would be sustainable if the minimum legal size were reduced to 77.0 mm.

The Western Pacific Regional Fishery Management Council has adopted a range of MSY of 200,000 to 435,000 lobsters/year in the NWHI. These estimates were based on a minimum legal size of 82.5 mm, but the yield per recruit analysis suggests that a higher yield is possible at the new minimum legal size of 77.0 mm. The estimates, therefore, are on the conservative side. The accumulation of commercial data will permit future analysis to derive more precise estimates.

Exploitation

GEAR COMPETITION EXPERIMENTS

It may be argued that a decline in catch per pot-night of spiny lobsters may not represent an actual decrease in numbers but may reflect instead the results of competition among the pots for the same lobster. If spacing distances are small, the capturing fields overlap, thus resulting in an apparent decline in catch per pot-night.

Studies conducted in 1977 during research and charter cruises showed that gear competition does exist and that it is density dependent (Polovina, 1980). The highest catch rates were obtained with pot spacing in the range of 35 to 46 m (20 to 25 fathoms). From experiments conducted on the NMFS research vessel, where five spaces of 18, 27, 36, 46, and 55 m (10, 15, 20, 25, and 30 fathoms) per location were tested, spacing effects were significant for medium density areas but not in low-density and high-density areas. For data obtained from a chartered commercial vessel, no significant differences in catch rates between 36 and 55-m (20 and 30 fathoms) spacings at either high-density or very high-density areas were found. Furthermore, the catch rate with pot spacing of 18 m (10 fathoms) was significantly lower than catch rates obtained with 36 and 55-m (20 and 30 fathoms) spacing.

ESCAPE GAP AND GHOST FISHING EXPERIMENTS

In a study to determine whether the use of escape panels or vents would significantly reduce the number of sublegal sizes taken by pots, tank experiments were conducted using different-sized escape gap widths (Paul, in preparation). She found that the overall escape rate of sublegal-sized lobsters was about 60 percent and that escape rate decreased linearly with an increase in CL. No significant differences were found in escape rates of males and females. There were, however, notable differences in escape rate depending on the types of vents used and Paul concluded that vent effectiveness depends more on total vent area than on width of the vent.

In all trials conducted, it was found that unbaited traps in which live lobsters were present attracted other lobsters or ghost fished. To examine the degree of ghost fishing in lost traps, several field trials were conducted. Although lobsters are attracted to and enter unbaited pots that contained live lobsters, there was also evidence that lobsters can easily escape through the pot entrance over a period of up to 1 week. There was also evidence of cannibalism and molting among trapped lobsters.

Longer-term tests over periods of 3 weeks to 1 month indicated that lost pots can and do attract lobsters. In one test, it was observed that of 38 live, marked lobsters left in unbaited traps, 22 individuals or 58 percent remained in the same pots after 4 days. One individual left one pot and entered another. The pots also captured 14 new, unmarked lobsters. The new entries were marked and left with the remaining 22 marked lobsters and the pots were reset. At the end of the experiment, 26 days after it began, only one marked lobster remained together with five new entries, three of which were dead. All other lobsters were missing and presumed to have escaped through the entrance. These results contrast with those of Paul who found ghost fishing to be a big problem; the study data indicate that although ghost fishing does occur, there is also a high escape rate over the long term.

REACTION TO OFFAL

It became apparent soon after the Hawaiian fishery began that the vessels would begin landing a large proportion of the catch as frozen tails for the export market. A question arose of whether the offal (heads) of tailed lobsters discarded on the trapping grounds would affect the distribution and catch rates of lobsters. Declines in catch rates caused by lobster offal have been documented, and discarding offal on lobster grounds has been banned in such places as Africa and Australia (Matthews, 1962; Chittleborough, 1974; Hancock, 1974).

To study the effects of offal on catches in the NWHI, field experiments were conducted by NMFS during Townsend Cromwell

cruises TC-81-04 and TC-82-05 (Gooding, in preparation). In the first experiment during cruise TC-81-04 at Maro Reef, catch rates of baited pots with offal tied on the outside were compared with those of controls which were baited only. During this experiment the catch rates were 4.56 individuals/pot-night for the control and 0.13 individuals/pot-night for the experimental traps. At Necker, the catch rate for control traps was 0.97 individuals/pot-night and that for experimental traps was 0.19 individuals/pot-night.

During the second experiment on cruise TC-82-05, five stations produced catch rates from 0.08 to 2.31 individuals/pot-night for controls whereas those obtained from the experimental traps ranged from 0.00 to 0.06 individuals/pot-night. Data from one station were not used in the analysis due to effects produced by rough seas resulting in heavy gear losses and zero-catch rates.

The experiments demonstrated that the presence of offal in or around the pots substantially decreases catch rates for P. marginatus in the NWHI.

PREDATORS

Among the management measures adopted for the spiny lobster fishery in Hawaii is the prohibition of retaining berried female and sublegal-sized lobsters. The usual practice aboard commercial boats is to sort out the berried female and sublegal-sized lobsters as the traps are retrieved and to return them to the water as quickly as possible. At the same time, the fishermen remove and discard the old bait and replenish the container.

What happens to lobsters that have been caught and released is of considerable importance to the fishery. Gooding (1979, in preparation) noted that when berried and sublegal-sized lobsters were hauled aboard a boat and later released, they are subjected to considerable stress, resulting primarily from long exposure to air and sunlight, rough handling, release over unsuitable or unfamiliar territory, disorientation, and predators.

Because used bait is discarded as a vessel moves along the string of traps, predators are easily attracted to the stern; thus, discarded bait as well as surface-released lobsters are both consumed. To determine the degree of this type of predation and to identify the predators, the Honolulu Laboratory conducted field experiments during cruises TC-79-02 and TC-81-04, as well as during the Easy Rider charter cruise ER-80-01.

Casual observations on several research cruises and those made by commercial fishermen indicated that there were at least two principal predators -- the hon-ulua (Caranx ignobilis) and the galapagos shark (Carcharhinus galapagensis). Gooding (1979) reported that predators such a omilu (Caranx melampygus), hon-ulua, reef whitetip shark (Triaenodon obesus), and gray reef

shark (Carcharhinus amblyrhynchos) were seen near the NMFS vessel but none showed any inclination to prey on surface-released lobsters. Likewise, on cruise ER-80-01, potential predators such as hon-ulua, galapagos shark, tiger shark (Galeocerdo cuvieri), and ono (Acanthocybium solandri) were observed around the vessel but underwater observations revealed no predation on surface-released lobsters.

Results obtained during cruise TC-81-04, however, demonstrated conclusively that hon-ulua are voracious predators. Gooding (1982) concluded that the state of satiation is always a factor and that the number of lobsters consumed is directly related to predator size, predator school size, and size of lobsters released. Furthermore, Gooding's observations showed that bottom-release of lobsters, even on substrata that offers good shelter, does not ensure high survival in the presence of voracious predators. The only practical safeguard to ensure high survival was to release lobsters near the bottom in protective bags or containers and only when there was reasonable assurance that large schools of predators were not following the boat.

ECONOMIC STATUS AND POTENTIAL

In early 1977, following the discovery of commercial concentrations of spiny lobsters at Necker, five commercial vessels began full-scale trapping operations and by the end of the year had produced a catch of 31,547 kg from the NWHI, thereby catapulting the statewide landings of spiny lobster to more than 13 times the previous year's landings. This early beginning of the fishery was not without problems. The market structure was unorganized and the boats returning from the NWHI lobstering grounds faced a local market that was chaotic and unable to absorb the sudden heavy influx of live, whole lobsters. Ex-vessel prices averaged $6.39/kg ($2.09/lb) and the year's statewide catch of 37,659 kg was worth about $240,600 to the fishermen.

The fishery experienced other "growing pains." Captains unfamiliar with transporting large numbers of live lobsters in their baitwells over the long distance from the NWHI lobstering grounds to Honolulu sometimes experienced losses of entire loads due to overcrowding and poor water circulation in the baitwells. Those vessels lucky enough to return with a full live load were faced with declining prices and attempted to maintain prices by marketing their catches in small amounts and over a longer period.

The chaotic market forced several marginal producers out of the fishery and by October 1977, only two vessels remained. These vessels continued to fish until October 1978 when they were joined by another entry into the fleet. The result was that landings from the NWHI declined to 12,440 kg, a 60 percent decrease from the previous year. The ex-vessel price, however, rose to $6.60 kg ($3.00/lb) making the 1978 statewide landings of 15,294 kg worth $82,100 to the fishermen.

Also about this time, the industry began looking for other outlets for their products, particularly the frozen lobster tail export market. This new impetus raised the hopes of the industry and landings again rose, reaching 45,372 kg; however, only two vessels participated, and presumably almost all of the catch was from the NWHI. At an ex-vessel price of about $7.05/kg ($3.20/lb), the 1979 catch was worth $319,900. At-sea processing required large vessels not only with freezing capabilities but also with the ability to exert greater fishing pressure.

By 1980, the fleet was composed of three vessels, and among them they had the potential of setting and retrieving 2,500 lobster pots per night. This resulted in a catch of 148,907 kg worth $1.1 million at an ex-vessel price $7.49/kg ($3.40/lb).

Encouraged by the rising prices and continued strong demand for frozen lobster tails, the fishery continued to produce record catches. By 1981, the fleet had increased to 10 vessels, which caught a record 354,200 kg worth $2.7 million at an ex-vessel price of $7.71/kg ($3.50/lb).

Although catch records for 1982 are incomplete, the annual catch, produced by six vessels, is estimated to be 83,711 kg, down considerably from 1981. Ex-vessel prices advanced little to $8.06/kg ($3.60/lb), making the 1982 catch worth an estimated $674,714 to the fishermen.

Annual estimated landings with ranges of MSY are given below. Using the average CL of the males and females at Necker and Maro Reef (Table 3) and converting these to average weight using the length-weight relationships (Figure 8), an average weight of 533 g for both sexes combined was calculated. Based on this average weight, the range in MSY is estimated to be 106,600 to 231,855 kg.

The landings in 1977-79 were far below the lower range MSY. In 1980 and 1982, the estimated landings fell within the range of MSY but in 1981, the upper limit of the MSY was exceeded by about 122,000 kg.

When the fishery first began, some believed that the potential was as good as that of other lobstering grounds throughout the world. Potential production from the NWHI grounds based on extrapolations of initial catch rates seemed encouraging; however, as with many new, developing fisheries, once the initial stock was reduced by heavy fishing and catch rates declined, enthusiasm subsided. By then, our surveys demonstrated that the NWHI catch rates of spiny lobster were nowhere near those of the major lobster fisheries of the world, for example Australia and South Africa. Furthermore, in the NWHI fishery, risks were greater as vessels had to travel 1,700 nmi round trip to fish at Necker and Maro Reef, the only two grounds with commercial concentrations of spiny lobsters.

Even with the most optimistic projection, it is not likely that the NWHI spiny lobster stock could support more than a few full-time vessels. Furthermore, profitability may depend on a multispecies operation. Places such as Nihoa, Pearl and Hermes Atoll, Gardner Pinnacles, and Midway can probably be fished profitably in combination with other types of fishing. Examples are bottomfishing for members of the snapper-grouper complex, trolling for coastal pelagic species such as wahoo (Acanthocybium solandri), and trapping for deepwater caridean shrimps. There are also several important species in the by-catches of lobster pots such as slipper lobsters (Scyllarides squammosus and S. haani) and frog or kona crab (Ranina ranina) which could add to a vessel's profitability.

MANAGEMENT GUIDELINES

Management of the spiny lobster fishery in Hawaii is achieved through a series of regulations which apply to two permit areas. Permit Area 1 encompasses the U.S. fishery conservation zone (FCZ) around the NWHI or all islands and banks west of long. 161° 00'W. Permit Area 2 includes the main Hawaiian islands or those islands and banks in the archipelago east of long. 161° 00'W.

Currently the management measures published in the Federal Register[3] include the following:

Size regulation. Whole lobsters of 77.0-mm CL or greater may be retained. If the CL cannot be determined, only lobsters with tails at least 50 mm wide may be retained, except for an allowance of up to 15 percent of the catch, by number, which may include tail widths between 45 and 49 mm.

Reproductive condition restrictions. Berried females may not be retained or stripped of eggs attached to the pleopods.

Closed areas. Spiny lobster trapping is not allowed within 20 nmi of Laysan and within the FCZ landward of the 10-fathom curve as depicted on National Ocean Survey charts 19022, 19019, 19016.

Gear restrictions. Spiny lobsters may be taken only with lobster pots or by hand. Other gears or chemical agents are prohibited. Furthermore, pot entrance may measure no more than 26.7 cm (10.5 in) at its greatest

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[3]Federal Register 47(126), June 30, 1982, contains the proposed rule; Federal Register 48(26), February 7, 1983, contains the final rule. The final rule contains no substantial changes from the proposed rule except minor revisions.

diagonal or diameter at the larger end and no more than 16.5 cm (6.5 in) at its greatest diagonal or diameter at the smaller end.

Permits. Any U.S. vessel trapping commercially in the NWHI management area (Permit Area 1) must have a permit issued by the director, Southwest Region, NMFS.

Recordkeeping and reporting. The operator of any vessel engaged in lobster trapping operations in Permit Area 1 shall maintain an accurate and complete logbook furnished by NMFS, recording all information as required.

Landing requirements. The operator of a fishing vessel that has fished in Permit Area 1 shall contact by radio or otherwise, an authorized officer at least 24 hours before landing and report to this officer the port, date, and time of unloading. An authorized officer is defined as any commissioned, warrant, or petty officer of the U.S. Coast Guard (USCG); a special agent of the NMFS; any officer designated by the head of any federal, state, or territorial agency which has entered into an agreement with the Secretary of Commerce and the Secretary of Transportation to enforce the provisions of the Magnuson Fishery Conservation and Management Act; and any USCG personnel accompanying and acting under the direction of any USCG commissioned, warrant, or petty officer.

Experimental fishing. The Secretary of Commerce may authorize experimental fishing for spiny lobster which would otherwise be prohibited. A NMFS scientific observer must be aboard the vessel while the vessel is engaged in such activity.

An additional provision of the regulations applies to protective measures established for the Hawaiian monk seal (Monachus schauinslandi) which was designated a depleted species under the Marine Mammal Protection act and listed as an endangered species effective November 23, 1976. Briefly, these measures specify that in the event that a monk seal dies from causes that appear to be related to the spiny lobster fishery, an investigation will be conducted by the director of the Southwest Region. If it is determined that the death is related to the spiny lobster fishery, emergency measures will be instituted, as required, to protect the monk seal population. In addition to the regulations established under the Spiny Lobster Fishery Management Plan, there are state laws and rules which are applicable to fishing for and landing of spiny lobsters and other crustaceans. State laws establish a seasonal closure, prohibit taking of ovigerous females, establish a minimum size, and prohibit the landing of lobsters from which the carapace and tail have been separated; however, the state law also provides that such measures shall not

apply if the catch was made outside of state waters and the possession or sale has been licensed (import permit) by the Hawaii Department of Land and Natural Resources.

SUMMARY

The investigation conducted by NMFS has elucidated several aspects of the spiny lobster resource in the NWHI. Particularly striking is the fact that P. marginatus is unevenly distributed and the only stocks which are of commercial potential are those at Necker and Maro Reef. The survey showed that the relative abundance of lobsters is highest at the 55 to 73 m depth in localities near the lower end of the NWHI chain and at the 19 to 54 m depth in those localities toward the northern end of the chain. Whereas a small female lobster from the NWHI may spawn just as many eggs as one in waters off Oahu, at larger sizes the NWHI female apparently spawns fewer eggs. The spawning season for NWHI populations is estimated to be all year at the lower end of the chain, peaking in summer. However, among the more northern localities, the spawning period is shorter and confined primarily to the summer months.

Studies on growth rate showed that a male lobster from Necker grows at about the same rate as one in waters around Oahu. For the Oahu stock, males mature at 63.6-mm CL whereas the females mature at 58.6-mm CL. For the stock at Necker, males mature at 59.2-mm CL and females at 60.7-mm CL. The difference between localities is not significant.

Lobsters tend to avoid baited traps in the presence of offal. Large schools of predators can inflict serious losses among surface-released berried and sublegal-sized lobsters.

The lobsters at Necker and French Frigate Shoals are, on the average, smaller than those found elsewhere in the chain. The legal to sublegal size ratio of the catch showed wide variation with no particular trend. The sex ratio of the stocks, however, showed that among the legal-sized lobsters in the catch, males predominated. Among sublegal-sized lobsters, however, there was a preponderence of females at most localities.

A legal-sized lobster of 77.0-mm CL weighs about 378.1 g, whereas a legal-sized female is heavier, weighing 402.4 g. There is sexual dimorphism in the growth pattern.

The relationship between CL and tail weight predicts a legal-sized male would have a tail weight of 130 g and a female 156 g.

Discriminant analysis based on tail width correctly classifies 94.8 percent of the sublegal-sized and 85.8 percent of the legal-sized lobsters. The tolerance factor adopted for the fishery management plan is that no more than 15 percent of the total

number of tails landed may be less than the specified tail width limit of 50 mm.

Studies on population dynamics provided a range of possible MSY of from 200,000 to 435,000 lobsters/year.

Experiments on gear competition showed that pot spacings of between 35 and 46 m produced the highest catch rates. Tests with escape gaps revealed that the overall escape rate of sublegal-sized animals was about 60 percent. Studies on ghost fishing of lost traps demonstrated that they continue to attract lobsters and, over the short term, continue to fish; however, over the long term, lobsters appear to escape through trap entrances.

Finally, the investigation showed that even with the most optimistic projections, it is not likely that the NWHI lobster fishery will expand significantly over the next few years. The upper limit of the MSY was exceeded in 1981. With reduced catch rates at this time, it is not likely that the present scale of production can support more than a few vessels. The future of the fishery will depend to a large extent on the operation of multispecies fishing boats that can participate in other fisheries being developed in the NWHI.

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STUDIES ON RECRUITMENT IN THE HAWAIIAN SPINY LOBSTER, PANULIRUS MARGINATUS

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ABSTRACT

In this paper several aspects of the biology of Panulirus marginatus are reviewed regarding their combined effect on recruitment and current regulations governing commercial fishing in the Hawaiian Archipelago. Among the factors believed to influence recruitment are seasonal and geographic patterns of puerulus larval settlement, stock homogeneity, rates of growth and natural mortality, and degree of movement of juvenile and adult lobsters. Recruitment to the fishery is especially dependent upon the level of settlement of puerulus larvae, the natural mortality of juveniles and adults, and the rate of growth of sublegal size lobsters on the commercial fishing grounds per se. The principal effect of prohibiting fishing in adjoining shallow-water areas in the Northwestern Hawaiian Islands will probably be to protect a portion of the reproductive stock and thereby provide a relatively reliable source of larval recruits with which to help sustain fishery production. At the densities investigated, closed areas will probably not be a substantial source for recruitment of lobsters to the commercial fishery.

spiny lobsters
Hawaiian Archipelago
recruitment
resource management

INTRODUCTION

In this paper selected results of several studies are summarized that pertain to recruitment in the Hawaiian spiny lobster, Panulirus marginatus (Quoy and Gaimard, 1825). All of

these studies are continuing and conclusions may be modified as additional data are collected and analyzed. The term "recruitment" is variously defined within the context of fisheries biology (Hancock, 1973). In this paper, two phases are considered: (1) recruitment to the fishable stock, and (2) recruitment to the fishery. Recruitment to the fishable stock occurs when spiny lobster puerulus larvae settle out of the plankton and become demersal. Recruitment to the fishery occurs when the juveniles and adults become subject to large-scale capture due to their growth and movement to the commercial fishing grounds.

The principal concern in managing the commercial fishery for spiny lobsters in Hawaii is that the short-term profitability for fishing enterprises be balanced against the risk of reduced recruitment which could lead to overfishing. Recruitment overfishing occurs when year-classes fall well below the recruitment occurring when adult stock is high (Cushing, 1977). Widespread recruitment overfishing appears to be a distinct possibility in spiny lobster fisheries generally. This is because minimum legal size limits are often set below or near the initial size of female maturity and because fishing mortality rates are usually very high (Kensler, 1967; Munro, 1974; George et al., 1979; Gregory et al., 1982).

The regulatory framework formulated to manage the spiny lobster resources throughout the Hawaiian Archipelago designates two management areas (Figure 1). This dichotomy achieves complementary management of the spiny lobster fishery in the federal fishery conservation zone (FCZ) and in waters under state jurisdiction. Accordingly, federal regulations apply in all waters adjacent to the Northwestern Hawaiian Islands (NWHI) which is designated Management Area 1. State regulations apply in all waters adjacent to the main Hawaiian islands (MHI) which is designated Management Area 2. The meridian, 161°00'W longitude, demarcates the two management areas. The boundary of the FCZ around the Hawaiian Archipelago is indicated in Figure 1.

Regulations intended to reduce the risk of recruitment overfishing of spiny lobsters in the Hawaiian Archipelago differ substantially between management areas (Table 1). This is because lobsters caught in the MHI traditionally are marketed live and whole, whereas lobsters caught in the NWHI are marketed as frozen, processed tails. The demand for processed tails places a significantly higher premium on smaller sizes being landed in the NWHI than does the demand for whole lobsters. If the fishery in the NWHI is to be economically viable, therefore, the demand for smaller lobsters needs to be accommodated. A second accommodation in regulation of the fishery in the NWHI in contrast with the MHI is required relative to season closure. Sea conditions generally are not conducive to lobster fishing in the NWHI at times other than during the summer, when lobster fishing is not permitted in the MHI. A large percentage of all spawning by lobsters in the NWHI occurs during the summer. But, to facilitate fishery operations in that management area, there

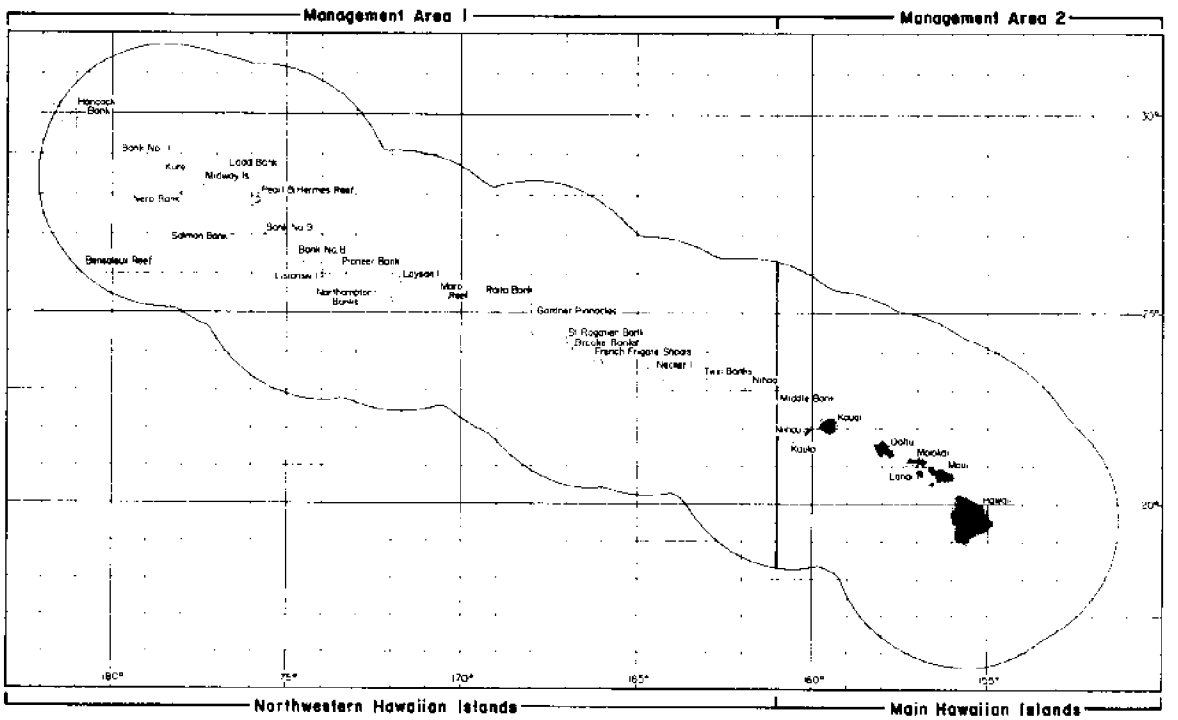

Figure 1. Management areas for spiny lobsters within the Hawaiian Archipelago

TABLE 1. REGULATIONS INTENDED TO REDUCE THE RISK OF PANULIRUS MARGINATUS RECRUITMENT OVERFISHING IN THE HAWAIIAN ARCHIPELAGO

Regulation	Management Area 1 (NWHI)	Management Area 2 (MHI)
Minimum size	7.7 cm C.L.	8.26 cm C.L.
Season closure	None	June - August
Gravid females	Prohibited	Prohibited
Area closure	<10 fathoms	None

is no season closure. Therefore, as a trade-off to mitigate against the increased risk of recruitment overfishing that these two accommodations may incur, lobster fishing is not allowed in water depths of less than 10 fathoms in the NWHI. This trade-off is based on the critical assumptions that (1) P. marginatus puerulus larvae regularly settle in shallow nearshore habitats throughout the archipelago, and (2) conditions there are suitable for P. marginatus survival, growth, and reproduction. In this paper these assumptions are tested and the appropriateness of certain regulations for managing the commercial fishery for this species throughout the Hawaiian Archipelago is considered.

RECRUITMENT TO THE FISHABLE STOCK

Consideration of the pelagic larval stages in managing the fishery for P. marginatus is important since the larvae have great potential for widespread dispersal. An exceptionally long pelagic existence extending over 4 to 22 months, in which phyllosoma larvae are transported passively by ocean currents, is typical of spiny lobsters (Phillips and Sastry, 1980). Maximum larval transport distances, in which no land mass lies between the nearest adult population and where larvae are found in the plankton, range between 483 and 2,414 km for several species of spiny lobster (Lazarus, 1967; Chittleborough and Thomas, 1969; Johnson, 1974; Phillips et al., 1979). The potential to disperse widely within the Hawaiian Archipelago increases the likelihood of extensive gene flow and the chance of P. marginatus larvae being recruited locally from distant adult stocks. Different patterns of larval recruitment could have different genetic consequences and could require different fisheries management strategies. Preliminary results of a long-term study of the seasonal and geographic patterns of P. marginatus puerulus recruitment were recently reported (MacDonald, 1983), and that study is summarized in this paper.

Phyllosoma larvae of P. marginatus pass through 11 dissimilar stages (Johnson, 1968) before metamorphosing to a postlarval form known as the puerulus (Cooke and MacDonald, 1981). The puerulus is a transitional stage between the phyllosoma larva and the settled juvenile. Typically, the puerulus is free-swimming and is the form which actively returns to nearshore benthic habitats where it settles out of the plankton. Upon settling, the puerulus molts into the postpuerulus stage which is essentially a very early juvenile.

Puerulus and postpuerulus stages of P. marginatus were collected using floating artificial habitat collectors of the improved "Witham Habitat" design (Little, 1977; Little and Milano, 1980). Twenty collectors were buoyed up at the surface and moored at permanent stations up to several hundred meters apart in the lagoon at Kure Atoll (28°25'N, 178°20'W) and within

the shelter of the barrier reef at French Frigate Shoals (23° 46'N, 166°18'W). Kure Atoll and French Frigate Shoals are state and federal wildlife refuges respectively. Ten collectors were buoyed up at the surface and moored at permanent stations in Kaneohe Bay, Oahu (21°30'N, 158°W) within a restricted area maintained by the Naval Ocean Systems Center. At all three islands, the collectors were situated amidst patch reef habitats supportive of postpuerulus stages or juveniles as ascertained by diver observations.

Larval collectors were deployed at Kure Atoll in June 1979, at Oahu in August 1980, and at French Frigate Shoals in June 1981. Initial sampling at each location revealed a lunar pattern of recruitment; puerulus larvae of P. marginatus settled predominantly during the new moon and first quarter phases. An entire month's settlement of puerulus larvae thus could be assessed accurately by sampling once each month around the time of the full moon phase as for other species of spiny lobsters (e.g., Phillips, 1972). Regular monthly sampling was conducted up to the present on that basis and is scheduled to continue throughout the next year.

Settlement was strongly seasonal at Kure Atoll (Figure 2). A Mann-Whitney U test of these data indicates that significantly more puerulus larvae settled during April through October than during November through March ($P < 0.001$, one-tailed test corrected for ties). Although the data are relatively few, settlement at Oahu also was seasonal but during essentially the oppsite time of the year than at Kure Atoll (Figure 2). A Mann- Whitney U test of these data indicates that significantly more puerulus larvae settled during September through May than during June through August ($P < 0.029$, one-tailed test corrected for ties). In contrast with these two localities, there was no seasonality associated with the settlement of puerulus larvae of P. marginatus at French Frigate Shoals (Figure 2). Instead, settlement there seemed to occur in an irregular fashion throughout the year.

The data gathered on the puerulus recruitment of P. marginatus provide support for the oceanographic climatic model of the Hawaiian region developed by Seckel (1962). According to Seckel's model, the Hawaiian Archipelago is bathed predominantly by the North Pacific Central water type which changes location in response to seasonal variations in the intensity and position of the major surface currents around its boundary (Figure 3). During spring and early summer, the California Current system intensifies and as a result the California Current Extension spreads and displaces the southern boundary of the North Pacific Central water type northward within the Hawaiian islands. In late summer and early autumn, as the California Current system weakens, the transitional water of the California Current Extension retreats southward and is replaced by the North Pacific Central water type. Although not as well documented, Seckel provides evidence that corresponding shifts in the northern boundary of the North

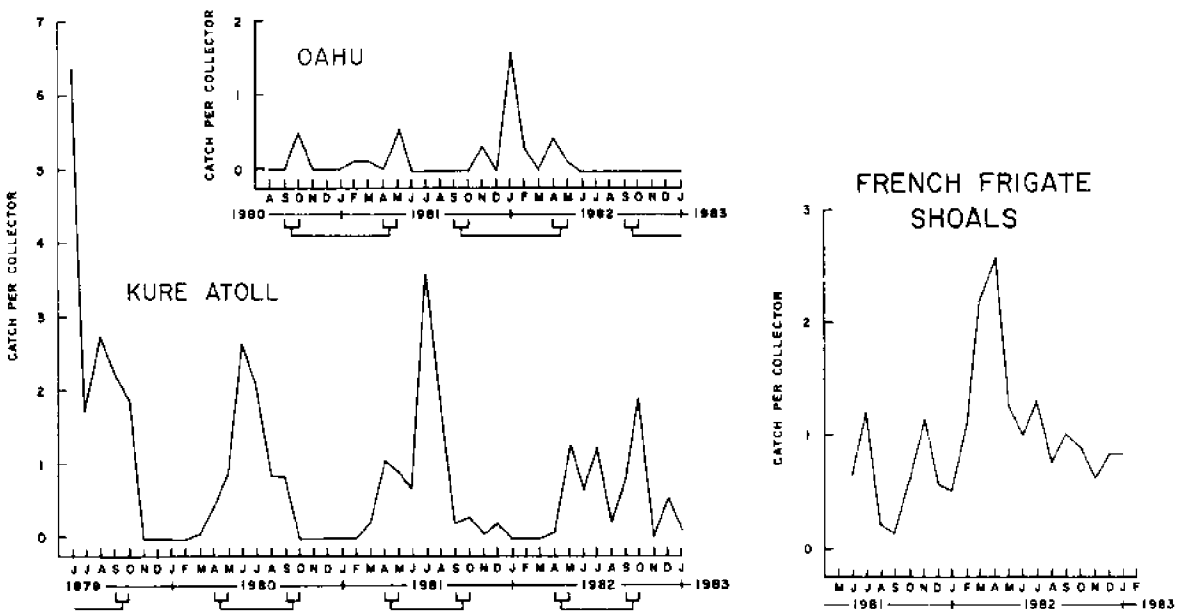

Figure 2. Catches of the puerulus and postpuerulus stages of Panulirus marginatus at Kure Atoll, Oahu, and French Frigate Shoals

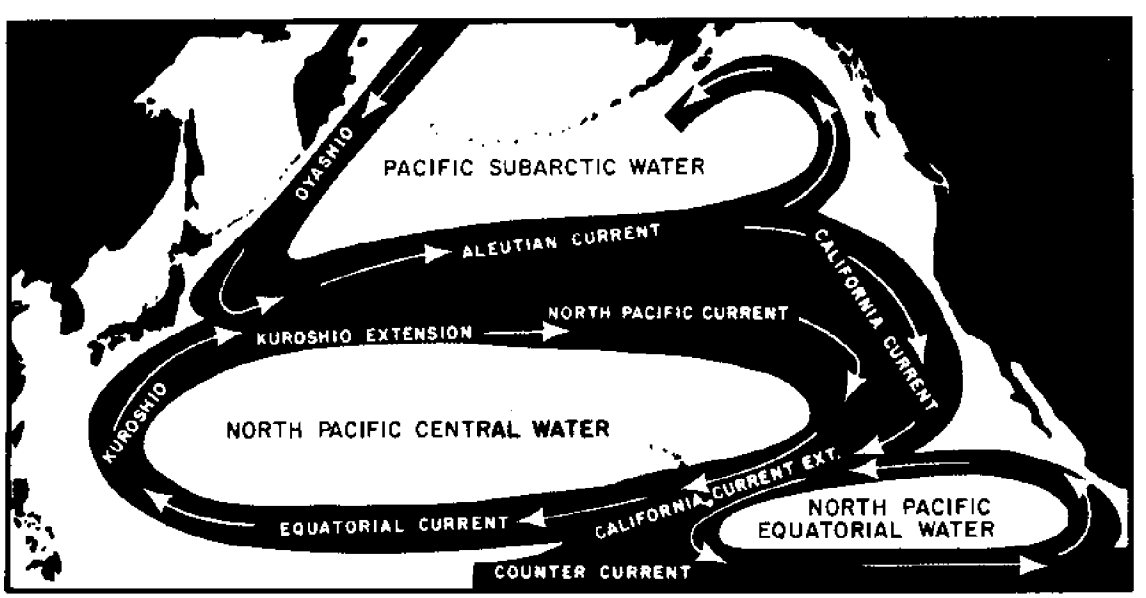

Figure 3. Schematic chart of the major North Pacific water types and currents (from Seckel, 1962)

Pacific Central water type occurs in the vicinity of Kure Atoll. The North Pacific Central water type is characterized by warm, high salinity water which extends to the bottom of the mixed surface layer (25 to 100 m deep) and is under the direct influence of physical processes taking place at the sea surface (Seckel, 1962). The degree of displacement of the North Pacific Central water type varies between years. The area investigated by Seckel is the rectangular shaded area in Figure 3.

Seckel's model is only a rough approximation of the oceanographic climate of the Hawaiian region, and it should be noted that there actually are no sharp distinctions between water types and currents but only broad transitions in water properties. However, with slight modification to this model, a simple scheme of puerulus larval recruitment can be devised. Assuming that puerulus larvae of P. marginatus are associated only with the North Pacific Central water type or some dynamic process(es) associated with it, the seasonal and geographic availability of the puerulus larvae may be determined to a large extent by an island's position relative to this water type's northern and southern boundaries. Hence, the North Pacific Central water type in the vicinity of the Hawaiian Archipelago might be envisioned as an ellipse which seasonally oscillates up and down the island chain (Figure 4). The ellipse is displaced southward during the winter and northward during the summer; the area of overlap is

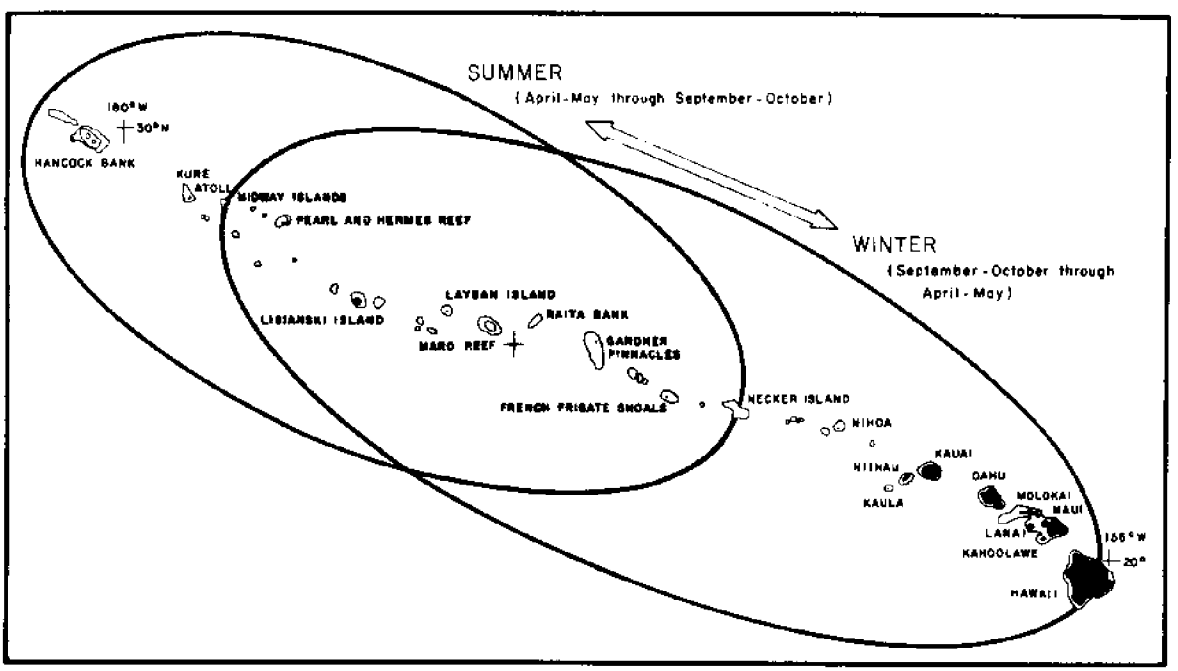

Figure 4. Schematic depicting the North Pacific Central water type in the vicinity of the Hawaiian Archipelago as an ellipse which seasonally oscillates up and down the island chain (based primarily on Chart III in Seckel, 1962)

shaded in Figure 4. According to this stylized scheme, settlement of puerulus larvae would occur during those times of the year that an island is encompassed by the ellipse (i.e., the North Pacific Central water type). Settlement of puerulus larvae thus would occur throughout the year at islands located where the ellipse continually overlaps during its annual oscillation. Settlement of puerulus larvae would be seasonal at islands located where the ellipse departs during its oscillation and thus would occur at reciprocal times of the year at opposite ends of the island chain. Since the geographic distribution of P. marginatus is limited to the Hawaiian Archipelago and Johnston Atoll, other finer-scale hydrographic conditions such as currents and eddies probably serve to generally retain the phyllosoma larvae of this species within the Hawaiian region (Johnson, 1968).

To date, the results of P. marginatus puerulus larval settlement generally support this scheme. Settlement occurred irregularly throughout the year at French Frigate Shoals. Settlement at Kure Atoll occurred in the summer, primarily during April or May through September or October when the North Pacific Central water type is displaced northward. Settlement at Oahu occurred primarily in the winter, the opposite time of the year from Kure Atoll, coinciding with the period from September or October through April or May when the North Pacific Central water type is displaced southward. The large brackets in Figure 2 indicate the period during which settlement is most likely to occur based on Seckel's (1962) oceanographic climatic model. The small brackets indicate months of probable boundary transition in the passage of the North Pacific Central water type by Kure Atoll and Oahu. The intervals used in the statistical tests, therefore, represent the broadest span of time during which P. marginatus puerulus larval settlement is likely to occur at Kure Atoll and Oahu based on the seasonal pattern of displacement of the North Pacific Central water type (Seckel, 1962).

RECRUITMENT TO THE FISHERY

Growth and Natural Mortality

Rates of growth and natural mortality are important variables in the process of recruitment. This is because the net rate of recruitment to a fishery is a compound factor which depends partly upon the time required for individuals to grow to the minimum legal size and partly upon the fraction of the year class remaining when individuals attain that size.

In this study, the rate of growth was calculated by the von Bertalanffy function using recapture data (Fabens, 1965). The rate of natural mortality was calculated using carapace length composition data and the von Bertalanffy growth parameters (Beverton and Holt, 1956). In unexploited stocks, such as within

the study areas at Kure Atoll and French Frigate Shoals, the total instantaneous mortality rate equals the rate of natural mortality. Therefore,

$$M = \frac{K\ (L_\infty - \bar{\ell})}{\bar{\ell} - \ell'}$$

where

M = instantaneous coefficient of natural mortality
K = intrinsic growth rate
L_∞ = asymptotic size
ℓ' = smallest carapace length (CL) fully represented in the catch samples
$\bar{\ell}$ = mean carapace length computed from ℓ' upwards.

For diver samples at both locations, ℓ' was concluded to be 4.6-cm CL. This technique is probably the most useful approach for estimating total mortality in the Palinuridae, given the inability to independently determine age for any of the palinurid species (Morgan, 1980).

A total of 2,629 P. marginatus was captured at Kure Atoll between June 1979 and August 1981 and 1,161 at French Frigate Shoals between June 1981 and September 1982. These totals are comprised entirely of lobsters collected by divers and are free of any size or sex bias that may be associated with trapping. Individual lobsters were identified using either numbered western Australia spiny lobster tags (Chittleborough, 1974) or a code based on punching holes in the uropods (modified after Engle, 1979) and then released. Carapace length was measured to the nearest millimeter along the middorsal line from the anterior end between the postorbital spines to the posterior edge. The presence of external eggs on females was recorded. All lobsters were caught in areas shallower than the 10-fathom depth contour where commercial trapping was restricted under fishery regulations for the NWHI. In addition, both study areas were located in wildlife refuges where there is no recent history of commercial fishing.

Population densities of P. marginatus in the study areas at Kure Atoll and French Frigate Shoals are similar. The mean catch per unit effort, based on the number of lobsters seen per diver hour, did not differ significantly between these locations ($t = -0.6944$, $df = 250$, $P < 0.4881$). This situation is fortunate because density-dependent differences in growth and natural mortality of P. marginatus between these locations are minimized.

Annual growth increments of P. marginatus at Kure Atoll and French Frigate Shoals are similar (Figure 5). The mean interval between capture and recapture for these lobsters was 366 days ± 6 days (standard deviation), and both sexes were sampled over a wide range of carapace lengths. Growth parameters and their 95 percent confidence limits were calculated using these data together with data based on capture-recapture intervals of more than a year (Table 2). For the sexes combined, there was no significant difference in lobster growth between islands. However, for the islands combined, there were significant differences between the sexes for both K (intrinsic growth rate) and L (asymptotic size). Females grew faster, but males attained a larger asymptotic size (Figure 6).

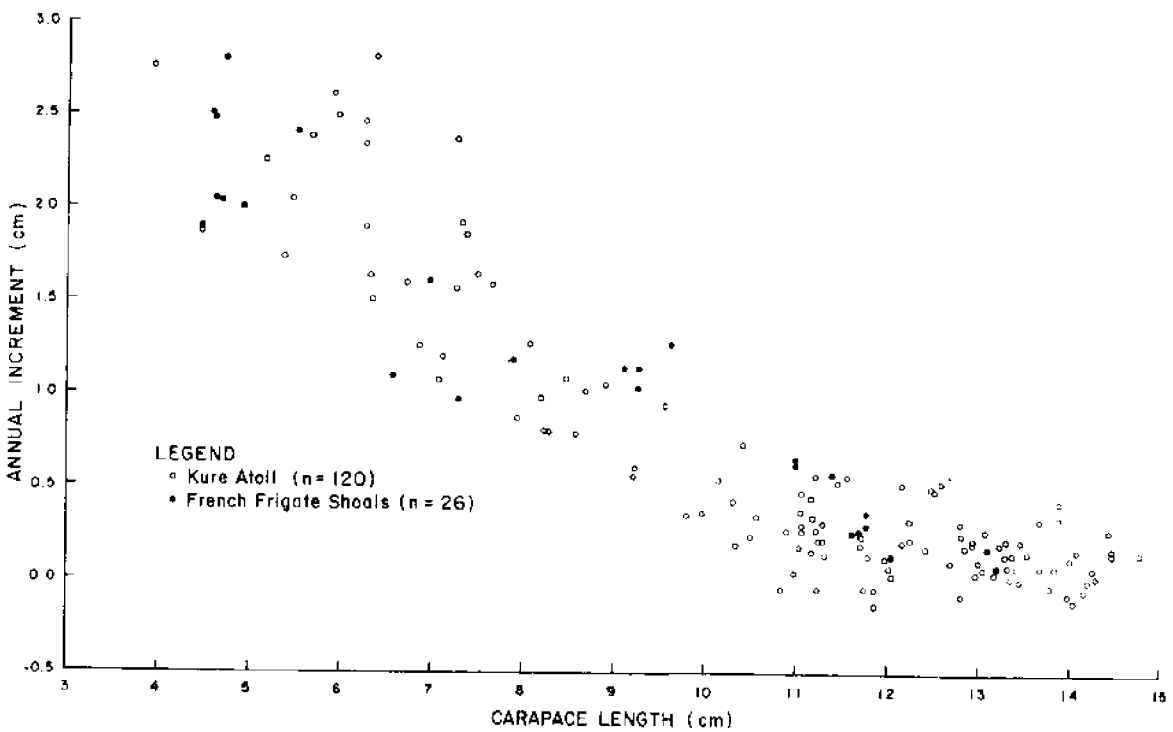

Figure 5. Annual growth increments of Panulirus marginatus at Kure Atoll and French Frigate Shoals

TABLE 2. COMPARISON OF GROWTH PARAMETERS FOR MALE AND FEMALE *PANULIRUS MARGINATUS* AT FRENCH FRIGATE SHOALS AND KURE ATOLL

ISLAND*	K	L_1	L_2	n
French Frigate Shoals	0.3046	0.2606	0.3485	43
Kure Atoll	0.2714	0.2428	0.3000	120
	L_∞	L_1	L_2	n
French Frigate Shoals	13.18	12.53	13.82	43
Kure Atoll	13.36	13.01	13.70	120
SEX†	K§	L_1	L_2	n
Male	0.2699	0.2430	0.2970	104
Female	0.3487	0.3000	0.3975	59
	L§	L_1	L_2	n
Male	13.61	13.30	13.92	104
Female	12.28	11.77	12.80	59

*sexes combined
†islands combined
§significant difference

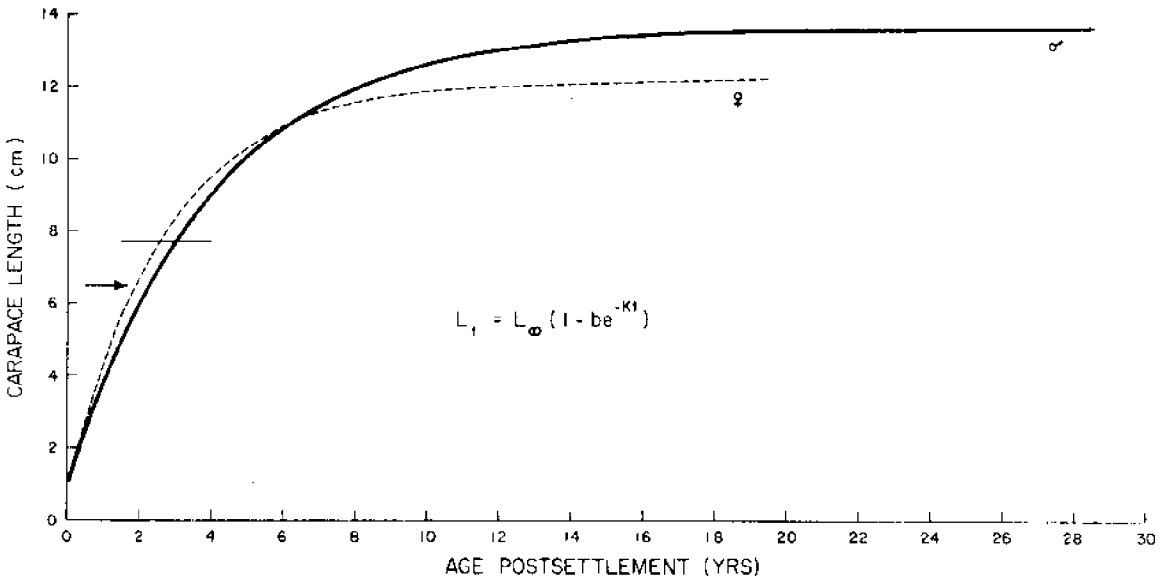

Figure 6. Von Bertalanffy growth curves of male and female Panulirus marginatus for Kure Atoll and French Frigate Shoals combined

The rate of natural mortality in P. marginatus appears to be greater for females than for males at both locations and is higher at French Frigate Shoals than at Kure Atoll. Correspondingly, carapace lengths of males and females were significantly greater at Kure Atoll than at French Frigate Shoals (two-way ANOVA: $F = 153$, $df = 3$, $P < 0.001$) (Figure 7). Estimates of selected demographic factors at both locations are presented in Table 3, where differences in natural mortality are expressed in terms of annual mortality rate ($1 - e^{-m}$) and average individual lifespan ($1/M +$ age at ℓ'). Mean carapace length in Table 3 is $\bar{\ell}$. All calculations of natural mortality were weighted for differences in sample size by season between June 1979 and January 1981 at Kure Atoll, and between June 1981 and September 1982 at French Frigate Shoals. The von Bertalanffy growth parameters for males and females were pooled over both locations.

All estimates of age are based on the von Bertalanffy growth curves. Age at entry to the fishery and age at minimum legal size at both locations are greater for males than for females (Table 3), corresponding to the differences in their rate of growth (Figure 6). In Figure 6, the size at entry to the fishery (6.6-cm CL) is indicated by the arrow and the minimum legal size (7.7-cm CL) is indicated by the horizontal line. Size at entry to the fishery was determined using the standard California two-chambered spiny lobster trap (MacDonald and Stimson, 1980). Age at sexual maturity for females is based conservatively on the smallest carapace length at which females were gravid. At both locations females became gravid (hatched area in Figure 7) at

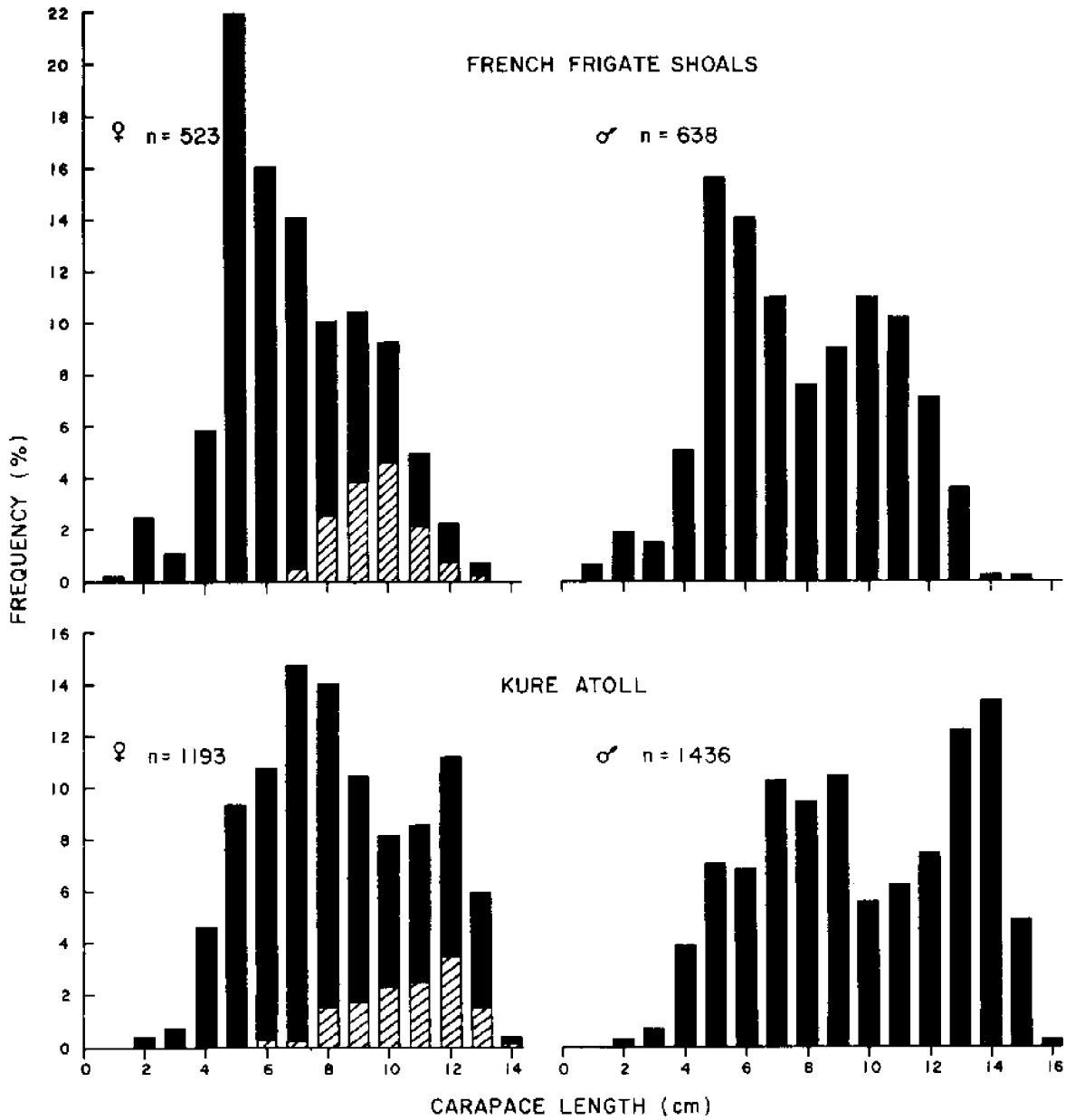

Figure 7. Size-frequency distributions of male and female Panulirus marginatus at Kure Atoll and French Frigate Shoals

TABLE 3. SELECTED DEMOGRAPHIC FACTORS FOR PANULIRUS MARGINATUS AT KURE ATOLL AND FRENCH FRIGATE SHOALS

Factor	Kure Atoll		French Frigate Shoals	
	Males	Females	Males	Females
Mean carapace length (cm)	10.3	8.9	8.3	7.2
Annual mortality rate (%)	15.1	25.1	31.9	45.4
Average individual lifespan (yrs)	7.4	4.6	3.8	2.8

	Both Locations	
	Males	Females
Age at entry to fishery (yrs)	2.3	1.7
Age at minimum legal size (yrs)	3.1	2.3
Age at sexual maturity (yrs)	2.7	1.7

about 6.5-cm CL which is approximately the size at entry to the fishery. Sexual maturity in males is assumed to occur at about the same carapace length as females, based on results of analyses of secondary sexual characteristics of P. marginatus at Oahu and Necker Island (J. Prescott, unpublished manuscript). Accordingly, males at Kure Atoll and French Frigate Shoals are expected to attain sexual maturity about a year later than females. Studies at Kure Atoll and French Frigate Shoals are continuing in order to verify this conclusion.

Movements

Spatially oriented movements of P. marginatus at Kure Atoll were investigated over time to assess the potential for exchange of lobsters between shallow areas closed to fishing in the NWHI and the adjacent commercial fishing grounds. Movements were based primarily on the distance and direction that tagged lobsters traveled between specific areas designated by 50 comercial-style lobster traps positioned at semipermanent sites within the study area. The data were collected by diver sampling.

Trap positions were established by triangulation with prominent shoreline features using an optical reading compass accurate to the nearest 0.5°. Positions were plotted on NOAA chart 19483. Topographic relief at trap positions plotted on the chart was consistent with water depth measured at actual trap sites, and distance between specific traps calculated using trap coordinates was consistent with a sample of distances measured between the same traps in the field. Gross deviation of trap positions from those plotted on the chart was prevented by regularly resiting traps by divers in January, June, and September each year. Each

trap was retained within a specific area through association with individually numbered lobster dens that were marked by a double set of plastic tags attached to the substratum. During this period, 1,054 lobster dens were tagged.

Distance was measured as the straight line between two traps and is a minimum estimate of the extent of movement. Direction was measured as the angle that a lobster moved from one trap to another relative to magnetic north. The mean distance between each trap and every other trap was 858 m; the range was 0 to 3,000 m. Between June 1979 and January 1981, 1,706 P. marginatus were tagged and released by divers. Between September 1979 and August 1981, 641 recaptures were made including multiple recaptures of some individuals. The time interval between each capture and recapture ranged between 90 and 793 days.

About 42 percent of all recaptures within the study area occurred at their respective release sites, indicating no net movement (Table 4). The sexes did not differ significantly in this regard. Among lobsters that moved a measurable extent, distances rarely exceed 1 km, and the distribution of directions was random (Raleigh's R = 15.74, n = 336) (Figure 8). Vector magnitudes in Figure 8 signify the number of times that lobsters moved in each direction. The pattern of predominantly localized movement was essentially the same for legal and sublegal size lobsters and persisted through time over both the short and long term (Figure 9). Collectively, there was no apparent seasonal difference in either the distance or direction of movement.

TABLE 4. SUMMARY OF DISTANCES MOVED BETWEEN CAPTURE AND RECAPTURE FOR PANULIRUS MARGINATUS AT KURE ATOLL

Sex	Percent		n	Maximum (m)
	0 m	<1 km		
Males	39.1	97.9	389	1729
Females	47.2	97.2	252	1499
Combined	42.3	97.5	641	
	95% Confidence Interval (0 m)			
Males	30.1 < 39.1 < 48.0		n = 152	
Females	37.5 < 47.2 < 56.5		n = 119	

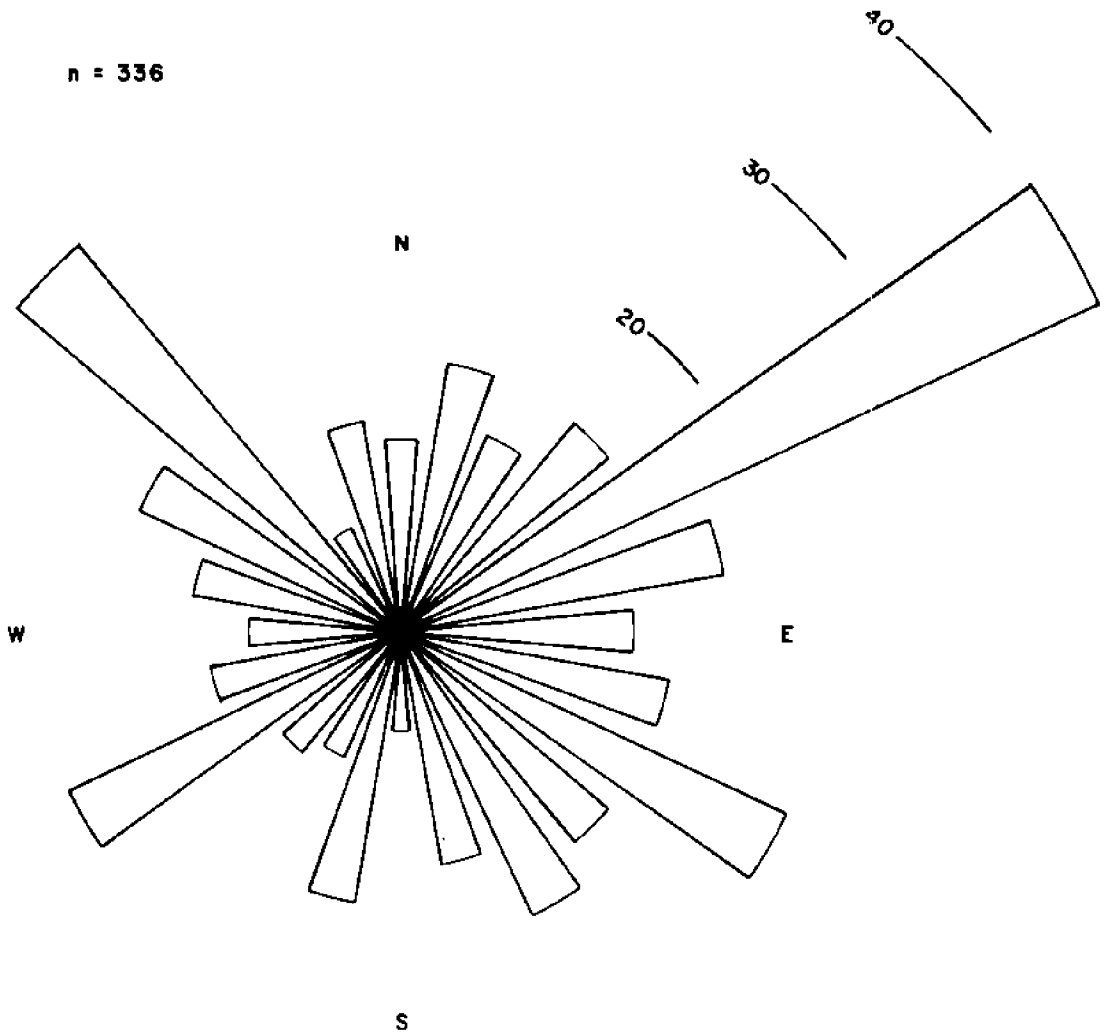

Figure 8. Vector diagram of movement of Panulirus marginatus between release and recapture at Kure Atoll

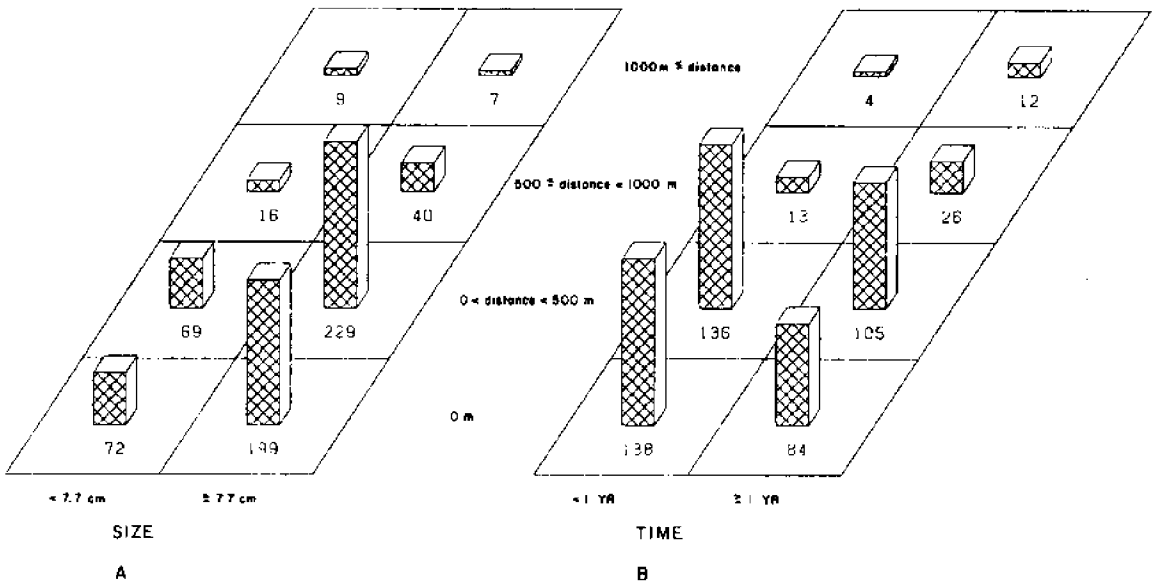

Figure 9. Frequency histograms of the distance moved between release and recapture by Panulirus marginatus of different size and over different intervals of time

Further information on movement was obtained by diver sampling at widely scattered locations across the atoll during the same time period to assess whether lobsters moved greater distances than could be detected within the study area. During 83 logged dives outside the study area from July 1979 through August 1981, project personnel captured 271 P. marginatus. Of these, a single tagged lobster was recaptured which had moved approximately 450 m in 265 days. In general, recaptures within the study area moved relatively short distances in random directions whereas recaptures outside the study area were rare, suggesting slow dispersal and a low rate of emigration. Preliminary results of similar research being conducted in shallow areas closed to fishing at French Frigate Shoals also indicate a generally local ized pattern of movement for this species. These results are consistent with Hernkind's (1980) postulation that species or populations of spiny lobsters at oceanic islands exhibit "residential" patterns of movement.

MANAGEMENT IMPLICATIONS

Assuming the model used to explain the seasonal and geographic patterns of settlement of P. marginatus puerulus larvae accurately reflects processes in nature, a number of ramifications emerge that pertain to the management of the commercial fishery for this species. A vital consideration is whether there is a single genetically homogenous population throughout the archipelago, or whether instead there is a heterogenous assemblage of genetically discrete stocks that

differ between islands or groups of islands. In a study of the genetic variation in P. marginatus, genetic variability was quite low and no evidence of subpopulation structure or stock heterogeneity was found (Shaklee and Samollow, 1980). The hypothesis that the puerulus larvae of P. marginatus may be associated with the North Pacific Central water type is consistent with this conclusion and may represent the underlying mechanism involved. As the North Pacific Central water type oscillates up and down the island chain, there may be sufficient mixing of the larvae while in the plankton that those produced around one island may settle elsewhere in the archipelago. This mechanism would be possible in the case of P. marginatus because of the long pelagic larval life which is typical of spiny lobsters in general (Phillips and Sastry, 1980). A fishery management plan that treats the spiny lobster resource as a unit stock is consistent with this interpretation.

Another important consideration is whether the season closure from June through August in the MHI actually enhances recruitment to the fishable stock. During this time, the California Current Extension has spread through the MHI and displaced the southern boundary of the North Pacific Central water type northward into the NWHI. Accordingly, phyllosoma larvae that hatch during the summer in the MHI may be especially liable to be swept away from the Hawaiian Archipelago to the southwest by prevailing currents. This could account for the presence of late stage phyllosoma larvae of P. marginatus and Arctides regalis, both Hawaiian endemic palinurids, at plankton stations in the vicinity of Johnston Atoll (Johnson 1968, 1971). Also, it is consistent with the suggestion that an established reproducing adult population of P. marginatus does not exist at Johnston Atoll, but rather that phyllosoma larvae occasionally are carried there from Hawaii by the North Equatorial Current (Brock, 1973). Reproduction in P. marginatus occurs at about the same level throughout the year at Oahu (Morris, 1968), but it is conceivable that the greatest contribution of phyllosoma larvae from the MHI to recruitment in the Hawaiian Archipelago is derived from spawning at times other than during the summer.

The annual level of recruitment of puerulus larvae to fishery stocks of spiny lobsters can vary greatly between years (Phillips, 1981), and the strength of settlement each year may influence future fishery production. In the case of the western Australian spiny lobster P. cygnus, for example, the long-term monthly monitoring of the settlement of puerulus larvae has enabled the successful forecasting of commercial fishery yields (Chittleborough and Phillips, 1975, 1979; Morgan, 1980) and has provided much of the basis for analysis of the stock-recruitment relationship (Morgan et al., 1982). If a similar program of long-term monthly monitoring of the settlement of puerulus larvae of P. marginatus is developed in Hawaii, for management purposes, several of the results of this study should be considered.

Notable, such a monitoring program preferably should be conducted at an island situated centrally in the Hawaiian Archipelago, such as French Frigate Shoals. Monitoring at islands situated near either end of the archipelago, such as Kure Atoll or Oahu, may be susceptible to sampling bias because of the different extent to which the North Pacific Central water type is displaced northward or southward between years. Under these circumstances, the choice of geographic location would be especially important if the monitoring program were to be established at only one island. In addition, French Frigate Shoals is situated ideally between Necker Island and Maro Reef, the principal commercial fishing grounds for P. marginatus in the NWHI.

At the densities investigated, closed areas in the NWHI are not expected to be a substantial source of lobsters for recruitment to the fishery because movement by P. marginatus is predominantly localized. Instead, closed areas will probably serve as a refuge for a portion of the reproductive adults, which should provide a relatively reliable source of larval recruits to the fishable stock.

Given the high degree of localized movement and the potentially high rate of natural mortality in P. marginatus, the need for a new regulation providing for escape gaps in lobster traps in the NWHI should be reconsidered. Since lobsters less than the minimum legal size might reside in the same general area for prolonged periods of time, they are especially susceptible to multiple recapture on the commercial fishing grounds. The combination of repeated handling and the potential damage that may result, together with the increased risk of predation upon release, may significantly decrease growth rates and increase the mortality of sublegal size lobsters, thereby seriously decreasing the overall rate of recruitment to the fishery.

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TROPHIC RELATIONSHIPS OF NEARSHORE FISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

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EXPANDED ABSTRACT

The shallow-water fish communities of the Northwestern Hawaiian Islands were studied over a period of 4 years in an effort to characterize the major trophic relationships of quantitative ecological importance. Major quantitative work was done at Midway Islands and French Frigate Shoals. Research was concentrated on the demersal fish fauna that was more or less resident over hard substrate. However, common, wide-ranging, semi-pelagic jacks and sharks were also studied because of their important role as high-level predators on this community. Quantitative description of the communities was based on visual underwater census at many locations and on quantitative collections of complete fish communities from isolated patch reefs. The numerical composition of the latter collections was used to define the communities for all results reported here. Diet information came from examination of gut contents of 129 fish species. All reports of various food items as a portion of fish diet were based on frequency of occurrence (number of predator specimens containing the prey item.) Natural abundance estimates of available benthic invertebrate prey items were based on extraction and enumeration of these animals from samples of hard substrate and sand cores. All results are preliminary and approximate, awaiting full computer analysis of large data sets.

The demersal, hard substrate fish fauna can be considered to consist of about 161 species observed in more than negligible numbers. The trophic base that supports about 63 percent of this demersal community was estimated based on predator species composition from quantitative fish community collections and frequency of occurrence of prey items from extensive predator collections. This base consisted of about 1 percent cephalopods, about 4.5 percent fish, over 4 percent zooplankton, about 8 percent algae, and about 82 percent benthic invertebrates (~6 percent molluscs, ~1.5 percent echinoderms, over 2 percent worms, and over 72 percent crustaceans). Crabs other than hermit crabs were an important component of the benthic fauna, averaging 166 individuals/m^2 of hard substrate. They were also important trophically, representing 17.4 percent of the known diet of the demersal fish community. They were clearly of major quantitative importance in the maintenance of 32 fish species, including 3 balistids, 3 cirrhitids, 6 labrids, 6 mullids, 4 scorpaenids, 3 muraenids, 2 holocentrids, 1 bothid, 1 ophichthid, 1 chaetodontid, 1 cheilodactylid, and 1 priacanthid. Major crab groups in the benthos were xanthids (77.3 percent), galatheids (11.7 percent), and majids (9 percent). At the family level, the composition of crabs in the diets of fishes was similar, but portunids and grapsids were also quite important (10.4 percent and 4.9 percent respectively of all crab occurrences in a sample of major crab consumers). Hermit crabs were also abundant in the benthos (77 individuals/m^2) and comprised 0.4 percent of the known diet of the demersal fish community. They were eaten in significant numbers by at least six fish species. For four species of large wrasses they provided 23 to 41 percent of the diet occurrences. Shrimp averaged 222 individuals/m^2 in hard substrate samples. They occurred significantly in 15 fish species, representing 5 percent of the demersal community diet. At the family level there was low correlation between the relative abundance in the benthos and in fish diets. Alpheids heavily dominated benthic samples (61.8 percent), followed distantly by palaemonids (14.7 percent) and hippolytids (11.4 percent). The latter two families and the rhynchocinetids were codominant items in the diets (22 to 25 percent each) of a sample of important shrimp consumers. Alpheids were eaten less commonly (6.7 percent). These differences probably reflect feeding selectivity and some sampling bias. Within the families Rhynchocinetidae and Hippolytidae, the most common species in the benthic samples also occurred most commonly in the fish diets. Stomatopods were rare in the benthic samples but occurred in moderate numbers in a considerable range of fish species. They comprised 1.2 percent of the diet for the demersal fish community and

were major diet components of at least five species. Pseudosquilla species, especially P. oculata, were important prey. Small crustaceans occurred widely in the fish diets. In many cases they appeared to be minor, supplemental diet items. Isopods (primarily suborder Flabellifera) were very important to a few very abundant fish species, e.g., about 75 percent in the three major Apogon species and over 84 percent in Adioryx diadema. This resulted in their providing nearly 15.0 percent of the demersal community's diet. In several species amphipods occurred with considerable frequency. They provided about 1.1 percent of the demersal community's diet. Amphipods were widespread and abundant in the benthos with 4,716 individuals/m^2. Gastropods were diverse and abundant on hard substrate (726 individuals/m^2) and on sand (3,960 individuals/m^2). Species composition was quantitatively quite different on the two substrates. The most common gastropods in the benthic samples were well represented in fish diets, particularly the sand-dwelling mollusc species. There was some evidence of partitioning the gastropod resource among fish predators. Of all fish species, 18.5 percent ate gastropods in significant quantities; they represented about 6 percent of the demersal fish community's diet. A wide range of fishes were heavy gastropod consumers, especially several wrasse species. Bivalves were much less abundant in the benthos and relatively unimportant in fish diets. At least eight species of echinoids were eaten by a considerable variety of fishes. Only five species -- mostly large wrasses -- ate significant quantities. Echinoids comprised about 1.0 percent of the demersal community's diet and were poorly represented in numbers and species in the benthic samples. Ophiuroids occurred in a variety of diverse fish groups (~11 percent of all species) but not in great numbers. Two species were common in the benthic samples in low abundance. Polychaetes were abundant in the benthic hard substrate (~2,644 individuals/m^2) and in the sand (~395 individuals/m^2). They occurred significantly in the diets of several diverse fish species and comprised over 2 percent of the demersal community's diet. The dominant prey groups were Terebellidae, Onuphidae, and Opheliidae. Twelve fish species ate cephalopods (mostly Octopus species), at least eight in substantial numbers, representing nearly 1 percent of the demersal community's diet. Only six species ate zooplankton, four in substantial numbers. This amounted to nearly 4.3 percent of the demersal community's diet. Sixteen species of fish ate significant amounts of algae, which represented about 8 percent of the demersal community's diet. No attempt was made to estimate the natural abundance of cephalopods, zooplankton, or algae in the habitat.

Thirty-six of the 119 demersal fish species examined showed evidence of piscivory. Based on frequency of occurrence, numbers and volume of fish prey in guts of over 1,000 predators, 14 species were categorized as major piscivores. These included 2 species of synodontids, 4 muraenids, 1 scorpaenid, 1 congrid, 1 aulostomid, 1 fistulariid, 1 cirrhitid, 1 mullid, 1 antennariid, and 1 labrid. Twenty-two species with lesser fish consumption were termed minor piscivores. These included 1 species of muraenid, 4 scorpaenids, 1 cirrhitid, 2 mullids, 5 labrids, 1 bothid, 1 ophidiid, 4 holocentrids, 1 congrid and 2 priacanthids. Major piscivores made up about 4 percent by number and about 21 percent by biomass of the demersal fish community (as defined by four complete, quantitative collections). Prey fish representing 23 families provided 4.5 percent of the total demersal fish community's diet based on numbers of demersal feeding fish, and just over 11 percent based on demersal fish biomass. Important prey included apogonids, gobiids, labrids, and mullids.

Diet data were collected on the three common inshore shark species and the seven common predaceous inshore jacks. Life history studies were carried out on the sharks, Carcharhinus amblyrhynchos, Carcharhinus galapagensis and Galeocerdo cuvier, and on the most abundant predaceous jacks, Caranx ignobilis and Caranx melampygus. The sharks were aged by staining and counting annual rings in vertebral centra, and these counts were used to generate von Bertalanffy growth curves. Respiratory metabolic requirements of the sharks were estimated by performing laboratory respirometry measurements on a congener, Carcharhinus melanopterus. These estimates and the growth estimates plus DeLury catch-per-unit-effort estimates of shark population size, led to estimates of the food requirements of shark populations (= predation pressure on the sharks' prey community). Otoliths of C. ignobilis and C. melampygus were marked in vivo with tetracycline to confirm that daily rings are formed. Counts of otolith rings were used to generate a von Bertalanffy growth curve for C. melampygus, and counting is in progress for C. ignobilis. Based on gonadosomatic indices and frequency of occurrence of ripe adults from year-round sampling, both these jack species appear to exhibit summer spawning peaks. Gut analysis of Galeocerdo cuvier revealed, in order of decreasing frequency of occurrence, seabirds, turtles, lobsters, cephalopods, and fish. C. galapagensis showed a more limited diet dominated by cephalopods and fish. C. amblyrhynchos was the most highly piscivorous shark, with perciform, demersal fishes occurring most frequently. Similar shallow-water fishes were important in the diets of

both jack species. Guts of Caranx ignobilis also contained many nocturnal and pelagic fishes and considerable crustaceans and cephalopods. The prey of C. melampygus consisted almost entirely of diurnally active reef fishes. Dietary similarity as measured by Pianka's index of overlap was significant (0.4) between C. ignobilis and C. melampygus and rather large (0.6) between C. ignobilis and Carcharhinus amblyrhynchos.

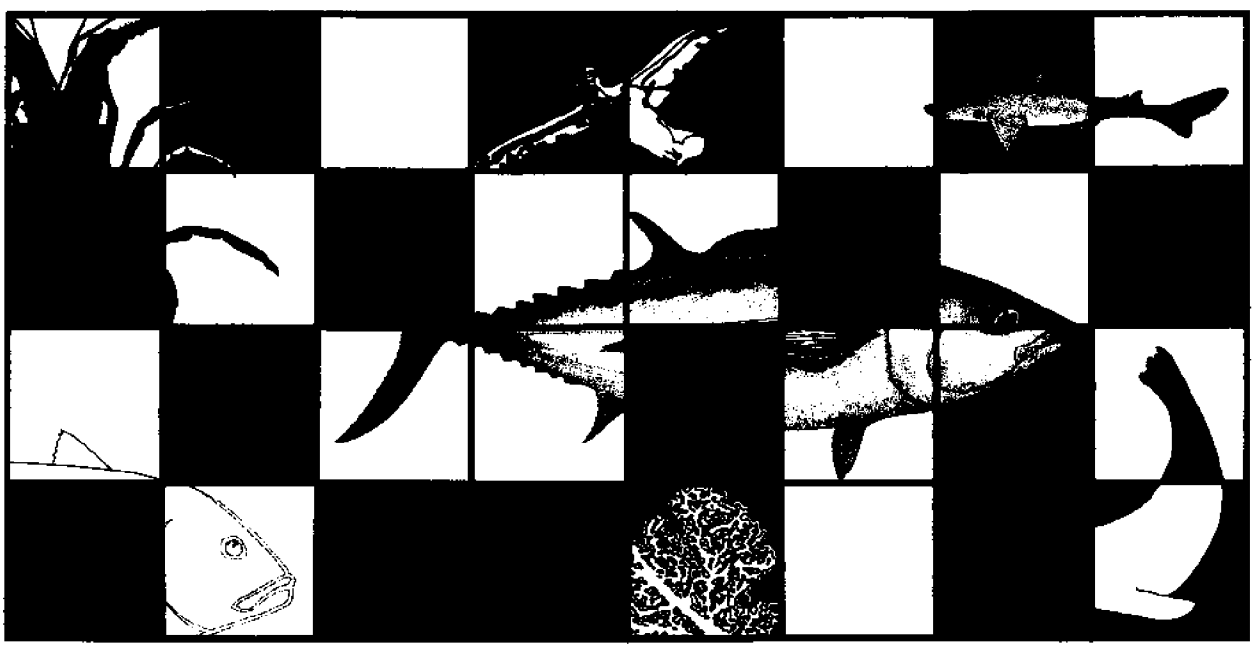
The results of the trophic studies of these communities have provided a rather complete and quantitative description of relationships essential to understanding how the resource is naturally supported and maintained.

predation	invertebrates
fish diets	piscivores
benthos	animal communities

Note: A full-length conference paper was delivered at the symposium; however, only an expanded abstract appears here to avoid duplication with other published work. Reference to the paper(s) can be found in part in the "Research Reports" and "Abstracts of Unpublished Papers" sections in Volume 2 of this proceedings.

This work is the result of research ("Trophic Analysis of Shallow-Water Fish Communities in the Northwestern Hawaiian Islands: Effects of Natural and Human Predation" project, NI/R-4) sponsored by the University of Hawaii Sea Grant College Program under Institutional Grant Nos. NA79AA-D-00085 and NA81AA-D-00070 from NOAA Office of Sea Grant, Department of Commerce. This is Sea Grant publication UNIHI-SEAGRANT-CP-84-03.

Offshore Research



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LIFE HISTORY, DISTRIBUTION, AND ABUNDANCE OF BOTTOMFISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Relative apparent abundance of the eight most important bottomfish species was examined for the major banks of the Northwestern Hawaiian Islands. Most noteworthy was the dominance of Pristipomoides filamentosus at Necker bank, French Frigate Shoals, and Brooks Banks and of Etelis carbunculus northwest of Lisianski bank. In general, catch rates and mean sizes increased at the northwestern end of the archipelago. Research on age and growth, length-weight relationships, reproductive biology, feeding habits, and the occurrence of ciguatoxin in bottomfishes was also reviewed.

age and growth
relative apparent abundance
bottomfishes
species composition

INTRODUCTION

The history of the fishery for snappers, grouper, and jacks, commonly referred to as bottomfishes, in the Northwestern Hawaiian Islands (NWHI) is not well documented. This fishery has been in existence in the NWHI at least since the mid-1940s (A.B. Amerson, 1971) and perhaps as early as the 1930s (see paper in this proceedings by Hau). From records maintained by the Division of Aquatic Resources (DAR), Hawaii Department of Land and Natural Resources, summaries of total annual catch, fishing effort (boat trip), and ex-vessel value per year were prepared for the period 1959 through 1977 by Polovina and Moffitt (1980) (Table 1). Annual catch statistics by species were also tabulated. During this period one vessel accounted for 95.5 percent of the catch. Starting in November 1976, a spiny lobster fishery developed in the NWHI; in addition to lobsters, vessels

in this fishery landed bottomfishes. When the jig boat albacore fishery expanded to the central North Pacific in 1979, some trolling vessels remained in Hawaii beyond the season for albacore and converted to bottomfishing in the NWHI.

TABLE 1. TOTAL VALUE, WEIGHT OF CATCH, AND NUMBER OF TRIPS IN THE BOTTOM HANDLINE FISHERY IN THE NORTHWESTERN HAWAIIAN ISLANDS

Year	Dollar Value	Kilograms Caught	Number of Trips
1959	26,896	32,164	10
1960	45,779	49,515	16
1961	30,115	34,476	11
1962	25,363	29,244	13
1963	32,653	40,730	18
1964	39,277	47,260	19
1965	20,118	25,154	9
1966	18,213	21,935	9
1967	13,775	14,822	6
1968	14,320	15,172	6
1969	14,812	18,113	4
1970	39,147	33,683	11
1971	50,206	34,180	17
1972	41,992	19,356	17
1973	62,759	28,050	20
1974	48,899	22,313	15
1975	63,873	27,012	14
1976	78,476	26,730	14
1977	95,659	35,576	20

Source: Polovina and Moffitt, 1980

In March 1977 the Magnuson Fishery Conservation and Management Act (FCMA) of 1976 extended federal jurisdiction over fishery resources from 3 to 200 nautical miles (nmi) around the islands in the Hawaiian Archipelago (Figure 1). The FCMA also established eight regional fishery management councils nationally to manage the resources in the fishery conservation zone (FCZ). The Western Pacific Regional Fishery Management Council was established with jurisdiction in the FCZs around Hawaii, Guam, Northern Marianas, and American Samoa and is currently examining the fishery for bottomfishes to determine whether a fishery management plan (FMP) is warranted.

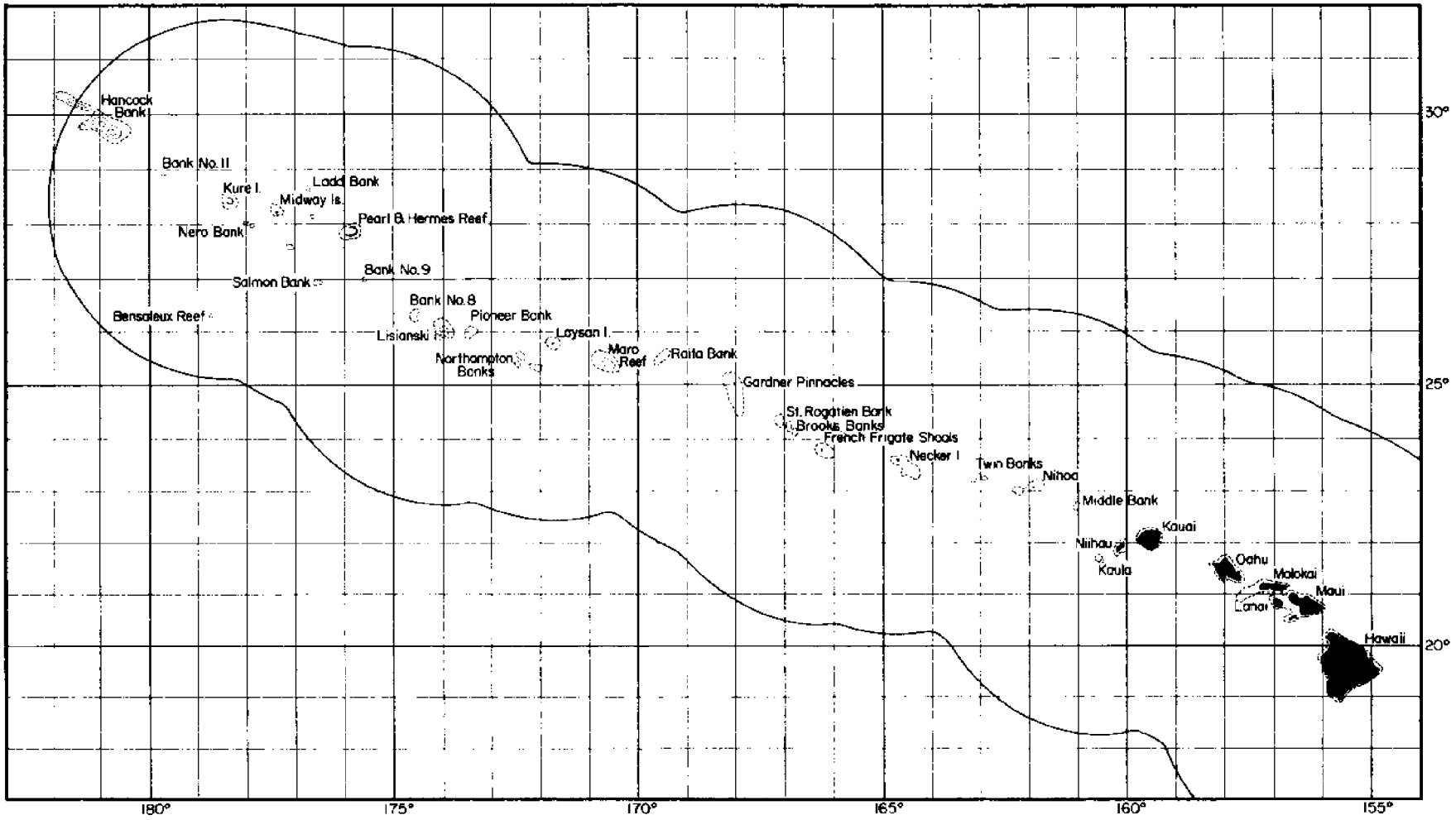

Figure 1. The U.S. Fishery Conservation Zone around the Hawaiian Archipelago

Because very little was known about the biotic resources in the NWHI, a cooperative research agreement was signed by the Division of Aquatic Resources; the Fish and Wildlife Service (FWS), U.S. Department of Interior; and the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service (NMFS) in 1977 to survey the resources. A year after the formation of the cooperative tripartite agreement, a fourth agency, the University of Hawaii Sea Grant College Program, became an active participant in the resource investigations. In the agreement, FWS was given the responsibility to survey and assess the terrestrial resources such as sea and land birds, DAR was assigned the assessment of inshore fishery resources, and NMFS was assigned the assessment of offshore fishery resources. Later, NMFS also assumed the responsibility for research on the Hawaiian monk seal, Monachus schauinslandi, and the Hawaiian green turtle, Chelonia mydas.

Among the offshore fishery resources are the bottomfishes. Various studies were conducted by NMFS to determine their distribution and relative abundance in the NWHI. Studies on age and growth, reproduction, feeding habits, and the occurrence of ciguatoxin in bottomfishes were also conducted. This paper is a review of the results of these studies conducted by the Honolulu Labortory since 1976.

SPECIES OF THE SNAPPER-GROUPER-JACK COMPLEX

The scientific names of bottomfish species commonly caught in the NWHI are listed in Table 2 along with synonyms and Hawaiian or local names which have remained in use for many decades. The fishes in the snapper-grouper-jack complex are also called deepsea handline fishes, but are referred to as bottomfish in this paper.

DISTRIBUTION AND APPARENT ABUNDANCE

A primary objective of the NMFS NWHI study was to conduct assessments of the resources in the area. Catch data at 283 handline stations were collected from the R/V Townsend Cromwell from October 1976 to September 1982. Effort was recorded as line-hour and catch as either the number or weight of fish.

Bottomfishes were widely distributed throughout the NWHI (Table 3). To determine their vertical distribution, traps, trawls, and handlines were used to sample various depths. The depth range of the various species was tabulated for each bank (Table 3) by Uchida and Uchiyama (in preparation). The true depth range for these species is probably wider than that estimated by the catch data.

TABLE 2. SCIENTIFIC NAME, SYNONYM, AND LOCAL NAME OF NORTHWESTERN HAWAIIAN ISLANDS BOTTOMFISHES

Scientific Name	Synonym	Local Name
Serranidae		
Epinephelus quernus		Hapuupuu
Carangidae		
Carangoides orthogramus[1]	*C. ferdau*	Ulua
Caranx ignoblis		Ulua
C. lugubris		Ulua
C. melampygus		Omilu
Pseudocaranx dentex[2]	*C. cheilio*	Pig ulua
Seriola dumerili		Kahala
S. lalandii		Kahala opio
Lutjanidae		
Aprion virescens		Uku
Etelis carbunculus[3]	*E. marshi*	Ehu
E. coruscans[3]	*E. carbunculus*	Onaga
Pristipomodies filamentosus[4]	*P. microlepis*	Opakapaka
P. sieboldii		Kalekale
P. zonatus[5]	*Rooseveltia brighami*	Gindai
Scorpaenidae		
Pontinus macrocephalus[6]	*Merinthe macrocephala*	Nohu

[1]Misidentification corrected by F.W. Smith-Vaniz (Randall, 1980)
[2]Revised by F.W. Smith-Vaniz, The Academy of Natural Sciences, Philadelphia, PA 19103, personal communication, 1981
[3]Revised by Anderson (1981)
[4]Revised by Kami (1973)
[5]Change proposed by W.D. Anderson, College of Charleston, Charleston, SC 29412, personal communication, 1981
[6]Revised by Eschmeyer and Randall (1975)

TABLE 3. DEPTH DISTRIBUTION (IN METERS) BY BANK OF BOTTOM FISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS DURING RESOURCE SURVEYS FROM OCTOBER 1976 TO AUGUST 1981

Bank	*Epinephelus quernus*		*Pseudocaranx dentex*		*Seriola dumerili*		*Etelis carbunculus*		*E. coruscans*		*Pristipomoides filamentosus*		*P. sieboldii*		*P. zonatus*	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Middle Bank	146	146	—	—	44	146	—	—	—	—	36	73	—	—	—	—
Nihoa	44	183	*	*	51	73	128	201	—	—	*	*	137	137	—	—
Twin Banks	183	183	27	46	29	91	183	183	256	256	—	—	91	91	—	—
Necker Island	27	229	66	174	2	229	139	229	*	*	31	328	110	120	183	183
French Frigate Shoals	58	194	110	165	26	186	113	152	—	—	46	186	113	201	128	128
Brooks Banks	183	183	—	—	51	201	—	—	—	—	36	161	—	—	201	201
St. Rogatien Bank	—	—	*	*	*	*	*	*	*	*	*	*	—	—	—	—
Gardner Pinnacles	110	347	16	183	16	128	128	183	*	*	27	183	128	128	—	—
Raita Bank	31	172	183	183	146	146	—	—	—	—	40	40	172	183	—	—
Maro Reef	38	201	102	201	2	201	102	201	—	—	31	183	102	102	102	201
Laysan Island	90	183	146	174	2	183	174	201	256	256	64	174	*	*	201	201
Northampton Seamounts	164	219	201	201	—	—	110	219	—	—	110	201	146	201	164	201
Lisianski Island and Pioneer	110	238	27	194	110	247	179	238	194	194	91	179	194	194	183	238
Bank No. 8	146	183	—	—	146	165	219	238	—	—	71	71	—	—	183	183
Pearl and Hermes Atoll	33	238	48	238	35	238	121	271	183	229	57	164	164	198	146	183
Salmon Bank	119	119	—	—	—	—	119	219	—	—	—	—	219	219	—	—
Ladd Island	66	216	*	*	—	—	146	216	—	—	—	—	146	216	—	—
Midway Islands	26	219	0	183	2	128	192	219	—	—	—	—	—	—	—	—
Nero and Pogy	146	146	183	183	111	111	183	183	—	—	108	108	—	—	—	—
Kure Atoll	18	218	2	183	9	9	219	219	183	183	—	—	*	*	—	—

Note: Information abstracted from Table 2 of Uchida and Uchiyama (in preparation)
* Depth uncertain

The catch rates varied among banks (Table 4). The catch rate of hapuupuu generally increased with distance away from the high islands. For pig ulua, the catch rate was high around Raita Bank, Maro bank, and Laysan bank, whereas for kahala, it was high from Gardner Pinnacles to Pearl and Hermes Atoll. West of Lisianski bank, the relative abundance of ehu increased greatly. Opakapaka were abundant at Necker bank and French Frigate Shoals but were not caught west of Nero Seamount. Although this species was not recorded at Midway bank, it is known to occur there (S. Ralston, 1983: personal communication). Furthermore, opakapaka were caught in lobster pots at bank no. 8, although none were caught on handlines. The relative abundance figures for onaga, kalekale, and gindai were too low to analyze by locality.

Species composition at each bank is presented in Table 5. Miscellaneous species listed previously by Moffitt (1980) were not included. A noticeable feature of species composition in the NWHI was the dominance of ehu west of Lisianski bank and opakapaka at Necker bank, French Frigate Shoals, and Brooks Banks. Catches west of Lisianski bank were composed of 45.6 to 86.5 percent ehu, excluding data from Midway Islands and Kure Atoll. Opakapaka represented 44.4 percent of the catch at Necker bank, 52.5 percent at French Frigate Shoals, and 40.0 percent at Brooks Banks. No gindai were caught west of Ladd Seamount. This pattern of species composition by banks was similar to that reported by Moffitt (1980).

For each species the fork or total lengths from all banks were pooled and compared by one-way analysis of variance. Mean sizes for seven species at the various banks varied significantly (Table 6). In general, significant differences in fish size existed between banks that were heavily fished and those that were pristine (NMFS, unpublished data). Because the fishes were larger on the northwestern end of the archipelago (except for pig ulua), it was not surprising that catch rates (kilograms per line-hour) also increased at that end of the NWHI (Table 7).

Catch and effort data to estimate sustainable yield from production analysis were unavailable for the NWHI. Annual maximum sustainable yields (MSY) of 111,300 kg for Oahu and 288,320 kg for Maui, Molokai, and Lanai have been estimated (Ralston, 1980; Ralston and Polovina, 1982; Polovina and Moffitt, 1980). These original estimates have since been revised. Assuming that abundance and population dynamics of these species are similar in the NWHI and the main Hawaiian islands, the MSY was estimated for these species in the NWHI (see paper in this proceedings by Ralston).

LIFE HISTORY STUDIES

Otoliths were collected for age and growth studies, gonads for reproductive studies, stomach contents and spew samples for feeding habit studies, and various tissue samples for ciguatoxin studies.

TABLE 4. SUMMARY OF CATCH RATES (NUMBER PER LINE-HOUR) FOR BOTTOMFISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Bank	Total Effort (Line-Hours)	*Epinephelus quernus*	*Pseudocaranx dentex*	*Seriola dumerili*	*Etelis carbunculus*	*E. coruscans*	*Pristipomoides filamentosus*	*P. sieboldii*	*P. zonatus*
Middle Bank	9.73	0.21	—	0.10	—	—	—	—	—
Nihoa	168.75	0.12	0.10	0.04	0.50	0.01	0.06	0.19	0.02
Twin Banks	29.47	0.10	—	0.14	0.07	0.03	0.07	0.07	—
Necker Island	363.85	0.14	0.08	0.11	0.33	0.00	0.63	0.08	0.04
French Frigate Shoals	297.17	0.33	0.18	0.12	0.11	0.00	1.05	0.10	0.10
Brooks Banks	61.27	0.05	—	0.03	—	—	0.07	—	0.02
St. Rogatien Bank	49.07	0.43	0.29	0.08	0.35	0.20	0.37	0.06	0.04
Gardner Pinnacles	117.62	0.16	0.15	0.16	0.16	0.03	0.14	0.03	0.04
Raita Bank	94.35	0.49	0.24	0.17	0.25	0.17	0.18	0.17	0.08
Maro Reef	101.47	0.55	0.40	0.22	0.24	—	0.45	0.02	0.10
Laysan Island	175.40	0.42	0.31	0.18	0.36	0.02	0.19	0.05	0.08
Northampton Seamounts	16.60	0.12	0.06	—	0.42	—	0.12	0.18	0.54
Lisianski Island and Pioneer	93.57	0.50	0.07	0.14	0.27	0.06	0.10	—	0.04
Bank No. 8	39.27	0.38	—	0.15	1.17	—	—	—	0.33
Pearl and Hermes Atoll	229.93	0.74	0.22	0.16	1.72	0.12	0.03	0.10	0.03
Salmon Bank	41.60	0.05	—	—	0.75	—	—	0.17	0.02
Ladd Island	52.80	0.15	—	—	1.04	0.04	—	0.09	—
Midway Islands	26.83	0.82	0.45	0.04	0.75	—	—	—	—
Nero and Pogy	18.80	0.53	0.05	—	4.10	—	—	0.05	—
Kure Atoll	75.33	0.42	0.20	0.01	0.20	0.03	—	0.01	—

TABLE 5. SPECIES COMPOSITION (PERCENTAGE) OF BOTTOMFISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Bank	*Epinephelus quernus*	*Pseudocaranx dentex*	*Seriola dumerili*	*Etelis carbunculus*	*E. coruscans*	*Pristipomoides filamentosus*	*P. sieboldii*	*P. zonatus*
Middle Bank	66.7	—	33.3	—	—	—	—	—
Nihoa	11.5	9.8	3.4	48.3	0.6	5.7	18.3	2.2
Twin Banks	21.4	—	28.6	14.3	7.2	14.3	14.3	—
Necker Island	10.2	5.7	7.7	23.5	0.2	44.4	5.5	2.8
French Frigate Shoals	16.5	8.9	5.9	5.7	0.2	52.5	5.2	5.0
Brooks Banks	30.0	—	20.0	—	—	40.0	—	10.0
St. Rogatien Bank	23.6	15.7	4.5	19.1	11.2	20.2	3.4	2.2
Gardner Pinnacles	18.1	17.1	18.1	18.1	3.8	16.2	3.8	4.8
Raita Bank	27.7	13.8	9.6	14.4	9.6	10.2	9.6	4.8
Maro Reef	27.9	20.4	10.9	11.9	—	22.9	1.0	5.0
Laysan Island	26.1	19.4	11.0	22.6	1.4	11.7	2.8	4.9
Northampton Seamounts	8.3	4.2	—	29.2	—	8.3	12.5	37.5
Lisianski Island and Pioneer	35.3	5.3	9.8	18.8	4.5	6.8	0.8	3.0
Bank No. 8	18.8	—	7.5	57.5	—	—	—	16.2
Bank No. 9	27.8	3.3	11.1	45.6	1.1	1.1	6.6	3.3
Pearl and Hermes Atoll	23.6	6.9	5.0	54.5	3.8	1.0	3.3	1.0
Salmon Bank	4.9	—	—	75.6	—	—	17.0	2.4
Ladd Island	11.4	—	—	78.6	2.8	—	7.1	—
Midway Islands	31.4	17.1	1.4	28.6	—	—	—	—
Nero and Pogy	11.2	1.1	—	86.5	—	—	1.1	—
Kure Atoll	48.5	22.7	1.5	22.7	3.0	—	1.5	—

TABLE 6. ONE-WAY ANALYSIS OF VARIANCE COMPARING MEAN LENGTHS OF SEVEN SPECIES OF BOTTOMFISHES

Species	Degrees of Freedom	F Value	Probability
Epinephelus quernus	18, 521	6.3347	0.0186
Pseudocaranx dentex	10, 252	6.8400	0.0
Seriola dumerili	13, 163	3.4110	0.0001
Etelis carbunculus	17, 734	6.6013	0.0
Pristipomoides filamentosus	9, 450	26.6070	0.0
P. sieboldii	10, 108	2.2649	0.0191
P. zonatus	10, 70	2.3507	0.0186

TABLE 7. SUMMARY OF CATCH RATES (KILOGRAMS PER LINE-HOUR) FOR BOTTOMFISHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Bank	*Epinephelus guernus*	*Pseudocaranx dentex*	*Seriola dumerili*	*Etelis carbunculus*	*E. coruscans*	*Pristipomoides filamentosus*	*P. sieboldii*	*P. zonatus*	Total
Middle Bank	0.92	—	0.42	—	—	—	—	—	1.34
Nihoa	0.52	0.52	0.26	0.77	0.04	0.25	0.13	0.03	2.52
Twin Banks	1.20	—	1.79	0.15	0.21	—	0.08	—	3.43
Necker Island	0.72	0.38	0.59	0.43	0.01	1.69	0.06	0.05	3.93
French Frigate Shoals	2.02	1.11	0.64	0.17	0.01	2.71	0.07	0.15	6.88
Brooks Banks	0.30	—	0.24	—	—	0.18	—	0.02	0.74
St. Rogatien Bank	3.11	1.93	0.79	0.52	0.65	1.37	0.04	0.06	8.47
Gardner Pinnacles	0.87	0.87	1.02	0.29	0.15	0.63	0.02	0.06	3.91
Raita Bank	3.81	1.61	1.33	0.54	0.90	0.80	0.12	0.16	9.27
Maro Reef	3.07	1.74	1.39	0.50	—	1.87	0.06	0.18	8.81
Laysan Island	3.67	2.05	1.40	0.69	0.10	1.10	0.02	0.14	9.17
Northampton Seamounts	1.25	0.54	0.10	0.84	—	0.55	—	1.02	4.30
Lisianski and Pioneer	3.49	0.62	1.31	0.64	0.30	0.45	0.00	0.08	6.89
Bank No. 8	3.95	—	1.41	2.58	—	—	—	0.51	8.45
Bank No. 9	11.85	0.70	4.37	3.29	0.28	0.16	0.17	0.22	21.04
Pearl and Hermes Atoll	4.07	1.20	1.45	2.97	0.65	0.15	0.07	0.07	10.63
Salmon Bank	0.58	—	—	1.63	—	—	0.10	0.03	2.34
Ladd Island	1.75	—	—	2.39	0.32	—	0.10	—	4.56
Midway Islands	3.94	1.79	0.41	1.53	—	—	—	—	7.67
Nero and Pogy	3.91	0.28	—	8.19	—	—	0.04	—	12.42
Kure Atoll	2.90	1.05	0.10	0.51	0.10	—	0.01	—	4.67

Age and Growth

Considerable effort has been expended in estimating age and growth of NWHI bottomfishes (Figure 2). All species were aged by enumerating daily increments on otoliths; two species were aged by counting the annuli. Evidence that increments are deposited daily was obtained only for the pig ulua (Uchiyama et al., in preparation). It is highly improbable that daily increments can be validated for species such as ehu, gindai, kalekale, and onaga that live at great depths. Thus, age and growth estimates are considered tentative for species in which daily increments were not validated.

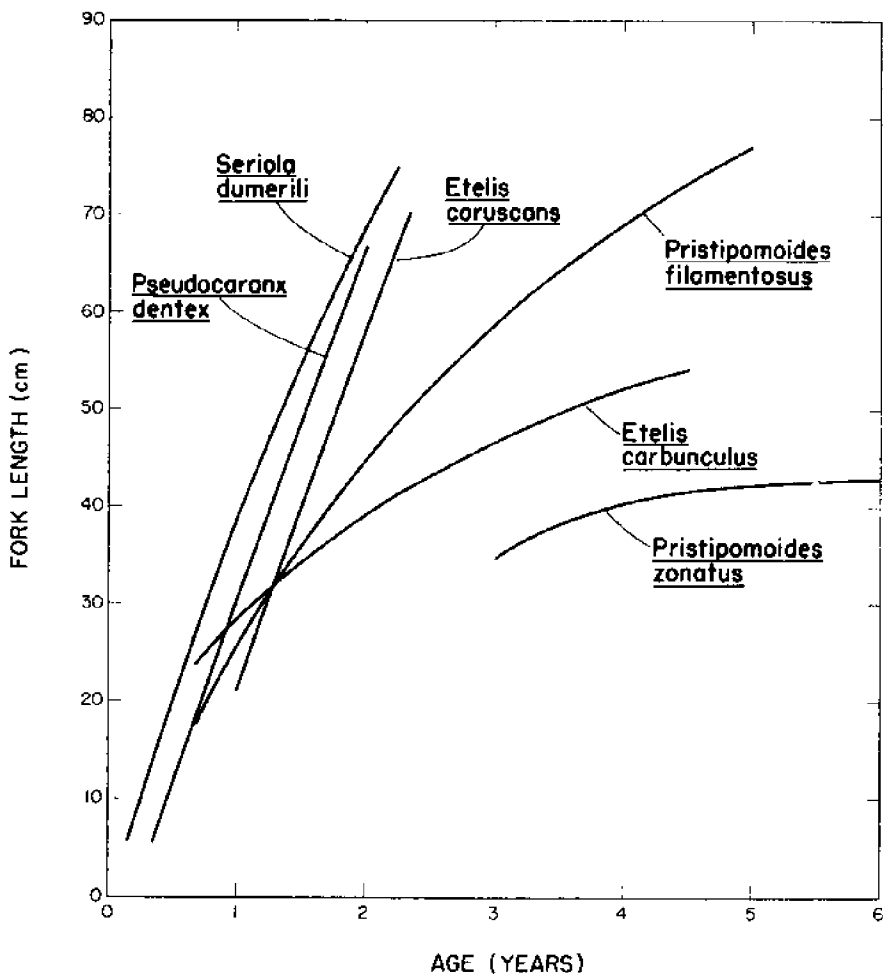

Figure 2. Estimated growth curves of the bottomfishes in the Northwestern Hawaiian Islands

Von Bertalanffy growth parameters (L_∞ = 97.1 cm, k = 0.31, t_0 = 0.02 yr) and a growth curve for opakapaka (Figure 2) were determined from age data (Uchiyama et al., in preparation). Annuli were validated by showing that they were formed at the same time (early summer) each year. The method was validated by comparing back calculated length at age with length at age of the von Bertalanffy growth curve. Annual marks make it possible to age more fish in less time and to age older fish. It was difficult to age opakapaka beyond 3 years with daily increment counts. Age determination by enumeration of daily increments agreed well with the growth curve based on annuli (Uchiyama et al., in preparation).

In need of a faster way to age fish using daily increments, Ralston and Miyamoto (in press) analytically integrated otolith growth rate to estimate age-length relationships. Their estimates of opakapaka age-length relationship suggested growth at 33 to 50 percent of the estimated rate determined by Uchiyama et al. (in preparation). R.L. Radtke (unpublished manuscript) enumerated daily increments on opakapaka otoliths with scanning electron microscopy. His estimates of the age-length relationship were similar to those of Uchiyama et al. (in preparation) for fish of 20 to 56-cm fork length (FL). His age estimates for fish greater than 60-cm FL were higher than those of Uchiyama et al. (in preparation), but lower than those estimated by Ralston and Miyamoto (in press).

Preliminary von Bertalanffy parameters (L_∞ = 43.1 cm, k = 1.09, t_0 = 1.51 yr) and a growth curve (Figure 2) were also estimated for gindai using annual marks (J.H. Uchiyama, unpublished data). However, due to a small sample size the annual marks were not validated. Only three age determinations were made using daily increment counts. These points were within the length ranges of estimated year classes.

All other species were aged by daily increments only. Von Bertalanffy parameters and growth curves were estimated for ehu (L_∞ = 63.9 cm, k = 0.36, t_0 = -0.60 yr) and kahala (L_∞ = 149.4, k = 0.31, t_0 = 0.04 yr) (Uchiyama et al., in preparation) (Figure 2). The estimated L_∞ of ehu (63.9 cm) was very close to the size of the largest ehu (63.5-cm FL) caught during the survey cruises. Ehu in the NWHI appeared not to grow as large as those from New Caledonia [105 cm, 19.0 kg; (R. Grandperrin, 1982: personal communication)] and the Indian Ocean (Forster et al., 1970). The estimated L_∞ of kahala (149.4 cm) was also very close to the size of the largest kahala (149.0-cm FL) caught during the survey cruises. Kahala are known to grow up to 155 cm off Florida (Burch, 1979).

Only linear growth stanzas were calculated for onaga (J.H. Uchiyama, unpublished data) and pig ulua (Uchiyama et al., in preparation) because the largest fish for either species examined had not reached the asymptotic growth phase (Figure 2). Furthermore, no attempt was made to estimate growth of onaga, kahala,

and pig ulua beyond the ages indicated in Figure 2 because the otoliths of older fish were not readable. The nucleus of the sagittae of larger fish became very opaque after age 2 and did not allow an accurate enumeration of daily growth increments.

Length-weight Relationships

Predictive and functional length-weight relationships have been calculated from lengths and weights of hapuupuu, ehu, onaga, opakapaka, kalekale, gindai, pig ulua, and kahala caught in the NWHI (see Table 4 of paper in this proceedings by Uchiyama et al.). For all species except onaga, the data were separated into groups by sex, cruise, and location of capture, and the slopes of the regression for each grouping were compared by ANCOVA. No significant differences in slopes between sexes were found for ehu, opakapaka, kalekale, gindai, pig ulua, and kahala. Slopes between sexes were not tested for hapuupuu. Among cruises, significant differences were found for hapuupuu and opakapaka. Since these two species are the most important in the NWHI handline fishery, changes in size composition may have caused the slopes to differ over a period of time. Unusually large or small opakapaka and hapuupuu caught during several cruises could have caused the significantly different slopes among cruises. Among locations, differences in slopes were not significant, except for hapuupuu. The body of hapuupuu is stout, compared with the elongated or laterally compressed body types of the other bottomfish species, which may result in a greater change in weight per unit of length.

Reproduction

Studies on reproduction of bottomfishes have centered on determining spawning seasons, size at sexual maturity, and fecundity. The spawning season was determined by the seasonal distribution of mean gonadal somatic indices. Kahala was found to spawn at a low level throughout the year, with increased activity between February and July and peaking in March and April (see paper in this proceedings by Kikkawa and Everson). Opakapaka spawning peaked in August (ripe ovaries were collected from June through December) (see paper in this proceedings by Kikkawa). Ehu spawned from May through October, peaking from July through September (see paper in this proceedings by Everson). The spawning season for kalekale was from June through September, peaking in August and September; whereas for onaga it was estimated to be in August and September based on ovaries collected primarily in the summer (A.R. Everson, 1983: personal communication). Ripe ovaries of gindai were collected in August, whereas those of pig ulua were collected in January and July and those of hapuupuu in January and February. There appeared to be a serial succession of spawning peaks by species groups: hapuupuu in the winter months, carangids in spring and early summer, and snappers in late summer.

Size at maturity has been determined for three species. Gonads began to develop when the kahala reached a length of 72 cm, and the smallest female with ripe ovaries was 78 cm long (see paper in this proceedings by Kikkawa and Everson). For opakapaka, the ovaries generally began to develop when the females were about 42.5 cm long. The females generally reached spawning condition at a length of about 48.7 cm, although the smallest female with a ripe ovary was only 38.4 cm long (see paper in this proceedings by Kikkawa). The ehu reached sexual maturity at a length of about 29.8 cm and spawned at about 31.8 cm (see paper in this proceedings by Everson). In terms of age, kahala reached sexual maturity at about 2.1 years and began spawning at about 2.4 years. Opakapaka reached sexual maturity at about 1.8 years and generally spawned at about 2.2 years. The ehu was about 1.1 years when it reached sexual maturity and spawned at about 1.2 years.

Fecundity for the same three species was estimated following the method of Van Dalsen (1977). The smallest examined kahala (83.0 cm long) yielded about 1.3 million eggs at one spawning and the largest (118.6 cm long) about 4.0 million eggs (see paper in this proceedings by Kikkawa and Everson). The relationship between the number of eggs spawned and length was linear. The smallest examined opakapaka (48.7 cm long) yielded about 457,090 eggs, at one spawning and the largest (76.3 cm long) about 1,461,875 eggs (see paper in this proceedings by Kikkawa). The relationship between eggs spawned and length for this species was curvilinear. The smallest examined ehu (38.3 cm long) yielded about 349,500 eggs at one spawning and the largest (50.8 cm long) about 1,325,600 eggs. The relationship between the number of spawned eggs and length was also curvilinear (see paper in this proceedings by Everson). All three species appeared to be partial spawners, but the number of times a fish spawned in a season was not determined (see paper in this proceedings by Kikkawa and Everson).

Feedings Habits

Studies of stomach contents and spew samples of hapuupuu, kahala, and pig ulua have been completed (see papers in this proceedings by Seki on hapuupuu and trevally; see paper in this proceedings by Humphreys and Kramer). Humpreys and Kramer found that the kahala could be separated into two size groups on the basis of their diet: small (<9 kg) and large (>9 kg). They also separated the prey into three general groups: bottom-associated prey, water column-associated prey, and prey that occupied both habitats. For small kahala from the NWHI, 83.8 percent of the stomach contents consisted of bottom-associated prey, 10.7 percent of water column organisms, and 5.5 percent of prey that occupied both habitats. On the other hand, large kahala preyed more heavily on water column organisms (38.1 percent); bottom-associated organisms comprised 58.0 percent of the prey and organisms associated with both the bottom and water column accounted for 3.9 percent. By volume, the content of small

kahala stomachs contained 66.3 percent fish, 31.1 percent cephalopods, and 2.6 percent crustaceans. The content of large kahala stomachs differed by containing 96.2 percent fish, 3.1 percent cephalopods, and 0.7 percent crustaceans. Seki (see papers in this proceedings on hapuupuu and trevally) described both hapuupuu and pig ulua as carnivorous, opportunistic bottom feeders. The hapuupuu fed primarily on fish (76.1 percent) and also consumed some crustaceans (14.6 percent) and molluscs (8.3 percent) (by volume). It appeared to prefer pandalid shrimps which accounted for 64.4 percent of the food items by number but only 7.2 percent by volume. The pig ulua's diet was composed of 64.2 percent fish, 9.4 percent molluscs, 4.3 percent crustaceans, and 21.2 percent rubble and unidentified remains. The stomach contents of ehu were also examined, but not analyzed and the ehu has been described as a carnivorous bottom feeder (M.R. Seki, 1983: personal communication). Spew samples of opakapaka were found to consist of fish, crustaceans, molluscs, and chordates (S. Ralston, 1983: personal communications).

Ehu, hapuupuu, kahala, opakapaka, and pig ulua all had a number of bottom-associated diet items in common, but, except for ehu, each also had preference for a unique prey item. Hapuupuu ate a large number of small crustaceans (see paper in this proceedings by Seki on hapuupuu). Large kahala had a preference for Decapterus, a benthopelagic fish (see paper in this proceedings by Humphreys and Kramer). Opakapaka spew samples uniquely consisted of 42.2 percent by volume of Pyrosoma sp. (S. Ralston, 1983: personal communication), pelagic tunicates (Kami, 1973), and other chordates. The pig ulua's diet contained a high proportion of rubble (21.2 percent by volume) (see paper in this proceedings by Seki on trevally). No unique preferred item was noticed for ehu perhaps because of the small number of spew samples available. These five species appeared to compete for food at least part of the time.

Ciguatoxin Studies

Preliminary progress reports on ciguatoxin in fishes from the NWHI have been published (Ito and Uchida, 1980; Uchida et al., 1979, 1981). Toxicity level is believed to be related to fish size. In their preliminary report, Ito and Uchida (1980) reported a low but significant correlation exists between toxicity level and fish size. This relationship, however, is still under review (B.M. Ito, 1983: personal communication).

Humphreys and Kramer (see paper in this proceedings) compared the diets of kahala which had high radioimmunoassay counts indicating possible presence of ciguatoxin with the diets of nontoxic kahala. Overall diets were quite similar. However, differences between diets of small kahala (<9 kg) and large kahala (>9 kg) were found. Humphreys and Kramer hypothesized that small kahala, which feed on benthic organisms, pick up ciguatoxin in

their diet and that large kahala, which feed primarily on pelagic Decapterus, contain accumulated toxin from an earlier benthic feeding phase.

Kikkawa and Everson (see paper in this proceedings) examined the occurrence of ciguatoxin in kahala in relation to the reproductive cycle and found no correlation.

CONCLUSIONS

The relative abundance and species composition of bottomfishes varied considerably throughout the NWHI. Most noteworthy was the dominance of opakapaka at Necker bank, French Frigate Shoals, and Brooks Banks, and of ehu west of Lisianski bank.

Members of the three families of bottomfishes studied spawn at different times, i.e., the grouper in winter, carangids in spring and early summer, and the snappers in August. Five species whose stomach contents and spews were examined all fed on an assortment of bottom-associated organisms, which suggested some degree of competition for prey. On the other hand, four species also fed on unique items, indicating niche sepration occurs for at least several species.

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BIOLOGICAL CONSTRAINTS ON PRODUCTION AND RELATED MANAGEMENT ISSUES IN THE HAWAIIAN DEEPSEA HANDLINE FISHERY

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ABSTRACT

Specifically designed to gather data and information to meet the management needs of the Hawaiian deepsea handline fishery for demersal bottomfishes, a Sea Grant project (NI/R-7) was undertaken from 1976 to 1981. The resource in the main Hawaiian islands was assessed by surplus-production and yield-per-recruit methods to identify the extent of recruitment and/or growth-overfishing. The former analysis revealed that around the Maui-Lanai-Kahoolawe-Molokai (MLKM) bank, the main producer in the state, fishing activity is excessive relative to obtaining a maximum in sustained yield (MSY). The latter treatment demonstrated that at Penguin Bank an optimal level of fishing mortality is in effect for maximizing the growth potential of opakapaka, Pristipomoides filamentosus. These two assessments are consistent with the literature where it has been shown that MSY fishing mortality is generally restricted to values less than that which maximizes yield per recruit. In contrast with the main islands, the bottomfish resource of the Northwestern Hawaiian Islands is underutilized at present, where it is estimated that an annual harvest of at least 330 metric tons (MT) with an ex-vessel value of $2 million may be taken.

bottomfish	yield per recruit
mortality	surplus-production
opakapaka	maximum sustained yield

INTRODUCTION

The Hawaiian Archipelago stretches 1,500 nautical miles (nmi) from Cape Kumukahi on the island of Hawaii to Hancock

Seamounts, far to the northwest (Figure 1). The main high islands are basaltic formations and support all population centers in the state of Hawaii, but many small islands, pinnacles, and atolls extend for miles to the northwest, including Nihoa, Necker Island, French Frigate Shoals, Gardner Pinnacles, Laysan and Lisianski Islands, Pearl and Hermes Atoll, Midway Islands, and Kure Atoll. In addition to these largely uninhabited islands there are extensive shoal areas in the Northwestern Hawaiian Islands (NWHI) (e.g., Neva Shoal, Brooks Banks, St. Rogatien, Raita Bank, Maro Reef, and Hancock Seamounts).

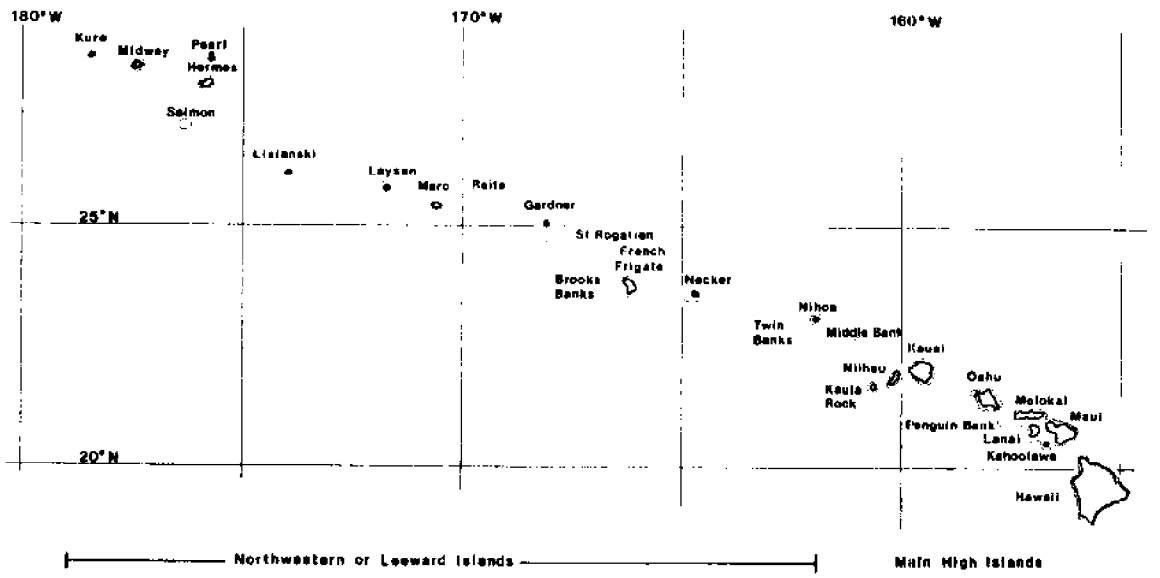

Figure 1. The Hawaiian Archipelago showing the approximate positions (dotted lines) of 100-fathom isobaths

Throughout the islands the myriad systems of submerged reefs, banks, and pinnacles harbor stocks or populations of commercially important bottomfishes. In particular, the snappers (Lutjanidae), groupers (Serranidae), and jacks (Carangidae) comprise some of the most valuable fishes harvested by the Hawaiian fishing industry, with some species at times commanding ex-vessel prices in excess of $15/kg. These are for the most part benthic fishes, in contrast with the pelagic tunas, living on or near the bottom in water depths of 20 to 200 fathoms. Most are found in regions of high physical relief which are thus unsuitable for trawling. They are caught almost exclusively with baited hook-and-line gear from fishing vessels which generally range in length from 7 to 30 m (Ralston, 1979). The mixed catch is marketed primarily in the round as fresh fish through several fish auctions and fishermen's cooperatives in the state.

In the past most fishing has been conducted around the main islands of the archipelago, especially at Penguin Bank off the island of Molokai (Figure 1) (Ralston and Polovina, 1982). However, as catch rates around the high Hawaiian islands declined and larger vessels entered the fishery, exploitation in the NWHI began to increase. Since 1976, when the extended 200-mile U.S. fishery conservation zone under the authority of the Magnuson Fishery Conservation and Management Act was implemented, interest in the bottomfish resources of the NWHI increased greatly. Recognizing these developments the Western Pacific Regional Fishery Management Council authorized the development of a fishery management plan for these stocks and emphasized the need to acquire biological information to manage the resource. At the time there had been no studies of these fishes in Hawaii and virtually nothing was known of their population dynamics (Ralston, 1979).

Accompanying this increased interest in the NWHI, the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, joined in a cooperative tripartite agreement in 1977 with the U.S. Fish and Wildlife Service (FWS) and the Hawaii Division of Aquatic Resources (DAR) to investigate the biotic resources of the area. Shortly thereafter the University of Hawaii Sea Grant College Program became a fourth active participant in the resource investigations of the NWHI. This Sea Grant project was initiated at that time with the intent of developing a basis for managing the deepsea handline fishery.

Since its inception, this project sought to gather data and information to meet the needs of fisheries management. This research project, "Development of a biological basis for managing the handline fishery for snapper and grouper population in the Hawaiian Archipelago", is now concluded and the proceedings of this second symposium on resource investigations in the NWHI offer an ideal forum for summarizing some of the project's more important findings. In this paper an overview is presented which specifically relates to management questions in the deepsea handline fishery. Almost all of the information presented here is a product of Sea Grant project NI/R-7, although relevant literature and outside data have been included where appropriate. However, most of the information resulting from this program has already been reported in a series of publications and manuscripts (Ralston, 1979, 1980a, 1980b, 1981a, 1981b, 1982; Ralston and Miyamoto, 1982, in press; Ralston and Polovina, 1982). Much of that which is presented here is summarized from this literature.

OBJECTIVES

From a management perspective the objective of the Sea Grant project was to assess the condition of bottomfish stocks in Hawaii relative to historical and present levels of exploitation. This fundamental problem was approached using two classical methods. In the first of these the entire bottomfish community was treated as a multispecies fishery and was analyzed by total

biomass surplus-production methods. Twenty years of DAR catch statistics were summarized and Schaefer analyses performed at different levels of species aggregation (Ralston and Polovina, 1982). Results from this type of study are used to identity the latent capability of fish stocks to respond to exploitation in a compensatory fashion, and thus this first approach deals in a general sense with the question of recruitment/stock-overfishing. The second approach to stock assessment involved studying growth-overfishing in opakapaka, Pristipomoides filamentosus, the single most important species in the Hawaiian handline fishery. This problem was evaluated at steady state using of the Beverton and Holt (1957) yield-per-recruit year-class model in which opakapaka growth dynamics were determined by analyzing the width of daily otolith increments (Ralston and Miyamoto, 1982, in press) and mortality rates were estimated from catch curves after a regression model was formulated to permit development of an age-length key (Ralston, 1981b). In addition to the stock-production and dynamic-pool analyses (Beverton and Holt, 1957), ancillary studies of gear selection (Ralston, 1982), bottomfish depth distributions, and opakapaka reproductive biology provided other types of information which were useful not only from a biological/statistical perspective but from management's viewpoint as well.

SURPLUS-PRODUCTION ANALYSIS OF BOTTOMFISH

The basic premise of most stock-production models is that the per capita (i.e., weight specific) net productivity of a stock ($dB/B \cdot dt$) is a monotonic decreasing function of standing crop biomass (B). However, because total net production also depends in a positive way upon B, the greatest net production usually occurs at an intermediate level of standing crop. A maximum in sustained yield can then be obtained from a stock by cropping it annually to this specific level while harvesting the "latent" or "surplus" production. The fundamental problem then is to estimate this intermediate level and also the annual fishing effort needed to reach it.

The usual procedure is to assume that the catch rate or catch per unit of fishing effort (C/f) is in simple proportion to the biomass of standing crop and that fishing effort (f) is in simple proportion to fishing mortality. The empirically observed functional relationship between C/f and f can then be used to predict the response of the stock to exploitation. The well-known Graham-Schaefer model asserts that these two variables demonstrate an inverse linear relationship, from which it follows that the growth of the stock follows the logistic equation.

This seems to make good sense but there are serious deficiencies in this kind of approach. The most obvious is the inability of these models to adequately describe variation in stock age structure (but see Deriso, 1980). A ton of larvae, for example, responds differently to attempts at exploitation than does a ton of adults. Thus, to model a stock using biomass as the only stated variable is clearly an extreme simplification.

Another deficiency which is somewhat more subtle arises when determining the statistical relationship between C/f and f. An inverse association between these variables is expected even in the situation where catch and effort are completely independent-orthogonal random variables (Schnute, 1977; Mohn, 1980). Nevertheless, when these are the only statistics available, the use of surplus-production models can provide a crude but useful means of assessing the condition of a stock.

Accordingly, the status of the deepsea handline fishery in Hawaii was evaluated by application of the Graham-Schaefer model to 20 years of DAR catch statistics (Ralston and Polovina, 1982). Several problems unique to this specific fishery complicated this analysis. The first is the question of stock definition. At the present time there is insufficient information available to determine the extent of bottomfish larval dispersal between discrete islands of the archipelago. A recent starch-gel electrophoretic analysis of opakapaka enzyme systems failed to detect genetic differences from populations as widely separated as Molokai and Maro Reef, a distance of 750 nmi (Shaklee and Samollow unpublished manuscript). Negative biochemical evidence such as this is difficult to interpret, but does not disprove isolation although it does suggest intermixing of the stocks. Another problem, however, is that the total biomass model which was used in the analysis (Pope, 1979) pools catch statistics across different species, a procedure which contradicts all conventional notions of the unit stock.

A third problem was that an extensive history of fishing and corresponding catch statistics were available for high island areas only and were completely lacking for the NWHI. Consequently, this approach could only be used for the former region. Problems also arose in formulating a suitable measure of fishing effort and there were difficulties in dealing with the unreported recreational catch of bottomfish as well. Needless to say, a variety of assumptions were made but the analysis did provide internally consistent results which gave a reasonably clear indication of the status of bottomfish resources in the high Hawaiian islands.

The study demonstrated that the fishery could be effectively described by aggregating the catch statistics of the 13 major bottomfishes into 3 species groups identified by cluster analysis. No interactive effects were detected among these multispecies groups, as they seemed to behave as independent entities. Although there were strong correlations in fishing mortality among the groups, this was apparently due to fishing activity rather than having a biological basis.

Acceptable statistical results were only obtained from the Maui-Lanai-Kahoolawe-Molokai stock which alone accounted for over 50 percent of the total state landings of bottomfish. The maximum in sustained yield for this stock was estimated to be 106 metric tons per year, equivalent to 272 kg/nmi of 100-fathom

isobath per year when standardized for habitat area. It was also determined that an annual fishing effort of about 900 fishermen (vessel)-days would result in a harvest equal to the projected MSY.

A plot of total annual landings of all bottomfish species reveals past trends as well as the current status of the MLKM fishery (Figure 2). It is apparent that from 1961 to 1963 an abrupt jump occurred in total landings (56 percent increase), leading to harvests moderately in excess of the estimate of MSY (18 percent above). In the 6 years after the peak harvests of 1963 and 1964 catches stabilized briefly around MSY but then a definite decline in bottomfish landings occurred which reached a nadir in 1970 at a level of 38 percent below MSY. Since that time catches of bottomfish increased for a while and as of 1980 the harvest hovered at a level somewhat less than MSY (10 percent below). At present there are no estimates available for the annual landings of 1981 or 1982.

This pattern of catches appears to be adequately explained by changing trends in fishing effort within the fishery (Figure 2). Rapid increases in effort during 1963 and 1964 were associated with the peak harvests of those years. These catches in excess of MSY may have been the results of disequilibrium and the "fishing up" effect (Ricker, 1975). The yield from the fishery then stabilized near MSY (1965-68) as fishing effort approached an optimal level. The reason for the abrupt decline in landings which occurred in 1970 is difficult to determine. The causality between the effects of catch on effort and, conversely, the effects of effort on catch are confounded in this instance. Although it is not certain whether the decline was due specifically to some kind of stock failure, there are at least two factors which support this possibility. The first is that fishing effort had been steadily increasing and was at a level in excess of optimal effort during 1968 and 1969, just prior to when landings fell. The second is that throughout the time period in question the ex-vessel price per pound of bottomfish was increasing. Figure 2 also shows that the average ex-vessel value of the catch rose from $0.58/lb in 1963 to $0.81/lb in 1970. These figures have been adjusted by consumer price indices for Honolulu and represent the actual deflated value of the catch measured in 1967 dollars. Thus, it is unlikely that the decline in landings could have been due to unfavorable market conditions for the product. Immediately following the decline of 1970, and perhaps as a result of it, fishing effort decreased to suboptimal levels in 1971 and 1972 and landings began to increase again. However, the level of fishing effort increased abruptly in 1973 and 1974 to levels substantially in excess of an optimal amount, and since that time yields have consistently been less than the Ralston and Polovina (1982) estimate of MSY. The obvious conclusion is that the fishery for bottomfish at the MLKM bank is now on the descending limb of the catch curve, with further increases in fishing effort likely to result in further decreases in catch. From the perspective of MSY the fishery appears to be overexploited.

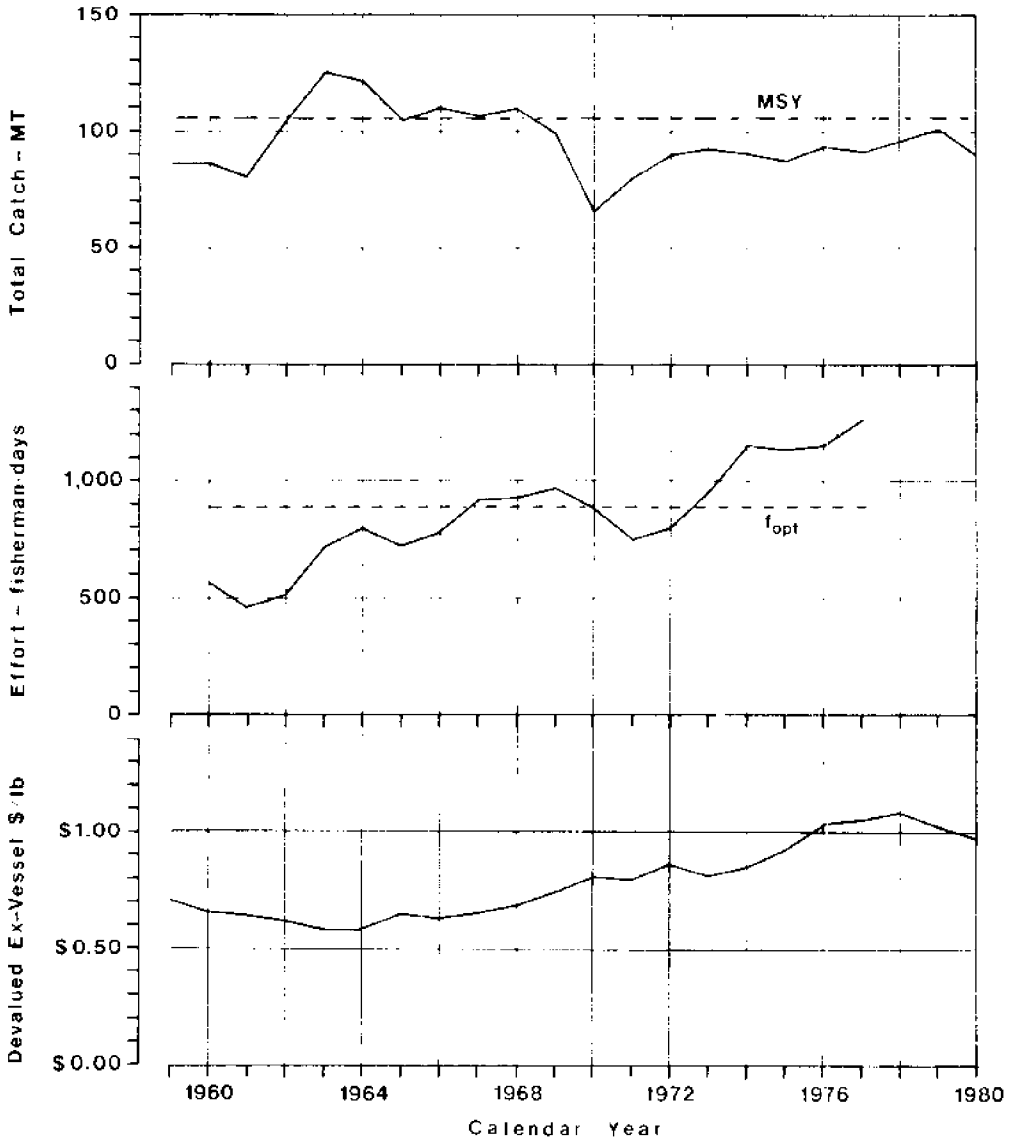

Figure 2. Trends (1959-80) within the fishery for bottomfish at the Maui-Lanai-Kahoolawe-Molokai bank. The top panel shows total catch relative to the estimate of maximum in sustanined yield, the middle panel shows annual fishing effort relative to the estimate of f_{opt}, and the bottom panel shows deflated ex-vessel price per pound in 1967 dollars.

Other aspects of the surplus-production study provide managers with food for thought if not concrete information on which to base policies. Two of these deserve mention here. The first relates to the estimate of MSY from the MLKM stock. Pope (1979) argued that if in a multispecies fishery exploitation is exerted in such a way that the fishing mortalities of the various species

remain in constant ratio to one another, then use of the total biomass Schaefer model may have real meaning. However, he also showed that it cannot be concluded that an MSY estimated from the model need be the global maximum. These are relevant considerations because, as alluded to previously, there are high correlations of fishing effort among the three species groups. Thus, it is theoretically possible that a yield larger than 106 MT per year could be sustained if one could alter the ratios of fishing mortality among the species groups. This may not be an unrealistic proposition because the three groups are for the most part spatially separated. In principle, appropriate management action could thus reduce fishing on one group while simultaneously increasing that on another, but with the present state of our knowledge it would be futile to speculate about the possible extent of any increase in MSY resulting from such action.

A second outcome of the study worthy of consideration by managers involves the notion of species succession in multispecies fisheries. The production analysis of the three species groups comprising the MLKM stock suggested that each of the groups is characterized by its own unique combination of Malthusian parameter and carrying capacity. The trajectory of the system's biomass approaching a new equilibrium point would therefore be likely to undergo shifts in composition of one group relative to the others. In particular, the species group composed of ulua species (Caranx and Carangoides spp.); taape (Lutjanus kasmira); uku (Aprion virescens); and aawa (Bodianus bilunulatus) has a Malthusian parameter estimated to be almost twice that of the remaining two groups. If fishing were relaxed abruptly one would thus expect a transitory increase in the relative contribution of these species to the total harvest of bottomfish from the MLKM stock. Given that the economic value of the different species of bottomfish varies greatly, this may or may not be a desirable result of managing the resource.

YIELD PER RECRUIT ANALYSIS OF OPAKAPAKA

Consider the progression of a single year-class or cohort of fish through time. Early in its lifespan there are many very small recruits. Later on, due to the inevitable force of natural mortality, there are fewer fish alive but these are larger through growth. Only very few individuals ultimately survive to reach old age and large size. It is also true that at any point in time the cohort biomass is equal to the product of the number of individuals alive at the time and their average weight. Because within a year-class these two quantities are inversely related, that is to say, either many small fish are present or a few big ones, the biomass of a fish cohort usually reaches a maximum value at some intermediate stage in its lifespan. An optimum combination of size at harvest and probability of capture therefore exists which will maximize expected yield.

Beverton and Holt (1957) formalized these ideas and showed that the yield of a cohort over its fishable lifespan ($t_c - t_r$)

equal to the integral of the product of instantaneous fishing mortality (F) and cohort biomass at time t. Yet, as noted previously, biomass is simply the product of the number of individuals alive times their average weight. Hence:

$$Y = \int_{t_c}^{t_\lambda} F \cdot B(t) \cdot dt = \int_{t_c}^{t_\lambda} F \cdot N(t) \cdot W(t) \cdot dt$$

They also showed that under equilibrium conditions the yield of a cohort over its fishable lifespan is in effect equal to the annual yield from a fishery composed of mixed cohorts. Equilibrium conditions imply a relatively constant supply of recruits, constant fishing mortality over a time period equal to $t_\lambda - t_c$, and similar constancy in all the parameters which characterize the mortality N(t) and growth W(t) functions.

The solution to this equation provides a means of selecting optimal fishing mortality and age at entry to the fishery (t_c) so as to maintain high yields. If too much fishing mortality is inflicted early in life, a year-class will not have had sufficient opportunity for growth. Conversely, if harvesting is delayed too long, many individuals will be lost to natural mortality and with it their potential contribution to total yield.

This type of calculation addresses the question of growth-overfishing or harvesting fish before their optimal size is attained. The basic problem is to characterize the growth and mortality functions, W(t) and N(t), and this was attempted for opakapaka.

The growth of opakapaka was studied by examining daily growth increments which are known to be deposited in the otoliths of many fishes (Ralston and Miyamoto, 1982, in press). Because these growth marks are frequently difficult to resolve throughout an otolith, a method was devised to estimate the age of individual opakapaka, based upon the pattern of otolith growth rate as indicated by increment width. Integration of regression equations of otolith growth rate on otolith size provided estimates of specimen ages in days. The method proved to be reasonably accurate (the median coefficient of variation of age estimates was 6 percent) and was also successful in accounting for most of the variation in otolith growth rate (the median r^2 for all regressions was 77 percent) (Ralston and Miyamoto, 1982). One major finding was that growth in mature opakapaka seemed to be discontinuous, requiring restrictive assumptions about growth in this size range. Nevertheless, increment periodicity was validated by tetracycline injection of experimental fish and shifts in size-frequency modes of samples from French Frigate Shoals closely matched estimates of growth rate derived from the study of otoliths. Both estimates compared favorably with the

available literature and a growth curve for opakapaka was ultimately obtained (Ralston and Miyamoto, in press).

Mortality rates were estimated from catch curves or age-frequency distributions. A regression approach to generating an age-length key for opakapaka was developed as a means of transforming length-frequency data into age-frequency distributions (Ralston, 1981b). In this procedure a nonlinear regression of age on length provided an equation for estimating mean age as a function of fish length. The squared deviations in age (i.e., residuals^2) from this fit were subsequently regressed on length as well, resulting in an equation for estimating the mean squared deviation in age (variance in age) as a function of length. These two equations provided estimates of mean age and variance in age as functions of length. An age-length probability matrix was then calculated using the normal distribution function which, when post-multiplied by a length-frequency column vector, resulted in another vector of estimated age frequencies (Ralston, 1981b).

This age-length probability matrix was applied to length-frequency samples of opakapaka from Penguin Bank, Necker Island, French Frigate Shoals, and Maro Reef (Figure 1). The resulting estimated age-frequency distributions were then analyzed by traditional catch curve methods and the total rate of instantaneous mortality (Z) and age at entry to the fishery were determined. Several estimates of Z were obtained from each locality, but ultimately a pooled mean estimate of total mortality rate ($\bar{Z}$), weighted by sample size, was calculated for each site under the assumption that populations were age-stationary. Figure 3 shows that $\bar{Z}$ is inversely related to distance to Honolulu. This is likely due to variation in fishing pressure along this gradient. At the time of the study, the stock at Maro Reef in the NWHI was for all practical purposes unfished. During the period 1959-78, only 31 catch records from this site were filed with DAR. For purposes of comparison, nearly 58,000 catch records were filed from Penguin Bank during the same period. Similarly, over 2,600 records were filed from Necker Island. If we assume that during the study fishing mortality (F) at Maro Reef was negligible, then the estimate of total mortality (0.22 per year) provides an estimate of natural mortality (M) because $Z = M + F$. This assumption seems to be reasonable because the calculated value of $\bar{Z}$ from Maro Reef is the lowest of all fishing banks examined. Natural mortality rate was predicted by the method suggested by Pauly (1980) as an independent check on this estimate, resulting in a predicted value of 0.32 per year. The agreement between the two estimates seems reasonable, and, as a representative figure for opakapaka natural mortality, a value of 0.25 per year was used in all subsequent analyses. Characterizing the rate of opakapaka natural mortality allowed separation of $\bar{Z}$ into its component parts. Thus, at Penguin Bank fishing mortality rate (F) was estimated to be 0.48 per year (0.73 minus 0.25).

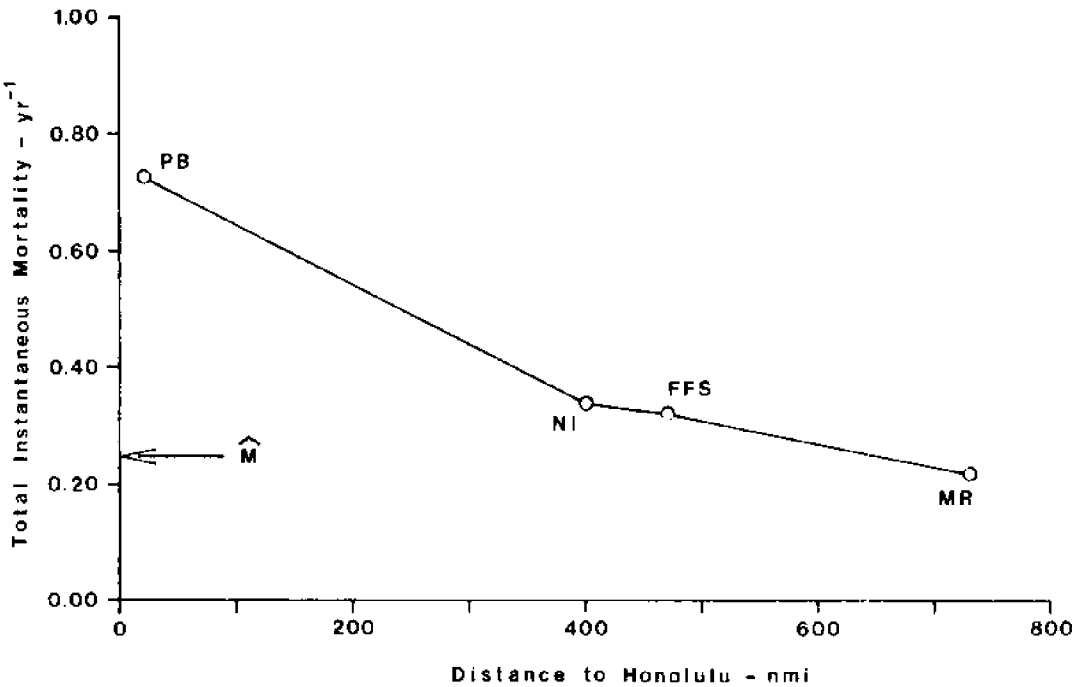

Figure 3. The relationship between the pooled mean total mortality rate ($\bar{Z}$) of opakapaka and distance to Honolulu. PB = Penguin Bank, NI = Necker Island, FFS = French Frigate Shoals, and MR = Maro Reef. The estimate of natural mortality is indicated by an arrow on the ordinate.

The foregoing results completed the determination of the opakapaka mortality function, N(t), which was then combined with the growth function, W(t), permitting numerical solution of the Beverton-Holt yield equation. The results are displayed graphically in Figure 4. In this figure constant values of yield per recruit (isopleths) are mapped onto a two-dimensional surface of management control (fishing mortality rate and age at entry to the fishery). Note that the eumetric fishing line is the locus of points which gives the maximum yield per recruit at fixed levels of fishing mortality. The single point on the isopleth surface represents Penguin Bank where $\hat{F}$ = 0.48 per year and $\hat{t}_c$ = 4.0 years.

From these results it is possible to conclude that there is little that could be done in the sense of growth-overfishing to improve the fishery for opakapaka at Penguin Bank. The specific combination of F and t_c at this site places it very close to the eumetric line. Estimated yield per recruit is about 0.36 kg per recruit and only very large increases in fishing mortality could increase this figure substantially. Such a policy would certainly risk recruitment-overfishing, violating a critical assumption of

the model. From these considerations it is clear that the fishery for opakapaka at Penguin Bank is fortuitously close to an optimum level of exploitation inasmuch as the fishery has never been seriously regulated.

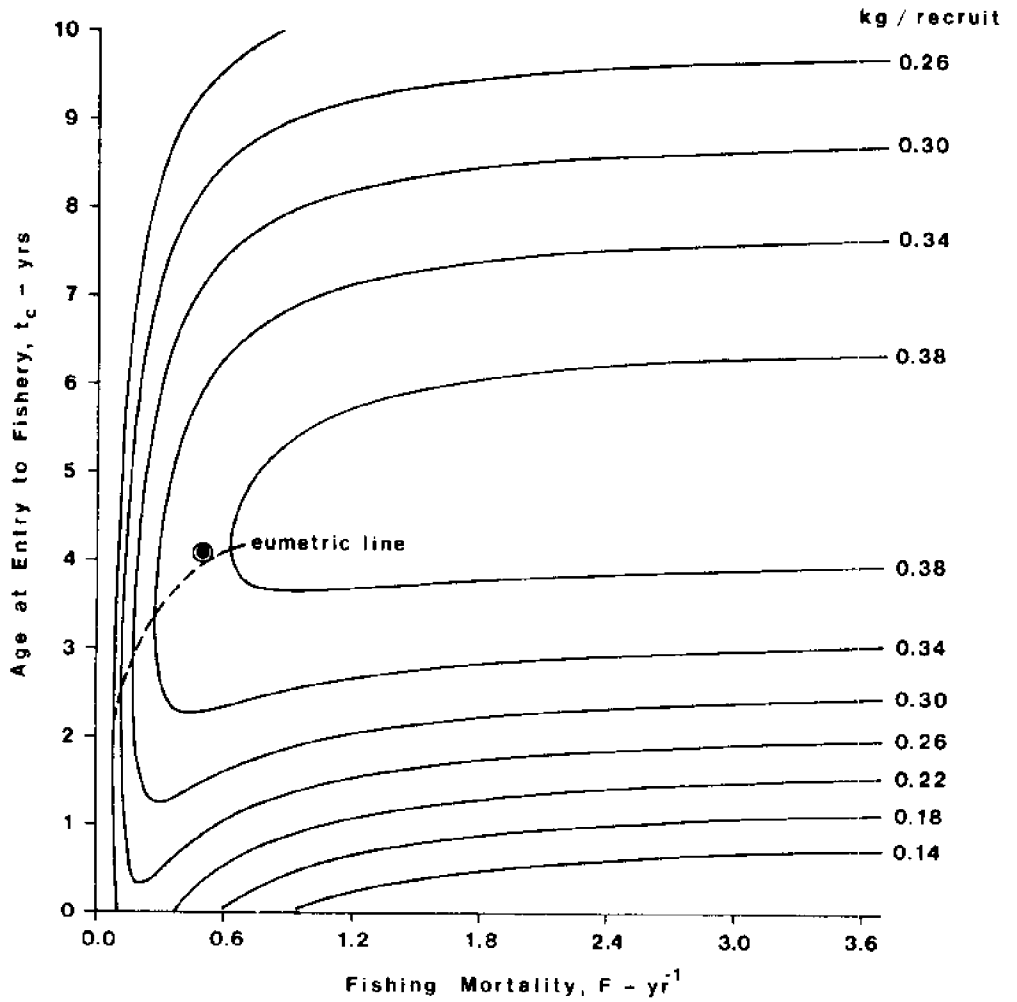

Figure 4. Beverton-Holt yield-per-recruit surface for opakapaka. The point represents the estimated position of Penguin Bank in 1980.

DISCUSSION

The results of both the surplus-production analysis of bottomfish from the MLKM stock and the yield-per-recruit analysis of opakapaka from Penguin Bank provide a coherent assessment of the present status of bottomfish populations. Landings from the fishery were estimated to be somewhat less than maximal in the former treatment, ostensibly as a result of overfishing. The latter study, on the other hand, suggested that in terms of optimizing the harvest of opakapaka growth potential few improvements were possible. On face value these two conclusions seem somewhat

contradictory although a brief examination of the literature will show otherwise.

Recall from the yield-per-recruit analysis that the natural mortality rate of opakapaka at Maro Reef was estimated to be 0.25 per year whereas the total mortality rate of this species at Penguin Bank was determined to be 0.73 per year. If natural mortality at these two sites is comparable, and at the present time there is no reason to think otherwise, this implies a fishing mortality rate at Penguin Bank which is nearly twice as high as that due to natural causes. Other studies suggest this may be excessively high if yields are to be maximized by avoiding recruitment/stock-overfishing.

Alverson and Pereyra (1969), based on the unpublished ideas of Gulland (1971) and an earlier Soviet study (Tiurin, 1962), first proposed that at MSY the optimum level of fishing mortality (F_{opt}) was approximately equal to natural mortality. This particular conclusion applied not only to surplus-production models such as the Graham-Schaefer formulation, but more loosely to the Beverton-Holt constant recruitment model as well (Gulland, 1971). Saetersdal (1973) also advocated using M as a direct estimate of F_{opt} when assessing unexploited resources and when catch statistics are unavailable.

Francis (1974) examined more critically the theoretical basis of this approximation within the framework of the logistic growth equation. He concluded that the equivalence of mortality factors held only when recruitment was density-independent over a range in stock size spanning unexploited levels to one-half the virgin level (i.e., $R_0 = R_{opt}$). More generally if the stock-recruitment relationship is best described by a Beverton-Holt type of spawner-recruit curve, or any other asymptotic form, then F_{opt} would likely be constrained to values less than M. Conversely, only when a Ricker or dome-shaped spawner-recruit relationship applies will F_{opt} likely exceed M.

Deriso (1982) expanded on these ideas and showed analytically two other factors of importance. The first and most significant of these is that MSY fishing mortality is often restricted to values less than the fishing mortality which maximizes yield per recruit. Thus, the relatively efficient utilization of opakapaka growth potential which characterizes the fishery at Penguin Bank is compatible with the notion of overexploitation from the perspective of MSY. The second point is that when a spawner-recruit curve is dome-shaped, F_{opt} can exceed M in the logistic model, but only in the situation where recruitment is severely depressed in the unexploited state (i.e., the stock displays strong recruitment compensation) will F_{opt} exceed 1.5(M). Other models such as Deriso's delay-difference formulation are more conservative in their behavior.

In view of the conclusions of these other studies it would seem that the analysis of the MLKM fishery presented here is

internally consistent. Fishing there is excessive relative to obtaining MSY but is near optimal in terms of maximizing yield per recruit. A danger of recruitment-overfishing likely exists in this situation and yet it is fortuitous that with the historical lack of any serious constraints on fishing the stocks of bottomfishes have been as stable as they have, given the extent of exploitation at the MLKM bank. The situation is tenuous, however, and management of bottomfish resources around the main Hawaiian islands should certainly be considered now.

In contrast, the resources of the NWHI apparently have much potential yet to offer. Estimates of the total mortality rate of opakapaka from Necker Island and French Frigate Shoals (Figure 3) indicate that further increases in fishing activity should be easily assimilated by the stocks. Other fishing grounds remain totally untapped to the northwest of Maro Reef, where little fishing has occurred to date. While conflicts between fishing activity and the conservation of other wildlife resources (e.g., monk seals) remain unresolved, there nevertheless exists a bottomfish resource in the NWHI capable of supporting increased harvests on biological grounds.

As a first approximation to the magnitude of bottomfish resources in the NWHI, we can assume productivity comparable with the main high islands and invoke the Ralston and Polovina (1982) estimate of MSY per unit of habitat area (272 kg/nmi of 100-fathom isobath per year) for the MLKM stock. Because this figure does not include the recreational catch it provides a very conservative estimate of the potential yield of bottomfishes from the NWHI. These islands have a combined habitat area equivalent to about 1,200 nmi of 100-fathom isobath. Thus, one might expect as a minimum a sustained bottomfish yield of 330 MT per year from the NWHI. Given that the ex-vessel price per pound for these species is currently averaging about $2.75, the value of the resource to the fishermen might be estimated to be roughly $2 million annually. This amounts to a harvest substantially greater than that currently being landed in the main high islands of the archipelago.

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ECONOMIC ANALYSIS OF DEEP BOTTOMFISHING IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Heavily fished bottomfish stocks of the main Hawaiian islands as well as recent research have renewed interest in the bottomfish resources of the Northwestern Hawaiian Islands (NWHI). During 1981 and 1982 the Hawaii Division of Aquatic Resources conducted bottomfish surveys in the NWHI. Three multipurpose commercial fishing vessels, Feresa, Kaimi, and Wicked Wahine, were contracted for eight survey trips. Annual vessel expenditures were extrapolated for a generalized bottomfish operation. NWHI bottomfishing trips were found to be marginally profitable. Ex-vessel prices for fresh bottomfish decreased with increased landings. Current limited local demand (fresh fish market system) and inconsistent ex-vessel bottomfish prices constrain NWHI bottomfishery development.

bottomfish
ex-vessel prices
fresh-fish market

INTRODUCTION

Fishing in the Northwestern Hawaiian Islands has occurred since the early 1900s. During the 1930s as many as five large fishing vessels ranging from 65 to 70 feet in length fished in NWHI waters for snappers (Lutjanidae), groupers (Serranidae), and jacks (Carangidae).[1] The number of large vessels operating in the area increased to as many as nine after World War II

[1]May 9, 1973 letter to Mr. Findlay, Regional Director, Bureau of Sport Fisheries and Wildlife, from H. Shinsato

(H. Shinsato, 1973: personal communication). Between 1946 and 1957, one operation shipped fresh akule (Selar crumenopthalmus), moi (Polydactylus sexfilis), other reef fish, and some bottomfish by airplane from Tern Island at French Frigate Shoals to Honolulu.

In the past (1945-60), sampans and converted navy surplus ships comprised the types of vessels regularly used in the NWHI. Some of these vessels were capable of landing more than 10,000 pounds of fresh fish at the Honolulu market. The prices paid to the producer or fisherman for bottomfishes ranged between $0.25 and $0.40 (equivalent to $0.85 and $1.83 in 1983 dollars) per pound (H. Shinsato, and L. Agard, Jr.: personal communication) The number of large vessels fishing in the NWHI declined during the 1950s because of vessel losses and low fish prices, and only a single vessel remained in operation in the 1960s (H. Okamoto: personal communication).

In recent years, the number of vessels capable of fishing in the NWHI has again increased. New vessels based in the state and vessels from the mainland United States are expanding Hawaii's long-range fleet. Since 1980, several multipurpose vessels trolling in the North Pacific albacore (Thunnus alalunga) fishery have bottomfished in the NWHI during their off-season to increase their productivity and reduce their dependency on one fishery to pay for fixed annual expenses.

Most vessels in the bottomfishing fleet still fish around the main Hawaiian islands, primarily for the fresh fish market. In 1980 local commercial fishermen reported catching 649,527 pounds of bottomfish which sold for $1,048,254 (DLNR, 1982). NWHI bottomfish catches accounted for 24 percent of the 1980 poundage (156,122 pounds) and 14 percent of the total value ($146,324).

Currently, heavy fishing pressures on the main Hawaiian island bottomfish stocks, which cause decreasing catch rates and smaller-sized fishes, are forcing fishermen with large vessels to travel greater distances to harvest bottomfish.

Preliminary assessments of fisheries resources in the NWHI by the Division of Aquatic Resources of the Hawaii Department of Land and Natural Resources and by the Honolulu Laboratory of the Southwest Fisheries Center of the National Marine Fisheries Service (NMFS) have suggested that NWHI stocks can support expansion of the Hawaiian bottomfish fleet. Surveys by both agencies have revealed certain areas of the NWHI in which good experimental catch rates seem to indicate significant bottomfish stocks (DLNR, 1979; Moffit, 1980; Ralston, 1979, 1980; Uchida et al., 1979, 1982).

Estimates of potential NWHI bottomfish landings have varied from a low range of 230,000 to 700,000 pounds (104 to 330 metric tons) to a high range of 1 to 2 million pounds (454 to 907 metric

tons) annually. The former figures, extrapolated by Ralston in 1980, are based upon production estimates derived for the high or main Hawaiian islands. The latter figures are projected as NWHI landings if the long-distance fleet and the market were to expand (DLNR, 1979).

Surveys were undertaken during 1981-82 to determine whether commercial bottomfishing in the NWHI is economically feasible for modern long-range vessels. The surveys were devised to determine if current fish prices for NWHI catches could offset expenses incurred to harvest these resources. Major economic factors and industry conditions that currently affect bottomfishing operations in the area were identified and evaluated.

METHODS

The Division of Aquatic Resources, through the Research Corporation of the University of Hawaii, contracted with three commercial fishing vessels to fish in the NWHI. An observer was present on each fishing trip to record catch and effort data. The fishing vessels, Feresa, Kaimi, and Wicked Wahine (Table 1) worked in prescribed areas from Brooks Bank to Ladd Seamount (Figure 1). The vessels were equipped with both refrigeration and freezing facilities. All used bottomfishing rigs that consisted of three hydraulic-powered bottom gurdies or pinch-pullers (stripper haulers) which are capable of handlining to a depth of 150 fathoms. A maximum of three lines, each with one to four hooks, were used at any one time.

TABLE 1. 1981-82 NORTHWESTERN HAWAIIAN ISLANDS BOTTOMFISHING SURVEYS: CONTRACT VESSEL SPECIFICATIONS

Specification	Feresa	Kaimi	Wicked Wahine
Year built	1981	1980	1979
Length/beam (ft.)	58/15.6	63/17	65/17
Average no. in crew	2-3	2	2
Deck space (sq. ft.)	315	800	800
Range (nautical miles)	3,200	7,250	2,500
Fish carrying capacity (tons)	17	40	24

Data on vessel expenses and revenue from catch sales were obtained from the captain or owner after each cruise. Information on fishing operations was obtained through private discussions. Annual vessel expenditures were extrapolated to calculate the economic return of a full-time bottomfish operation in the NWHI (see "Discussion" section).

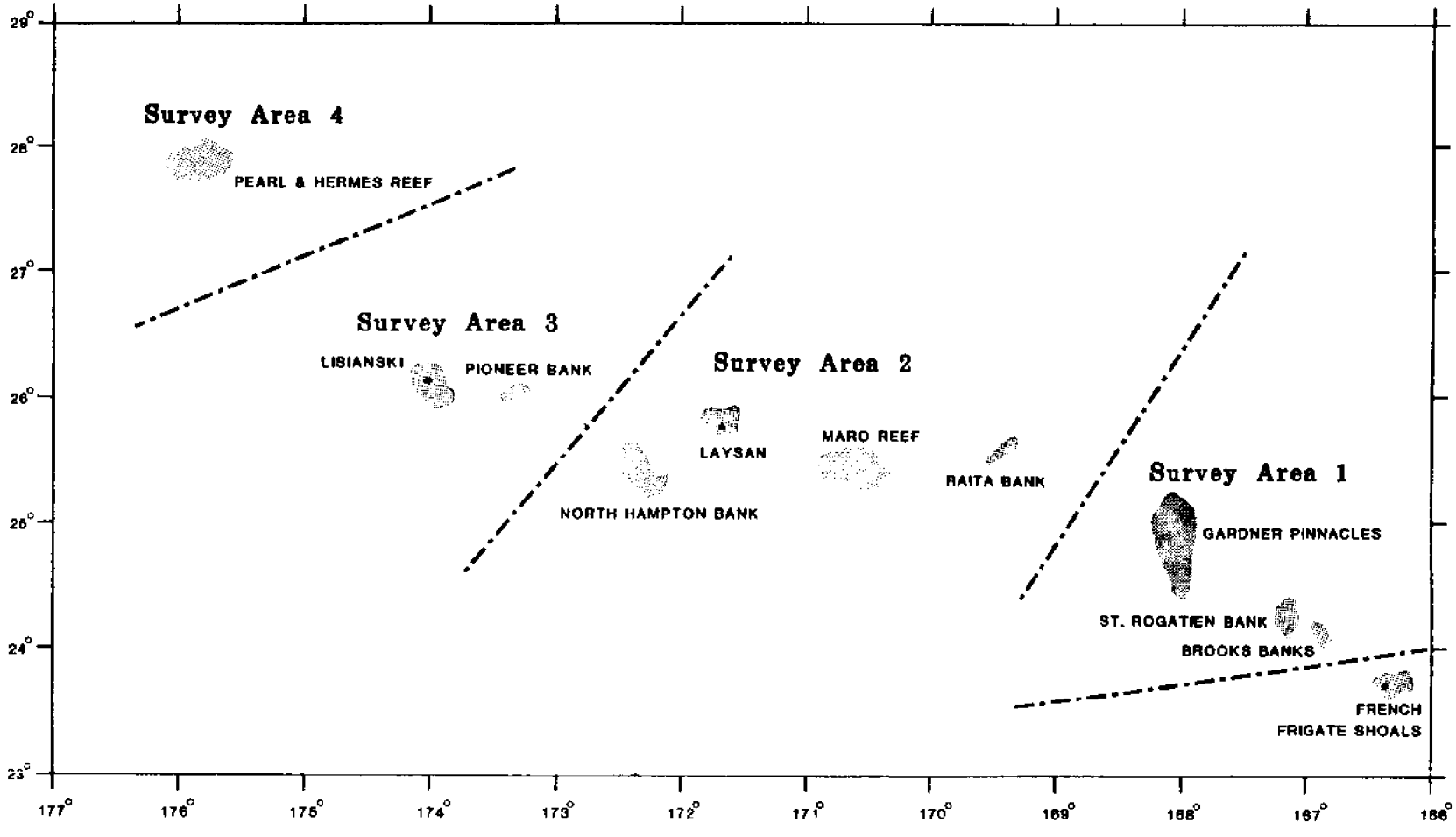

Figure 1. 1981-82 bottomfishing survey areas

RESULTS

The three fishing vessels made a total of eight fishing trips to the NWHI between October 1981 and May 1982. The cruises were 12 to 46 days in duration (23 days average). Catch rates varied from 217 to 1,916 pounds per fishing day (886 pounds per day average). Ninety-six of the total 185 trip-days were spent fishing. The fishing effort resulted in 71,684 pounds of fresh and frozen fishes (incidental catches from trolling included), which sold for a gross ex-vessel value of $107,555. Landings from individual trips ranged from 433 to 15,454 pounds (8,961 pounds average). Gross receipts ranged from $1,661 to $18,749 ($13,444 average). The average price of fish paid to the fishermen for the individual trips ranged from $1.18 to $3.84 per pound; the overall average price received for fresh and frozen fish was $1.50 per pound (Table 2). A significant inverse correlation was found between overall catch prices and landing volumes: increasing the volume of catches resulted in lower overall catch prices.

The white ulua (Caranx ignobilis), butaguchi (Pseudocaranx dentex, also referred to as pig-lipped ulua), hapuupuu (Epinephelus quernus), and opakapaka (Pristipomoides filamentosus) accounted for 83 percent of the total number of fishes caught. The fresh-fish price ranges for these species, based on six trips, were: (1) white ulua -- $0.40 to $2.50; (2) butaguchi -- $0.90 to $2.75; (3) hapuupuu -- $1.30 to $3.15; and (4) opakapaka -- $2.40 to $9.00. High values varied from two to six times the low values (Table 3). Average prices generally decreased on the second day when fish were sold over a 2-day period ($t = 0.005$). The decrease from the first to the second day averaged 17 percent (Table 4).

Frozen bottomfish were sold directly to wholesalers for negotiated prices ranging from $0.75 to $3.00 per pound (Table 5). There was no significant difference in price between catches partially processed (gutted) before freezing (trips 7 and 8) and unprocessed frozen catches.

DISCUSSION

The survey fishing trips were carried out with as few restrictions as possible on commercial fishing operations. In reviewing the data, factors such as physical/mechanical differences in vessels, captains' strategies, and degrees of crew experience, as well as the limited number of survey trips were taken into account. Results of the eight survey trips demonstrated the potential for extremely good as well as poor catches and the uncertainty of fish prices as shown by their wide ranges and resulting catch values.

TABLE 2. 1981-82 NORTHWESTERN HAWAIIAN ISLANDS BOTTOMFISHING SURVEY CATCH RESULTS SUMMARY

Survey Trip	1*	2*	3*	4†	5†	6†	7§	8§	Total
Fishing days	7	9	2	9	12	9	24	24	96
Non-fishing days#	7	5	10	11	8	8	22	18	89
Total days	14	14	12	20	20	17	46	42	185
Reported number of pounds caught	10,824	3,960	433	11,596	9,838	17,242	7,839	12,893	74,625
Catch per fishing day	1,546	440	217	1,288	819	1,916	327	537	886
Pounds sold	10,824	3,960	433	11,163	9,438	15,454	7,839	12,573	71,684
Gross value	$18,720	$10,049	$1,661	$15,363	$18,749	$18,306	$9,401	$15,306	$107,555
Gross value per fishing day	$2,674	$1,117	$831	$1,707	$1,562	$2,034	$392	$638	$1,120
Average price per pound	$1.73	$2.54	$3.84	$1.38	$1.99	$1.18	$1.20	$1.22	$1.50

*Fresh fish catch
†Fresh and frozen fish catch
§Frozen catch (partially processed)
#Including travel time

TABLE 3. BID PRICES* OF FOUR MAJOR NORTHWESTERN HAWAIIAN ISLANDS BOTTOMFISH SPECIES SOLD AT THE HONOLULU FISH AUCTION

Survey Trip	Auction Date	Bid Range (Daily Average) in U.S. Dollars			
		White Ulua	Butaguchi	Hapuupuu	Opakapaka
4	10/30/81	0.95-1.80 (1.48)	1.25-1.60 (1.37)	1.50-2.05 (1.72)	3.80-3.80 (3.80)
	10/31/81	1.00-1.45 (1.14)	—	1.35-1.80 (1.55)	3.60-3.80 (3.69)
1	11/23/81	1.00-1.55 (1.37)	0.90-1.10 (0.97)	1.30-1.70 (1.51)	2.65-3.30 (3.13)
	11/24/81	0.85-1.55 (1.29)	0.90-0.95 (0.91)	1.45-1.75 (1.68)	2.40-3.55 (3.11)
2	03/02/82	1.80-2.40 (2.17)	1.25-1.60 (1.39)	2.40-2.85 (2.58)	4.30-4.60 (4.51)
3	03/29/82	2.50-2.50 (2.50)	2.50-2.75 (2.63)	2.75-2.75 (2.75)	6.95-7.00 (6.98)
5	04/02/82	1.30-2.30 (1.64)	1.00-1.15 (1.04)	2.00-2.90 (2.58)	8.85-9.00 (8.92)
	04/03/82	1.10-1.55 (1.34)	1.00-1.40 (1.14)	1.60-3.15 (1.86)	7.65-7.70 (7.68)
6	05/07/82	0.45-1.45 (1.10)	1.00-1.00 (1.00)	1.30-1.80 (1.60)	4.50-5.25 (5.01)
	05/08/82	0.40-0.75 (0.61)	—	—	3.40-3.90 (3.60)
Overall bid range		$0.40-$2.50	$0.90-$2.75	$1.30-$3.15	$2.40-$9.00
High/low ratio		6.25	3.06	2.40	3.75

*Prices in dollars per pound of fresh (whole) fish

TABLE 4. DAILY NORTHWESTERN HAWAIIAN ISLANDS BOTTOMFISH AVERAGE PRICE CHANGES BY TRIP

Survey Trip	Auction Date	Price in U.S. Dollars (Pounds Sold)			
		White Ulua	Butaguchi	Hapuupuu	Opakapaka
4	10/30/81	1.48 (2,547)	1.37 (305)	1.72 (1,032)	3.80 (214)
	10/31/81	1.14 (2,320)	--	1.55 (1,053)	3.69 (252)
	Price change (%)	-23	--	-10	-3
1	11/23/81	1.37 (2,015)	0.97 (1,334)	1.51 (2,113)	3.13 (1,661)
	11/24/81	1.29 (2,366)	0.91 (190)	1.68 (178)	3.11 (690)
	Price change (%)	-6	-6	+11	-1
2	03/02/82	2.17 (2,231)	1.39 (272)	2.58 (580)	4.51 (367)
3	03/29/82	2.50 (3)	2.63 (70)	2.75 (56)	6.98 (19)
5	04/02/82	1.64 (1,035)	1.04 (1,477)	2.58 (136)	8.92 (152)
	04/03/82	1.34 (273)	1.14 (601)	1.86 (2,641)	7.68 (384)
	Price change (%)	-18	+10	-28	-14
6	05/07/82	1.10 (3,954)	1.00 (146)	1.60 (1,029)	5.01 (375)
	05/08/82	0.61 (3,337)	--	--	3.60 (245)
	Price change (%)	-45	--	--	-28

TABLE 5. NEGOTIATED FROZEN NORTHWESTERN HAWAIIAN ISLANDS BOTTOMFISH SPECIES

Survey Trip	Landing Date	Price in U.S. Dollars (Pounds Sold)			
		White Ulua	Butaguchi	Hapuupuu	Opakapaka
4	10/30/81	0.80 (1,500)	0.75 (1,500)	1.00 (150)	3.00 (100)
7*	12/03/81	0.75 (1,751)	0.86 (57)	1.06 (4,124)	2.10 (1,394)
5	04/02/82	1.00 (1,505)	0.75 (720)	1.25 (190)	—
6	05/06/82	1.00 (5,045)	0.75 (700)	—	—
8*	05/18/82	1.00 (300)	0.75 (3,250)	1.15 (6,425)	2.00 (2,448)

*Processed before frozen (partially cleaned)

Fishing Strategy

Experienced fishermen can selectively fish for bottomfish on the basis of depth and bottom topography using depth recorders. In order to maximize catch values and fishing efficiency, four major bottomfish species are sought for the market. These species are opakapaka, hapuupuu, butaguchi, and white ulua.

Opakapaka is one of the primary target species due to the relatively high price it commands as a result of its constant demand at the auction (Table 3). Hapuupuu and white ulua are sought because of their sturdiness and ability to retain good flesh quality. In addition, white ulua can be caught in rough sea conditions when other species are difficult to fish. Prices for hapuupuu, butaguchi, and white ulua are not as high as for opakapaka, but larger catches of these three species can offset the lower prices they bring.

Economic Analysis

The estimated costs derived for an annual full-time bottomfishing operation in the NWHI are based upon a composite view of cost and expense data for the Feresa, Kaimi, and Wicked Wahine. Although the characteristics of the vessels are quite different, their expenses are relatively similar (except for the fuel and oil cost of the sail-assisted vessel Feresa). The operation is based on the following criteria: (1) a three-man crew, including the captain, on a 60-foot multipurpose fishing vessel (cost between $250,000 and $500,000); (2) a diesel-powered vessel capable of both refrigeration and freezer storage; (3) the northern fishing grounds of Survey Area 2 being the farthest point

(900 nm) to which the vessel could travel and still remain within reasonable traveling time (3 to 5 days) back to the Honolulu market; (4) fishing trips of moderate length, averaging approximately 19 days; (5) each trip including 10 fishing days and 9 non-fishing days (travel time included); (6) 11 trips (209 trip-days) per year; (7) 1 month set aside for annual scheduled maintenance, including dry-docking and delays due to weather conditions.

FIXED EXPENSES

Fixed expenses are annual costs paid by the owner whether the vessel is being used for fishing or not. For the full-time operation, fixed expenses total $69,483 (Table 6). Loan payments (principal and interest) total $32,200 (46 percent). (Present interest rates for vessel loans can vary from 7.5 percent, offered by the State Large Vessel Loan Program, to 18 to 20 percent offered by commercial institutions.) Unscheduled maintenance and repair costs amount to $16,667 (24 percent). Scheduled maintenance (dry-docking and regular servicing) costs total $8,167 (12 percent). Premiums for insurance (hull, liability, and crew coverage) amount to $10,967 (16 percent). Annual moorage fees are $1,482 (2 percent).

TABLE 6. ANNUAL FIXED EXPENSE SUMMARY FOR FULL-TIME COMMERCIAL FISHING VESSEL

Fixed Expense	Annual Cost
Loan payment	$32,200 (± 3,995)
Unscheduled maintenance and repairs	16,667 (± 4,163)
Insurance	10,967 (± 1,704)
Scheduled maintenance	8,167 (± 9,385)
Moorage fee	1,482 (± 590)
TOTAL	$69,483

DEPRECIATION

Depreciation is a business allowance for the decrease in value of an asset due to age or wear. However, the increasing demand for an asset such as a fishing vessel sometimes causes its actual market value to increase. Vessel owners do take advantage of the allowable "tax deductions" or credits for depreciation. Based on the surveys, a fishing vessel less than 5 years old has an approximate annual depreciation value of $56,000.

VARIABLE EXPENSES

Variable expenses are operational costs incurred by the vessel while at sea. Figures were calculated by multiplying the projected number of trip days by the average daily cost. Based on the surveys, the estimated annual variable expenses for a full-time commercial fishing operation total $64,995 (Table 7). This figure is made up of fuel and oil costs of $47,197 (73 percent), miscellaneous costs of $6,753 (10 percent), bait and ice costs of $5,881 (9 percent), and food costs of $5,164 (8 percent).

TABLE 7. ANNUAL VARIABLE EXPENSE SUMMARY FOR FULL-TIME COMMERCIAL FISHING VESSEL

Item	Daily	Trip	Annual
Fuel and oil	$225.82 (± 100.43)	$4,291	$47,197
Miscellaneous	32.31 (± 11.13)	614	6,753
Bait and ice	28.14 (± 10.23)	535	5,881
Food	24.71 (± 4.78)	469	5,164
TOTAL	$310.98	$5,909	$64,995

REVENUES

Net revenues are split 40:60. Forty percent is shared among the crew with the remaining 60 percent going to the owner, who pays for fixed expenses and deducts depreciation costs. An owner who is also captain of a vessel is entitled to the captain's portion of the crew share.

ANNUAL FINANCIAL STATEMENT

Assuming 11 trips per year and a selling price of $1.50 per pound (overall average of experimental fishing trips), 203,061 pounds (18,460 pounds per trip) of fish would have to be caught to produce an annual break-even income of $304,592 (Table 8). Expenditures for the NWHI operation can be broken down into the following categories: auction commission, variable expenses, crew share, fixed expenses, and depreciation. Ten percent, or $30,459 of the gross value, is paid out as auction commission. The largest single cost for the operation is the crew share which amounts to $83,655 (28 percent). Fixed expenses total $69,483 (23 percent), variable expenses $64,995 (21 percent), and depreciation $56,000 (18 percent) (Table 8).

TABLE 8. ANNUAL NWHI BOTTOMFISH OPERATION FINANCIAL STATEMENT

			Balance
GROSS REVENUE			$304,592
Auction Commission		$ 30,459	
			$274,133
Variable Expenses		$ 64,995	
Fuel and Oil	$47,197		
Miscellaneous	$ 6,753		
Bait and Ice	$ 5,881		
Food	$ 5,164		
NET REVENUE (40:60 split between the crew and owner)			$209,138
Crew Share		$ 83,655	
Owner's Share			$125,483
Fixed Expenses		$ 69,483	
Loan Payment	$32,200		
Unscheduled Maintenance	$16,667		
Insurance	$10,967		
Scheduled Maintenance	$ 8,167		
Moorage Fee	$ 1,482		
			$ 56,000
Depreciation		$ 56,000	
Net Profit/Loss			$0

BREAK-EVEN POINT BEFORE DEPRECIATION

In determining break-even figures (total cost equals total revenue), depreciation was excluded to reflect actual costs paid. A full-time NWHI bottomfish operation would require $200,900 in annual gross revenue to break-even before depreciation. To obtain this amount an average of $18,263 would have to be earned on each of the 11 fishing trips. The relationship of the fish price and break-even trip catch is shown in Figure 2. At an average fish price of $1.50 per pound, a trip catch of 12,176 pounds would be required to break-even.

Marketing

FRESH BOTTOMFISH

Catches from the NWHI are primarily brought back as iced fish for sale on the fresh-fish market. Fishermen usually market their bottomfish catches through the Honolulu Fish Auction which charges fishermen a 10 percent commission (based upon gross catch value) for its services.

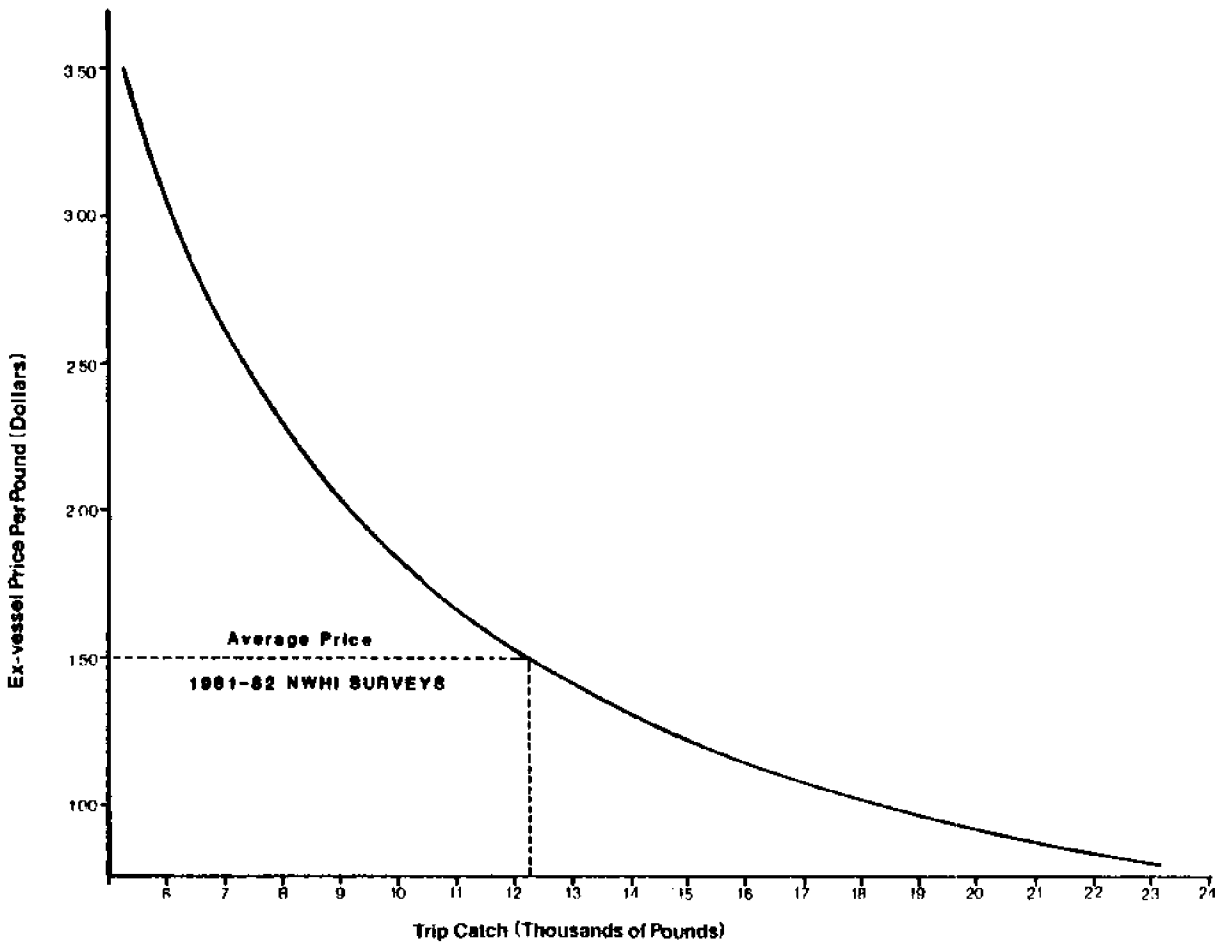

Figure 2. Estimated break-even trip catches (before depreciation)

Bottomfish are auctioned fresh, whole, and in lots, usually grouped by species and size. The fish are either placed in galvanized cans or on pallets before being lined up on the auction floor. Auction prices serve as an important indicator of the market supply and demand. Daily fish prices (retail and wholesale) are closely related to prices originating at the auction (Garrod and Chong, 1978). The auction is capable of handling large volumes of NWHI catches, but prices often decline in response to a temporary oversupply.

The other alternative for bottomfish fishermen is to sell directly to a fish dealer (Peterson, 1973) for negotiated prices. These prices are usually lower than auction prices. Depending upon available storage space and current market conditions, several of the larger dealers are capable of handling several thousand pounds of bottomfish directly from a vessel.

To obtain prices that reflect market conditions, all fresh bottomfish catches from the NWHI are sold through the Honolulu Fish Auction. It is assumed that the present market system can

absorb a steady supply of NWHI catches and that the volume of bottomfish at the auction will expand commensurately with near-future increases in both local fresh and frozen bottomfish catches.

Generally, fish prices are the result of present, as well as expected, daily supplies and demands. The present Hawaiian fish marketing system is subject to an inconsistent bottomfish supply (irregular and unpredictable landings) from a variable number of full-time and part-time bottomfishermen. Based on the surveys, total revenue increased with higher volume landings, although the overall average price per pound declined (Table 2).

Many factors directly and indirectly influence fish prices in the established marketing system. A few of the major factors include landing and marketing timing, quantity of supply, quality of catch, and size of fish.

Timing for landing and marketing NWHI catches is very important. Bottomfish caught around the main islands are iced for only 1 to 2 days before being marketed, whereas NWHI fresh catches may be packed in ice for up to 10 or more days. Catches from the NWHI must compete with bottomfish caught around the main Hawaiian islands and occasional imported landings from out of state (e.g., Samoa). Prices for bottomfish caught in the NWHI, like bottomfish air freighted from the neighbor (main) Hawaiian islands and elsewhere, depend upon when they can be marketed. Prices change daily and the value of a particular catch can vary dramatically with time of arrival at the auction and even in the order that it is placed on the floor for bidding. Once on the auction floor, the day's bottomfish catches are compared by the buyers for quantity, quality, and size. Early bottomfish prices are likely to establish the bid ranges for the rest of the day.

The available supply of bottomfish directly influences prices. Large catches of bottomfish, such as those landed from the NWHI, may temporarily exceed normal market demand and decrease prices. The quality of bottomfish also affects the level of pricing. If the catches are of poor quality (limited shelf-life), fish must be sold sooner and will not receive as high a price as the same type of fish of superior quality. Iced bottomfish are perishable and the quality of the fish decreases with time. The sooner NWHI catches can be sold at the market, the better the quality and prices should be.

The size of bottomfish may also affect prices. Wholesalers who supply restaurants prefer medium to large sized bottomfish because of their higher conversion ratio (higher proportion of processed product to waste). Retail markets, on the other hand, prefer smaller, whole bottomfish for home consumption. Bottomfish from the NWHI are predominantly medium to large in size and are bought mostly by wholesalers and retail markets that process -- scale, fillet, and skin -- their products.

When there are adequate supplies of bottomfish for the market, prices vary with quality and size as a result of buyer selectivity. When supplies are low, prices are higher and are not influenced as much by size and quality. Wholesalers, due to competition, are willing to pay higher than normal prices to assure supplies of bottomfish to their regular customers (e.g., opakapaka purchased at $9.00 per pound will likely go to a restaurant supplied by a wholesaler).

FROZEN BOTTOMFISH

Local landings of frozen bottomfish have been irregular and fish dealers have not had opportunities to expand the market for locally caught frozen fish. The high prices for frozen Hawaiian bottomfish are about 50 percent less than the respective fresh fish (auction) prices. Local frozen bottomfish must compete with fish imported from the mainland and other countries (e.g., New Zealand snapper). These imports are often lower in price, regular in supply, and of uniform quality.

SUMMARY AND CONCLUSIONS

For a fishery as distant as the Northwestern Hawaiian Islands, long-range vessels equipped with large fish-carrying capacities and the capability to withstand rough sea conditions are necessary. Modern vessels equipped with advanced technology incur higher capital, operational, and maintenance costs, which increase with distance to fishing grounds. Greater distances mean increased traveling time and less time available for fishing, making higher productivity essential. Present market conditions require landing bottomfish catches fresh to obtain the best prices. The largest variable expense is fuel and oil (73 percent). The largest fixed expense, which is paid by the vessel owner, is the loan payment (43 percent; principal and interest). The goal of each trip to the NWHI should be to land sufficient quantities of good quality bottomfish, at the right time in order to obtain optimum prices.

At present, a full-time bottomfishing operation handlining in the NWHI is economically unfeasible, although there is a potential for a full-time bottomfish fishery in the future if local fresh and frozen fish markets are developed. The development of an independent seasonal bottomfish fishery, or as a component of a multi-species fishery (e.g., establishment of a Tern Island fishery support station), is plausible. These topics are not addressed in this paper. Although some NWHI bottomfishing operators at this time seem to be breaking even before depreciation, increases in the number of trips and of vessels entering this fishery will probably affect existing fish stocks and the marketing system.

To develop a stable price for NWHI bottomfish, the Hawaiian market must first be assured of a consistent supply of fresh bottomfish. The market structure can then be expanded to handle

an increased volume of bottomfish. With consumption of seafood in Hawaii already ranking as one of the highest in the nation, further increases in local demand probably will be limited. Bottomfish from the NWHI should allow the market to replace some of the imported bottomfish and expand export markets to the mainland and other countries. Consistent, regular NWHI landings to the markets will help stabilize prices. If prices remain sufficiently high, returns from NWHI bottomfishing trips should be attractive enough for further expansion and development; if prices remain too low, it will probably be unfeasible for most vessels to continue fishing in the NWHI without improvements in productivity.

Three possibilities for increasing bottomfishing productivity for the fresh-fish market include: (1) better refrigeration and handling procedures to improve fish quality; (2) increasing catch effort by increasing the number of hooks, lines, or fishing time; and (3) improving or changing to more efficient type of bottomfishing gear or methods. Improving quality should be given the highest priority. Landings of better quality should result in better prices at the market which in turn should lessen the need to increase the catch volume. The quality of fresh bottomfish can be significantly improved by landing catches earlier.

If fish are to be frozen on the fishing vessels, a market for frozen Hawaiian bottomfish must be developed. The buyers at the auction are accustomed to fresh bottomfish. Frozen bottomfish were warily accepted when adequate supplies of fresh bottomfish were available. With consistent supplies and dependable quality, frozen bottomfish catches could be marketed directly to dealers for negotiated prices. The quality of locally frozen bottomfish will have to be maintained at a level comparable or superior with that of the imports. Poor quality frozen products will reduce any chances for establishing a frozen-fish market in locally caught fish. However, supplying frozen Hawaiian bottomfish is a possible way of providing the Hawaiian consumer with a familiar but lower-priced bottomfish alternative.

The present situation, with an undeveloped local frozen-fish market and competition from frozen imports, makes total landing of frozen bottomfish catches from the NWHI unfeasible. However, if portions of the total catch were frozen, vessels could increase the volume of their catches without causing a decrease in fresh-fish prices. This would also help to establish a regular supply of the frozen product which is essential for market development.

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SEAMOUNT FISHERY RESOURCES WITHIN THE SOUTHERN EMPEROR-NORTHERN HAWAIIAN RIDGE AREA

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ABSTRACT

The summits of the seamounts comprising the southern Emperor Seamount Chain and northern Hawaiian Ridge (Koko-Hancock Seamounts) lie at depths of 250 to 400 m; Russian data indicate that the topography produces much surface current meandering and upwelling in the region. In 1967, Soviet trawl fishermen discovered vast quantities of pelagic armorhead, Pentaceros richardsoni, and to a lesser extent alfonsin, Beryx splendens, closely associated with summits of these seamounts. Two years later, Japanese trawlers entered the fishery. They achieved their highest annual catch per unit of effort in 1972 with a sharp decline after 1976. With the advent of the 200-mile U.S. fishery conservation zone, the Hancock Seamounts came under U.S. jurisdiction. Comparison of the U.S. foreign observer data obtained on Japanese trawlers in 1978-82 with earlier Japanese data show trawl catches on Hancock have generally been declining since the high catch of 1972. Seamounts of the Hawaiian Ridge located south of Hancock and east of 180° longitude differ in having shallower summits, higher summit water temperatures, and fish faunas dominated by subtropical reef and snapper-grouper species. Meristic and electrophoretic work on pelagic armorhead indicates the existence of one stock inhabiting the range of seamounts between Koko and Hancock. Morphological variation among pelagic armorhead is little understood.

alfonsin
pelagic armorhead
seamounts

INTRODUCTION

The islands, banks, reefs, and seamounts of the Hawaiian Ridge extend northwesterly from the island of Hawaii some 3,500 km to Colahan Seamount. To the northwest of Colahan the Emperor Seamounts extend from the Milwaukee Seamount Group northward 2,300 km to Meiji Seamount (Jackson et al., 1980). The Emperor-Hawaiian Ridge area is composed of at least 107 identifiable volcanoes from which all the associated topographical features originate. These volcanoes are thought to have been produced by the northward movement of the Pacific plate over a "hot spot" with the bend at the junction of the Emperor-Hawaiian Ridge area caused by a shifting of the plate to the northwest. Results from a variety of dating techniques on samples obtained from sites throughout the Emperor-Hawaiian Ridge area show a pattern of increasing age with distance from the island of Hawaii (Dalrymple et al., 1981). This indicates that the seamounts are among the oldest of topographic features within the Emperor-Hawaiian Ridge area. The seamounts discussed in this review are Koko, Yuryaku, and Kammu of the southern Emperor Seamounts Chain and Colahan, C-H, NW Hancock, SE Hancock, Ladd, Nero, and unnamed seamounts 8 to 11 of the northern Hawaiian Ridge. All are situated within an area bounded by lat. 26° to 36°N and long. 174°W to 171°E (Figure 1). A seamount is defined as a more-or-less isolated elevation of the sea floor appearing circular or elliptical in cross-section, with a minimum relief of 1 km, comparatively steep slopes, and a relatively small summit area. Most, if not all, seamounts are volcanic in origin (Menard, 1964).

The seamounts of the southern Emperor-northern Hawaiian Ridge area from Koko to Hancock Seamounts (hereafter designated SE-NHR), lie within the mean flow of the North Pacific Current. Results of Soviet investigations in this region indicate a substantial perturbance in the surface current field, apparently produced by the seamounts (Borets, 1980). Fedosova (1974) reported the existence of cyclonic and anticyclonic eddies over the SE-NHR seamounts. These eddies fluctuated seasonally in location and dimension, but apparently persisted throughout the year.

The sea-surface temperature (SST) annually ranges from 15 to 26°C at Koko Seamount, 18° to 27°C near the Hancock Seamounts, and 22° to 29°C to the south in the vicinity of seamounts 8 and 9. Maximum SST usually occurs during August-September and the temperatures are lowest in February-March (Eber et al., 1968). Unfortunately, temperature data for the seamount summits are scarce, and comparisons are complicated by the wide range in summit elevations. Available data indicate an annual range in summit temperatures of 8° to 15°C among the more northerly seamounts (summit depths of 250 to 400 m) from Yuryaku to SE Hancock. The southern seamounts, from Ladd to seamount 8, have shallower summit depths of 50 to 200 m and temperatures of 14° to 24°C (Japan Marine Fishery Resource Research Center, 1973; Japan Fisheries Agency, 1974; Gooding, 1980).

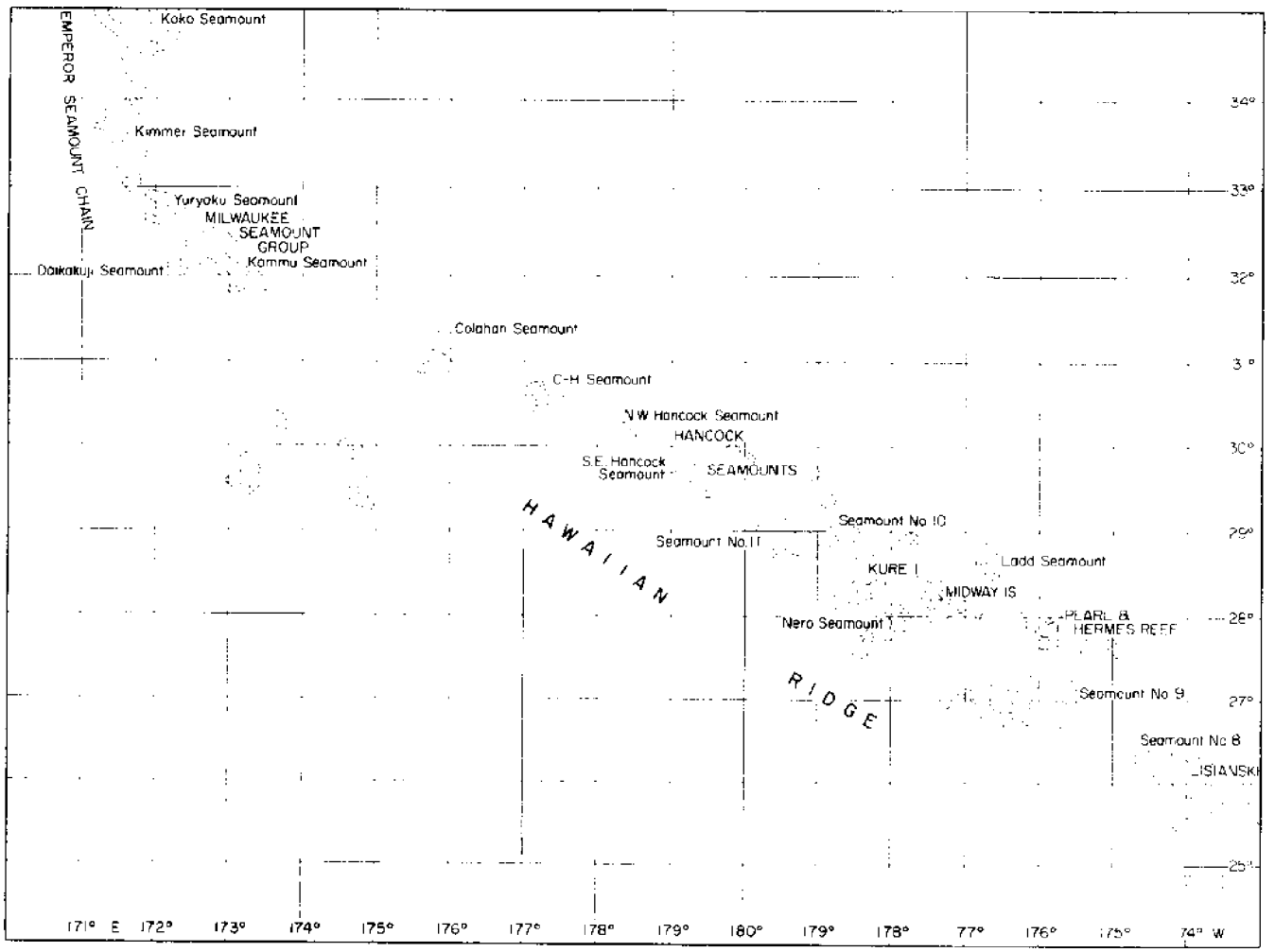


Figure 1. The southern Emperor-northern Hawaiian Ridge seamounts

Besides fluctuations in the current field and water temperature, seasonal changes in plankton biomass over the seamounts have been observed in the area between lat. 27° and 37°N, long. 170°E and 178°W. Soviet investigators found areas of highest plankton biomass in the spring. These areas were displaced downcurrent of upwelling zones in the winter-spring period, whereas in spring-summer they were found near eddies. The winter-spring conditions were explained relative to the intensification of the North Pacific Current and the directional coincidence of prevailing winds, whereas during spring-summer there was a weakening of this current (Fedosova, 1974). Pontekorvo (1974) suggested that zones of upwelling are produced on opposite sides of a seamount. These zones are roughly aligned with the prevailing current and intensified during the winter. Bezrukov and Natarov (1976) attributed the formation of high biological productivity over the SE-NHR seamounts to a favorable abiotic regime produced by the intense vertical water circulation.

SEAMOUNT TRAWL FISHERY -- PAST AND PRESENT

The discovery of a bottom trawl fishery resource on the SE-NHR seamounts was made by a Soviet commercial trawler in November 1967. The resource consisted primarily of pelagic armorhead, Pentaceros richardsoni, and alfonsin, Beryx splendens (Figures 2 and 3). Shortly thereafter, a Soviet trawl fishery began on the SE-NHR seamounts. From December 1969 through July 1970, Soviet trawlers harvested approximately 133,400 metric tons (MT) of pelagic armorhead from the seamounts (Sakiura, 1972). This is the only catch data available for the Soviet trawl fleet although Soviet trawlers have probably continued to fish the seamounts to the present. In 1968-69, two Soviet research cruises surveyed an area from lat. 21° to 36°N, and long. 160°E to 165°W. Seamounts surveyed were Koko, Milwaukee (consisting of Kammu, Yuryaku, and Daikakuji Seamounts), Hancock (refers to NW and SE Hancock Seamounts), and two unidentified seamounts. Pelagic armorhead was the principal species caught on each seamount. Total catch of alfonsin ranged from 5 to 30 percent at Koko and accounted for 25 percent at Milwaukee. The catch of alfonsin on the other seamounts was not given. Catches of pelagic armorhead at each seamount were found to vary diurnally. Catches would generally increase after 1800 hours and peak just before sunrise (Sakiura, 1972).

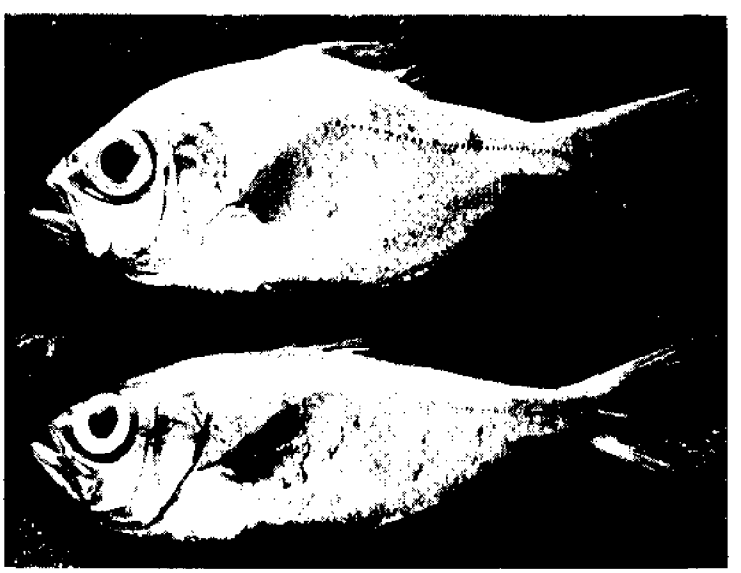
The Japanese seamount trawl fishery began in August 1969. An initial 2-year exploratory phase defined suitable trawl grounds and developed markets for the catch. Unlike the Soviets, the Japanese have made available their trawl catch and effort data, by seamount, for pelagic armorhead and alfonsin caught during 1969-81 (Takahashi and Sasaki, 1977; Sasaki, unpublished data). These data cover trawling on the following seamounts: Koko, Milwaukee, Colahan, C-H, Hancock, and others.

Figure 4 shows the annual effort (in trawl hours) at each of the seamounts during 1969-81. During the exploratory phase Milwaukee was surveyed intensively, whereas during 1972-73 effort was more equitably partitioned among all the seamounts. Effort during the following years (1974-81) was concentrated at Koko and Milwaukee.

The annual catch of pelagic armorhead is shown in Figure 5 for 1969-81. The annual catches fluctuated widely at Milwaukee during 1969-77, whereas they fluctuated less at Koko, Colahan, and Hancock. The fluctuations in catch at Koko and Milwaukee during 1969-71 and 1974-76 appear to coincide with fluctuations in effort. Outside of these fluctuations, the catch record shows two remarkable events. First was the high annual catches at Colahan in 1972 and Hancock in 1973 with a decline and modest increase in effort, respectively. Also, the 1972 catch at Milwaukee showed a large increase compared with the 1971 catch in spite of a decrease in effort. The second event was the plummeting of catches starting in 1977 at Koko and Milwaukee despite increased effort and a subsequent depression in catches at all seamounts through 1981, regardless of changes in effort.

Figure 2. Morphological variation in specimens of pelagic armorhead, Pentaceros richardsoni. Upper specimen represents the lean type, middle specimen the intermediate type, and lower specimen the fat type.

Figure 3. Specimens of alfonsin, genus Beryx. Upper specimen is B. decadactylus and the lower specimen, B. splendens.



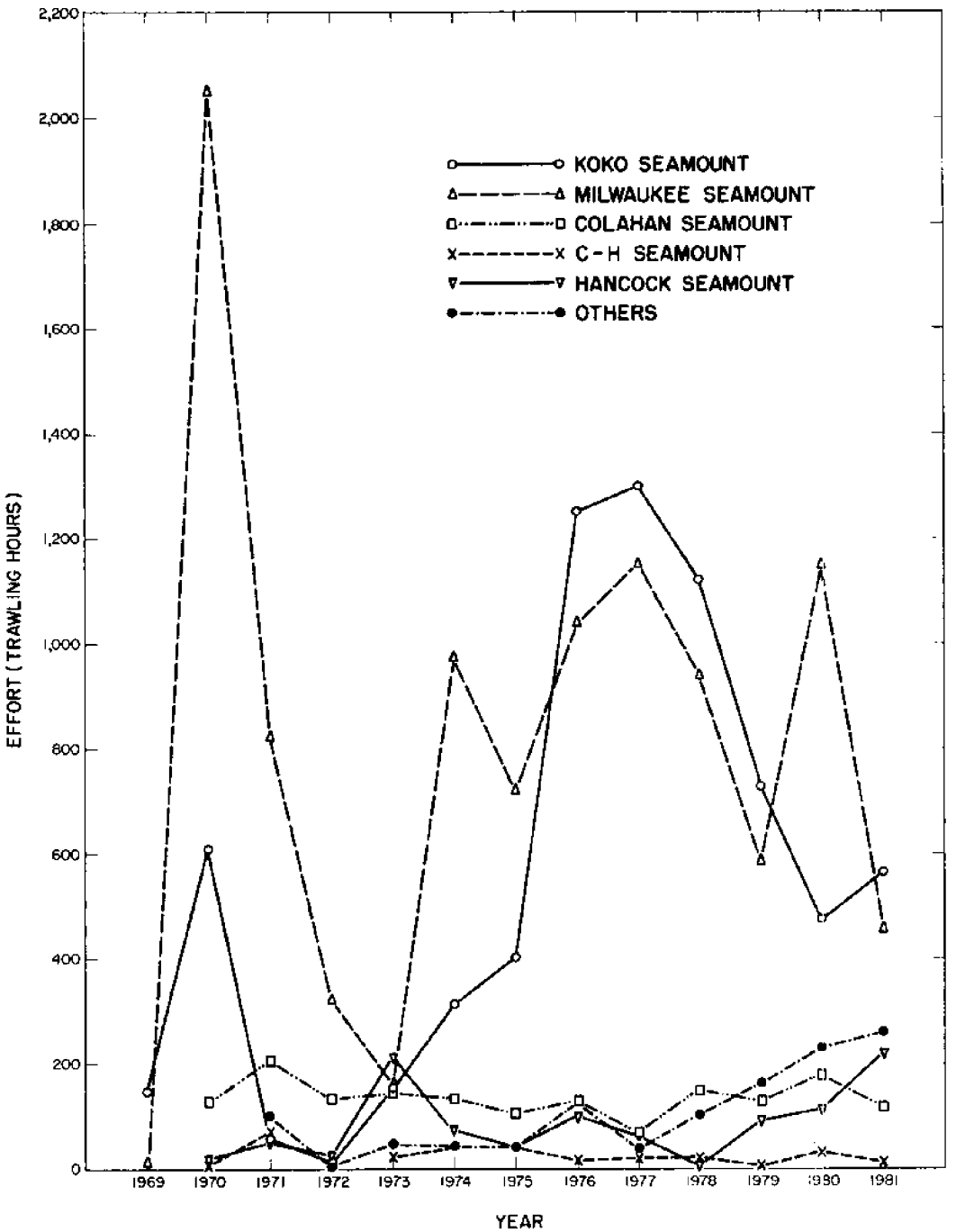


Figure 4. Yearly effort of Japanese trawl fishery for pelagic armorhead and alfonsin at six seamounts within the Emperor-Hawaiian Ridge

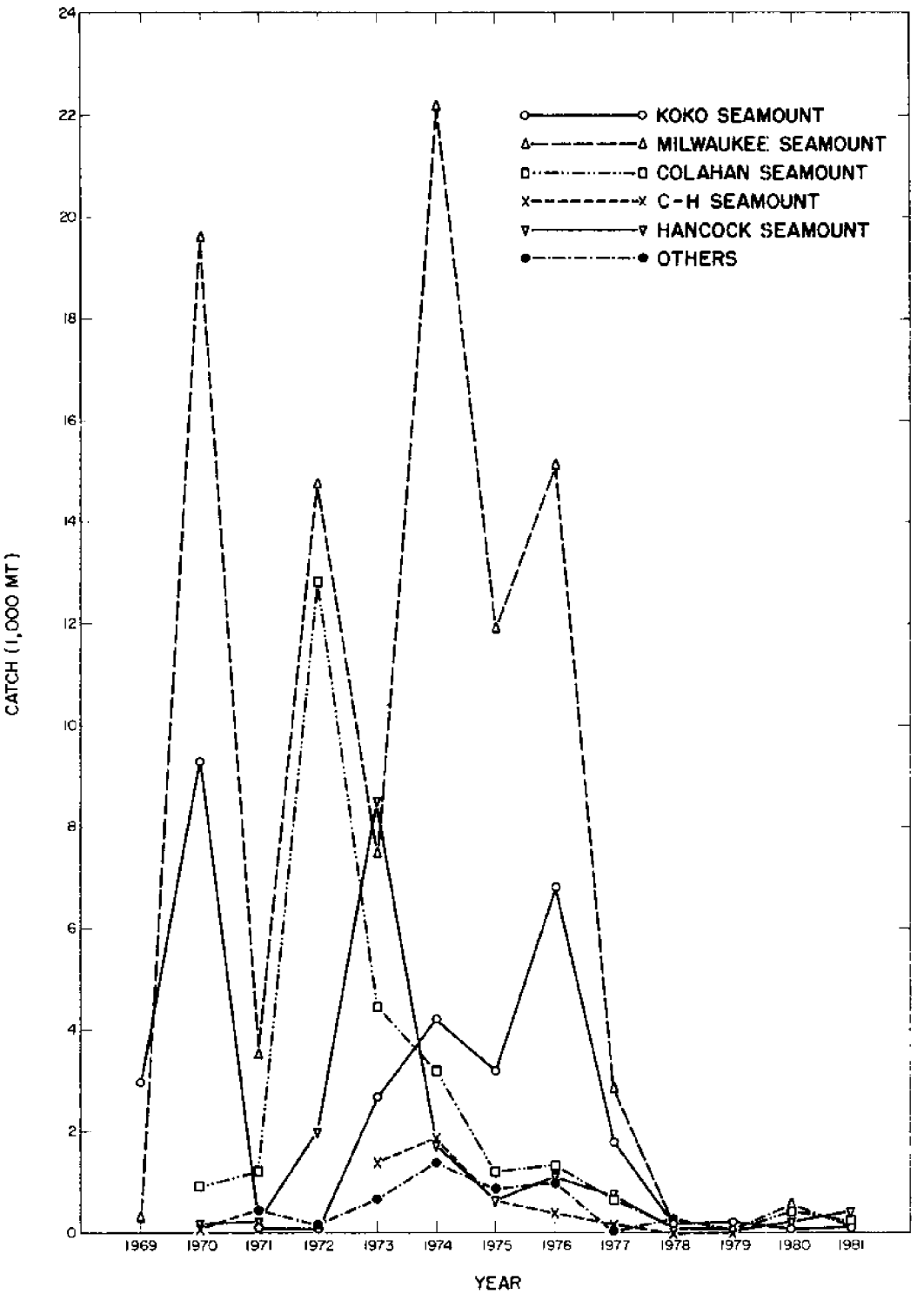


Figure 5. Yearly catch of pelagic armorhead taken by Japanese trawlers at six seamounts within the Emperor-Hawaiian Ridge

The annual Japanese catch per unit effort (CPUE) of pelagic armorhead during 1969-81 is shown in Figure 6. The depressed CPUE during 1969-71 is probably indicative of the exploratory nature of the fishery during this time. The CPUE for all seamounts rose during 1972-73, declined at most seamounts until 1978, and thereafter, remained at a low level through 1981. The general decline reflects the decline in catch over each seamount with the exception of Hancock in 1978 and C-H in 1981. The increased CPUE at Hancock in 1978 resulted from a 178-MT catch during 6 trawling hours in May. A 51-MT catch during 5 trawling hours in January and a 99-MT catch in 7 hours in February accounted for the increase at C-H in 1981. Also the peak CPUE at Hancock in 1972 resulted from a 1,870-MT catch in 24 trawling hours during July. All these CPUEs appear to represent fortuitous increases in pelagic armorhead availability over very short periods of time.

Figure 7 shows a plot of annual catch, effort, and CPUE of pelagic armorhead for all seamounts combined during 1969-81. Although CPUE steadily declined throughout 1973-79, catches were fairly steady during 1972-76 even if more effort was expended during 1974-76 than during the previous 2 years. Although only 5.7 percent (1,236 hours) of the total effort (21,625 hours throughout 1969-81) over all the seamounts was expended during 1972-73, the catch amounted to 29.8 percent (54,927 MT) of a total 184,109 MT harvested from all seamounts during 1969-81. In contrast, the total catch during 1977-81 was only 5.8 percent (10,679 MT) despite the fact that 48.5 percent (10,494 hours) of the total effort was expended.

The highest total catch of pelagic armorhead during 1969-81 occurred at Milwaukee (Figure 8). Milwaukee contributed 53.6 percent toward the total catch and also received the greatest effort (48.0 percent). Hancock contributed 8.7 percent toward the total catch with 4.7 percent of the total effort.

The second species of importance in the Japanese trawl fishery was alfonsin. The annual catches at each seamount, shown in Figure 9, were either small or incompletely reported during 1969-75. Since armorhead is the primary target species of the trawl fishery, catches of alfonsin, although important, are incidental. Apparently no alfonsin catch data were collected and/or published for 1974-75. From 1976 to 1981, all seamounts showed an overall catch increase with the exception of Hancock. Figure 10 also shows a similar trend in CPUE with the exception again at Hancock. These increases in alfonsin catch and CPUE closely coincide with the sharp decreases and sustained depression in catch and CPUE of pelagic armorhead.

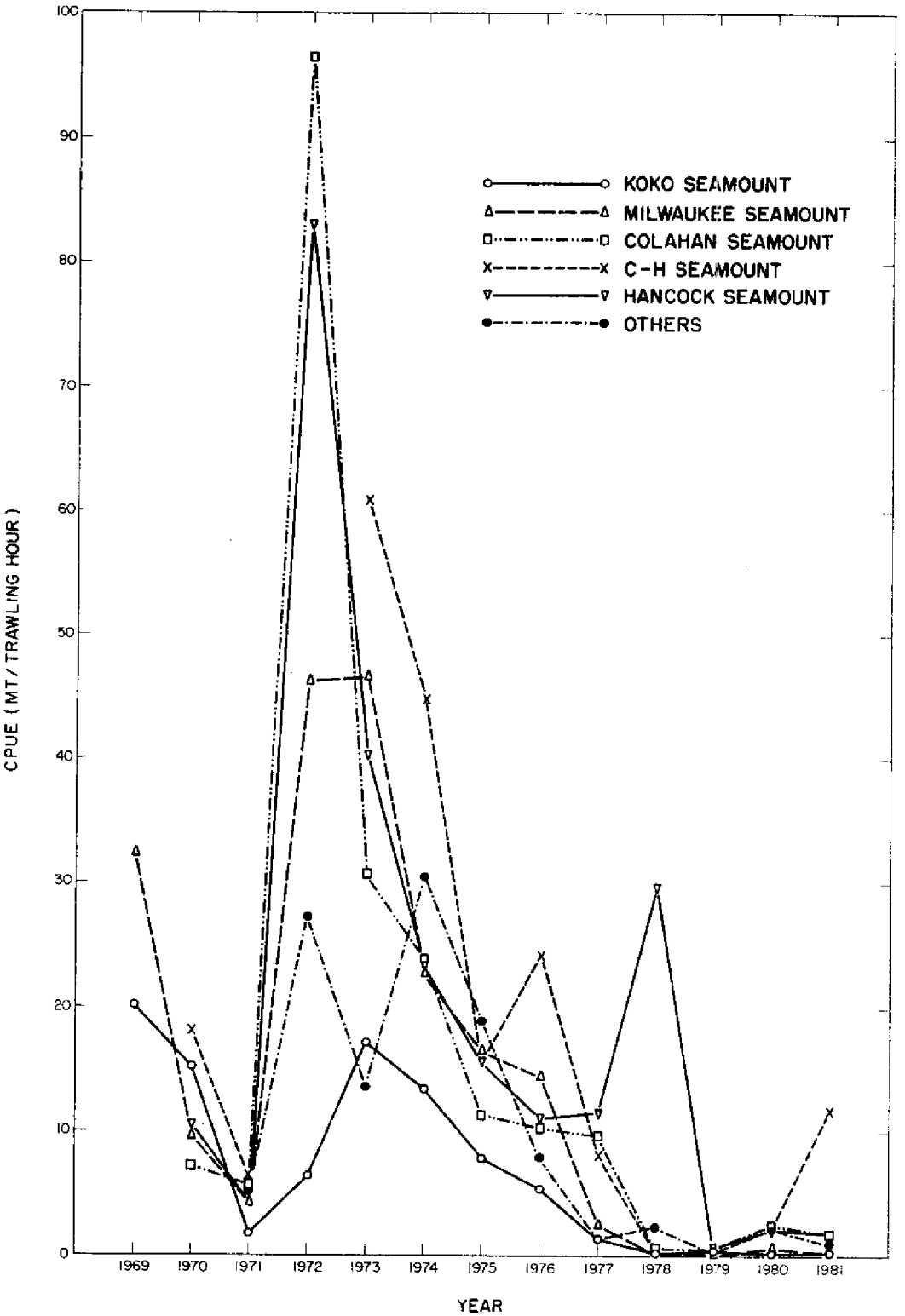


Figure 6. Yearly catch per unit effort of pelagic armorhead taken by Japanese trawlers at six seamounts within the Emperor-Hawaiian Ridge

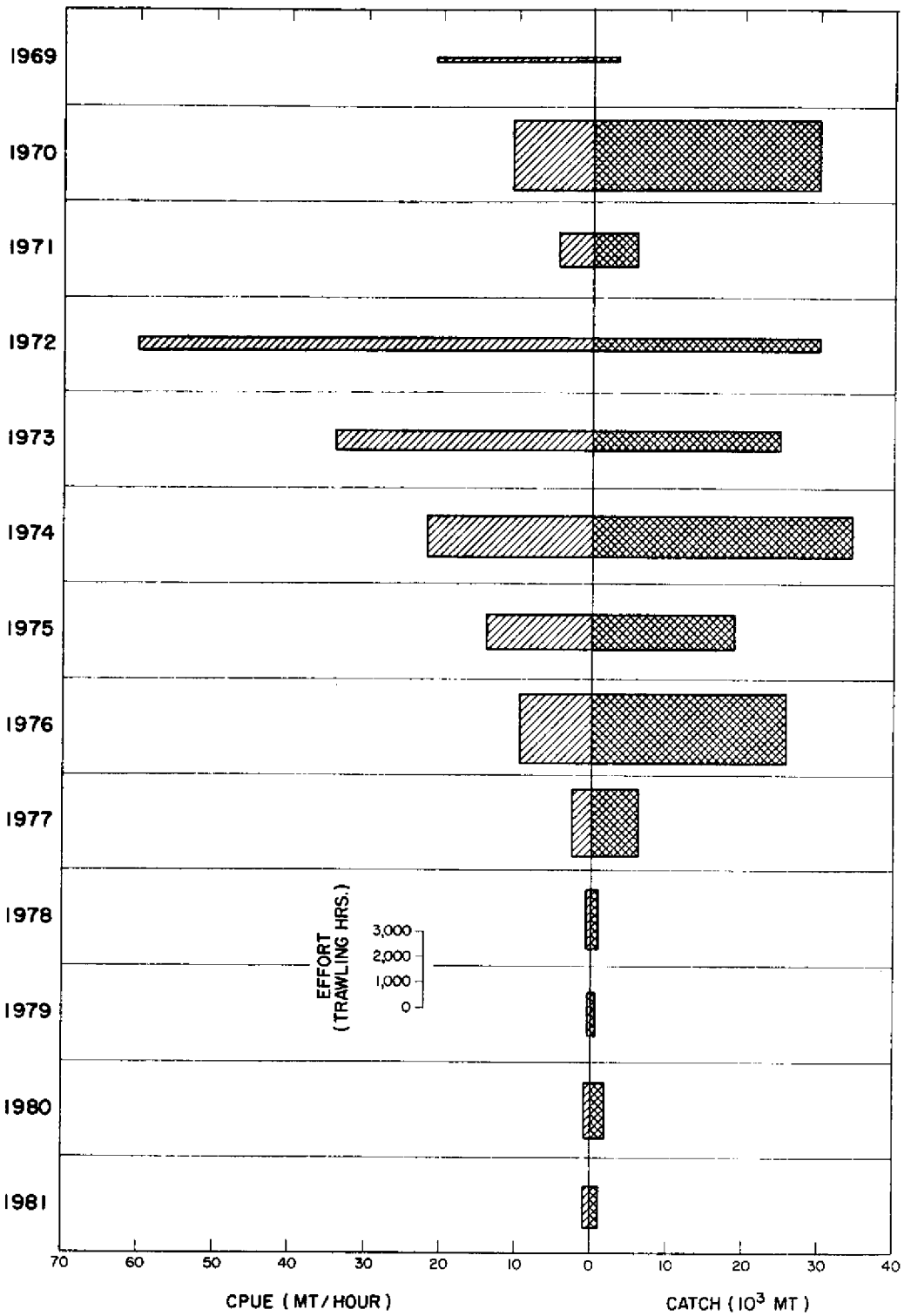


Figure 7. Three-way plot of yearly effort, catch, and catch per unit effort of pelagic armorhead from Japanese trawl fishery data; all seamounts combined

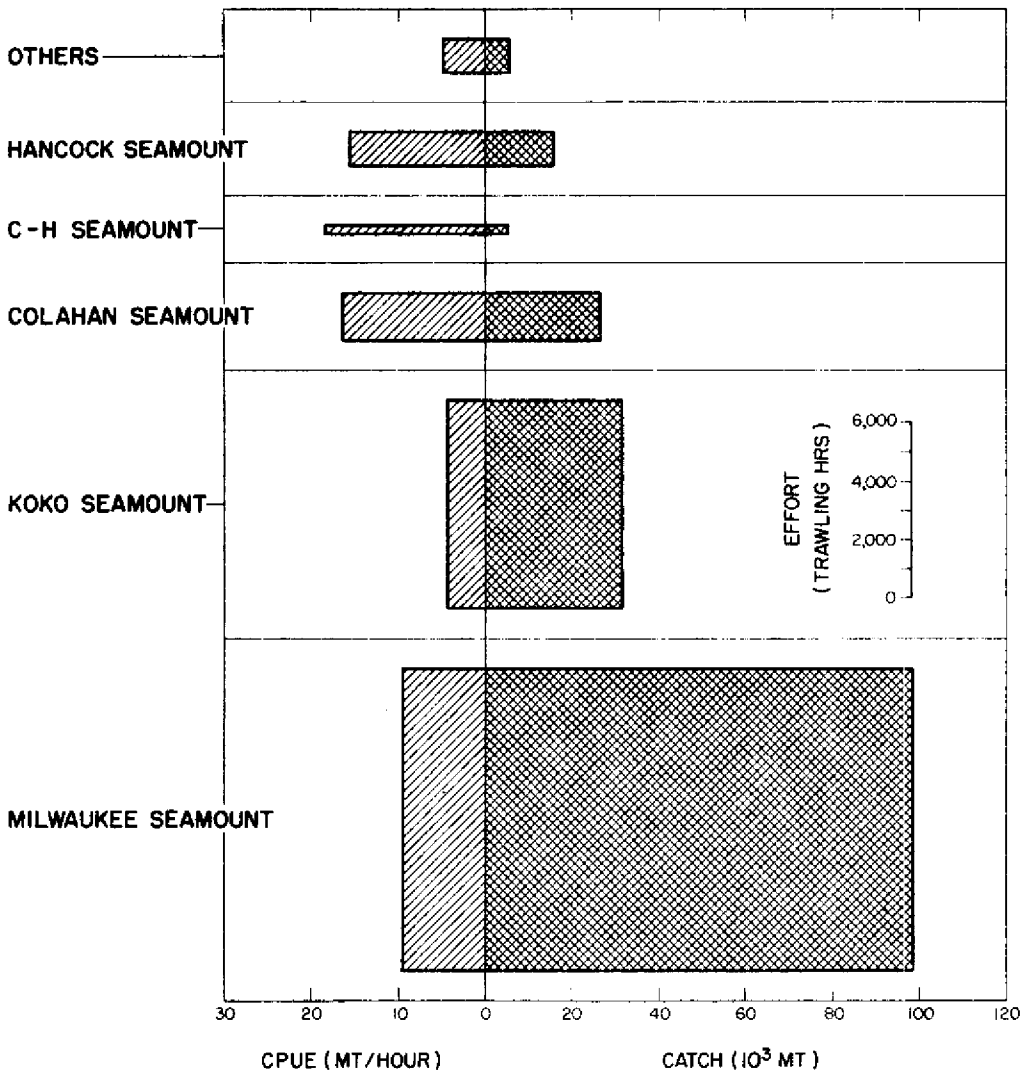


Figure 8. Three-way plot of effort, catch, and catch per unit effort of pelagic armorhead from Japanese trawl fishery data; years 1969-81 combined

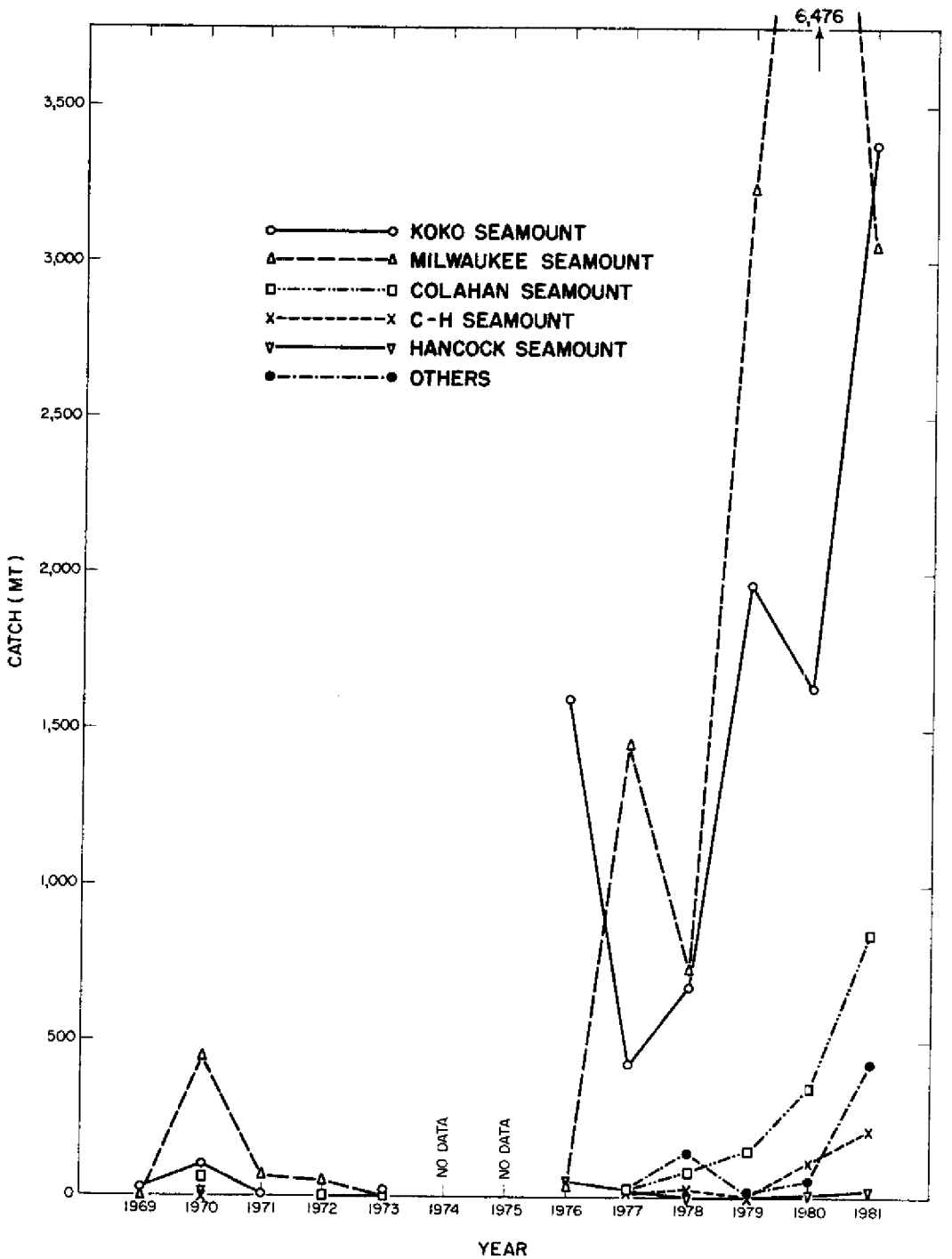


Figure 9. Yearly catch of alfonsin taken by Japanese trawlers at six seamounts within the Emperor-Hawaiian Ridge

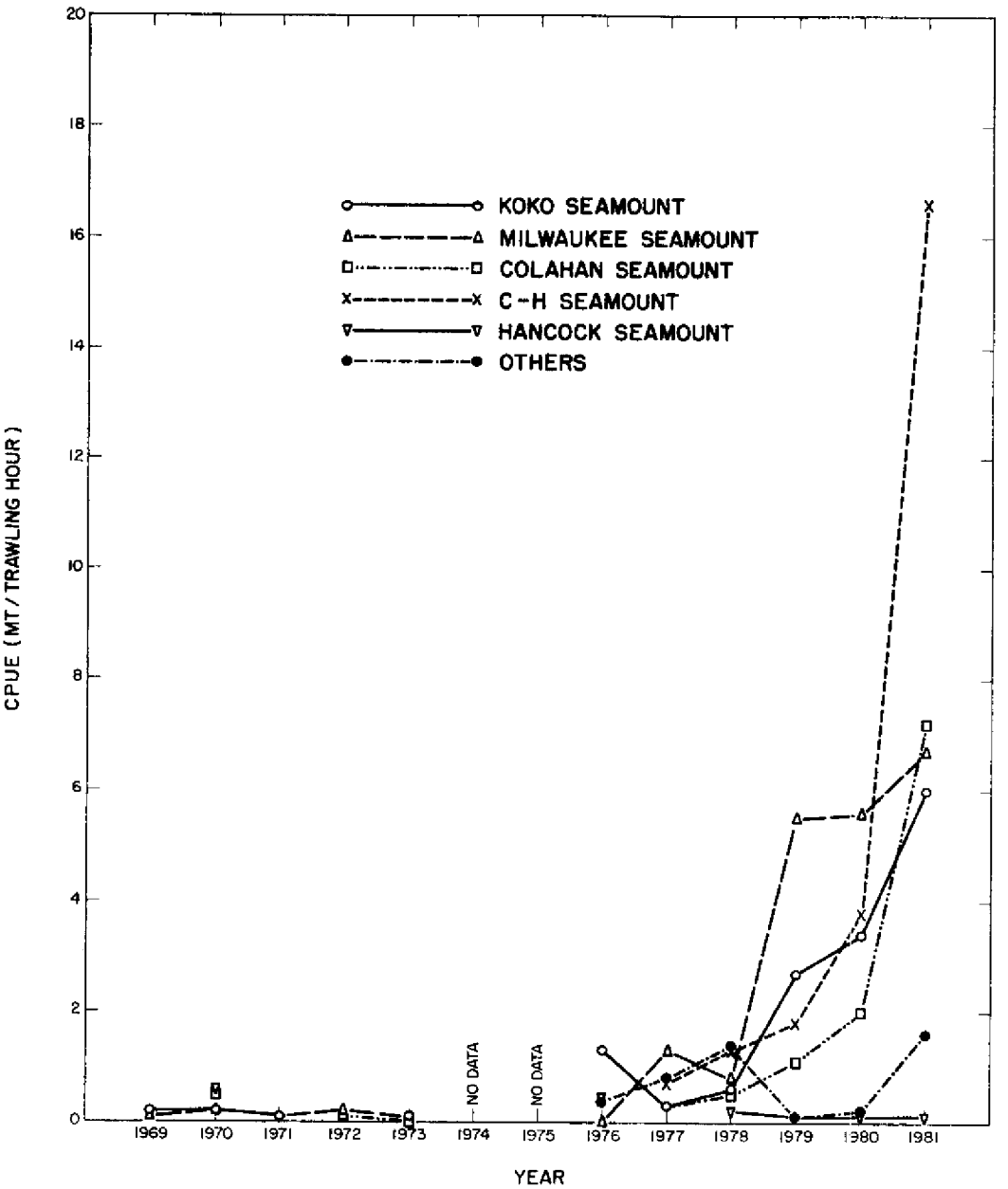


Figure 10. Yearly catch per unit effort of alfonsin taken by Japanese trawlers at six seamounts within the Emperor-Hawaiian Ridge

The largest catches of alfonsin were made during 1980-81, accounting for 59.0 percent (16,558 MT) of a total 28,063 MT reportedly harvested throughout 1969-81. During 1969-76 before pelagic armorhead catches dropped at all seamounts, its contribution to the total catch (only pelagic armorhead and alfonsin are considered here) was 98.6 percent (173,430 MT) and alfonsin 1.4 percent (2,532 MT). For 1977-81, when catches of pelagic armorhead remained low, it accounted for only 29.5 percent (10,679 MT) of the total catch while alfonsin rose to 70.5 percent (25,531 MT). The effort expended during the two periods was 11,131 trawling hours for 1969-76 and 10,494 trawling hours for 1977-81. In 1969-81, the largest amount of alfonsin was taken at Milwaukee, contributing 55.4 percent (15,534 MT) toward the total catch. The effort expended there was 48.0 percent (10,373 hours) of a total 21,625 hours for all seamounts.

Like the Soviets, the Japanese also observed diurnal fluctuations in the CPUE of pelagic armorhead. Results of trawl survey work at Kammu, Colahan, and Hancock showed two peaks in CPUE over a 24-hour day (Kitani and Iguchi, 1974). The CPUE generally peaked between 0300 to 0700 and 1600 to 1800 hours. With the possible exception of the exploratory phase, it is assumed that trawl hauls were mostly made at night.

The inclusion of Hancock within the 200-mile U.S. fishery conservation zone (FCZ) in March 1977 placed management of the fishery resources there under jurisdiction of the United States. Regulations were implemented and an annual catch quota for bottom trawling and bottom longlining of 2,000 MT and a limit on effort of 60 vessel-days were set. A license and complete catch reports for each trip are also required. Another requirement is the placement of a U.S. fishery observer onboard all vessels permitted to operate within the FCZ. This latter requirement allowed an onsite inspection of this fishery and the opportunity to independently gather catch data. Japan's total yearly catch quota for all species (except for nonretention ones) at Hancock was 1,000 MT. During 1978-82, nine Japanese trawlers operated under permit at Hancock, each with a U.S. observer onboard. In 1977, Japanese trawlers fished Hancock only during the period before its inclusion in the FCZ. The number of Japanese trawlers that fished at Hancock was one each in 1978 and 1979, two each in 1980 and 1981, and three during 1982.

The effort data collected by U.S. observers[1] at Hancock during 1978-82 are not in agreement with published Japanese data which apparently exclude effort and catch at SE Hancock during

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[1]U.S. foreign observer reports for Japanese permit trawling at Hancock Seamounts during 1978-82 are available from Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, HI 96812. They include reports on the Ryuyo Maru No. 2, Aso Maru, Kitakami Maru, and Takachiho Maru.

1978-81, thereby explaining the higher effort and catches reported by U.S. observers (Figure 11). Since no independent estimates of catch and effort exist for earlier fishing conducted at Hancock, it is not known whether earlier data were also excluded for SE Hancock. In addition, the trawler fishing at Hancock in 1978 used a different measure of effort from the conventional one, i.e., elapsed time the trawl net was submerged. Effort was therefore roughly adjusted using data from a comparable-sized Japanese trawler. These discrepancies probably account for the differences in effort, catch, and CPUE at Hancock during 1978. The other discrepancies for 1979-81 may solely result from the exclusion by the Japanese of SE Hancock from the Hancock category. Despite these discrepancies, observer data collected during 1978-82 show a similar sustained trend of low pelagic armorhead catches.

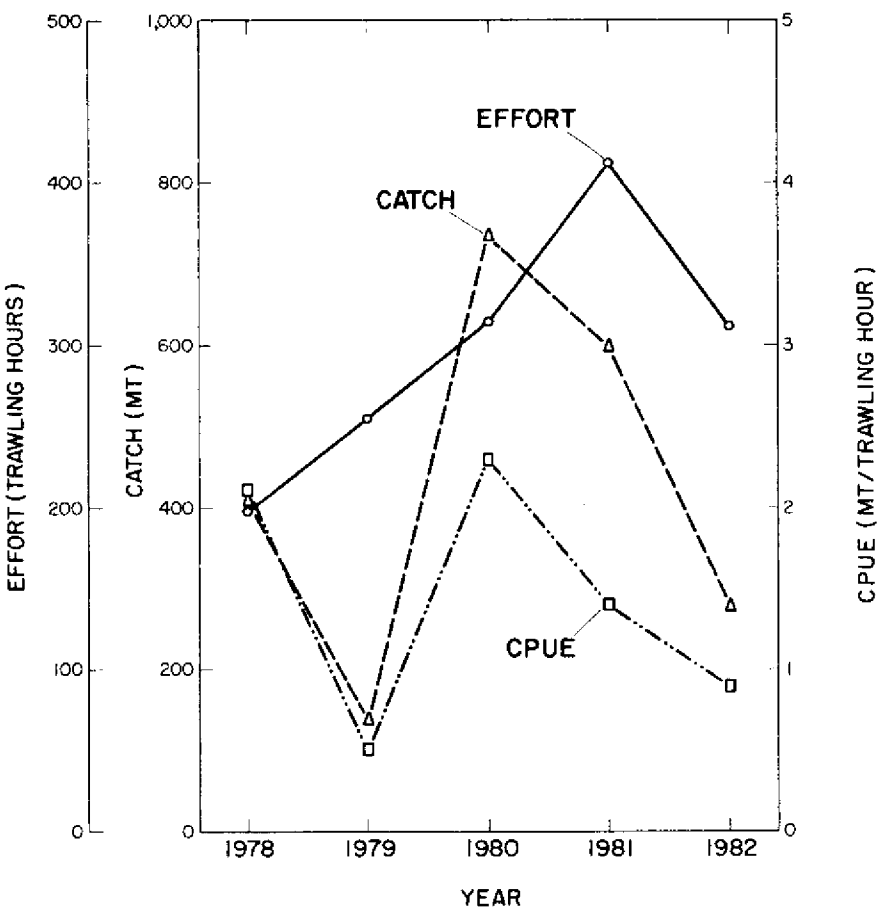

Figure 11. Yearly effort, catch, and catch per unit effort of pelagic armorhead taken by Japanese trawlers at Hancock Seamounts as determined by U.S. foreign observers

The observer data also show low alfonsin catches at Hancock during 1977-82, a trend apparent in earlier years (Figure 9) according to a report by Takahashi and Sasaki (1977). The 1982 observer data show a slight increase in catch and CPUE for alfonsin with less effort than that made in 1981 (Figure 12).

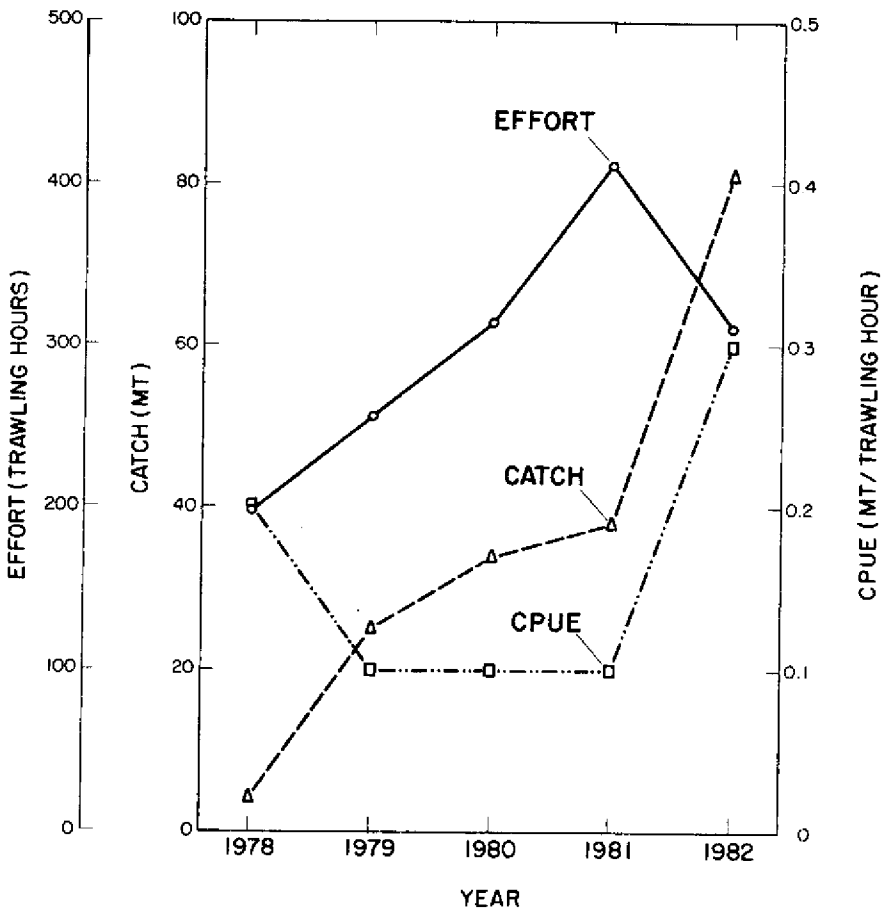

Figure 12. Yearly effort, catch, and catch per unit effort of alfonsin taken by Japanese trawlers at Hancock Seamounts as determined by U.S. foreign observers

Since 1976, the Southwest Fisheries Center Honolulu Laboratory of the National Marine Fisheries Service (NMFS) has made several very limited surveys of the fishery resources of the Emperor-Hawaiian Ridge seamounts as an adjunct to the tripartite and Sea Grant investigations of the Northwestern Hawaiian Islands (NWHI). Most of the effort was concentrated at Hancock. Because of differences in gear and technique, and the small amount of trawling effort, data from NMFS surveys are not directly comparable with the Japanese data. The NMFS surveys, however, were

important as initial exploratory work and as a means for determining species composition of the seamount community and collecting samples for life history studies.

Besides trawling, NMFS investigated the Hancock summits with bottom handlines and traps. Bottomfishing was conducted primarily with 10-hook and 20-hook handline rigs powered by hydraulic gurdies. Catches consisted primarily of pelagic armorhead and spiny dogfish, Squalus sp. At Koko, the handline catch consisted solely of the rockfish, Helicolenus avius. Trapping was also conducted at Hancock using a variety of fish traps. Catches were dominated by Squalus sp. and pelagic armorhead was rare. Although catches of Squalus sp. were relatively high from handline and trap fishing, they were incidental in the trawl catches.

OTHER SEAMOUNT FISHERIES

Bottom longlining

Although emphasis has been on trawl fishing, other fisheries operate on and around the seamounts. In 1972-73, a bottom longline fishery which primarily targeted alfonsin was initiated at Milwaukee. Other species caught in this fishery are Hyperoglyphe japonica, Erilepus zonifer, Helicolenus avius, and Sebastes spp. (Sasaki, 1978). The gear is used to fish the summit and slopes and can be set in areas inaccessible to trawlers. I.I. Ikehara (1976: personal communication) reported that bottom longlining at Koko yielded an unspecified quantity of E. zonifer at depths of 800 to 900 m. However, no catch and effort data on the seamount bottom longline fishery are available. An interview with one of the fishing masters revealed that catches of alfonsin and Sebastes spp. were declining by 1976 and fewer Japanese vessels were fishing the area (Suisan Sekai, 1976). The fishing master also stated that a number of Korean vessels were involved in this fishery.

Gill netting

It was reported that 79 Taiwan gill net vessels began fishing in 1981 for the squid, Ommatrephes bartramii (Suisan Sekai, 1981). Fishing was conducted in the area of the Emperor Seamounts. However, since no specific locations were given it is unknown whether this fishery included the southern Emperor Seamounts. These vessels were reportedly catching 3 to 6 MT per day. Approximately 200 Japanese squid jigging vessels and 200 gill net vessels were also operating on the Emperor Seamounts.

Other Taiwan vessels were reported to be fishing for saury, Cololabis saira, in the same area. It was reported that larval and juvenile saury are abundant in waters around the SE-NHR (Selitskaya, 1972).

Coral dragging

The first fishery resource to be discovered on the SE-NHR seamounts occurred in 1965 when Japanese fishermen found extensive beds of pink coral at Milwaukee. H. Ozawa (1970: personal communication) revealed that 113 MT of pink coral was harvested at Milwaukee in 1969 by Japanese fishermen. The harvesting method employed in this fishery involves the dragging of a weighted object across the bottom. Tangle nets attached to the weight collect the pieces of dislodged coral. This fishery apparently targets two species of pink coral: Corallium secundum, present at depths of 275 to 458 m, and Corallium sp. nov., found between 915 and 1,281 m.

Precious coral resources are present at seamount 10 (Grigg, 1974) and at Hancock although precious corals at the latter have apparently been harvested by foreign fishermen prior to 1977. With the advent of the 200-mile U.S. FCZ, foreign harvesting of precious corals and their retention through incidental catches by foreign trawlers or longliners, under permit to fish Hancock, are prohibited. However, R.W. Grigg (1983: personal communication) has found that 20 MT of precious corals were illegally harvested within the FCZ by foreign fishermen during 1980-82. During this time, about 600 MT of precious corals were harvested throughout the Emperor Seamounts by Japan and Taiwan. Reports from U.S. foreign observers[2] indicate few incidental trawl catches of precious corals occur at Hancock; all such catches are not retained.

ICHTHYOFAUNA OF THE SEAMOUNTS

During the early 1970s, Japanese efforts to expand the trawl fishery for pelagic armorhead extended to various seamounts located throughout the NWHI. Survey results showed a distinct change in the ichthyofauna at the seamounts located southeast of Hancock. The commercial and incidental species of the SE-NHR seamounts were absent from the predominantly subtropical ichthyofauna on the southern seamounts (Ladd, Nero, and seamounts 8 to 11). These results indicated a sharp demarcation of the ichthyofauna coinciding with the 180th meridian (Iguchi, 1973; Japan Marine Fishery Resource Research Center, 1973; Japan Fisheries Agency, 1974). Seamount survey data collected by NMFS, plus published information (Barsukov, 1973; Barsukov and Fedorov, 1975; Katayama, 1975; Chen, 1980: Nakaya et al., 1980; Kanayama, 1981; Borets, 1982; Dolganov, 1982; Parin and Mikhailin, 1982; Nakabo et al., 1983; Yabe, 1983) and a personal communication (I.I. Ikehara, 1976) have provided new records of the distribution of species (Table 1). The few species reported from Colahan and seamounts 10 and 11 reflect the small effort expended there. No data on C-H seamount are available.

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[2]See footnote 1

TABLE 1. DISTRIBUTION OF FISH SPECIES BY SEAMOUNT

Species	Family	KS	MS	CS	HS	SS	LS	NS	S9	S8
Neoscopelus microchir	Myctophidae	x								
Beryx splendens	Berycidae	x	x	x	x					
Beryx decadactylus	Berycidae	x	x	x	x					
Gephroberyx japonicus	Trachichthyidae	x	x		x					
Diretmus argenteus	Diretmidae	x								
Zenopsis nebulosa	Zeidae	x	x	x	x					
Psenopsis anomala	Centrolophidae	x								
Epigonus atherinoides	Apogonidae	x	x							
Sebastes flammeus	Scorpaenidae	x	x							
Podonema longipes	Moridae	x								
Macrorhamphosus scolopax	Macrorhamphosidae		x	x	x					
Ariomma lurida	Nomeidae				x					
Antigonia rubescens	Antigoniidae		x		x					
Helicolenus avius	Scorpaenidae	x	x							
Halargyreus sp.	Moridae		x							
Lophiodes miacanthus	Lophiidae		x	x	x					
Scomber japonicus	Scombridae				x					
Chascanopsetta prorigera	Bothidae		x		x					
Lotella maximowiczi	Moridae		x							
Erythrocles scintillans	Emmelichthyidae				x					
Dalatias licha	Squalidae		x							
Nansenia ardesiaca	Bathylagidae		x							
Gonostoma elongatum	Gonostomatidae		x							
Maurolicus muelleri	Gonostomatidae		x							
Astronesthes ijiami	Astronesthidae		x							
Chauliodus sloani	Chauliodontidae		x							
Chlorophthalmus albatrossis	Chlorophthalmidae		x							
Coelorhynchus sp.	Macrouridae		x							
Trachipterus iris	Trachipteridae		x							
Malthopsis tiarelle	Ogcocephalidae		x							
Chaunax fimbriatus	Chaunacidae		x							
Parabothus coarctatus	Bothidae		x		x					
Microstomus pacificus	Pleuronectidae		x							
Bembradium roseum	Platycephalidae		x							
Foetorepus kammuensis	Callionymidae		x							
Peristedion engyceros	Peristediidae		x		x					
Lepidopus calcar	Trichiuridae		x							
Benthodesmus tenuis	Trichiuridae		x							
Anthias rubromaculatus	Serranidae		x							
Chimaera owstoni	Chimaeridae	x								
Helicolenus sp.	Scorpaenidae	x								
Hozukius guyotensis	Scorpaenidae	x	x							
Adelosebastes latens	Scorpaenidae	x								
Caprodon unicolor	Serranidae					x				
Lepidion inosimae	Moridae	x								
Lepidion schmidti	Moridae	x								
Marukawichthys pacificus	Ereuniidae	x								
Pentaceros japonicus	Pentacerotidae		x							
Plectranthias kelloggi	Serranidae		x		x					
Grammatonotus laysanus	Serranidae		x		x					
Bembrops filifera	Bembropsidae		x							
Rhynchocymba nystromi nystromi	Congridae				x					
Symphysanodon typus	Lutjanidae				x					
Antigonia steindachneri	Antigoniidae				x					
Emmelichthys struhsakeri	Emmelichthyidae				x					
Neopercis roseoviridis	Mugiloididae				x					

TABLE 1. DISTRIBUTION OF FISH SPECIES BY SEAMOUNT (continued)

Species	Family	KS	MS	CS	HS	SS	LS	NS	S9	S8
Etmopterus pusillus	Squalidae				x					
Isistius brasiliensis	Squalidae				x					
Argyropelecus aculeatus	Sternoptychidae				x					
Symphysanodon maunaloae	Lutjanidae				x					
Astronesthes lucifer	Astronesthidae				x					
Arnoglossus debilis	Bothidae				x					
Ruvettus pretiosus	Gempylidae				x					
Argyripnus atlanticus	Gonostomatidae				x					
Hoplichthys sp.	Hoplichthyidae				x					
Physiculus edelmanni	Moridae				x					
Myctophum nitidulum	Myctophidae				x					
Diaphus trachops	Myctophidae				x					
Parapercis multifaciata	Mugiloididae				x					
Tosanoides filamentosus	Serranidae				x					
Meadia abyssalis	Synaphobranchidae				x					
Glossanodon struhsakeri	Argentinidae				x					
Dasyatis matsubarai	Dasyatidae				x					
Echinorhinus cookei	Squalidae		x							
Paratrachichthys sp.	Trachichthyidae		x							
Etmopterus villosus	Squalidae				x					
Helicolenus fedorovi	Scorpaenidae	x								
Lepidopus lex	Trichiuridae		x							
Laemonema rhodochir	Moridae				x					
Stethopristes eos	Zeidae				x					
Hoplostethus mediterraneus	Trachichthyidae				x					
Prionace glauca	Carcharhinidae				x					
Hexanchus griseus	Hexanchidae				x					
Chlorophthalmus oblongus	Chlorophthalmidae				x					
Hollardia goslinei	Triacanthidae				x					
Brama orcini	Bramidae				x					
Alopias sp.	Alopiidae				x					
Erilepis zonifer	Anoplopomatidae	x								
Centroscyllium nigrum	Squalidae				x					
Decapterus tabl	Carangidae				x		x			
Hyperoglyphe japonica	Centrolophidae	x	x	x	x		x			
Cookeola boops	Priacanthidae				x	x	x	x		x
Antigonia eos	Antigoniidae	x	x	x	x	x				
Physiculus grinelli	Moridae				x		x	x		
Squalus sp.	Squalidae	x	x		x	x	x	x		
Promethichthys prometheus	Gempylidae				x		x	x		
Pentaceros richardsoni	Pentacerotidae	x	x	x	x		x			
Polymixia berndti	Polymixiidae	x	x		x			x		
Fistularia villosa	Fistulariidae						x			
Velifer multispinosus	Veliferidae						x			
Decapterus sp. (not tabl)	Carangidae						x			
Pseudocaranx dentex	Carangidae						x	x	x	
Seriola aureovittata	Carangidae						x		x	
Upeneus sp.	Mullidae						x			x
Pseudupeneus sp.	Mullidae									x
Bleekeria sp.	Ammodytidae						x			
Carapus sp.	Carapidae									x
Chaetodon miliaris	Chaetodontidae						x			x
Chaetodon fremblii	Chaetodontidae						x			x
Lactoria sp.	Ostraciontidae						x			
Canthigaster cinctus	Canthigasteridae									x
Amanses sp.	Balistidae						x			

TABLE 1. DISTRIBUTION OF FISH SPECIES BY SEAMOUNT (continued)

Species	Family	KS	MS	CS	HS	SS	LS	NS	S9	S8
Pristipomoides filamentosus	Lutjanidae							x	x	x
Caranx delicatissimus	Carangidae									x
Naso unicornis	Acanthuridae									x
Priacanthus meeki	Priacanthidae					x				
Caprodon schlegelii	Serranidae					x				
Dendrochirus barberi	Scorpaenidae									x
Cheilodactylus vittatus	Cheilodactylidae									x
Congrina aequoria	Congridae						x			
Ariosoma marginatum	Congridae						x			
Etelis carbunculus	Lutjanidae						x	x	x	x
Gymnothorax steindachneri	Muraenidae						x	x		
Gymnothorax berndti	Muraenidae						x			
Epinephelus quernus	Serranidae					x	x	x	x	x
Seriola dumerili	Carangidae							x	x	x
Gymnothorax undulatus	Muraenidae							x		
Conger oligoporus	Congridae					x				
Caranx ignoblis	Carangidae									x
Pristipomoides zonatus	Lutjanidae								x	x
Pristipomoides sieboldii	Lutjanidae						x	x	x	
Etelis coruscans	Lutjanidae						x		x	
Pontinus macrocephalus	Scorpaenidae						x	x	x	
Sphoeroides cutaneus	Tetraodontidae						x			
Bodianus vulpinus	Labridae							x		

Note: KS = Koko Seamount; MS = Milwaukee Seamount Group; CS = Colahan Seamount; HS = Hancock Seamounts; SS = Seamounts 10 and 11; LS = Ladd Seamount; NS = Nero Seamounts; S9 = Seamount 9; S8 = Seamount 8

Most fishes occurring on the summit of northern seamounts are deep-water, benthic-demersal forms. The predominance of these types is hardly surprising since the collections were derived almost solely from bottom trawls. Some mesopelagic types were also collected, although it is uncertain whether these species were collected in the water column above the seamount or represent mesopelagic species which exhibit more demersal affinities. Most fishes collected from the northern seamounts were small and of no commercial value. Of the 80 fish species found only among the northern seamounts, more than 50 percent are known to occur elsewhere within the Hawaiian archipelago. Table 1 also shows that 9 of the 90 species found at the northern seamounts are distributed beyond the 180th meridian. Most of the transitional species occurred at Ladd and Nero Seamounts. Two of them, Hyperoglyphe japonica and pelagic armorhead, have distributions centered in the northern seamounts. Only one specimen of H. japonica and two of pelagic armorhead were taken within the southern seamounts. The remaining seven transitional species are known from elsewhere in the Hawaiian archipelago.

Apart from the transitional species, subtropical reef fishes and members of the commercially important snapper-grouper complex

characterize the ichthyofauna of the southern seamounts. Seamounts 10 and 11 may be exceptions. Although these new results confirm a distinct ichthyofaunal change near the 180th meridian, the ichthyofauna of Ladd and Nero (and probably seamounts 10 and 11) may be of a more transitional nature than originally thought. Since most of the fishes inhabiting the northern seamounts occur elsewhere in the deeper waters of the Hawaiian Archipelago, the shallower summits and warmer temperatures characteristic of southern seamounts apparently offer an unsuitable habitat for these species.

LIFE HISTORY OF TARGET SPECIES

Pelagic armorhead

Distributional information on the smallest reported sizes of pelagic armorhead came from results of Soviet ichthyoplankton surveys over the SE-NHR seamounts in 1969 and 1976 (Borets, 1979). These specimens ranged from 5 to 20 mm long and occurred more frequently south of 33°N. The egg, larval, and juvenile stages inhabit the surface layers and their distribution is subject to the meanderings of the surface currents (Borets, 1979). The first report of a juvenile was a 35-mm specimen collected off Cape Horn, South America and was initially given the name Pentaceros kneri by Steindachner in 1866 (Smith, 1964). Since then, juveniles have been collected off New Zealand (Smith, 1964), from south of the Aleutian Islands (Honma and Mizusawa, 1969; Randall, 1980), and off Gough Island in the southeast Atlantic (Borets, 1980).

Pelagic armorhead was first described in 1844 from a 530-mm adult specimen taken in deep water off Cape Point, South Africa (Smith, 1964). Adults are known elsewhere in the southeast Atlantic from Valdivian Seamount in the Walvis Ridge area (Borets, 1980). In the Pacific, adults are known from both hemispheres. Besides the large population inhabiting the SE-NHR seamounts, adults also occur at Mellish Bank (Takahashi and Sasaki, 1977) and at Ladd Seamount and Kure Atoll (from a single specimen collected at each) (Randall, 1980). In Japanese waters, adults occur around the Boso Peninsula (Abe, 1957) and off Hachijo Island and the Ogasawara Islands (Abe, 1969; Zama et al., 1977b). A few adult specimens have also been collected in waters along western North America from British Columbia (Welander et al., 1957; Clemens and Wilby, 1961; Hart, 1973), Oregon (Wagner and Bond, 1961), and California (Follett and Dempster, 1963; Smith, 1965). Adults and juveniles also inhabit waters south of the Aleutian Islands and around the Gulf of Alaska in the northeast Pacific (Welander et al., 1957; Chikuni, 1970). In the South Pacific, the Soviets collected five adult specimens from one of the seamounts located on the Sala y Gomez Ridge in the vicinity of Easter Island (Borets, 1980). The Japanese obtained three large adults off the east coast of Australia at Derwent Hunter Seamount.

Apparently, pelagic armorhead in the Pacific have an antitropical distribution. The lowest latitudinal records are at Kure Atoll (lat. 28°30.82'N, long. 178°20.86'W) in the North Pacific (Randall, 1980) and Sala y Gomez Ridge (lat. 24°57'S, long. 97°41'W) in the South Pacfic (Borets, 1980). A preliminary effort to locate pelagic armorhead in the Hawaiian islands (lat. 20° to 22°N) was unsuccessful (Okamoto, 1982). Borets (1980) recognized two distributional centers of reproductive adults: the SE-NHR seamounts and Walvis Ridge. Aside from these areas, "good" fishing grounds were reported near Hachijo Island (Abe, 1969). A number of pelagic armorhead have also been caught in oceanic waters of the northeastern Pacific by Japanese whaling ships. These fish were taken by night handlining at the surface under ship's lights. They have also been found in the stomachs of sei whales captured from this area (Chikuni, 1970; Sasaki, 1974). The presence of large numbers of pelagic armorhead in sei whale stomachs infers an epipelagic existence in these waters since these whales are known to preferentially feed on surface-dwelling fish (Chikuni, 1970).

Pelagic armorhead in the northeast Pacific are known only from surface or nearsurface waters during June-September (Welander et al., 1957; Honma and Mizusawa, 1969; Chikuni, 1970; Randall, 1980). Pelagic armorhead school in the surface waters of the northeast Pacific during daylight and nondaylight hours. Among the SE-NHR seamounts, pelagic armorhead are commercially taken from depths of 200 to 490 m (Takahashi and Sasaki, 1977). Aggregations of pelagic armorhead have been recorded on the slopes of seamounts at the 800- to 900-m depth (Sakiura, 1972; Borets, 1980). Chikuni (1970, 1971) suggested that the horizontal and vertical distribution of pelagic armorhead is correlated with a certain temperature range. He surmised that the absence of pelagic armorhead during northeast Pacific winters indicated a lower tolerance limit of 5°C, and that their year-round occurrence on the SE-NHR seamounts and during summer in the northeast Pacific suggested an upper limit of 15° to 20°C. Chikuni suggested a preferred range of 8°to 15°C and reasoned that their absence on the Emperor Seamounts north of Koko (depths of 1,000 m or more) and on Hawaiian Ridge seamounts east of the 180th meridian (shallow summits) was due to intolerably low and high temperatures, respectively.

As stated earlier, the catches of pelagic armorhead vary diurnally on the seamounts. The Soviets report that this is due to a vertical migration upwards from the summit as daylight approaches and a descent to the summit at dusk. The fish remain on the summit during darkness and in the upper water layers (80- to 100-m depth) during daylight (Sakiura, 1972). Barnett[3] reported a correlation between poor night catches and shipboard

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[3]See footnote 1, specifically W.B. Barnett, 1981, Southwest Fisheries Center Administrative Report H-81-9.

fish finders showing concentrations of fish (presumed to be pelagic armorhead) at levels either above or beyond the summit. A variation of the hypothesis reported by Sakiura was proposed by Kitani and Iguchi (1974). They agreed that the fish rise off the summit during daylight, but they also maintain that the fish descend past the summit during the night. Consequently, it was felt these fish pass through the summit level twice during the night: once after dusk and again before dawn. Both Soviet and Japanese investigators suggest that these vertical movements are related to the foraging activity of pelagic armorhead. Soviet results (Sakiura, 1972) indicate that pelagic armorhead preferentially feed during daylight, especially between 0800 and 1000, and feed little or not at all during the night. The findings of Kitani and Iguchi (1974) are contrary to Soviet results since they found a higher proportion of stomachs with food between midnight and dawn. However, field observations by U.S. foreign observers[4] indicate that feeding takes place only during daylight, primarily in the morning and late afternoon.

The Soviets report that surface-dwelling crustaceans are important prey items of pelagic armorhead (Sakiura, 1972). A portion of the diet consists of deep-scattering layer organisms (Sasaki, 1974). Prey items are primarily amphipods, copepods, pteropods, euphausiids, sergestids, macrura, tunicates, and myctophids. Borets (1979) reported that juveniles feed on smaller plankters, particularly copepods, whereas adults prey chiefly on tunicates, euphausiids, and mesopelagic fishes. Stomach contents examined during a Japanese survey cruise consisted of copepods, krill, mysids, myctophids, and other mesopelagic fishes (Japan Fisheries Agency, 1974). Chen (1980) found two species of red deepsea shrimp to be the principal prey of pelagic armorhead taken at Kammu. The U.S. foreign observers[5] identified amphipods, copepods, euphausiids, salps, shrimps, myctophids, and other small fishes as principal prey items.

The spawning season of pelagic armorhead at the SE-NHR seamounts has been determined from several sources (Japan Fisheries Agency, 1974; Sasaki, 1974; Bilim et al., 1978; Borets, 1979) to extend from December to March. Spawning peaks during January-February. The proportion of spent individuals increases from February to March although some ovaries were found in a pre-spawning condition in March (Sasaki, 1974). The U.S. foreign observers[6] found most females in an early developing stage during April-June whereas Chen (1980) found well-developed ovaries in

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[4]See footnote 1, specifically T.K. Kazama, 1978, Southwest Fisheries Center Administrative Report 15H, 1978 and W.B. Barnett, 1982, Southwest Fisheries Center Administrative Report H-82-21.
[5]See footnote 1
[6]See footnote 1, specifically T.K. Kazama, 1978, Southwest Fisheries Center Administrative Report 15H, 1978 and W.B. Barnett, 1982, Southwest Fisheries Center Administrative Report H-82-12.

May. Soviet investigators found ovaries in an early developmental stage in summer and fall; moderate development began in September (Sakiura, 1972). Pre-spawning conditions were present among some females in mid-November (Bilim et al., 1978). No eggs were collected in plankton tows over the seamounts during spring; however, large numbers of juveniles were reported in March-April (Sakiura, 1972; Sasaki, 1974).

Fecundity estimates for 30-cm females of pelagic armorhead from three SE-NHR seamounts ranged from 99,000 to 110,000 eggs (Borets, 1979). Studies by Bilim et al. (1978) indicate that during spawning, eggs are released in four to six batches. Chikuni (1970) reported that 6-year-old fish are sexually mature and suggested that first maturity occurs at an earlier age. Age estimates of 3 years for 22-cm fork length (FL) and 6 years for 32-cm FL fish were determined by annular ring counts on scales. Chikuni estimated the age groups of pelagic armorhead taken in the trawl fishery (mean FL of 30.0 cm) are 5 to 7 years old. Results of spectrophotometric analysis on scales by Vasil'kov and Borets (1978) and information reported by Borets (1979) indicate ages of 6 to 8 years for 26- to 30-cm fish.

A growth of 7.5 cm in 3 years (from an initial length of 25.4 cm) was reported by Hart (1973) for a pelagic armorhead held in captivity at Vancouver Aquarium, British Columbia. However, yearly increment growth data indicate that a growth of 7.5 cm in the wild (from a similar initial length) requires more than 4 years (Borets, 1979). Borets showed a 7.5 to 7.7 cm growth from age 0 to 1 and growth between subsequent year classes decreasing to 1.0 to 1.4 cm from age 9 to age 10. At present, NMFS is conducting an otolith analysis to determine age and growth.

A perplexing aspect of pelagic armorhead biology is the presence of morphological variants among adults on the SE-NHR seamounts (Figure 2). A number of reports (Japan Fisheries Agency, 1974, Sasaki, 1974; Takahashi and Sasaki, 1977; Chen, 1980) have commented on this variation and recognized two or three types. Observations by NMFS personnel on Townsend Cromwell research cruises and on foreign vessels indicate three types of pelagic armorhead based on body depth and color. The "lean" type is more elongate and is brown to brownish-gray. The "fat" type has a relatively greater body depth, somewhat "square-shaped," with a bluish dorsal region and a white ventral region. An "intermediate" type has a body depth in-between the other types and a lean type coloration. It has also been noted by NMFS researchers and Takahashi and Sasaki (1977) that certain lean types captured at Hancock appear rather emaciated, with skin that is easily ruptured. Gonads are poorly developed in these fish and the viscera discolored. All of these apparent abnormalities indicate an unhealthy condition. These fish also lack fat deposits in the visceral cavity and other lean fish had limited amounts. Fat types and intermediate types to a lesser degree have large fat deposits in the visceral cavity.

All three types of pelagic armorhead are found within the SE-NHR seamounts although lean and intermediate types predominate in the catches. The fat types are relatively rare in the trawl catches on the seamounts. However, only the fat types have been found in the northeast Pacific. The distribution and coloration of fat types suggest a primarily epipelagic existence.

The variability in body type of adult pelagic armorhead is apparently absent in the juveniles. Photographs of juveniles appearing in Smith (1964) and Honma and Mizusawa (1969) show them to be relatively deep bodied with a mottled coloration, primarily in the dorsal region. Juveniles of a congeneric, P. japonicus, show similar coloration during the epipelagic phase. This coloration eventually disappears when juveniles shift to a deeper demersal existence (Zama et al,, 1977a).

To better define the nature and significance of the variations between types, a preliminary morphometric and meristic study was begun at NMFS. A breakdown of the sample size according to seamount, sex, and type appears in Table 2. The morphometrics and meristics of specimens by seamount, sex, and type are shown in Table 3. The means were analyzed within each of the three sources (plus their four possible combinations) using a three-way univariate ANOVA (Statistical Analysis System, 1979) (Table 4).

Highly significant differences within sex and type occur among all morphometric variables measured. However, there is also a significant sex-type interaction which probably influenced the results within each of the two previous sources. The sample sizes shown in Table 2 indicate that the lean sample was dominated by males, whereas in the intermediate sample, females predominated. Sex-type differences in body length may also have influenced the results. Maximum body depth is plotted against standard length by sex in Figure 13 and by body type in Figure 14. Aside from the sex and type variation in body depth, these plots also indicate that the males and lean types were smaller compared with females and intermediate types. Whether these tendencies within the sample accurately reflect the seamount population of pelagic armorhead is unknown. In light of probable interactive effects and possible sample bias, the results for sex and type are inconclusive. Results of the seamount-sex and seamount-type comparisons indicate that each particular sex and type alone are not significantly different morphometrically between seamounts. However, there were significant differences, especially in weight, between pelagic armorhead of different seamounts. Borets (1979) presented results of a morphometric study indicating no significant differences among samples of pelagic armorhead taken at four seamounts within the SE-NHR area.

TABLE 2. SAMPLES OF PELAGIC ARMORHEAD USED IN MORPHOMETRIC AND MERISTIC STUDIES

Specimen	SE Hancock	NW Hancock	C-H	All Three Seamounts Combined
Leans				
Female	11	19	24	54
Male	28	27	32	87
Total	39	46	56	141
Intermediates				
Females	32	44	31	107
Male	26	7	10	43
Total	58	51	41	150
Fats				
Females	7	2	0	9
Male	13	6	0	19
Total	20	8	0	28
Total by Sex				
Female	50	65	55	170
Male	67	40	42	149
TOTAL	117	105	97	319

The meristic results shown in Table 4 do not separate the three body types. Borets (1979) presented similar meristic results for four seamounts although no comparisons were made for sex, type, and their possible combinations. These meristic results are of interest because of speculation on whether the types represent genetically distinct species or subspecies. To better address this question, tissue samples from these types were collected for electrophoretic analysis; results are not yet available. An earlier electrophoretic study on 10 protein systems from samples collected at four SE-NHR seamounts detected no genetic differences in fish (Borets, 1979).

The ecological significance of the different body types is little understood. Borets (1980) reported that the young are pelagic until a certain size and later shift to a demersal habitat, especially over the seamounts. This shift occurs around age 7, which corresponds to the sizes constituting the bulk of pelagic armorhead taken in the trawl fishery. Borets, however, makes no specific mention of polymorphic variation in relation to the habitat change.

TABLE 3. MEAN VALUES DERIVED FROM THE MORPHOMETRICS AND MERISTICS STUDY OF PELAGIC ARMORHEAD

Characteristic	Location			Sex		Type		
	SE Hancock	NW Hancock	C-H	Female	Male	Lean	Intermediate	Fat
Morphometric								
Weight (g)	503.3	514.8	455.0	543.7	433.4	385.3	573.3	590.3
Standard Length (mm)	255.8	256.7	255.3	262.8	248.1	246.6	265.1	253.8
Fork Length (mm)	295.9	298.5	296.8	304.7	288.3	287.0	307.0	295.8
Greatest Orbit Length (mm)	24.1	24.5	25.0	24.7	24.3	25.0	24.5	22.6
Least Interorbital Length (mm)	26.5	26.7	25.5	27.1	25.4	24.7	27.5	28.1
Snout Length (mm)	32.3	32.3	31.9	33.2	31.1	30.6	33.5	33.0
Head Length (mm)	84.2	84.7	84.4	86.5	82.1	81.8	87.0	83.5
Predorsal Length (mm)	103.7	103.2	102.0	105.8	99.9	98.1	106.9	106.8
Predorsal to Prepelvic Length (mm)	96.4	94.8	91.7	97.9	90.4	85.4	100.7	105.6
Maximum Body Depth (mm)	94.0	92.3	89.2	95.5	88.0	82.9	98.2	103.5
Meristics								
Lateral Line Scales in Standard Length	72.9	73.1	72.1	72.8	72.7	72.7	72.8	72.5
Upper Gill Rakers on First Arch	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.5
Lower Gill Rakers on First Arch	17.8	17.8	17.6	17.7	17.8	17.7	17.7	17.8
Dorsal Spines	13.9	13.9	13.9	13.9	13.9	13.8	13.9	13.9
Anal Spines	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Dorsal Soft Rays	8.9	8.8	8.8	8.8	8.9	8.9	8.8	8.9
Anal Soft Rays	7.3	7.4	7.4	7.4	7.4	7.4	7.3	7.4
Pectoral Rays	17.8	17.7	17.7	17.7	17.7	17.7	17.8	17.7
Precaudal Vertebrata	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Caudal Vertebrata	12.9	13.0	12.9	13.0	12.9	12.9	12.9	13.0
Total Vertebrata	25.0	25.0	24.9	25.0	25.0	25.0	25.0	25.0

TABLE 4. RESULTS OF ANOVA ON MORPHOMETRIC AND MERISTIC DATA FROM PELAGIC ARMORHEAD

Characteristic	Seamount	Sex	Type	Seamount x Sex	Sex x Type	Seamount x Type	Seamount x Sex x Type
Degrees of Freedom	2	1	2	2	2	3	3
Morphometric							
Weight (g)	**	***	***	NS	***	NS	*
Standard Length (mm)	NS	***	***	NS	**	NS	*
Fork Length (mm)	NS	***	***	NS	**	NS	*
Greatest orbit Length (mm)	*	***	***	NS	*	*	NS
Least Interorbital Length (mm)	*	***	***	NS	***	NS	*
Snout Length (mm)	NS	***	***	NS	NS	NS	NS
Head Length (mm)	NS	***	***	NS	**	NS	*
Predorsal Length (mm)	NS	***	***	NS	***	NS	NS
Predorsal to Prepelvic Length (mm)	NS	***	***	NS	***	NS	NS
Maximum Body Depth (mm)	NS	***	***	NS	***	NS	NS
Meristic							
Lateral Line Scales in Standard Length	NS	NS	NS	NS	NS	NS	NS
Upper Gill Rakers on First Arch	NS	NS	NS	NS	NS	NS	NS
Lower Gill Rakers on First Arch	NS	*	NS	NS	*	NS	NS
Dorsal Spines	NS	NS	NS	NS	NS	NS	NS
Anal Spines	NS	NS	NS	NS	NS	NS	NS
Dorsal Soft Rays	NS	NS	NS	NS	NS	NS	NS
Anal Soft Rays	NS	NS	NS	NS	NS	NS	NS
Pectoral Rays	NS	NS	NS	NS	NS	NS	NS
Precaudal Vertebrata	NS	NS	NS	NS	NS	NS	NS
Caudal Vertebrata	NS	NS	NS	NS	NS	NS	NS
Total Vertebrata	NS	NS	NS	NS	NS	NS	NS

Note: NS = $P > 0.05$; * = $0.01 < P \leq 0.05$; ** = $0.001 < P \leq 0.01$; *** = $P \leq 0.001$

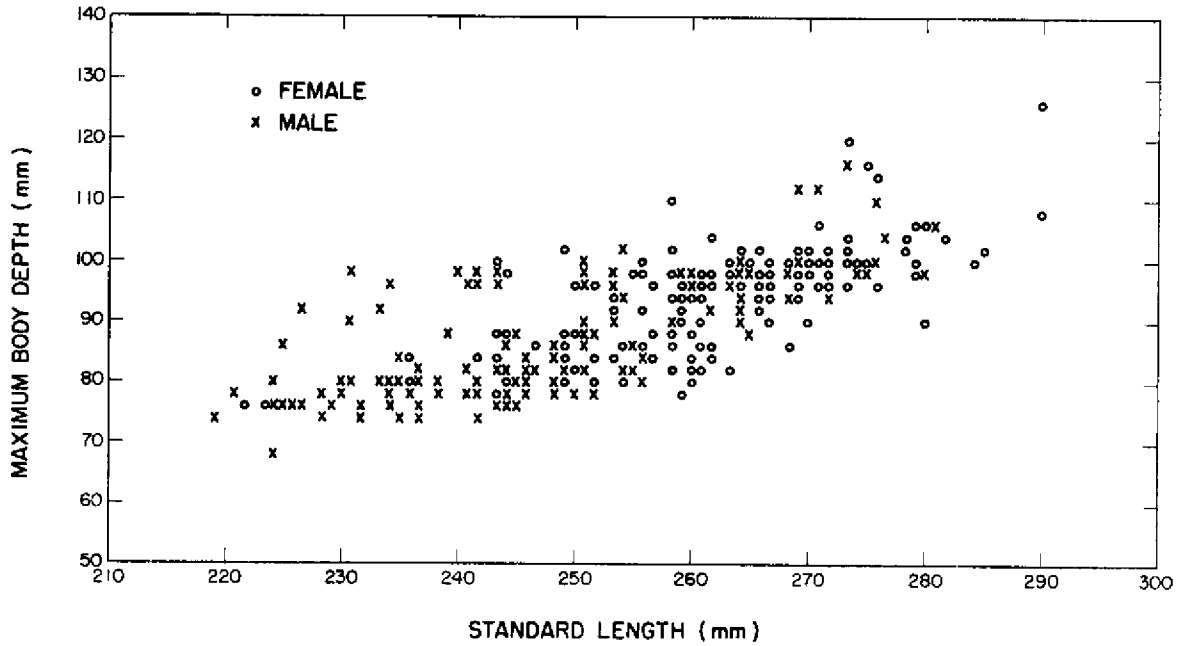

Figure 13. Relationship between maximum body depth and standard length, by sex, for pelagic armorhead

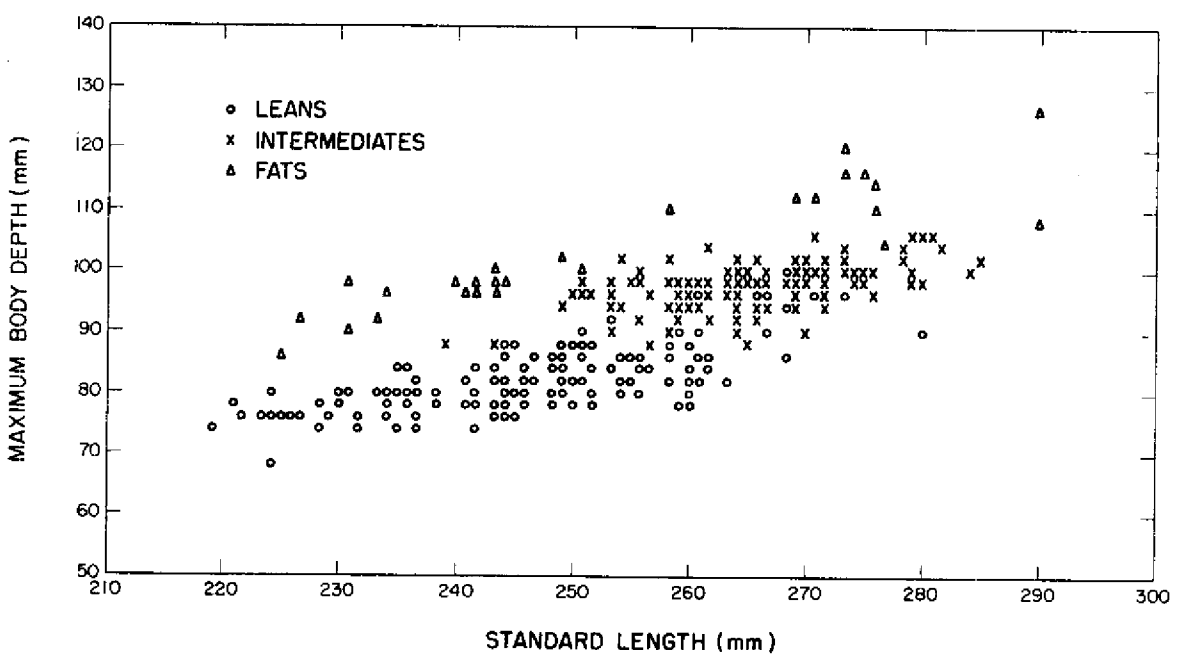

Figure 14. Relationship between maximum body depth and standard length, by body type, for pelagic armorhead

The annual mean FL of pelagic armorhead pooled for all seamounts is available from 1969 to 1976 (Takahashi and Sasaki, 1977) and for 1977-79 and 1981 (Sasaki, unpublished data) (Table 5). For 1972, the mean FL was apparently smaller than earlier and succeeding years. Perhaps coincidentally, the CPUE for 1972 was the highest recorded for three of the seamounts, and the CPUE was higher at the remainder (Figure 6). Length data from the Japanese trawl fishery at Hancock during 1971-74 and 1976 are given in Table 6, and NMFS data for 1978-82 are plotted in Figure 15. Data from all seamounts combined and those from Hancock show a tendency toward slightly higher mean FL in the later years of the fishery compared with the earlier years. The FL ranges at all seamounts combined and for those at Hancock indicate the trawl fishery is harvesting a very narrow length range. Apparently the smaller and larger pelagic armorhead are relatively rare inhabitants of the seamounts since the trawls are capable of retaining much smaller fish. The largest known specimens from the seamounts area are a 495-mm total length (TL) female and a 498-mm TL male (Randall, 1980). The largest recorded pelagic armorhead is a 555-mm TL specimen from Cape Point, South Africa (Smith, 1964).

Annual mean FL by sex was derived from data collected at Hancock by NMFS during 1978-82. Females have a slightly larger mean FL than males. Table 7 gives the results of a two-way univariate ANOVA which indicated a highly significant difference in mean FL between the sexes and that the pattern of this difference is also highly significant in each year. Pooled NMFS and Japan Fisheries Agency (1974) sex ratio data for Hancock indicate no departure from a 1:1 ratio.

A parasitic copepod, Pennella hawaiiensis, on pelagic armorhead has been reported by Borets (1979). This ectoparasite is commonly found attached to the musculature of the dorsal region. The infestation rate of this parasite was 44 percent at Koko and 55 percent at Milwaukee. The Japan Fisheries Agency (1974) reported the frequent occurrence of small unidentified ectoparasites on pelagic armorhead taken at SE Hancock. Numerous small, unidentified parasites were found in this study on the gill filaments of virtually all pelagic armorhead. Intermuscular parasites were rare.

TABLE 5. COMBINED FORK LENGTH DATA OF PELAGIC ARMORHEAD TAKEN BY JAPANESE TRAWLERS AT SEAMOUNTS

Year	Sample Size	Mean (cm)	Range (cm)
1969	375	29.2	24-36
1970	166	29.2	26-34
1971	4,400	28.9	24-40
1972	6,410	27.4	20-34
1973	3,138	29.0	25-35
1974	20,724	28.8	21-37
1975	11,736	28.9	23-35
1976	8,517	29.5	15-35
1978	5,508	31.3	23-44
1979	2,412	30.9	21-39
1981	2,664	32.1	27-40

TABLE 6. FORK LENGTH DATA OF PELAGIC ARMORHEAD TAKEN AT HANCOCK SEAMOUNTS BY JAPANESE TRAWLERS

Year	Sample Size	Mean (cm)	Range (cm)
1971	1,199	28.8	25-34
1972	599	27.8	26-34
1973	200	28.7	27-33
1974	900	28.5	24-33
1976	93	28.8	27-31

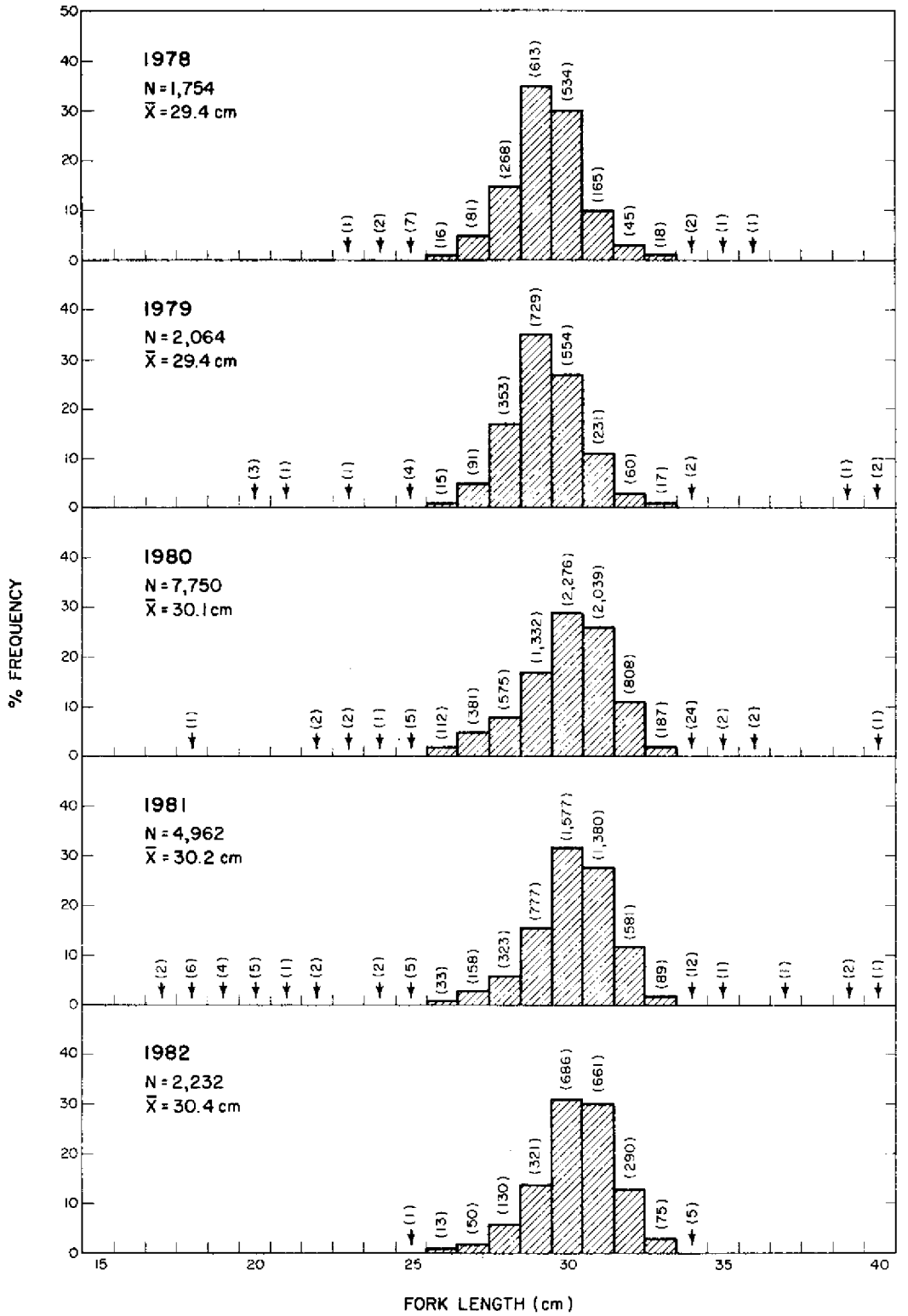

Figure 15. Yearly frequency distribution of pelagic armorhead at Hancock Seamounts from data collected by the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service. Values above bars represent the number of measurements within the interval.

TABLE 7. ANOVA ON LENGTH DATA, BY SEX, FOR PELAGIC ARMORHEAD TAKEN AT HANCOCK SEAMOUNTS BY JAPANESE TRAWLERS

Year	Number of Males	Mean Fork Length of Males (cm)	Number of Females	Mean Fork Length of Females (cm)	ANOVA		
					Source	d.f.	PR > F
1978	222	29.1	325	29.7	Sex	1	***
1979	461	29.0	577	29.7	Year	4	***
1980	2,302	29.7	1,759	30.5	Sex and	4	NS
1981	620	29.7	817	30.7	Year		
1982	578	29.9	790	30.7			

Note: NS = $P > 0.05$; *** $P \leq 0.001$

Alfonsin

Alfonsin are primarily distributed within two areas of the Pacific northern hemisphere. Within the central North Pacific, alfonsin are found from Koko to Hancock within the Emperor-Hawaiian Ridge Area. In the western Pacific, an alfonsin fishery has existed for many years in Sagami Bay, Japan. Their distribution also extends south of Honshu, Japan to Izu, Kinansho, and further south to Komabashi Seamount near Palau (Chikuni, 1971; Sasaki, 1978). In the central North Pacific alfonsin are only found on seamounts, whereas in the western Pacific they are also found on continental shelf areas. Information on the worldwide distribution of alfonsin is given in Busaklin (1982).

Alfonsin apparently have a pelagic early life history; they subsequently adopt a demersal habit by age one. In the western Pacific, dispersal of eggs and larvae is strongly affected by the Kuroshio current. No information is available on eggs and larvae over the SE-NHR seamounts. Chikuni (1971) suggested that early life stages may be recruited between the two central areas, especially toward the SE-NHR seamounts.

In a tagging study conducted in Sagami Bay, most alfonsin were recaptured offshore. Alfonsin length-frequency data from several locations in the western Pacific indicate a pattern of increasing size with depth and a decreasing size with latitude. The length range of alfonsin in Sagami Bay (representing higher latitudes) was 17 to 20 cm compared with 35 to 50 cm from southern areas (Chikuni, 1971). Length-frequency data collected by NMFS in 1978-82 for Hancock are shown in Figure 16.

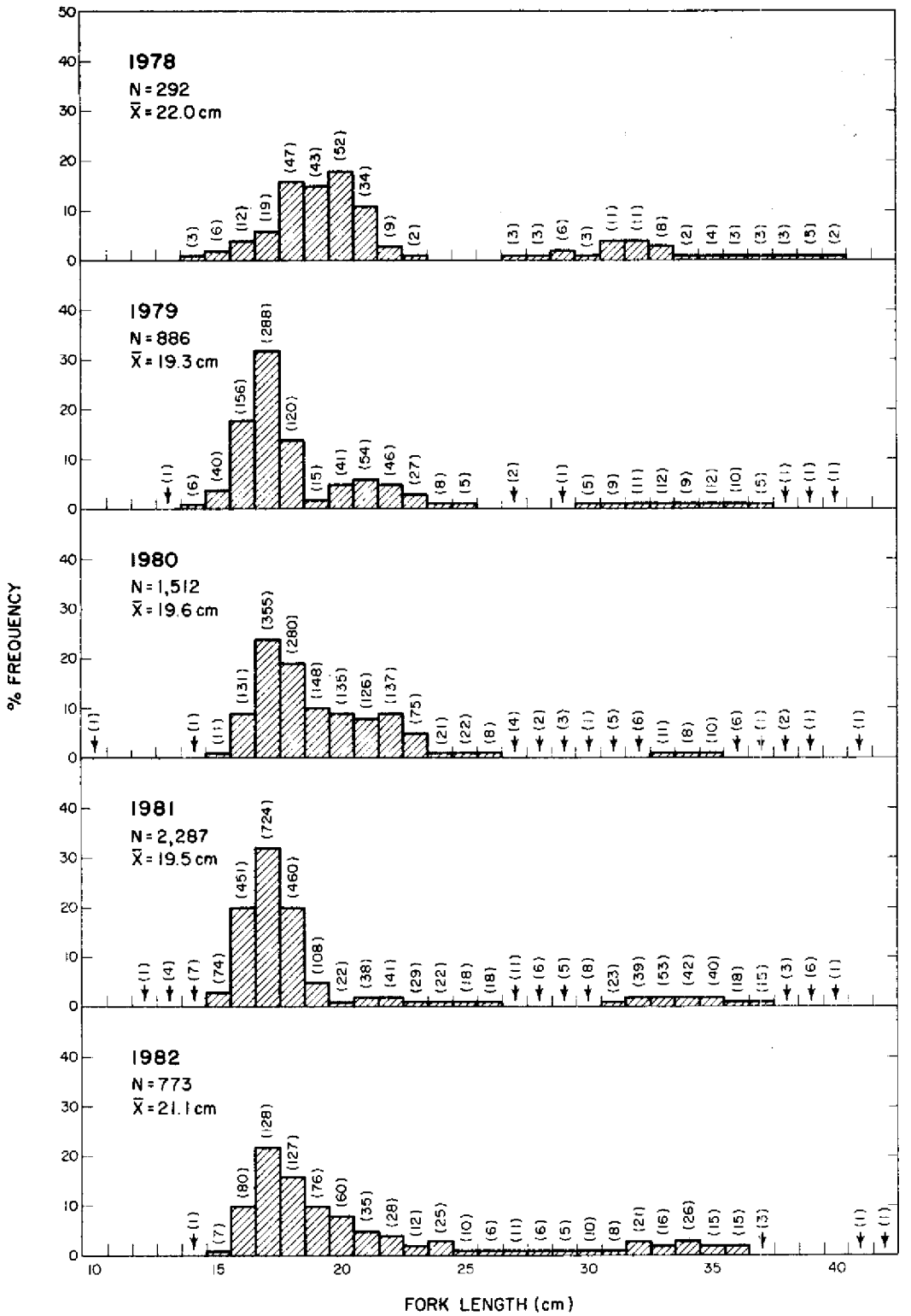

Figure 16. Yearly frequency distribution of alfonsin at Hancock Seamounts from data collected by the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service. Values above bars represent the number of measurements within the interval.

Although the smaller size group (similar to that from Sagami Bay) predominates, a larger size group is also sometimes present. The size distribution of alfonsin at Hancock apparently does not follow the distributional patterns reported for the western Pacific by Chikuni (1971). Figure 17 shows the distribution, by sex, of alfonsin from Hancock (NMFS data from 1978 to 1982). The distribution of the two sexes indicates that sexual dimorphism is not responsible for the existence of different size groups. Combined NMFS and Japan Fisheries Agency (1974) data show a nearly equal sex ratio at Hancock.

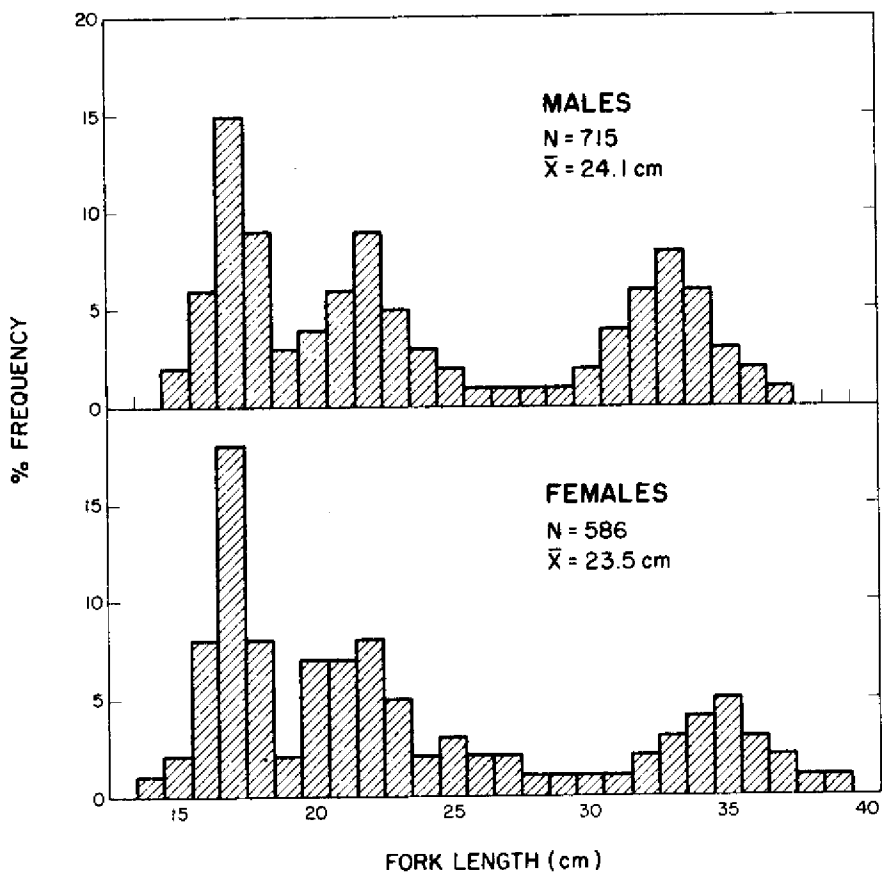

Figure 17. Frequency distribution for 1978-82 combined of alfonsin, by sex, at Hancock Seamounts from data collected by the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service

No information is available on spawning season (or the existence of reproductive alfonsin) at the SE-NHR seamounts.

U.S. foreign observers[7] have reported that many of the small, trawl-caught alfonsin appear sexually immature. Chikuni (1971) reported that in the western Pacific the spawning season is from August to October.

Based on a study of otoliths, Ikenouye (1969) determined the following age-length relationships for alfonsin:

Age	FL (cm)
1	9
2	19
3	26
4	30
5	33

These results suggest that the bulk of the alfonsin caught in the seamount trawl fishery are 2 years old (Figure 16). Ikenouye reported that alfonsin in the western Pacific first reach maturity by age three.

The feeding habits of alfonsin on the SE-NHR seamounts are not well known. Krill, mysids, copepods, myctophids, and other mesopelagic fishes have been found in alfonsin stomachs (Japan Fisheries Agency, 1974). Results of other Japanese survey cruises (Aomori Prefectural Fisheries Experimental Station, 1976) showed small fish to be the most abundant prey, followed by decapod and schizopod crustaceans. Barnett[8] identified prey items consisting of benthic shrimp, fish, and tunicates and also found relatively large amounts of fine silt in the gut.

MANAGEMENT

Japan is the only foreign nation thus far to fish under permit at Hancock since the establishment of the FCZ in 1977. Beginning in 1978, Japan was allocated half of a yearly total allowed level of foreign fishing (TALFF) of 2,000 MT (all species included). However, the Japanese have never attained the allotted quota. The total yearly Japanese catches at Hancock, determined by U.S. foreign observers[9] are as follows: 1978, 393.0 MT; 1979, 205.4 MT; 1980, 795.4 MT; 1981, 662.0 MT; and 1982, 393.0 MT.

The 1982 ex-vessel value (in U.S. dollars) was $763/MT (dressed) for pelagic armorhead and $240/MT (round) for alfonsin landed in Japan (R.T.B. Iversen, 1983: personal communication).

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[7]See footnote 1
[8]See footnote 1, specifically W.B. Barnett, 1982, Southwest Fisheries Center Administrative Report H-82-21.
[9]See footnote 1

No U.S. fishermen have yet fished commercially at Hancock.

Set forth in the preliminary management plan for the seamount groundfish fishery of the Pacific, as published in the Federal Register, U.S. management policy ideally requires the determination of a maximum sustainable yield (MSY). Given MSY it would then be possible along with other considerations, to calculate optimum yield. After assessing the level or potential level of harvesting by U.S. fishermen, a TALFF could then be derived.

Determination of MSY requires an accurate assessment of stock structure. Available biological information on pelagic armorhead indicates that one common stock exists among the seamounts of the SE-NHR. Hence, catch and effort data from all these seamounts could be incorporated in determining MSY. In this regard, the Japanese fishery data could serve as a basis for this determination. Also needed is an accurate delineation of the stock's home range. A determination of the home range requires a consideration of the distribution of pelagic armorhead by body type. All three body types have been found on the seamounts; however, only fat types inhabit the northeast Pacific during summer, their whereabouts after summer being unknown. Consequently, there is a question of whether the home range of the fat type extends well beyond the seamounts or whether the fat type represents an independent stock. Available biological information is still insufficient to conclude that the fat type represents a pelagic, predemersal phase and that ultimately these fish return to the seamounts. Until the status of the fat type is better understood, the determination of MSY based on seamount catches alone may be of little value for management purposes. Another management problem is the accessibility of this fishery to other fishing nations. Because most of the SE-NHR seamounts are located in international waters, there is some question as to how effectively the pelagic armorhead resources within the FCZ could be independently managed. The most effective management plan would ultimately adopt a holistic approach and thereby require the involvement and cooperation of all nations participating in this fishery.

SUMMARY

Until fairly recently, investigations of the SE-NHR seamounts were principally geological. With the Soviet discovery in 1967 of fishery resources on the seamounts, a series of biological and oceanographic studies began. Soviet oceanographic studies show the existence of intense vertical circulation and the meandering of surface currents near the seamounts. These physical processes are believed to be responsible for the higher plankton biomass found in this area compared with the more oligotrophic environment of surrounding waters.

The main fishing activity in this region has been the initiation of a trawl fishery on the SE-NHR seamounts. Of principal commercial importance is the pelagic armorhead and, to a lesser

extent, alfonsin. During a 7-month period at the beginning of the fishery, the Soviets reportedly harvested 133,400 MT of pelagic armorhead. In 1969, the Japanese also entered the seamount trawl fishery. Annual Japanese catches for all seamounts combined ranged from 19,000 to 35,000 MT during 1972-76. However, catches sharply declined during 1977-81, ranging from 500 to 6,200 MT. With the establishment of the U.S. FCZ, the Hancock Seamounts came under U.S. jurisdiction and consequently various regulations were developed. Japan was the only foreign nation to fish under permit at Hancock during 1978-82. During this period, catches of pelagic armorhead were very low, reflecting a similar trend among the rest of the SE-NHR seamounts. No U.S. fishermen have fished in the seamount fishery. Other smaller scale fisheries operating on the SE-NHR seamounts were bottom longlining, primarily for alfonsin; bottom dragging for precious corals; and gill netting for squid and saury.

Surveys of Hawaiian Ridge seamounts south of Hancock revealed large differences in the ichthyofauna. The primarily deep water, benthic, and demersal fishes of the SE-NHR seamounts are replaced by subtropical reef and snapper-grouper fishes of the shallower southern seamounts. Seamounts 10-11, Ladd, and Nero appear to have a more transitional ichthyofauna.

Little is known about the life history of pelagic armorhead. Evidence indicates a common, reproductive stock on the SE-NHR seamounts. These fish apparently undergo diurnal vertical movements, becoming closely associated with the summits at night and the upper water column during daylight. Mesopelagic organisms appear to be an important food resource.

A still unresolved problem concerns the existence of three different morphological types among pelagic armorhead. The lean and intermediate type are brownish and predominate over the seamounts. The fat type has blue and white pelagic coloration, is infrequently caught over the seamounts and is the only type known to inhabit oceanic waters far from the seamounts. No meristic differences were found among the three types. Although the fat type is suspected to be representative of a pelagic, predemersal stage common to all members of this species, conclusive evidence is lacking. Resolving the status of the fat type in the population is needed before stock structure can be determined. Until then estimates of MSY must be based solely on seamount commercial catch data.

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PELAGIC FISHERIES RESOURCES OF THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Included in this paper are reviews of data collected by the Hawaii Division of Aquatic Resources on the fish catch in the Northwestern Hawaiian Islands (NWHI) by longlining and trolling in recent years, the relatively new fishery for albacore, Thunnus alalunga, in the vicinity of the NWHI that is being carried out by U.S. West Coast albacore trollers, and some of the longline, live-bait, and gill-net fisheries that are being carried out by Japanese and Taiwan vessels in the North Pacific Ocean.

gill net	live bait
longline	pelagic fisheries
troll	Northwestern Hawaiian Islands

INTRODUCTION

The purpose of this report is to review some of the pelagic fisheries within the 200-mile U.S. fishery conservation zone around the Northwestern Hawaiian Islands.

DOMESTIC CATCHES IN THE NORTHWESTERN HAWAIIAN ISLANDS

The commercial fish landing reports of the Division of Aquatic Resources (DAR) of the Hawaii Department of Land and Natural Resources from 1971 through 1980 show that fish harvested in the NWHI ranged from 23 to 108 metric tons (MT) (Table 1). Besides the total landings, shown in parentheses are the catches of pelagic species. The amount of pelagic species caught fluctuated from 1.7 to 9.4 MT and represented 2 to 26 percent of the fish caught in the NWHI, with an average of 11 percent. Table 2 shows the catch by species for the same years. The catches of 245 to 6,700 kg of yellowfin tuna, Thunnus albacares, and 760 to

3,730 kg of wahoo, Acanthocybium solandri, were the largest contributors to the pelagic fish landings. Kawakawa, Euthynnus affinis, made a noticeable contribution of 1,200 kg in 1975, as well as skipjack tuna, Katsuwonus pelamis, with a catch of 3,260 kg in 1979. These data show that the amount of pelagic species caught in the NWHI contributed less than 1 percent of the state's annual fish landings. This indicates that the pelagic fish resources are either very scarce in the NWHI or that pelagic species are not being fished very hard. It seems that the latter is true -- that pelagic resources in the NWHI are not being utilized to any significant extent by Hawaiian fishermen.

TABLE 1. COMMERCIAL LANDINGS OF FISH CAUGHT IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1971-80

Year	Metric Tons Sold	Value
1971	36.5 (2.4)	$ 52,848
1972	23.4 (4.0)	46,282
1973	30.8 (2.8)	65,979
1974	25.2 (2.7)	53,277
1975	36.4 (9.4)	70,439
1976	35.0 (8.1)	89,272
1977	64.0 (2.2)	279,366
1978	94.9 (1.7)	360,742
1979	66.4 (8.8)	260,655
1980	107.5 (2.5)	623,479

Source: Data from Hawaii Division of Aquatic Resources

Note: Contribution to the landings by pelagic species given in parentheses

PELAGIC FISH OBSERVATIONS IN THE NORTHWESTERN HAWAIIAN ISLANDS

The data collected from the bird flock and fish school observations made on the cruises of the Townsend Cromwell in the NWHI from 1976 to 1982 were analyzed since bird flocks are known to be associated with fish schools. Their abundance would theoretically reflect pelagic fish school abundance. The recorded observations were summarized by three subareas (Figure 1). Subarea I includes Nihoa, Necker Island, and French Frigate Shoals. Subarea II includes Gardner Pinnacles, Laysan Island, and Lisianski Island. Subarea III includes Pearl and Hermes Atoll, Midway Islands, and Kure Atoll.

TABLE 2. COMMERCIAL LANDINGS (KILOGRAMS) OF PELAGIC SPEICES FROM THE NORTHWESTERN HAWAIIAN ISLANDS, 1971-80

Species	Year									
	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Yellowfin tuna	1,043	1,069	374	1,152	6,700	4,266	1,106	660	1,699	245
Kawakawa	40	80	146	373	1,204	109	197	100	496	301
Mahimahi	240	161	334	235	151	30	9	54	14	160
Wahoo	975	2,717	1,909	910	747	3,727	758	907	3,268	1,688
Rainbow runner	36	—	—	—	11	—	—	7	36	48
Skipjack tuna	38	—	—	—	632	—	97	—	3,260	—
Broadbill	—	—	—	—	—	—	—	—	64	—
Blue marlin	—	—	—	—	—	—	—	—	—	79
Shortbill spearfish	—	—	—	—	—	—	—	—	—	8
TOTAL	2,372	4,027	2,763	2,670	9,445	8,132	2,167	1,728	8,837	2,529

Source: Data from Hawaii Division of Aquatic Resources

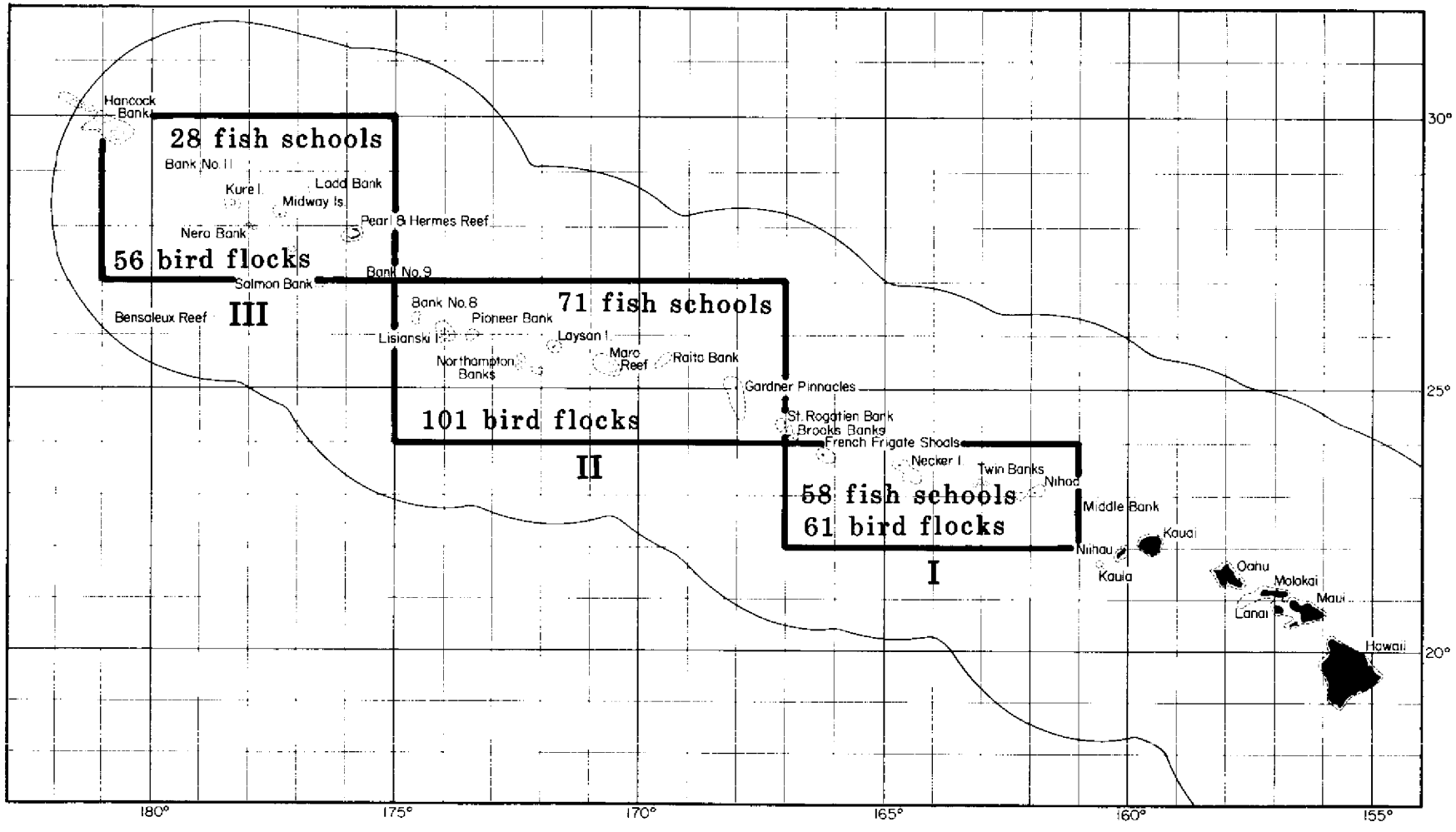

Figure 1. The number of fish schools and bird flocks observed on cruises of the Townsend Cromwell in three subareas in the Northwestern Hawaiian Islands, 1977-82

Bird Flocks

The total numbers of bird flocks and fish schools sighted were 61 in subarea I, 101 in subarea II, and 56 in subarea III. Well over 50 percent of the bird flocks seen in each area were made up of flocks estimated to have 26 to 100 seabirds. It was noted that the larger flocks of over 100 birds were more numerous in subareas II and III where they accounted for 29 to 34 percent of the flocks recorded.

Fish Schools

Of the 58 fish schools recorded for subarea I, 12 were porpoises (Delphinidae), 9 were skipjack tuna, 5 were kawakawa, 3 were yellowfin tuna, and 4 were mixed tuna schools. Of the 71 fish schools observed in subarea II, 16 were porpoises, 13 were yellowfin tuna, 6 were kawakawa, 4 were skipjack tuna, and 3 were flyingfish (Exocoetidae). Of the 28 schools sighted in subarea III, 4 were porpoises, 4 were yellowfin tuna, 3 were kawakawa, and 2 were flyingfish. Thirty-eight percent of the fish schools sighted could not be identified.

Trolling

Besides observing bird flocks and fish schools while on the cruises of the Cromwell, trolling was conducted whenever possible. Trolling catches were also summarized by the same three subareas. The trolling records show that 284 fishes were caught in subarea I, 332 fishes in subarea II, and 123 fishes in subarea III. Of the 284 fishes caught in subarea I, 190 (67 percent) were kawakawa, 44 (16 percent) were yellowfin tuna, and 19 (7 percent) were wahoo. In subarea II, of the 332 fishes caught, 181 (54 percent) were kawakawa, 55 (17 percent) were yellowfin tuna, and 46 (14 percent) were wahoo. Of the 123 fishes caught in subarea III, 72 (58 percent) were yellowfin tuna, 22 (18 percent) were skipjack tuna, and 20 (16 percent) were kawakawa. The average size of the species caught were as follows: skipjack tuna, 2.8 kg; yellowfin tuna, 8.6 kg; wahoo, 13.9 kg; kawakawa, 2.8 kg,; and mahimahi, Coryphaena hippurus, 6.2 kg.

FOREIGN FISHERIES IN THE NORTHWESTERN HAWAIIAN ISLANDS

Longliners

Yong and Wetherall (1980) made estimates of catches by Japanese longliners within the 200-mile U.S. fishery conservation zone in the NWHI for the years 1971 through 1977 (Table 3). The catches of albacore, T. alalunga, ranged from 170 to 910 MT during these years. Yellowfin tuna catches ranged from 120 to 470 MT and bigeye tuna, T. obesus, catches ranged from 100 to 1,300 MT. Only negligible catches of skipjack tuna and bluefin tuna, T. thynnus, were made. The annual tuna catches ranged from 500 MT in 1974 to 2,400 MT in 1976.

TABLE 3. ESTIMATED CATCH (METRIC TONS) BY JAPANESE LONGLINERS IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1971-77

Species	Year						
	1971	1972	1973	1974	1975	1976	1977
Albacore	398	478	348	281	170	912	446
Yellowfin tuna	467	268	133	119	171	330	304
Bigeye tuna	821	1,284	496	95	512	1,155	1,510
Skipjack tuna	2	2	2	2	2	1	1
Bluefin tuna	1	2	1	1	1	1	1
Total tunas	1,689	2,034	980	498	856	2,399	2,262
Blue marlin	81	62	18	24	14	22	26
Striped marlin	261	173	78	20	70	136	113
Broadbill	63	192	89	45	27	220	57
Black marlin	4	2	1	1	1	1	2
Spearfish and sailfish	8	8	10	7	7	8	5
Total billfishes	417	437	196	97	119	387	203
Grand total	2,106	2,463	1,176	595	975	2,786	2,465

Source: Data from Yong and Wetherall, 1980

Among the billfishes, catches ranged from 27 to 220 MT for swordfish, Xiphias gladius, 20 to 261 MT for striped marlin, Tetrapturus audax, and 14 to 81 MT for blue marlin, Makaira nigricans. Only small amounts of black marlin, M. indica, shortbill spearfish, T. angustirostris, and sailfish, Istiophorus platypterus, were caught. The annual billfish catches ranged from 97 to 437 MT. The annual catches of tunas and billfishes by Japanese longliners during these years ranged between 600 and 2,800 MT and averaged 1,800 MT.

The number of days fished in the NWHI by the Japanese longliners from 1971 to 1975 ranged from a low of 444 to a high of 1,747. Based on 2,000 hooks fished per day, Yong and Wetherall calculated catch per unit of effort for these vessels to be 14 to 19 tunas per 1,000 hooks fished (28 to 38 per day). The catch per unit of effort for billfishes ranged from two to three per 1,000 hooks fished (four to six per day).

Bait Boats

Yong and Wetherall also made estimates of catches by Japanese bait boats within the 200-mile U.S. fishery conservation zone in the NWHI from 1972 through 1977 (Table 4). The annual skipjack tuna catches ranged from 823 to 4,375 MT. Annual catches of some of the other tunas ranged from 20 to 337 MT for yellowfin tuna, and 71 to 734 MT for bigeye tuna. Albacore and bluefin tuna were, at times, caught only in small quantities. The annual catches made by these bait boats ranged from 964 to 5,619 MT.

It was reported that bait boats fishing within 200 miles of the NWHI made catches of 20 to 90 MT per day of mixed small skipjack, yellowfin, and bigeye tunas when fishing was good in May of 1977 and 2 to 4 MT per day when fishing was poor in June and July of 1977 (Tanaka, 1978). It was also reported that four to five bait boats fishing within 200 miles of the NWHI in May of 1979 made catches of 7 to 38 MT of mixed skipjack, yellowfin, and bigeye tunas per day, averaging 8 to 10 MT per day (Tanaka, 1980).

TABLE 4. ESTIMATED CATCH (METRIC TONS) BY JAPANESE BAIT BOATS IN THE NORTHWESTERN HAWAIIAN ISLANDS, 1972-77

Species	Year					
	1972	1973	1974	1975	1976	1977
Albacore	26	0	0	89	0	49
Yellowfin tuna	19	20	50	167	124	337
Bigeye tuna	105	109	147	71	92	734
Skipjack tuna	1,282	823	1,971	1,906	4,294	4,375
Bluefin tuna	26	0	1	25	0	0
Total tunas	1,458	952	2,168	2,258	4,510	5,495
Others	37	12	25	94	37	124
Grand total	1,495	964	2,193	2,352	4,547	5,619

Source: Data from Yong and Wetherall, 1980

NORTH PACIFIC ALBACORE FISHERIES

The North Pacific albacore fisheries extends throughout the North Pacific. The albacore landings made by Japanese longline

and surface (pole-and-line) fisheries, the North American fishery, and the total landings from 1961 through 1981 as presented by Majors et al. (1982) are shown in Figure 2. The catch figures are complete only up to 1979 for all fisheries.

The catches made by the Japanese longline fishery have not fluctuated very widely with a low of 10,000 MT in 1975 and a high of 29,000 MT in 1967. The Japanese longliners fish in the North Pacific subtropical zone during winter. It has been estimated that 40 percent of the catch (by number) is albacore (Laurs et al., 1981). The area where they operate centers on lat. 32°N and extends from 800 nmi off the coast of California westward across the Pacific. The total albacore landings fluctuated between 47,000 MT in 1962 and 124,000 MT in 1976 in the North Pacific and reflect the fluctuations of the Japanese surface catches which ranged from a low of 9,000 MT in 1962 to a high of 85,000 MT in 1976. The catches made by U.S. jig boats have fluctuated between 10,000 MT in 1977 and 25,000 MT in 1963.

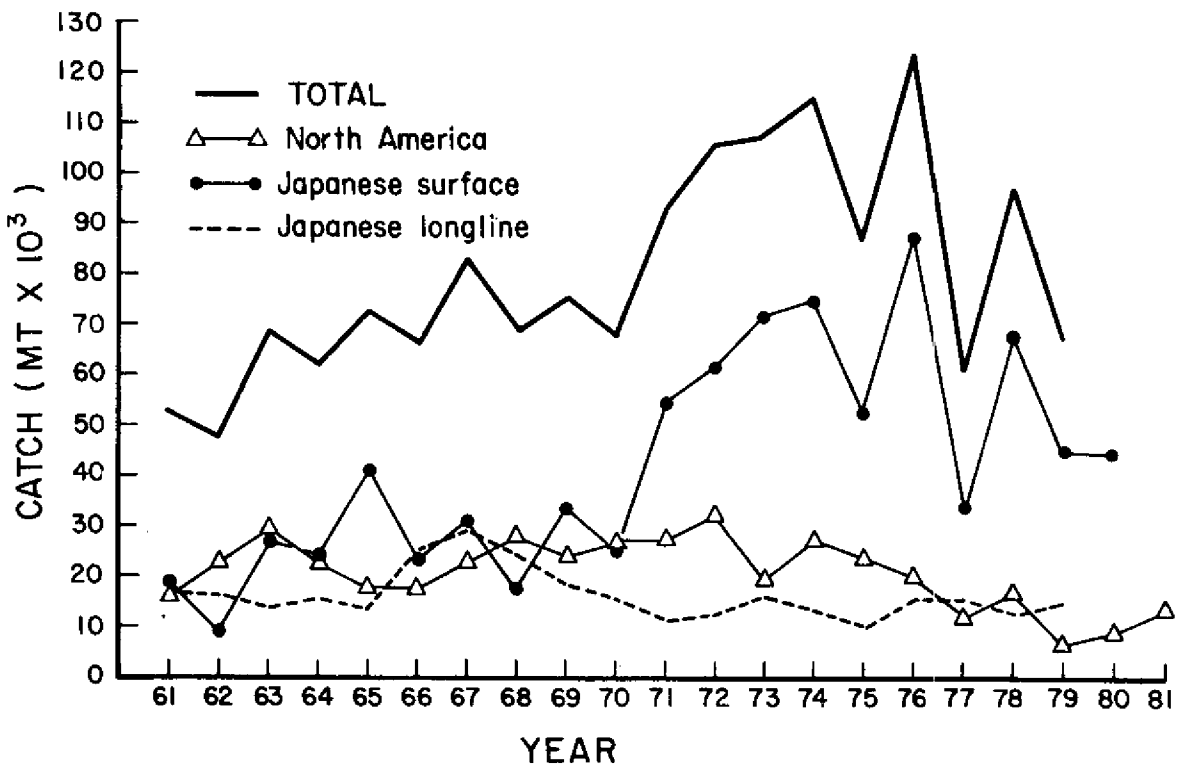

Figure 2. The total albacore catch in the North American and the Japanese longline and surface fisheries, 1961-81 (Majors et al., 1982)

In recent years, there has been increased interest by U.S. West Coast trollers to fish in waters northwest of Midway. The Pacific Tuna Development Foundation sponsored exploratory fishing surveys by West Coast trolling boats in areas northwest of Midway

from 1975 to 1978. The surveys showed that trolling for albacore in this area was practical for U.S. fishermen. In 1979, the state of Hawaii and a private seafood processor obtained a 1-year use permit from the Navy and organized a mother ship operation at Midway supporting 20 albacore trollers that fished to the northwest of the island. This undertaking resulted in a catch of 2,000 tons of albacore which was valued at more than $3 million.

The state attempted to organize support operations for the albacore trollers in 1980, 1981, and 1982 but were not able to do so. The albacore trollers, however, fished the area northwest of Midway in increased numbers and unloaded most of their catch in Dutch Harbor, Alaska.

In 1981, an estimated 47 albacore trolling boats fished in the area and landed an estimated 754 tons of mostly albacore in Honolulu (B.M. Ito, 1983: personal communication). This catch was made in 38 trips which gave a catch rate of 20 tons per trip. In 1982, about 54 boats fished in the area and landed their catch in Honolulu (B.M. Ito, 1983: personal communication). The catch from 73 trips amounted to 1,858 tons which gave a catch rate of 25 tons per trip.

In 1982, the Hawaii Legislature appropriated funds to do a feasibility study for establishing a Midway fishery support base. DAR was given the responsibility for implementing the project.

At the present time, about a dozen albacore trolling boats have left Honolulu and are headed for the fishing grounds to the northwest of Midway.

OTHER PELAGIC FISHERIES

One of the fisheries that is distant from the NWHI is a gill-net fishery for squid centered on the Emperor Seamount fishing grounds. The primary species is Ommastrephes bartramii. It was reported that 79 Taiwan gill-net vessels, 200 Japanese squid jigging vessels, and about 200 Japanese squid gill-netting vessels were fishing in August of 1981 (Suisan Sekai, 1981). The Taiwan vessels reportedly made good catches of 3 to 6 tons of squid per day.

The Japanese made a gill-netting survey from April 1979 to January 1980 in subarctic waters in the North Pacific for pomfret, Brama japonica, and salmon shark, Lamna ditropis (Japan Marine Fishery Resource Research Center, 1980-81). Catches on five cruises within that timespan included the following: pomfret, 247 MT; blue shark, Prionace glauca, 180 MT; albacore, 180 MT; and salmon shark, 86 MT. Total catch amounted to 806 MT.

Closer to Hawaii, a Japanese gill netter operating for 29 days within 200 miles of the NWHI during February and March caught 57 striped marlin, 12 swordfish, 872 albacore, 2,191 skipjack tuna, 331 mahimahi, 659 pomfret, 152 amberjack, Seriola

sp., 682 squids, 32 sharks, and 23 bigeye tuna (NMFS unpublished data).

A Japanese gill-net fishery for North Pacific albacore, which made nominal catches of between 1,000 and 4,000 MT per year since its inception in the early 1970s up until 1980, caught an estimated 15,000 to 20,000 MT in 1981 (Bartoo and Kume, 1982).

CONCLUSIONS

This review shows that pelagic fisheries resources in the NWHI area have been utilized by Japanese bait boats and long-liners. It also shows that U.S. West Coast trollers are increasing effort to harvest albacore and possibly other species in the area.

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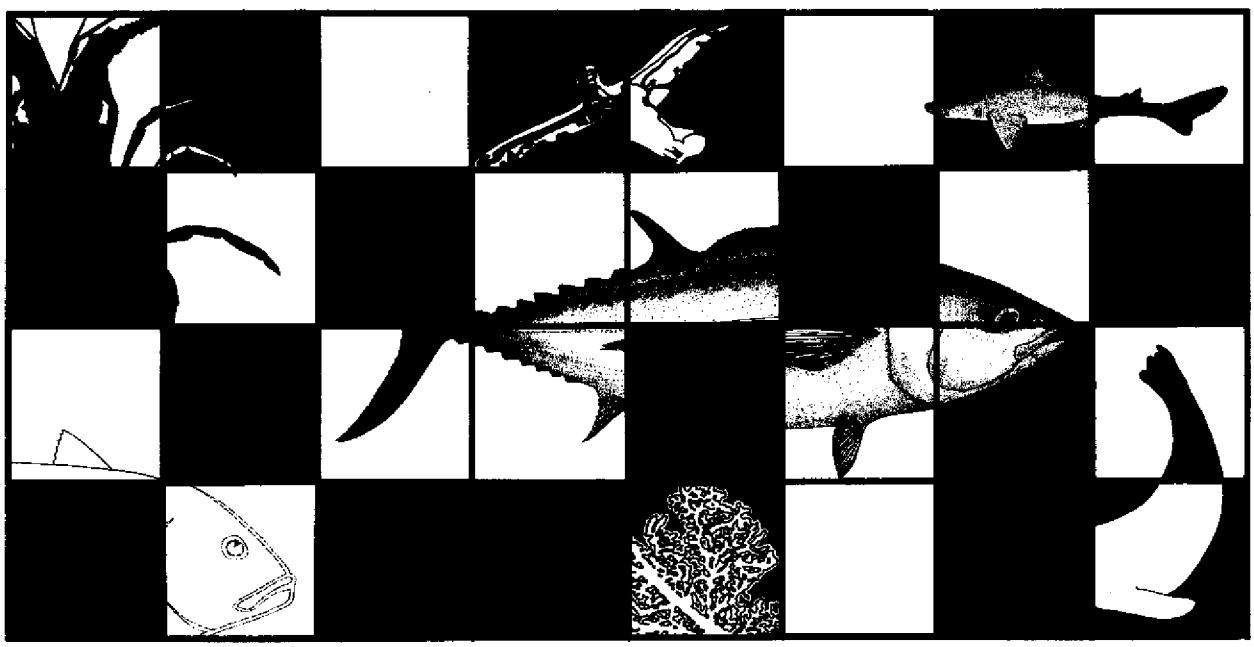
Productivity and Ecosystem Modeling



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ECOLOGY AND PRODUCTIVITY OF CORAL REEFS IN THE HAWAIIAN ARCHIPELAGO

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EXPANDED ABSTRACT

Coral reefs provide habitat (food and shelter) for a variety of nearshore commercially important species (lobsters, reef fish, etc.), as well as species which are threatened or endangered (the Hawaiian green sea turtle and the Hawaiian monk seal). Corals also provide the building blocks for structures which protect all the islands from the erosive effects of storm waves. For these reasons, a major objective of the tripartite-Sea Grant 5-year study was to analyze the basic processes important in the development of corals and reef structures throughout the Hawaiian Archipelago.

Extensive surveys were conducted on all major islands in the chain. The results highlight the significance of coral reefs in terms of island formation and habitat. Were it not for coral reefs, the Hawaiian Archipelago would end at Gardner Pinnacles, approximately 600 miles shorter and five major islands fewer than the present chain. All of the islands north of Gardner Pinnacles are built entirely of calcium carbonate, including Laysan, Lisianski, Pearl and Hermes, Midway, and Kure. Since all islands in the chain are gradually drifting to the northwest and sinking, were it not for coral growth the northern islands would all have "drowned" near the latitude of Gardner Pinnacles millions of years ago. Instead, corals and other calcifying organisms have built reefs which have kept pace with sinking and erosion, maintaining the northern islands at sea level at least to the latitude of Kure Atoll (29°N). Measurements of reef development due to corals across the archipelago show that at Kure Atoll this rate is only about 2 percent of the rate at the

southeastern end of the chain. Because all "islands" northwest of Kure Atoll have drowned, the rate of reef development at Kure approximates the threshold rate necessary for atoll development. This threshold has been dubbed the Darwin Point and explains why the Hawaiian Archipelago ends where it does.

Coral reefs also provide habitat for numerous associated species on all the Hawaiian islands. The species composition of corals on all reefs in the archipelago was found to be remarkably uniform. Although the fauna is depauperate due to isolation from the Indo-West Pacific, coral species which are present in Hawaii are apparently generalized ones. Their uniform patterns of distribution throughout the chain suggest that most have wide tolerance ranges and are characterized by high fecundity and/or long-lived larvae (i.e., high rates of interisland recruitment).

In contrast with uniform patterns in species composition, patterns of abundance of all corals exhibit highly patchy distributions. This appears to be a result of unpredictable disturbance events. On exposed coastlines the most important source of disturbance was found to be long-period swell. Thus, differences in community structure between all islands appear to be a function of differences in successional age due to different historical patterns of recent disturbance. This finding provides strong support for Connell's Intermediate Disturbance Hypothesis as the major force maintaining diversity and controlling community structure of shallow marine ecosystems in general.

Rates of reef development, species composition, and community structure of coral reefs are important determinants of habitat for a number of associated species of commercial or environmental significance. Coral reefs are also of vital importance in terms of trophic dynamics (food requirements of associated species). Measures of primary productivity of algae and corals at French Frigate Shoals during both winter and summer periods demonstrated that production is sufficient to support all levels of the atoll ecosystem. The average gross production to respiration ratio (P:R) of all benthic ecosystems of the atoll turned out to be about 1.10.

Average net primary production at French Frigate Shoals integrated over the year and averaged for various habitats turned out to be about 6.1×10^6 kg (wet biomass)/ km^2/yr. This figure roughly corresponds to the estimate produced by the ECOPATH model for French Frigate Shoals (4.3×10^6 kg). Considering the numerous

sources of error that go into developing both reef productivity and model estimates, the degree of agreement is surprisingly good. This agreement suggests that the model is probably a very good approximation of the real ecosystem at French Frigate shoals and can be used as a management tool to qualitatively predict the impacts of man-induced perturbations such as those that would be produced by directed fisheries.

reef development	Darwin Point
species composition	productivity
community structure	fisheries yield

Note: A full-length conference paper was delivered at the symposium; however, only an expanded abstract appears here to avoid duplication with other published work. Reference to the paper(s) can be found in the "Abstracts of Published Papers" section in Volume 2 of this proceedings.

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PRIMARY PRODUCTIVITY, THE CYCLING OF NITROGEN, AND SPATIOTEMPORAL VARIABILITY IN COMPONENTS OF THE EPIPELAGIC ECOSYSTEM IN HAWAIIAN WATERS

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ABSTRACT

The transport fluxes, cycling, and variability in organic nitrogen and carbon of both dissolved and sestonic components in epipelagic Hawaiian waters were studied to improve the understanding of time-space changes in the lower trophic components of an oceanic food web, and elucidate principal factors which determine the levels of primary carbon fixation and plankton stocks in this region of the tropical ocean. In seasonal oceanographic surveys of Hawaiian waters in 1979, relatively strong uniformity of both abiotic and biotic variables were found between Midway Islands and the island of Hawaii, with low variability of properties in both space and time. Only slightly higher levels (ca. 10 to 40 percent) of plankton stocks and daily primary productivity were observed in the Northwestern Hawaiian Islands (NWHI) compared with the major Hawaiian islands by subarea. Since this initial study, results from intensive time series observations in 1980-81 at inshore stations (locations within 20 km of shore) at Kawaihae, Hawaii and French Frigate Shoals (FFS) in the NWHI have essentially confirmed the notion that the tropical oceanic ecosystem within the epipelagic zone operates under quasi-steady state conditions with respect to the major nitrogen fluxes and components measured. However, these inshore stations were found to have daily rates of organic carbon and nitrogen formation averaging 67 percent higher (ca. 150 versus 90 mgC $m^{-2}d^{-1}$) than values previously measured along the Hawaiian Archipelago in 1979, and waters off French Frigate Shoals are about twice as productive as those

at Kawaihae Bay (ca. 200 versus 120 mgC $m^{-2}d^{-1}$). In addition to these comparisons of inshore subregion productivity along the archipelago, the 1980-81 studies enabled the construction of a vertical and inter-compartmental mass flux balance model for various key nitrogen components of the epipelagic zone. The measured vertical fluxes of particulate matter in traps near the base of the euphotic zone suggest that only about 14 percent of the daily particulate organic nitrogen (PN) formed by plants is lost from that zone via sinking. Most of this PN is in the form of zooplankter fecal pellets and other fine particulate detritus, with only a negligible fraction being lost from this zone as live plant biomass (chlorophyll *a*). The results of the model study show that more than 80 percent of the uptake of dissolved fixed inorganic nitrogen by the phytoplankton is from regenerated sources as excretions from animals and activities of microbial populations. The major factors controlling daily primary productivity levels are the vertical eddy diffusive flux of "new" nitrogen in the form of nitrate through the nitracline, and the highly complex interactions among vertical mixing, solar quantum flux, the nitracline gradient, and rates of nitrogen uptake by plants in relation to consumption by grazers. This study of nitrogen cycling in the tropical ocean demonstrates the need for more information about the stocks and excretion rates of larger nekton and micronekton, the dynamics of particulate detritus-microbial interactions, and the turnover of dissolved organic nitrogen pools.

Time series studies in 1980-81 in the nearshore lagoon and backreef region at French Frigate Shoals suggest that currents and an inferred physical mixing mechanism most likely account for the observed spatial distributions of water properties, plankton stocks (especially their concentrations, patchiness, and variability compared with like offshore oceanic data), and enhanced daily primary productivity on a unit volume basis. At FFS levels of daily primary productivity per unit area for the water column are nearly the same (ca. 200 mgC $m^{-2}d^{-1}$) for the nominal 20-m photic zone of the lagoon (water depths less than about 30 m) as well as the outer more oceanic water with a 175-m photic zone over deep water. This means that the lagoon water is nearly an order of magnitude more productive per unit volume of water, and that this enhanced productivity most likely is being derived from nutrient infusions into the lagoon by the prevailing circulation of trade-winds and tides interacting with the atoll platform, or nutrients regenerated from the benthic community, or both. Since the daily (net) primary productivity of the water column at FFS is nearly the same for all

regions on a unit area basis in water deeper than 10 m, this simplifies the computations for the potential food supply to and secondary production by higher level consumers such as planktivorous fishes. A production level of 200 mgC $m^{-2}d^{-1}$ is equivalent on a live biomass basis to 0.9 x 10^6 kg $km^{-2}yr^{-1}$ (using a live biomass/carbon ratio of 12). This would potentially make available 450 x 10^6 kg yr as net phytoplankton production in the offshore region over the 55 to 365-m isobath zone, and 270 x 10^6 kg yr^{-1} for the nearshore lagoon region over the 18 to 55-m isobath zone. The total potentially harvestable planktivorous fish production in this nearshore lagoon region of about 300 km^2 is estimated to be the order of 10^5 kg live biomass per annum.

Hawaiian waters
primary productivity
nitrogen cycling and fluxes
spatiotemporal variability of nitrogen
secondary production of planktivorous fish

INTRODUCTION

In previous oceanographic surveys of waters along the Hawaiian Archipelago, relatively uniform distributions of water properties, plankton abundances, and *in situ* primary productivity have been observed with only slightly higher average levels (ca. 10 to 40 percent) being found in the Northwestern Hawaiian Islands subarea compared with the main Hawaiian islands (Figure 2, Tables 1 and 2 in Hirota et al., 1980). Despite this relative uniformity along the archipelago, some significant differences in mixed layer depth, C/N ratio of seston, and larval fish occurrences were noted between subareas. Since these surveys were carried out in both winter (April) and summer (June-July) at several stations over a substantial area, it was presumed that the variability observed included small-scale patchiness in distributions of properties within stations and analytical errors.

Temporal variability in stocks of plankton and primary productivity in tropical oceans (excluding regions of divergences and upwelling) generally shows low amplitude, irregularly patterned fluctuations (Blackburn et al., 1970; Heinrich, 1962; Hirota et al., 1980; Owen and Zeitschel, 1970; Sournia, 1969) presumed to be associated with short-term weather variations; however, day to day variations exceeding a factor of two or three are also observed and may be attributed to fluctuations in recycled nutrients supply (Bienfang and Szyper, 1981; McCarthy and Goldman, 1979). Despite relative constancy in the physical-chemical habitat and relatively low seasonal changes in plankton abundances of tropical ocean areas suggestive of nearly steady-state ecosystem dynamics, the biotic complexity of tropical systems, vertical gradients of important parameters (light,

nutrients, plant pigments, etc.), and "input" problems in measuring low nutrient fluxes have largely precluded attempts to construct and quantify a preliminary nitrogen cycling model for the epipelagic zone. Some of the best descriptions of shallow tropical ocean production dynamics can be found in Eppley et al. (1973), Eppley and Peterson (1979), Eppley et al. (1979), and Herbland and Voituriez (1979).

The principal purpose for the research described below is to examine the time-space scales and levels of variability in the various key structural components and daily fluxes of nitrogen important for its cycling in epipelagic Hawaiian waters off Kawaihae Bay and French Frigate Shoals. Emphasis in the overall research effort was placed on the study area at French Frigate Shoals because of its importance as a wildlife refuge and as the focal point of an entire atoll ecosystem model for the reef, lagoon, and adjacent waters. Secondary goals included comparisons of productivity levels between subareas; determinations of the transitions or linkages, if any, between offshore oceanic water and nearshore lagoon water at French Frigate Shoals possibly due to an island mass effect (Gilmartin and Revelante, 1974); and a limited study of scad mackerel (akule, Selar crumenopthalmus) abundance, estimated growth rate, and secondary production and the total potential harvest of planktivorous fish in the water column at French Frigate Shoals.

METHODS

The field sampling effort of the present study was divided into two parts: (1) offshore research at Kawaihae Bay and French Frigate Shoals, which emphasized work on in situ primary productivity, nitrogen components and fluxes, and the hypothesized steady-state dynamics of mineral cycling in the epipelagic zone of Hawaiian waters as inferred from time series measurements at fixed stations; and (2) nearshore coastal water research in the northwestern quadrant of the lagoon at French Frigate Shoals, which was directed toward a comparison of primary productivities and plankton stocks between offshore and nearshore areas, distributions of water properties, and the secondary production by planktivorous fish. The offshore research was carried out aboard two cruises of the National Marine Fisheries Service (NMFS) R/V Townsend Cromwell from August 16 to September 3, 1980 and from May 12 to 29, 1981. The nearshore field work based at Tern Island, French Frigate Shoals was completed during September 3 to 13, 1981. The three station locations for the offshore time series measurements were 20° 0'N, 156° 0'W (Kawaihae Bay) and 23° 38'N, 166° 18'W and 23° 48'N, 166° 21'W (French Frigate Shoals).

The measurements of seawater and hydrographic properties (temperature, salinity, sigma-t, inorganic plant nutrients), incident and submarine quantum flux, suspended particulates and plankton stocks (total particulate nitrogen and carbon, chlorophyll a and phaeo-pigments, macrozooplankton and microzooplankton), and daily primary productivity all were made following the

procedures and methods given by Hirota et al. (1980). The principal new measurement added to the set of observations being made during each of three offshore, time series stations occupied is the vertical particulate matter flux from deployment of timed, automatically closing traps based on the design of Shuman (1978). Pairs of these traps were taut moored for 3 to 5-day periods at approximately 200 and 350 m in water over 600 m deep. Particulate matter data collected from these trap samples, the mouth area (.0184 m^2) of each trap, and the deployment period were used to measure the downward fine particle flux of nitrogen. At steady state nitrogen must be replaced by vertical eddy diffusive transport of "new" inorganic nitrogen principally as nitrate (Eppley and Peterson, 1979; Eppley et al., 1979). From all of the measured components of particulate and dissolved nitrogen, two principal fluxes (uptake by phytoplankton and vertical transport due to sinking), and literature values to fill in needed missing data (e.g., size-specific and temperature-specific zooplankter excretion rates, stocks of micronekton and nekton), a proposed two-layer vertical and intercompartmental nitrogen mass balance model was constructed. Two specific limiting assumptions of the model are that steady states exist for uptake and supply of dissolved organic nitrogen (DON) and that allochthonous inputs to the ecosystem such as nitrate in rainfall and nitrogen fixation are small compared with the fluxes measured.

Transect sampling for the horizontal distributions of water properties and plankton stocks was carried out at French Frigate Shoals between the two offshore stations and La Perouse Pinnacle (ca. 23°46'N, 166°16'W). Surface sampling, hydrographic casts, and vertical plankton net tows were taken in the upper 200 m or from just above the bottom, whichever depth was shallower. Primary emphasis was given to the determination of spatial patterns in nitrate + nitrite, chlorophyll _a_, and zooplankton concentrations. From these patterns it was determined where the transition occurs between oceanic and coastal waters, and what mechanism(s) account for the maintenance of the observed spatial patterns.

Research of nearshore lagoon waters at French Frigate Shoals included the following measurements: (1) velocity of currents from tracking of drogues; (2) distributions of temperature, nutrients, chlorophyll _a_, macrozooplankton stock, and levels of _in situ_ primary productivity; and (3) abundance, growth rate, and secondary production of akule and total potential harvest of planktivorous fish based on Ryther's (1969) method of primary productivity and an assumed 10 percent food chain efficiency. Weighted drogues made of parachute nylon formed as two intersecting planes (ca. 1 m^2 each) were set at depths of 2 to 3 m, each being attached through a flat surface float to a supporting flagpole. Positions of groups of three drogues per deployment were determined by triangulation to landmarks using a sextant and hand compass at periods of 1 hour or more during about 6 hours in daylight. The distributions of seawater

properties given above were determined on three dates by surface sampling along transects from a skiff. Horizontal control points were previously determined by mooring four bouys in places forming a trapezoid with La Perouse Pinnacle and Tern and Shark Islands. Analyses of these samples for nutrients, chlorophyll *a*, surface macrozooplankton, and *in situ* daily primary productivity are essentially the same as given in Hirota et al. (1980), except that primary productivity was measured during daytime incubations dockside at Tern Island using seawater samples collected just after sunrise from six different stations around the lagoon and backreef areas of Tern, Trig, and Shark Islands and La Perouse Pinnacle. Estimates of daytime akule stocks were made by Mr. Louis Agard, Jr. (a commercial fisherman and fish spotter) during aerial reconnaissance of the entire French Frigate Shoals atoll on August 10 and September 1, 1981 within shallow depths to about 20 m. Growth rate was estimated for akule juveniles and adults from counts of "ring" increments on otoliths dissected from fish collected at French Frigate Shoals by hook and line and around Oahu, Hawaii for other sizes expanding the range of data. Daily and annual weight-specific growth rates for the akule were calculated assuming that the otolith increments are daily markings. Secondary production was calculated as the product of growth rate times the stock, assuming that fish in schools are 100 to 600 g live weight sizes and that the stock remains steady over time.

RESULTS

Typical vertical profiles of water column properties from the time series measurements at Kawaihae Bay indicate a shallow mixed layer, with depths of the euphotic zone (1 percent Q_o, surface quantum flux), top of the nitracline, and subsurface chlorophyll *a* maximum layer (CML) all coinciding between approximately the 100 and 125 m depth (Figure 1). Although daily carbon fixation rates tend to decline sharply by a factor of three to four within the euphotic zone, note that a significant amount of productivity occurs down to the 100 m depth. Particulate nitrogen levels show no trend with depth until they drop off below the CML, but not as rapidly as does chlorophyll *a*.

The combined data from time series measurements in both years and all three stations indicate levels of variability in parameters from within station replicate observations and short periods of a few days at one place, to between station and interannual variability of nutrients and nitracline structure (Figure 2), various seston components and levels of daily primary productivity (Figures 3 to 6). These data indicate that the dissolved "new" inorganic nitrogenous nutrients and total particulate nitrogen are temporally and spatially consistent in their pattern of distributions with low variability. For example, the average depth at the top of the nitracline (Z_N=0) is 84 to 111 m and the nitracline gradient is essentially 0.03 mg-at N $m^{-3}m^{-1}$; levels of total particulate nitrogen integrated over the upper 200 m of the epipelagic zone are about 1.0 ± 0.25 gN m^{-2}, independent of time

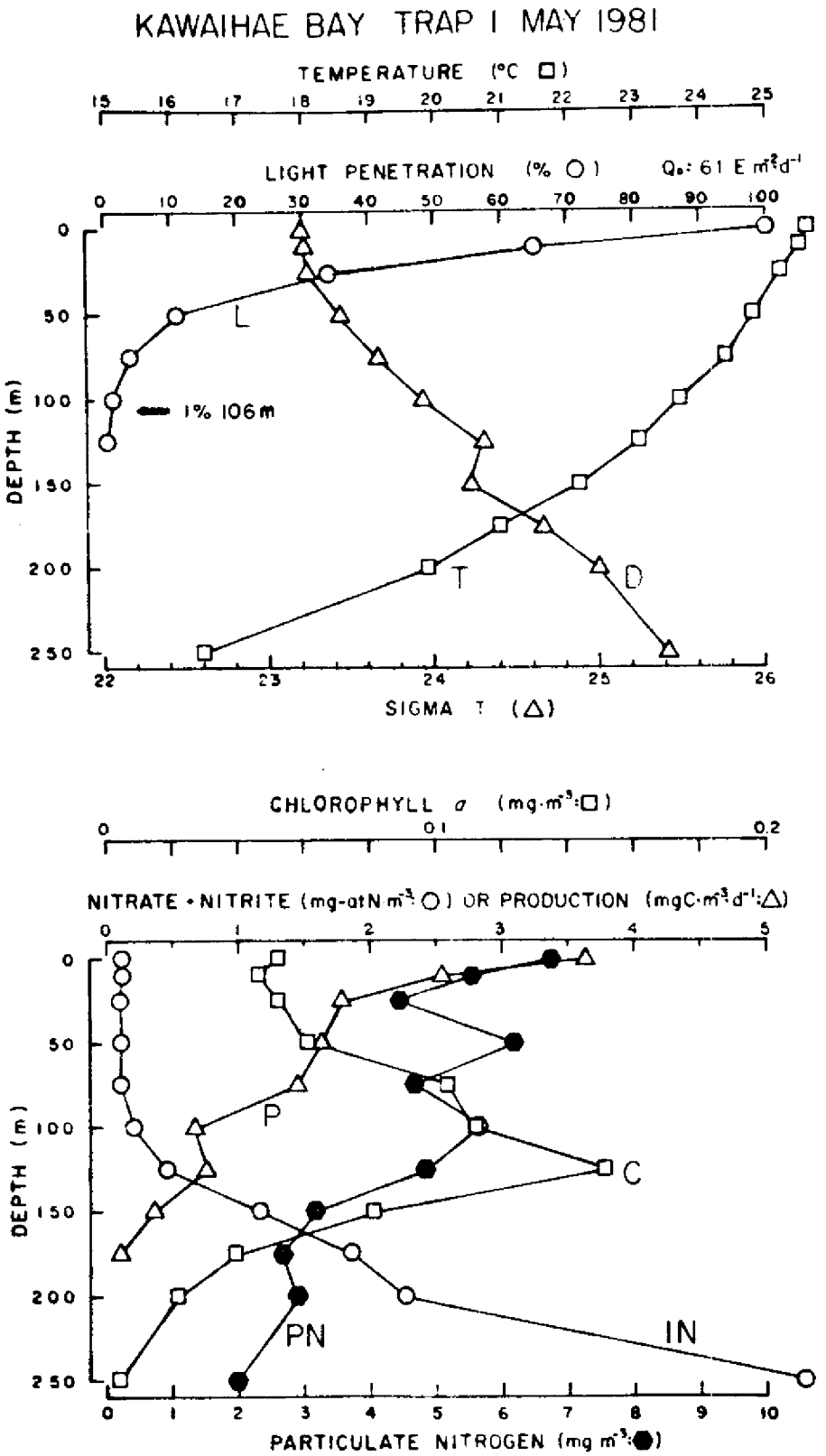


Figure 1. Typical vertical profiles of water column properties and primary productivity at Kawaihae Bay, May 12-16, 1981

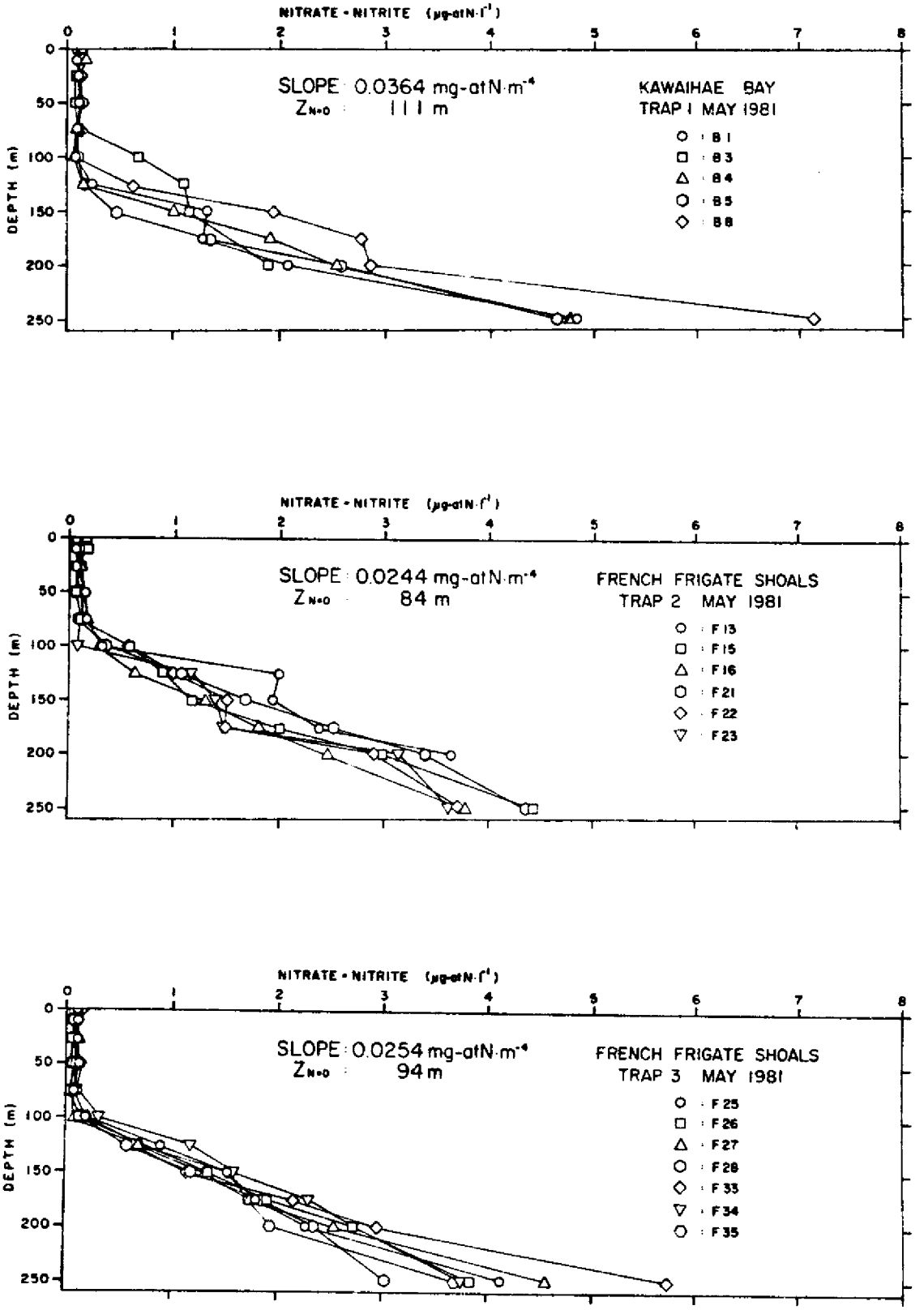


Figure 2. Time series profiles of nitrate + nitrite in May 1981; each symbol type represents a hydrocast, Z_N is nitracline top in m

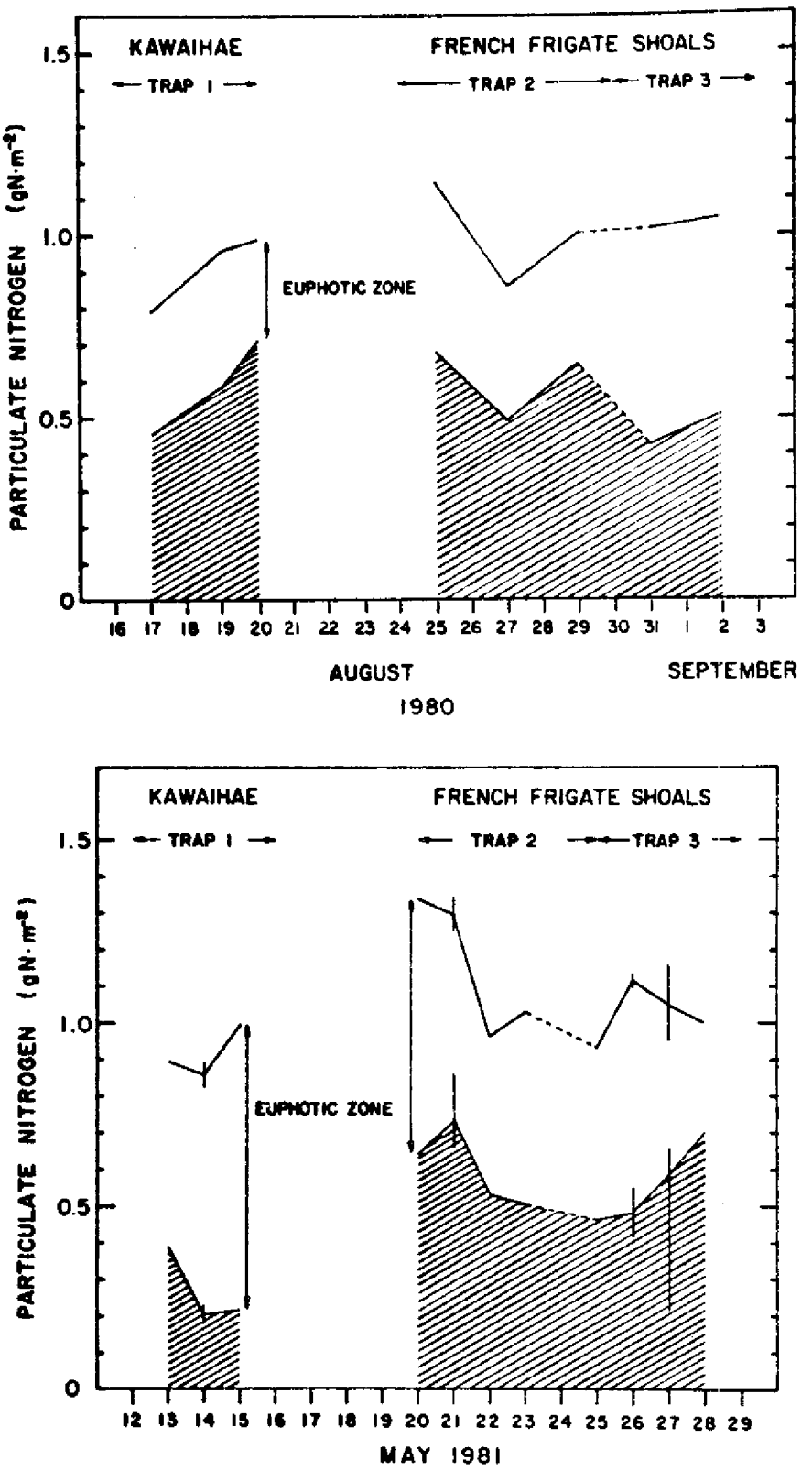


Figure 3. Variability of particulate nitrogen in the upper 200 m and euphotic zone (1 percent Q_0); vertical bars show ranges

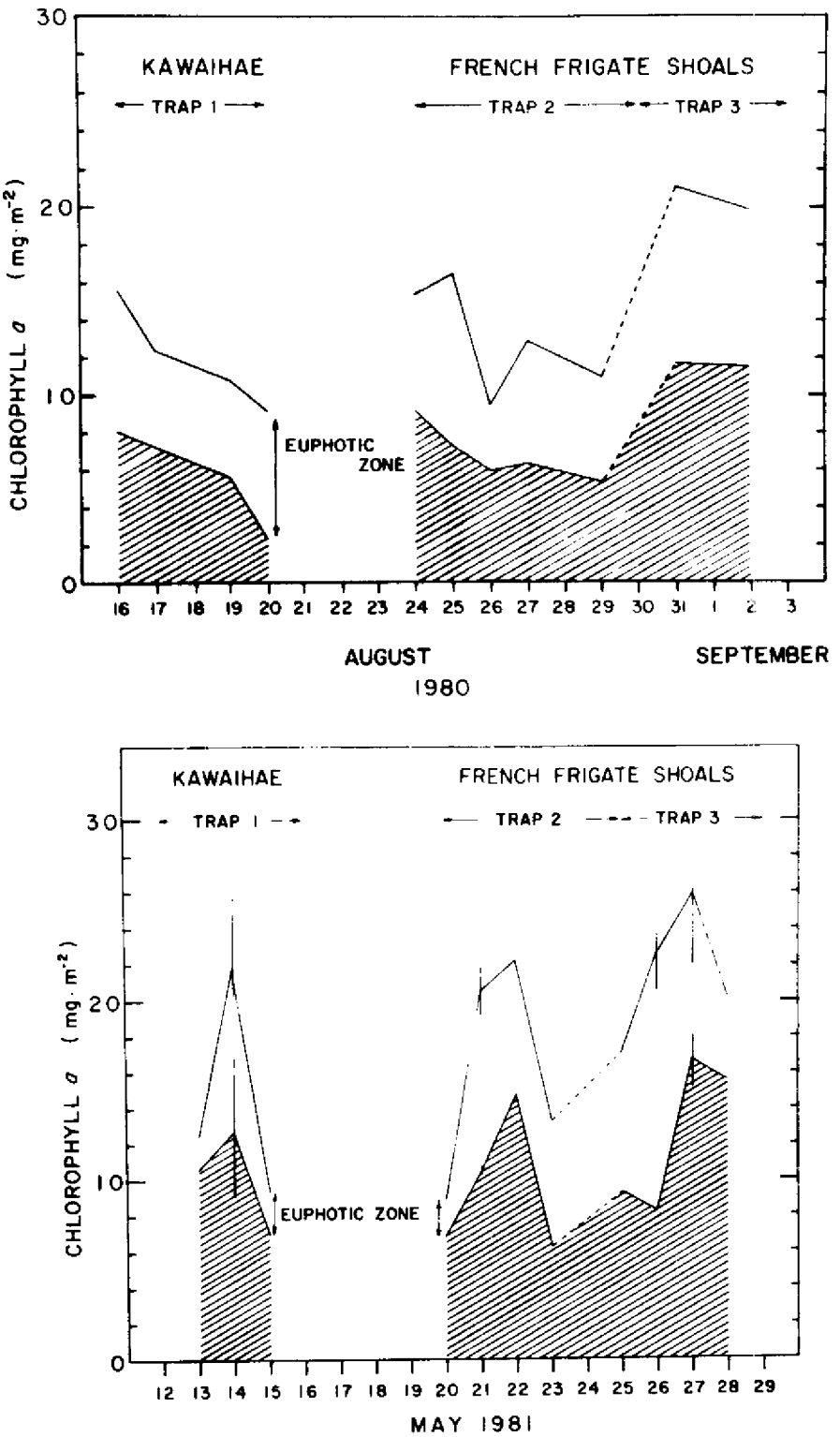
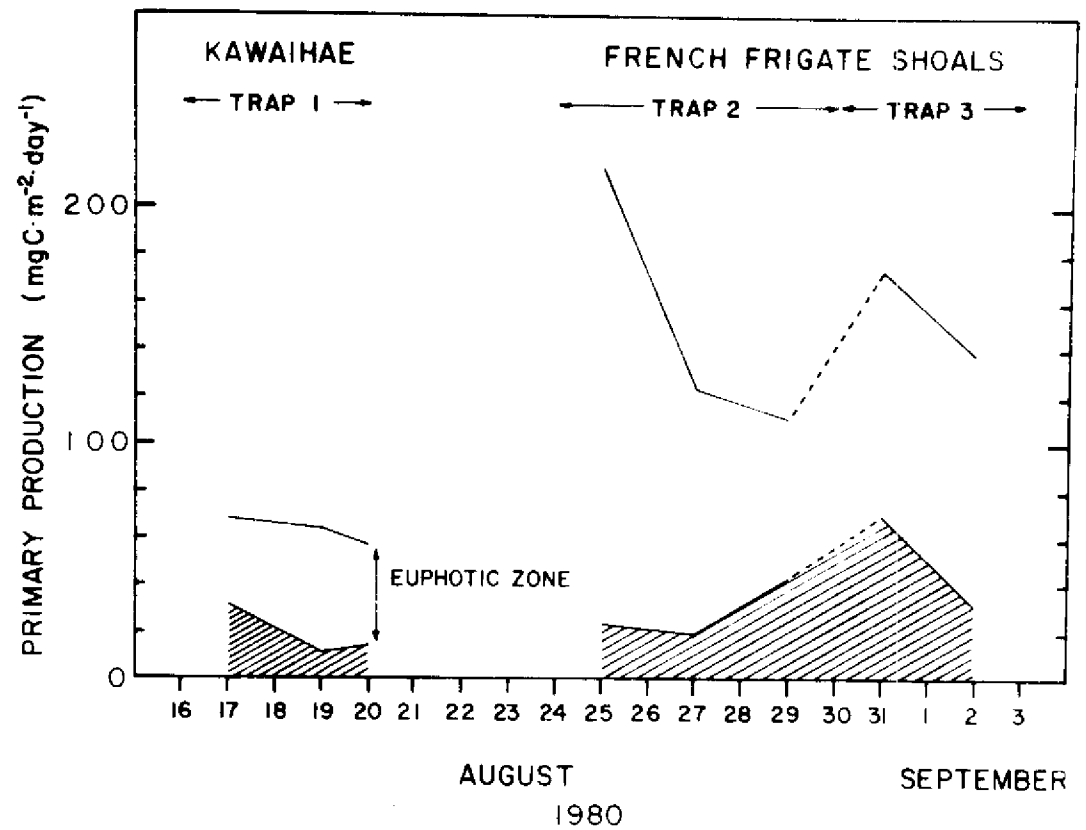


Figure 4. Variability of chlorophyll a in the upper 200 m and euphotic zone (1 percent Q_o); vertical bars show ranges



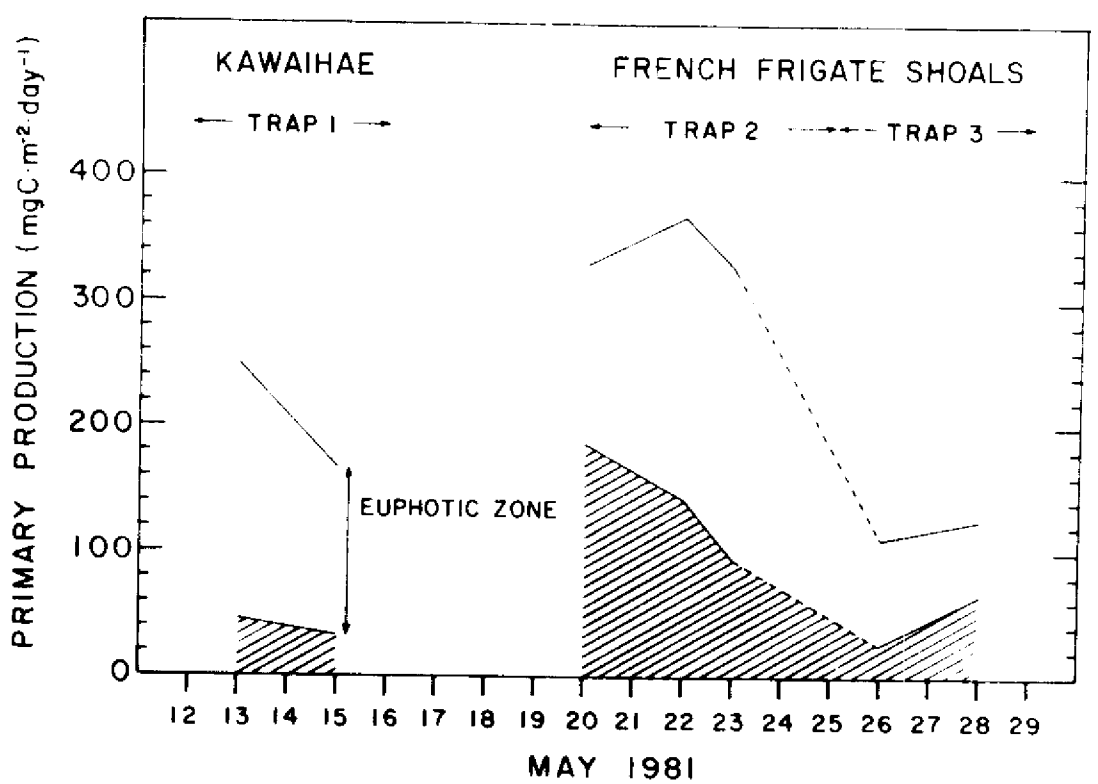


Figure 5. Variability of daily primary productivity in the upper 200 m and euphotic zone (1 percent Q_0); each value is based on nine depths and three replicates per depth

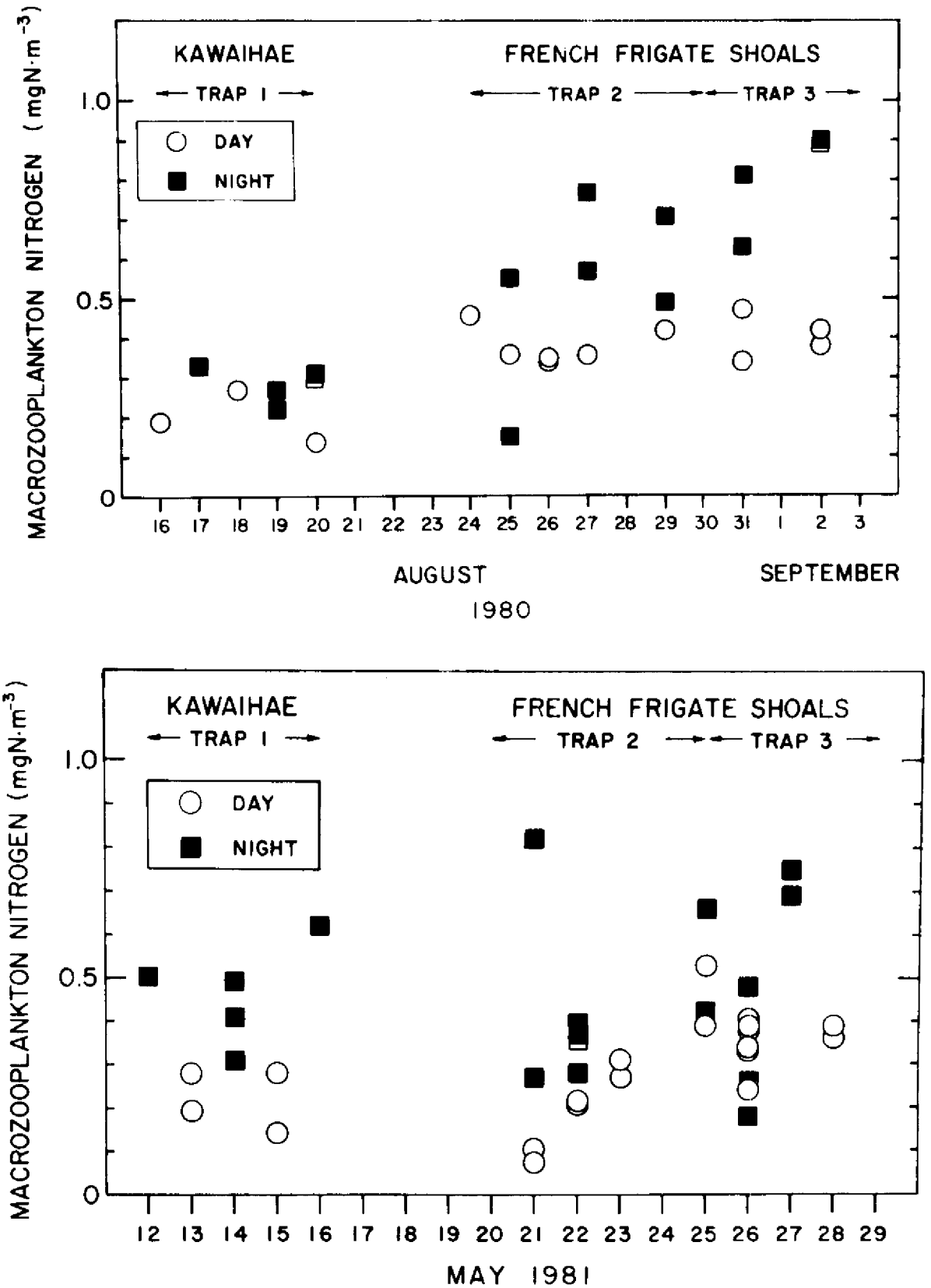


Figure 6. Variability in concentrations of macrozooplankton nitrogen for day and night vertical tows from 200 m

or location, with roughly equal amounts above and below the euphotic zone depth (Figures 2 and 3). Depth-integrated water column amounts of chlorophyll *a* (Figure 4) and *in situ* daily primary productivity (Figure 5) are more variable than the nitrogen data, especially the 1981 pigment values. However, for these measures of phytoplankton stock and carbon assimilation, the absolute range for all station data is a factor of about three, and average levels are about 17 ± 7 mg m^{-2} and 150 ± 90 mgC $m^{-2}d^{-1}$ for chlorophyll *a* and carbon fixation rates, respectively (Figures 4 and 5). Concentrations of macrozooplankton in the upper 200 m (Figure 6) showed nighttime values exceeding daytime ones by 50 to 100 percent, with very low replicate tow variance (except for one pair of nightime tows on May 21, 1981). The overall average day/night macrozooplankton stock is 0.45 mgN m^{-3} or 90 mgN m^{-2}, with a range from 0.1 to 0.9 mgN m^{-3} for approximately 70 tows.

The flux of particulate matter in the upper 200 m from measurements on particle trap collections and as daily primary productivity is summarized in Figure 7. These results show that

UPPER 200-M CARBON & NITROGEN FLUX

Location	Experiment	Primary Production Carbon ($mg \cdot m^{-2} \cdot d^{-1}$)	Primary Production Nitrogen ($mg \cdot m^{-2} \cdot d^{-1}$)	Trap Depth (m)	Chlorophyll	Z-Flux Phaeopigments ($mg \cdot m^{-2} \cdot d^{-1}$)	Z-Flux Carbon ($mg \cdot m^{-2} \cdot d^{-1}$)	Z-Flux Nitrogen ($mg \cdot m^{-2} \cdot d^{-1}$)	% Carbon of Production (%)
				AUGUST-SEPTEMBER 1980					
Kawaihae Bay	Trap 1	63 (3)	9.0	215	0.002	0.046	35.5	3.78	56
French Frigate Shoals	Trap 2	153 (3)	21.8	200	0.005	0.026	37.1	3.37	24
	Trap 3	156 (2)	22.3	200	0.011	0.213	45.9	5.33	29
				MAY 1981					
Kawaihae Bay	Trap 1	208 (2)	29.7	181	0.0 (U.D.)	0.035	16.4	2.47	8
French Frigate Shoals	Trap 2	341 (3)	48.7	143	0.034	0.113	70.0	2.59	20
	Trap 3	119 (2)	17.0	171	0.004	0.081	35.1	2.09	29
	Median	150	22		0.004	0.064	36.3	2.98	25
	Range	63-341	9-49		0-0.034	0.026-0.213	16.4-70	2.1-5.3	8-56

Figure 7. Summary of carbon, nitrogen, and plant pigment fluxes at Kawaihae Bay and French Frigate Shoals in 1980 and 1981; carbon production rates are means of 2 to 3 values (N) and nitrogen rates are assumed to be one seventh of the carbon rates

primary carbon fixation accounts for an average (median) of 150 mgC $m^{-2}d^{-1}$, with average trap flux of 36.3 mgC $m^{-2}d^{-1}$ or 25 percent of carbon production settling out of the euphotic zone daily. The corresponding values for particulate nitrogen are 22 mgN $m^{-2}d^{-1}$ assimilated (assuming a C/N uptake ratio of 7), 2.98 mgN $m^{-2}d^{-1}$ lost as downward transport, which equals 14 percent daily loss rate as a percentage of nitrogen formation. The relatively high C/N ratio in the trap material of 12:1 by mass suggests that the nitrogen is conserved relative to carbon by roughly 50 percent over the average C/N ratio of 8 for water column particulates (Hirota et al., 1980). Moreover, inspection of the chlorophyll *a* and phaeopigment particulate fluxes as measured in trap samples indicates that no significant amounts of live phytoplankton as chlorophyll *a* are lost from the euphotic zone via sinking on a daily basis. Instead, more phaeopigments than live chlorophyll *a* by sixteenfold are lost from the upper water column, most probably in the form of fecal pellets and other detrital flocs. From these observations the picture emerges that on a daily basis only 1/7 to 1/4 of the primary formation rate of nitrogen and carbon are lost from the euphotic zone via gravitational settling, and roughly 85 percent of the apparent utilization of nitrogen by phytoplankters is as regenerated forms (ammonium, urea). The data also show that only about 0.3 percent of the total particulate nitrogen and 0.02 percent of the total chlorophyll *a* are lost from sinking through the 200 m depth horizon on a daily basis, indicating very small loss rates and excellent retention of (fine) particulate seston in the epipelagic zone.

A simplified, conceptual, and time-space averaged mass balance model for nitrogen with a two-layer tropical ocean epipelagic zone is proposed from the measurements of "compartment sizes" and vertical fluxes of materials (Figure 8). The two-layer system is divided into the upper mixed layer of ca. 100 m and the lower nutricline zone. Explicitly, the rather difficult problems of dissolved organic nitrogen (DON) forms (except for urea excretion) and fluxes and rates of nitrogen fixation (N_2-fix) were not considered in this study. The particulate matter stocks indicated within the compartment boxes represent phytoplankton (P_N assuming a nitrogen/chlorophyll *a* ratio of 10), macrozooplankton plus microzooplankton (ZF), micronekton plus nekton (M+N), and "residual" particulate detritus and microbial heterotrophs (PN_R is given as organic detritus, D; bacteria, B; and other unspecified microheterotrophs, μH). Values for day/night mean micronekton stocks are from Maynard et al. (1975) and nekton are estimated from skipjack tuna catch rates in Hawaiian waters assuming that stock equals annual landings (see discussion in Hirota et al., 1980). The daily nitrogen fluxes between compartments and in the vertical direction at steady state are:

1. Phytoplankton production (P) being ingested (I) by macrozooplankters and microzooplankters at rates of 22 mgN $m^{-2}d^{-1}$

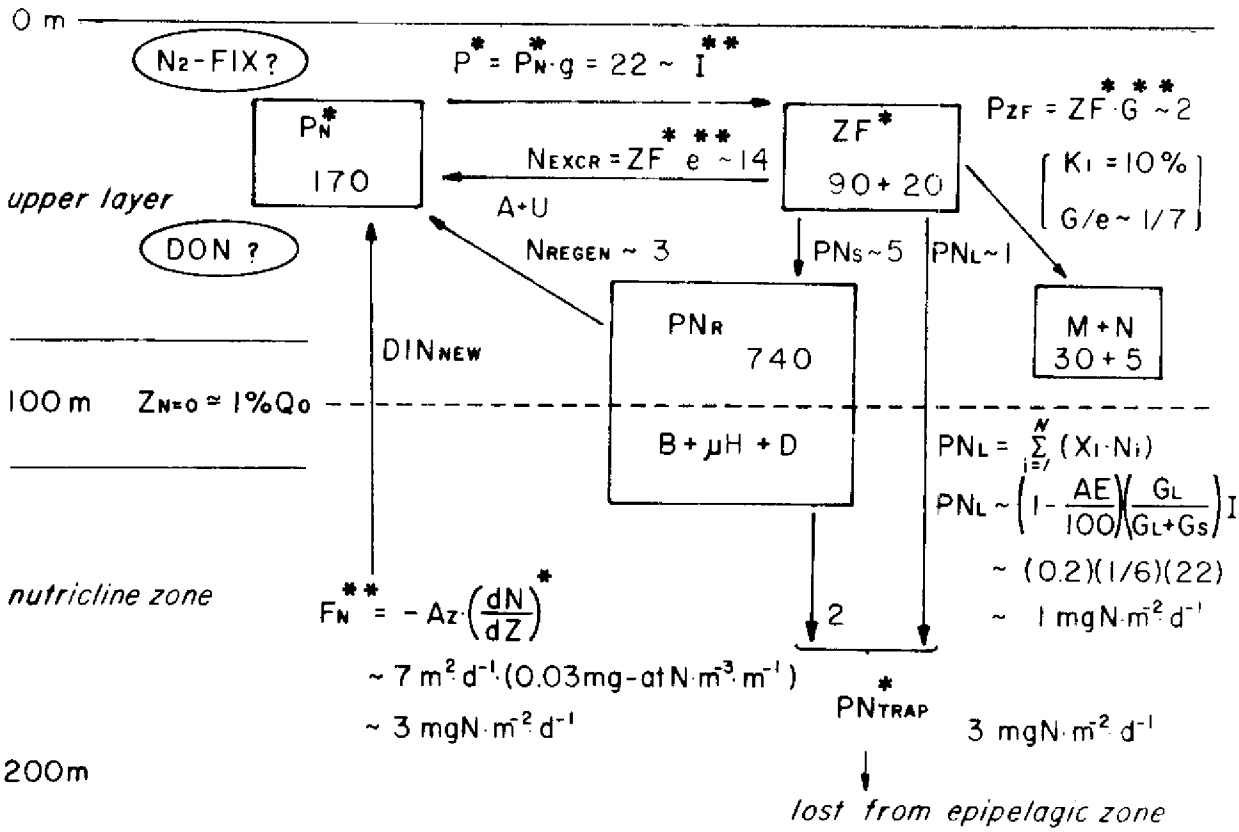


Figure 8. Proposed nitrogen components (boxes, mgN m^{-2}) and daily flux (mgN $m^{-2}d^{-1}$) mass balance model for the epipelagic zone in Hawaiian waters based on direct observations (*) and literature or assumed steady-state values (**); refer to the text for details and parameter definitions

2. Nitrogen excretion (Nexcr) as ammonium plus urea (A+U) from the macrozooplankters and microzooplankters equals the stock, ZF, times the mass specific excretion rate of A+U on a daily basis, e, (Mullin et al., 1975; Ikeda and Motoda, 1978; Szyper et al., 1976) corrected for temperature, animal size, and habitat of about 14 mgN $m^{-2}d^{-1}$
3. Secondary production by zooplankton (P_{ZR}) estimated from assuming a daily mass specific growth rate (G) of 0.02, or a gross growth efficiency of 10 percent (K_1), or a growth per unit excretion ratio (G/e) of 1/7
4. Downward sinking transport of nitrogen as measured in particle flux traps (PN_{Trap}) is 3 mgN $m^{-2}d^{-1}$ (see medians, Figure 7, which would equal the upward eddy diffusive flux (F_N) of nitrate (DIN_{new}) through the nutricline at steady state
5. The vertical flux of nitrate is given as the product of the nitracline gradient (dn/dz) and the vertical eddy diffusivity coefficient (-Az is 7 $m^{-2}d^{-1}$) to equal the trap flux
6. The particulate flux generated by zooplankters (as egested pellets, moults and carcass parts) was calculated by difference between ingestion and excretion plus growth, 6 = 22 - (14+2) mgN $m^{-2}d^{-1}$, which is equivalent to assuming that assimilation efficiency (A_E) for the plankters is 73 percent
7. The contribution to total particulate flux generated from larger, macrozooplankters (PN_L) versus smaller, microzooplankters (PN_S) was estimated from examination of the trap samples and converting total fecal pellet volumes (average of 16 mm^3 $m^{-2}d^{-1}$) into mass of nitrogen assuming a 3 percent nitrogen content per unit wet weight, giving roughly 1 mgN $m^{-2}d^{-1}$, or approximately 1/6 of total ingestion [GL/(GL+GS)]
8. Other "detrital" fluxes calculated by difference are PNs = 5 = 6 - PN_L, fine particulates trapped = 2 = PN_{Trap}-PN_L, and regeneration from PN_R = 3 = PNs - 2

Note that total mass flux does not balance by 2 mgN $m^{-2}d^{-1}$, because of uncertainty in the accuracy of estimates for stocks and excretion rates of micronekton and nekton (M+N) and their daily migrations. The importance or significance of this attempt to account for nitrogen levels and fluxes in the epipelagic zone of the tropical ocean is in clarifying the perception of the small magnitudes and complexity of nitrogen fluxes and the interaction of many processes to achieve a steady-state system -- vertical mixing, light attenuation, supply rates of nitrogenous nutrients, plant uptake rates coupled to zooplankter feeding, and the potential importance of larger animals in both the regeneration and removal processes (excretion, defecation, mortality, and vertical migrations) in the upper ocean.

The spatial distributions of surface nitrate plus nitrite and chlorophyll a (Figures 9 and 10) and the average macrozooplankton stock per unit volume (Figure 11) at French Frigate Shoals show patterns with two major features: (1) slightly elevated levels of nutrients and pigments are found at the northwestern and southern ends of the atoll, with slightly lower levels toward the west-southwest from La Perouse Pinnacle; and (2) macrozooplankton stocks are about fivefold higher around La Perouse Pinnacle than at offshore stations (Figure 11), with a transition occurring near the 20 to 100 fathom isobaths. As described below, these and other patterns of water properties and productivity at French Frigate Shoals may be attributed to postulated physical mixing mechanisms which supply nutrients along the

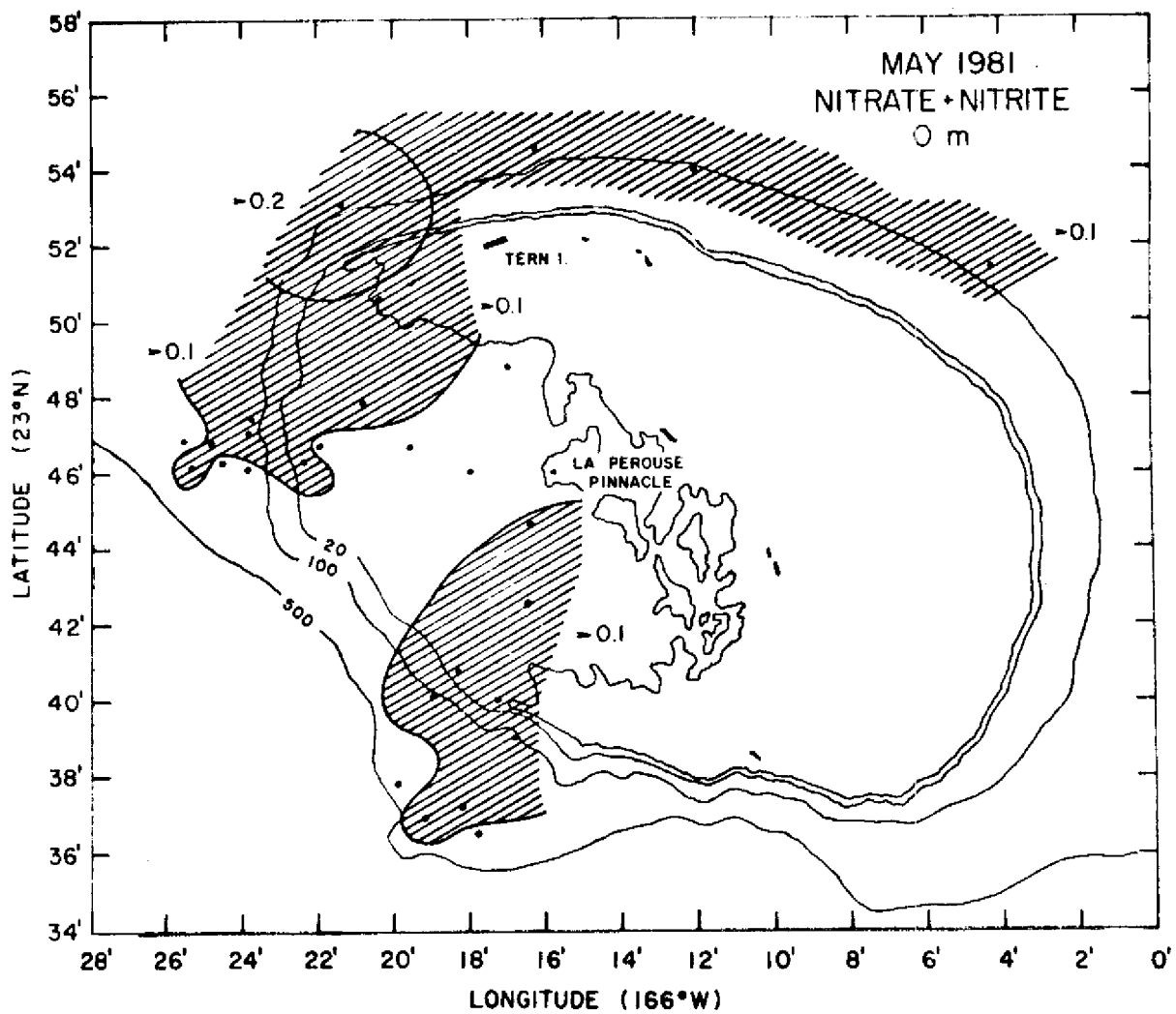


Figure 9. Spatial distribution of nitrate + nitrite (μM/liter) from surface sampling at French Frigate Shoals in May 1981; each dot is a sampling point and the isobath contours are given in fathoms

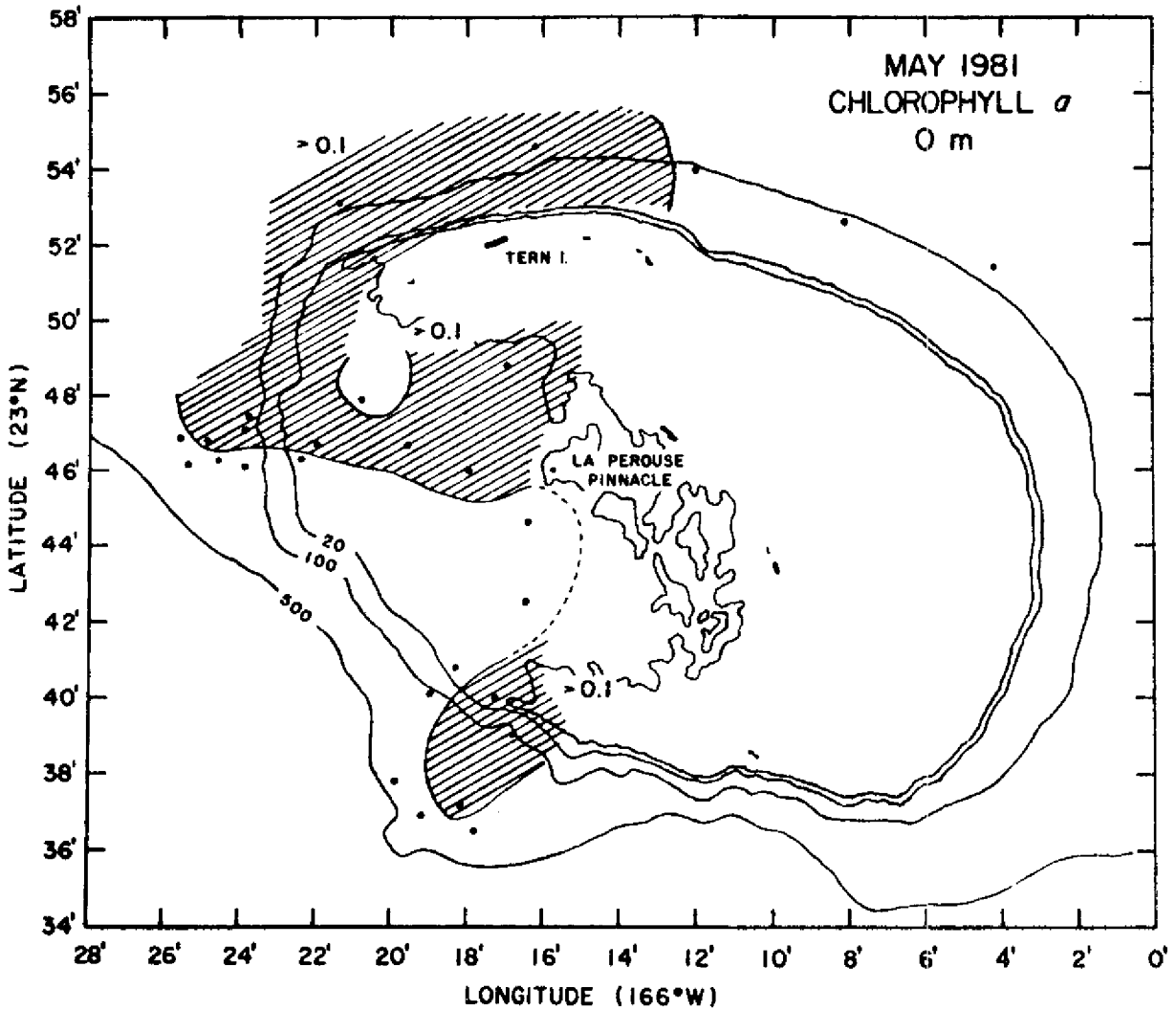


Figure 10. Spatial distribution of chlorophyll a (µg/liter) from surface sampling at French Frigate Shoals in May 1981; each dot is a sampling point and isobath contours are in fathoms

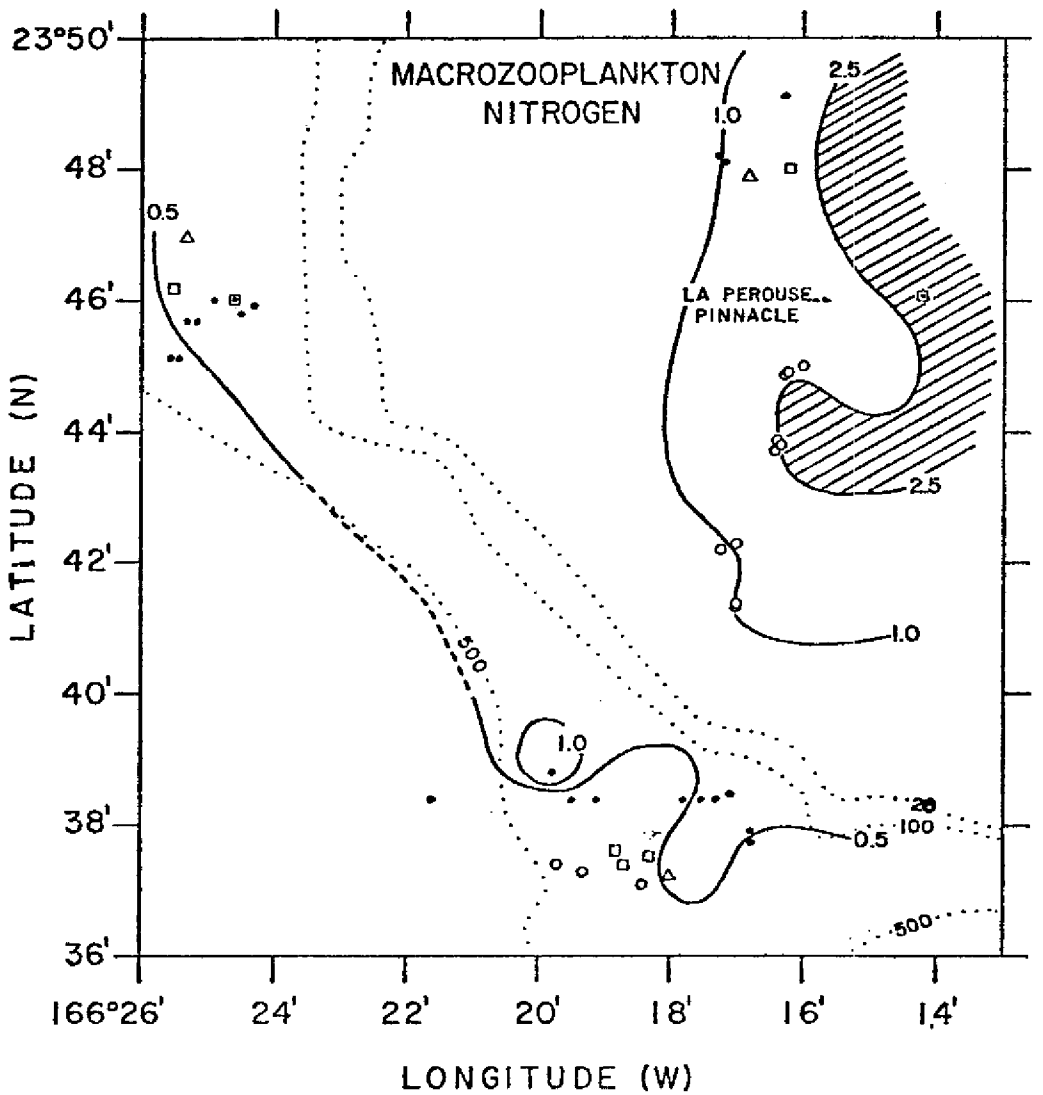


Figure 11. Spatial distribution of macrozooplankton stock as nitrogen (mgN m^{-3}) from day (open symbols) and night (closed symbols) vertical tows at French Frigate Shoals during August 24 to September 3, 1980; the dotted lines are isobath contours given in fathoms

perimeter of the atoll near the 20 to 100 fathom contours followed by the subsequent uptake of nitrogen and dispersal by currents and horizontal mixing.

One consistent mechanism to horizontally displace surface water and which may induce turbulent mixing in the nitracline zone (between 20 and 100 fathoms) is the tides. During a drogue tracking on September 9, 1981, surface flow persisted toward the east and southeast approaching La Perouse Pinnacle at speeds of about 30 cm/sec (Figure 12). Thus, such a current (probably tidal because of calm winds from the east-northeast during these

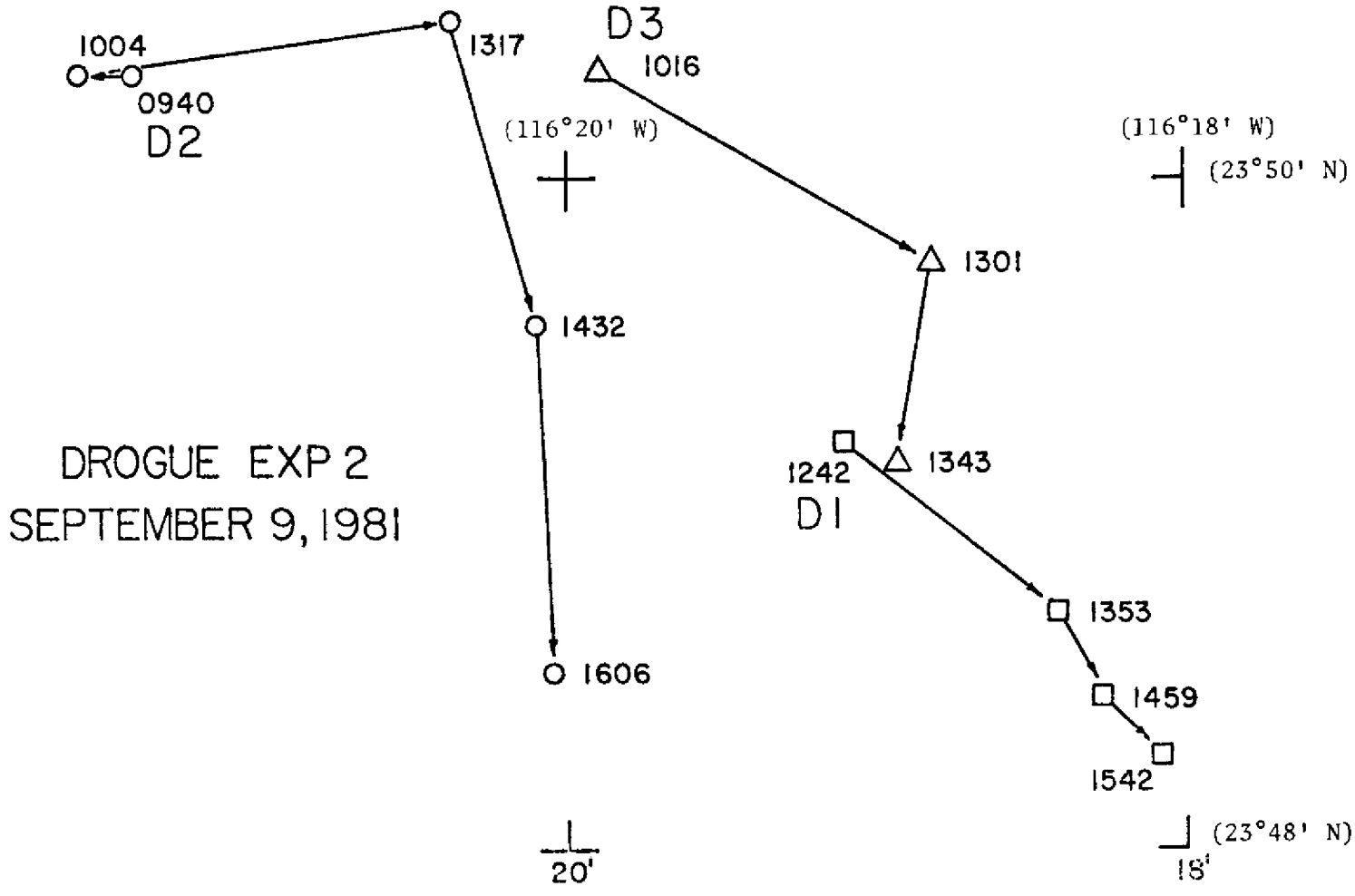


Figure 12. Surface currents as measured by three drogue trajectories (positions reckoned at local times) on the northwestern edge of the French Frigate Shoals atoll platform; hatch marks showing latitude and longitude positions are about 3 km apart

measurements) could horizontally displace water up to 4 miles in 6 hours. The observed current speeds are within the range previously found at French Frigate Shoals, and tidal flow is known to reverse in and out of the lagoon during tidal ebb and flow (Dollar and Grigg, 1981; R.W. Grigg: personal communication).

The spatial distributions of sea surface temperature, nitrate plus nitrite, and chlorophyll *a* in the northwestern quadrant of the lagoon at French Frigate Shoals were examined on three dates in September 1981, and the results of one such set of transect data serve to illustrate the general results observed (Figures 13 to 15). The pattern observed is that cooler (typically 0.5°C), nitrate-rich, and turbid water containing relatively high crops of phytoplankton is found along the north-northwestern end of the atoll away from La Perouse Pinnacle. While these observed values for sea surface temperature and nutrients are not highly elevated compared with offshore oceanic values, the chlorophyll *a* levels are about fivefold greater than surface values 20 km offshore. Highest chlorophyll *a* levels on other dates were observed in the direction of flow of observed currents, namely between buoys N and I, and toward La Perouse Pinnacle. This pattern is consistent with the presumption that nitrate and nitrite are supplied to the surface layer by physical (tidal?) mixing along the 20 to 100-fathom edge of the atoll, converted rapidly into algal biomass, and moved horizontally by tidal currents into the lagoon. Reef locations at Trig and Tern Islands had relatively constant and low to moderate levels of both carbon fixation and pigments (Figure 16), while similar measurements at buoys N and I, Shark Island, and buoy TI-I were more variable in time but had higher maximum values (Figure 17). Considering the shallow depth of backreef and lagoon areas, and that little variation with depth in rate of primary production was previously found in the 0 to 15 m depth range, a primary production rate for lagoon water of 200 mgC $m^{-2}d^{-1}$ is a reasonable estimate of the average. This rate of carbon fixation is essentially the same value for stations offshore at French Frigate Shoals, in which the euphotic zone is over 100 m deep, indicating significant elevation of surface productivity of lagoon water versus offshore oceanic water.

Assuming a seasonal average of 200 mgC $m^{-2}d^{-1}$ for net phytoplankton production, and converting this to live biomass (using a live biomass/carbon ratio of 12), a production level of 0.9×10^6 kg live algal weight $km^{-2}yr^{-1}$ is obtained for the depth zones exceeding 10 m but less than 55 m. By depth region (0 to 365 m = 1,200 km^2; 0 to 55 m = 700 km^2 nearshore; and 55 to 365 m = 500 km^2; J. Polovina, personal communication) this level of phytoplankton production would give 450×10^6 kg live weight yr^{-1} in the offshore zone, and roughly 270×10^6 kg live weight yr^{-1} in the nearshore zone, using the approximation that 300 km^2 of the 700 km^2 area are deeper than 10 m. The total planktivorous fish production (using a 10 percent food chain efficiency and the presumption that planktivorous fish ingest larger crustaceans, larval fish, and other first-order carnivorous plankters) would

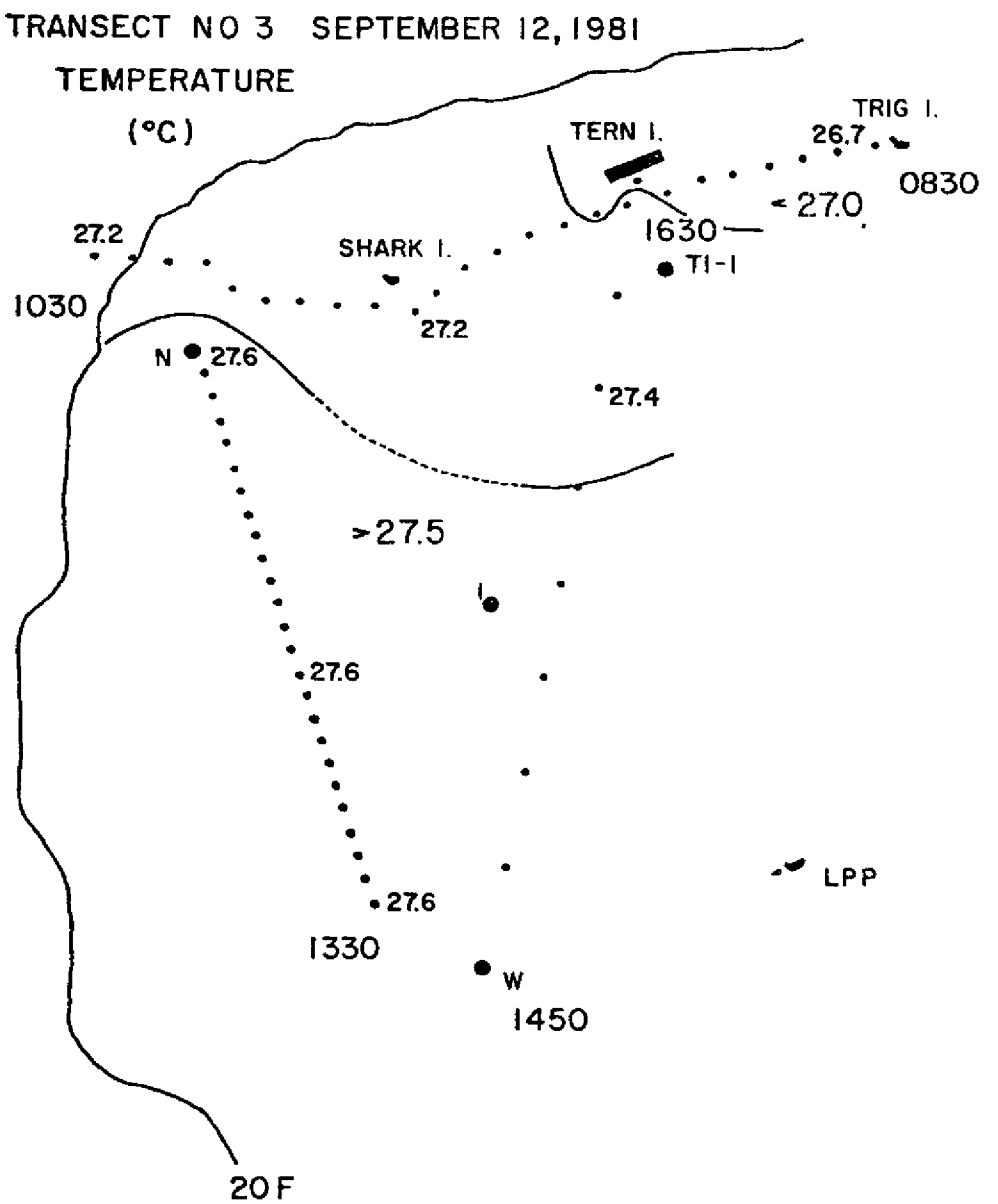


Figure 13. Distribution of sea surface temperature within the 20-fathom (F) isobath in the northwestern quadrant of French Frigate Shoals atoll; local times at beginnings and ends of transects are given, with marked islands (LPP is La Perouse Pinnacle) and four moored bouys (N, I, W, TI-I) as reference points (large dots)

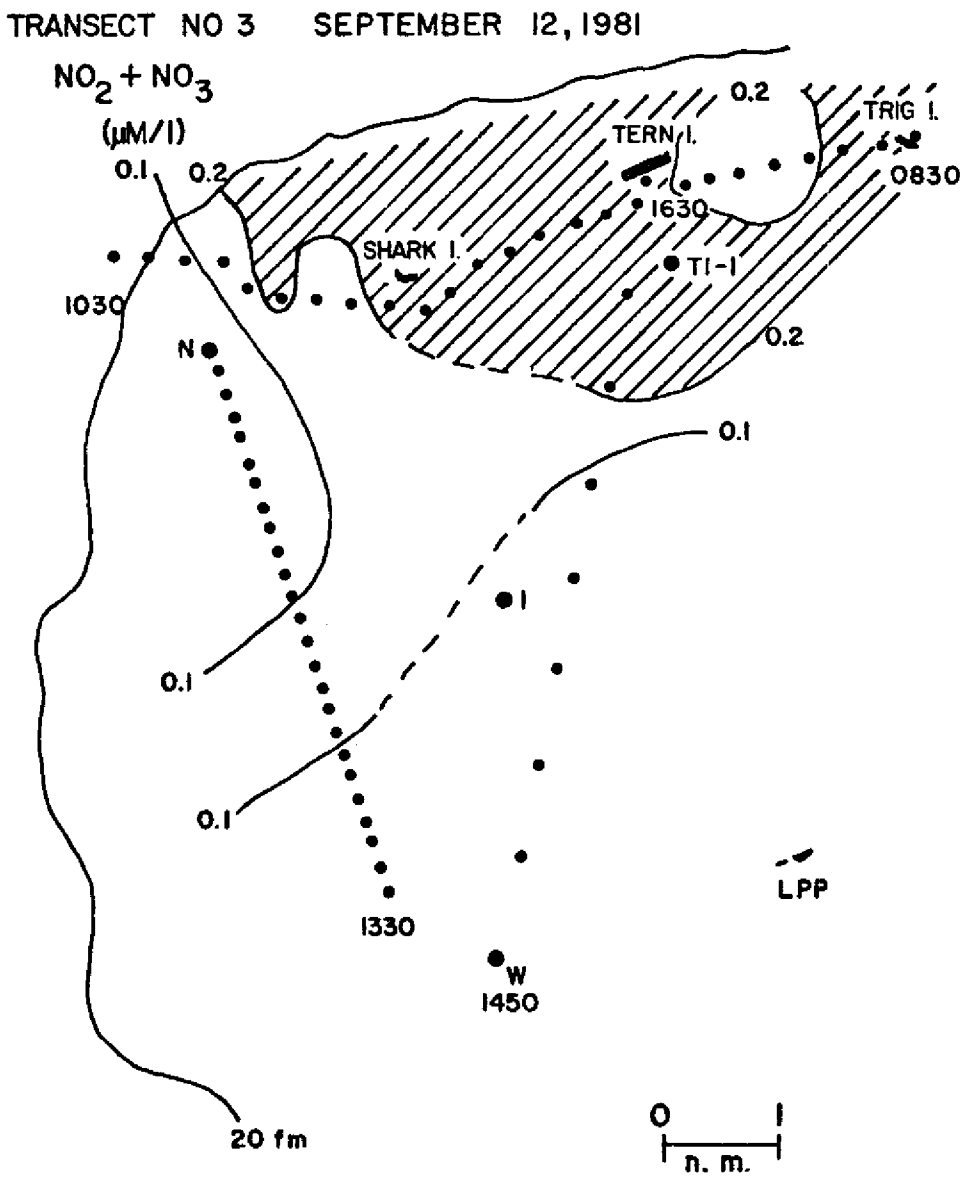


Figure 14. Distribution of sea surface nitrate + nitrite within the 20-fathom (F) isobath at French Frigate Shoals atoll; symbols as in Figure 13

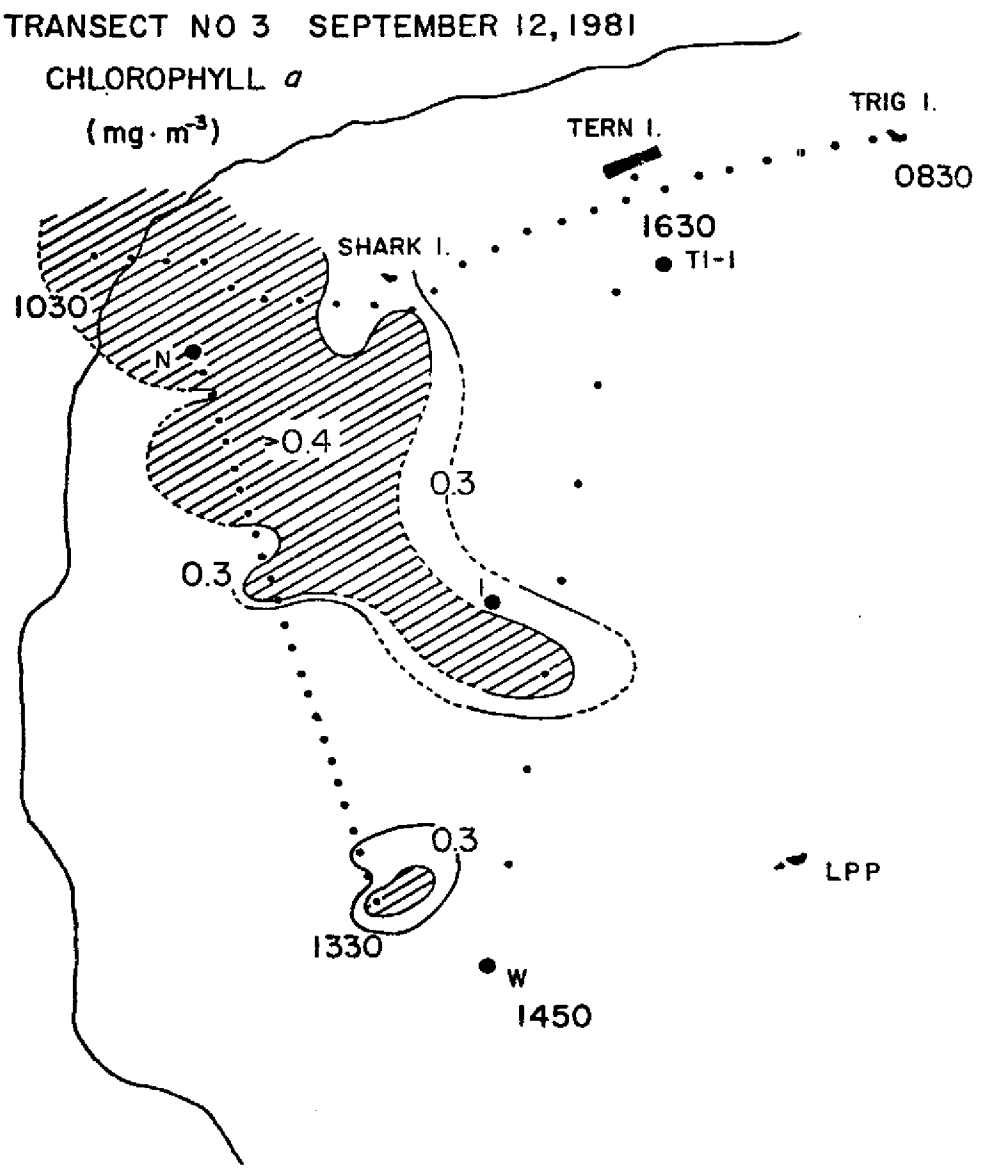


Figure 15. Distribution of sea surface chlorophyll a within the 20-fathom (F) isobath at French Frigate Shoals atoll; symbols as in Figure 13

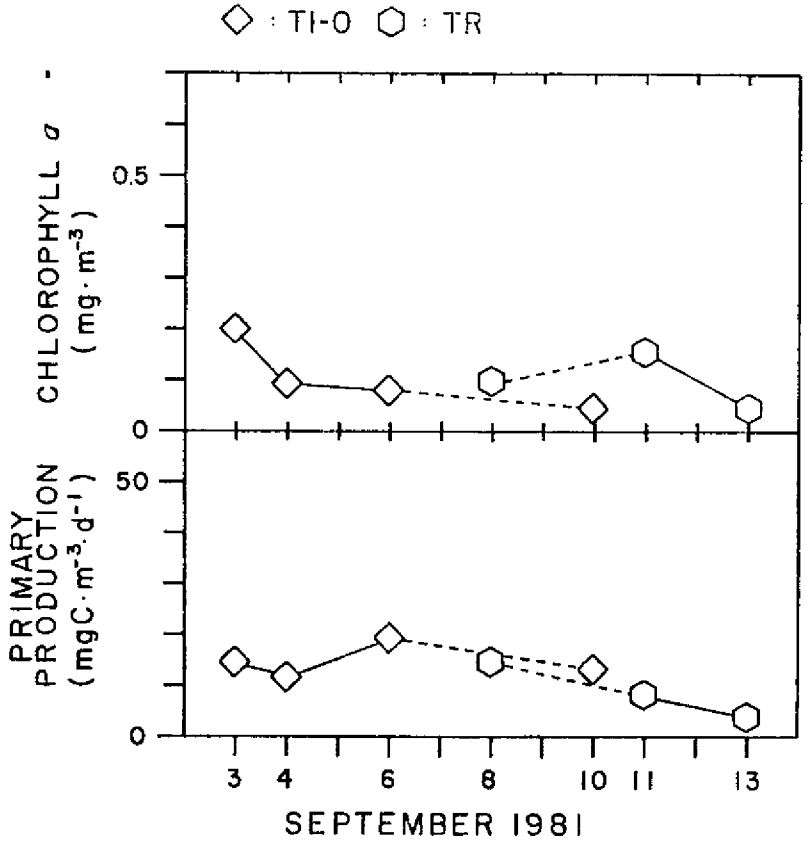


Figure 16. Daily sea surface primary productivity and chlorophyll a levels at Trig (TR) and Tern (TI-O), French Frigate Shoals, during September 1981

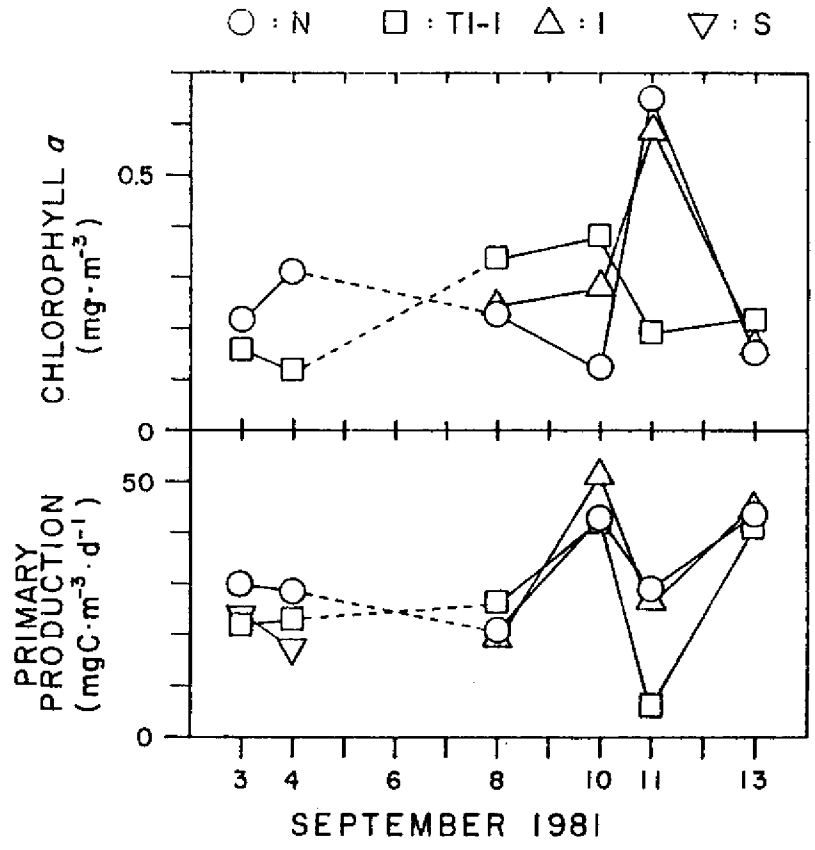


Figure 17. Daily sea surface primary productivity and chlorophyll a levels at Shark Island (S) and bouys N, I, and TI-I, French Frigate Shoals, during September 1981

be 2.7 x 10^5 kg yr^{-1}, or a total potential harvest of about 10^5 kg yr^{-1}, since only 25 to 50 percent of total production can be harvested for protracted periods (Sheldon et al., 1977). This planktivorous fish production of 2.7 x 10^5 kg yr^{-1} within 300 km^2 of the 10 to 55 m depth zone would nominally include production by akule. At French Frigate Shoals, Agard estimated the akule stock during daytime to be 12,500 kg, with most schools located off Disappearing, East, Shark, and Tern Islands. The estimated instantaneous growth rate for akule juveniles and adults between 47 and 547 g (Figure 18) is 0.006 d^{-1} or 2.2 yr^{-1}, which would equal the daily and annual P:B turnover ratios at steady-state biomass. Thus, total net secondary production of akule within the 10 to 55 m depth zone at French Frigate Shoals would be the order of 75 kg d^{-1} or 27,500 kg yr^{-1} by this one species alone. This independent production estimate for akule represents 10 percent of the total planktivorous fish estimate for the depth zone. This small fraction of the total planktivorous fish production seems reasonable, because several other species such as opelu (Decapterus sp.), half-beaks (Hemiramphidae), flying fish (Exocoetidae), piha (Spratelloides delicatulus), and iao (Pranesus insularum) also occur at French Frigate Shoals.

DISCUSSION

Historically, the structure and cycling dynamics of nitrogen within a plankton ecosystem in the epipelagic zone of tropical oceanic habitats has largely been examined as many separate parts in different locations (e.g., Bienfang and Szyper, 1981; Eppley et al., 1973; Gundersen et al., 1976; Herbland and Voituriez, 1979; Ikeda and Motoda, 1978), without a coherent approach to simplify and approximate functioning of the entire ecosystem. This non-coherent approach has probably been due in part to methodological limitations (e.g., direct observations of vertical fluxes of particulate nitrogen in the ocean are relatively recent outcomes of particle trapping technology) as well as the inherent complexity of real versus simplified systems. Furthermore, simplification of the ecosystem is difficult in the absence of nearly steady-state dynamics. The results of our study on epipelagic ecosystem dynamics in Hawaiian waters demonstrate that while the upper water column is indeed variable in its components in time and space, some parameters such as nitracline gradients, seston components, and various key fluxes range by a factor of only three to five at locations separated by roughly 800 km and about 9 months in time (Figures 2 to 7). The magnitudes of these stocks and fluxes are generally consistent with previously reported values, e.g., 80 to 400 mgC $m^{-2}d^{-1}$ (Bienfang and Szyper, 1981) versus our values of 63 to 341 mgC $m^{-2}d^{-1}$ for primary productivity based on 15 in situ measurements; and our median values of 36.3 mgC $m^{-2}d^{-1}$ for vertical particulate carbon flux for the 200 m depth horizon versus 30.2 mgC $m^{-2}d^{-1}$ (equation 1 in Suess, 1980). Our measured vertical fluxes of particulate carbon and nitrogen at 200 m in Hawaiian waters (Figure 7) also fall within the ranges reported for the oceanic North Pacific gyre between 75

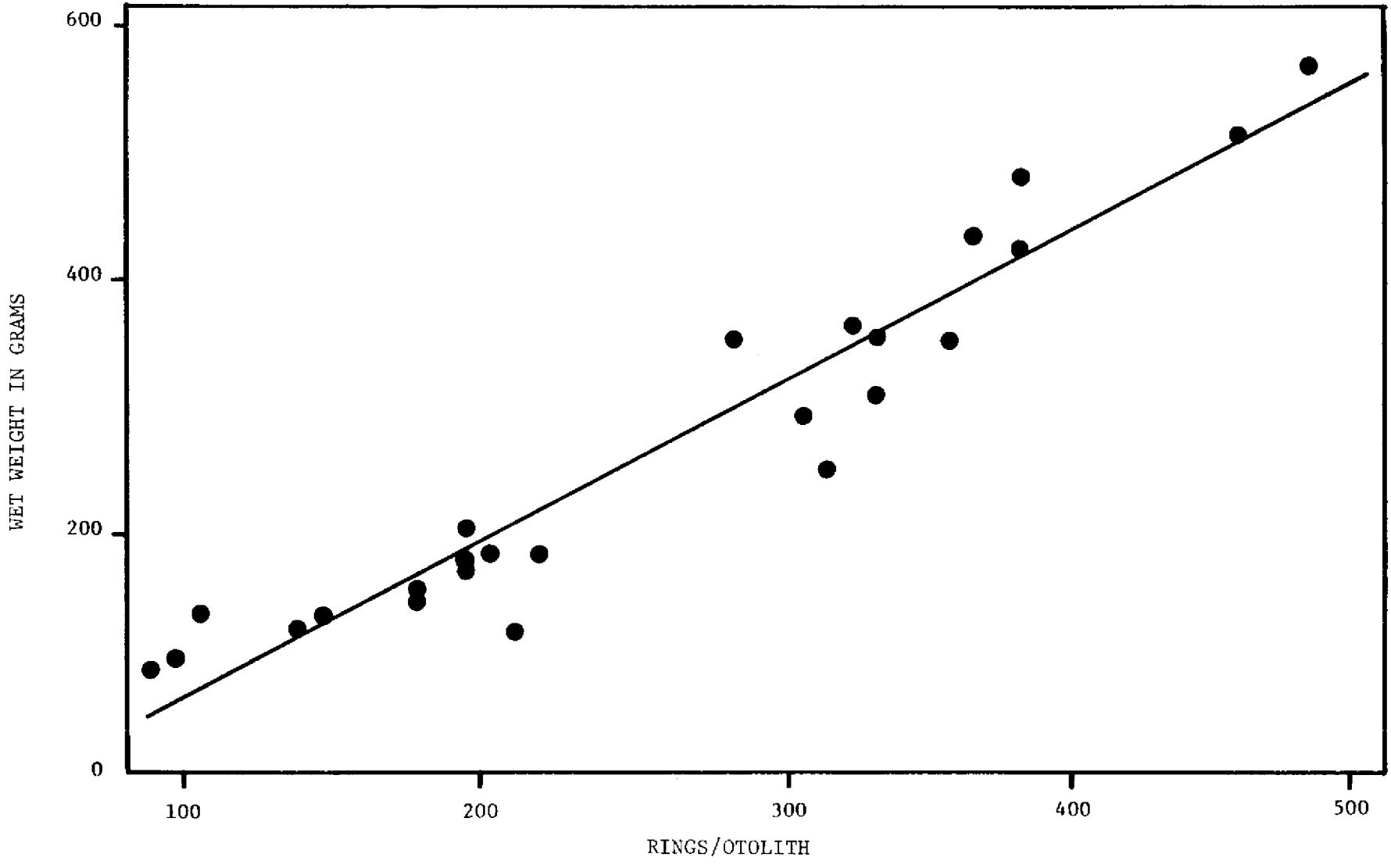


Figure 18. Regression of wet weight in grams (W) on rings per otolith (T) for juvenile and adult Selar crumenopthalmus; W = -78.2 + 1.25T (N = 28, R = .91)

and 575 m (Knauer et al., 1979). Similarly, the estimated nitrogen excretion flux from macrozooplankton and microzooplankton of 14 mgN $m^{-2}d^{-1}$ and 64 precent of plant nitrogen uptake, respectively, is near the upper range of values reported from the Kuroshio and adjacent areas (Ikeda and Motoda, 1978). Our overall nitrogen flux results are also consistent with the notion that the bulk of plant nutrient supply is from regeneration, with only a small (ca. 14 percent) fraction being supplied as "new nitrogen" (nitrate) from vertical diffusive transport (Eppley et al., 1979). Our nitrogen flux and process studies also stress the importance of the size and relative activity rates of organisms from smallest microbial heterotrophs to large nekton, and especially the regeneration of dissolved nitrogen from detritus produced from small plankters (Hofmann et al., 1981). Lastly, the obvious weak links in this study of the upper water column are: (1) the disregard for nitrogen fixation rates as an input process to the particulate pool (nitrogen fixation rate) was estimated on two occasions by Gundersen et al., 1976 to supply 1.9 mgN $m^{-2}d^{-1}$ in Hawaiian waters, but it is unclear whether this nitrogen flux is used by the system in the same manner as other plant production); (2) limits in our knowledge of DON chemical forms and their specific fluxes; and (3) the direct measurement of net dissolved regeneration of nitrogen forms from the huge detritus-microbial pool.

The combined horizontal transect measurements at French Frigate Shoals (Figures 9 through 11) and the nearshore research from Tern Island (Figures 12 through 17) suggest that there may be an important physical mixing and current transport mechanism, which is responsible for observed distributions of water properties and elevated stocks of plankton and primary productivity. The horizontal distributions indicate that the transition between offshore oceanic water and nearshore or coastal lagoon water at French Frigate Shoals occurs near the 20 to 100-fathom isobath, but this transition zone is unlikely to be fixed in space or time. Some of the variability in productivity and chlorophyll *a* at all three offshore stations (Figures 4, 5, and 7) may be a result of leeward nearshore water eddies moving seaward surrounded by nutrient-poor oceanic seawater. The results of nutrient enrichment at nearshore areas may in part explain the elevated levels of primary productivity observed at French Frigate Shoals compared with Kawaihae Bay with a mean value of 150 mgC $m^{-2}d^{-1}$ versus 90 mgC $m^{-2}d^{-1}$ (Hirota et al., 1980).

As a result of slightly higher values for primary productivity at French Frigate Shoals for the water column, 200 mgC $m^{-2}d^{-1}$, the potential planktivorous fish yield there over the 18 to 55 m depth zone (ca. 300 km^2) is estimated at 10^5 kg yr^{-1} living biomass. Of this potentially harvestable fish yield, a significant amount could be landed for table fish (e.g., 10^4 kg as akule alone in addition to opelu and other edible species) or as baitfish (piha, iao, etc.). However, these fish resources are currently being consumed directly (presumably near an optimum rate) by many top carnivores, including seabirds, tunas, jack

crevally, and other piscivores. The extent to which a harvest of planktivorous fish would change the natural ecosystem balance at French Frigate Shoals is the subject of an ecosystem model by Polovina (see paper in this proceedings). However, these and other studies presented in the NWHI resource investigations must be carefully evaluated on balance by managers and policymakers before a best use scenario can be formulated between the conflicts of conservation and resource utilization.

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ECOPATH - AN ECOSYSTEM MODEL APPLIED TO FRENCH FRIGATE SHOALS

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ABSTRACT

A simple model to estimate mean annual biomass, production, and consumption for components of an ecosystem is presented. The approach partitions the ecosystem into groups of similar species and requires estimates for these species groups of production to biomass, diet, and food consumption.

The approach was applied to an ecosystem at French Frigate Shoals in the Northwestern Hawaiian Islands where field work provided estimates of some of the input parameters as well as estimates of mean annual biomass and production, for some of the species groups modeled, to validate the estimates generated by the model. Simplified, the model depicts an ecosystem composed of four major trophic levels. The primary pro duction consists of benthic algae and phytoplankton, the second level is composed of zooplankton and heterotrophic benthos, the third level consists of reef fishes, lobsters, crabs, bottomfishes, and small pelagic species including squid, flyingfish, akule, and opelu, and the top trophic level is composed of sharks, jacks, tunas, seabirds, and monk seals.

Simple sensitivity analysis was performed to measure the sensitivity of the estimates of the model to errors or uncertainties in the input parameters.

biomass
ecosystem model
French Frigate Shoals
Northwestern Hawaiian Islands
tropical marine ecosystem

INTRODUCTION

The investigation of the resources of the Northwestern Hawaiian Islands (NWHI) is a multidisciplinary program with researchers from the National Marine Fisheries Service (NMFS), University of Hawaii Sea Grant College Program, U.S. Fish and Wildlife Service (FWS), and Hawaii Division of Aquatic Resources (Shomura, 1980) conducting studies on specific species which are important components of the marine ecosystem in the area. An ecosystem modeling project evolved out of a desire of many of the researchers to bring together common elements from the various research projects to form a quantitative picture of the entire marine ecosystem. Initially several existing ecosystem models were considered for application to the NWHI ecosystem, particularly the Prognostic Bulk Biomass (PROBUB) model (Laevastu and Larkins, 1981) developed for the Bering Sea and the Andersen and Ursin (1977) North Sea model. However, the models require a level of understanding which has not yet been achieved for a tropical ecosystem. Similar sentiments are expressed by Larkin and Gazey (1981):

> As in the case of the Bering Sea simulation, it seems reasonable to conclude that the North Sea model has little utility for multispecies fisheries management in tropical waters. To even construct a model at a comparable level of detail for tropical fish communities is at present impractical. Even if the data were available for estimating the several thousand parameters involved, it would take many years of observation and experiment to verify the utility of the model. It is also difficult to visualize what kind of experimental management might be adopted to test the validity of such a model.
>
> The moral, it seems, is to simplify....

Although neither the PROBUB model nor the Andersen and Ursin model seemed appropriate for modeling the NWHI ecosystem, given the current level of knowledge, much of the philosophy and approach, particularly in the PROBUB model, was applicable to the NWHI ecosystem. Hence, a simple ecosystem model, termed the ECOPATH model was developed.

The ECOPATH model partitions the ecosystem into species groups and, given a set of parameter estimates as inputs, produces estimates of mean annual biomass, annual biomass production, and annual biomass consumption for each of the species groups. A species group is an aggregation of species with similar diet and life history characteristics and which has a common physical habitat. Computationally and conceptually the model is very simple. The mean annual biomass estimates are obtained from the solution of a system of simultaneous linear equations.

THE ECOPATH MODEL

The objective of the ECOPATH model is to estimate the mean annual biomass for each species group and produce a biomass budget for the ecosystem, all under the assumption of equilibrium conditions. Such conditions are defined to exist when the mean annual biomass for each species group does not change from year to year. This condition results in a system of biomass budget equations which, for species group i, can be expressed as:

Production of biomass for species i - all predation on species i - nonpredatory biomass mortality for species i = 0 for all i . (1)

The ECOPATH model expresses each term in the budget equation as a linear function of the unknown mean annual biomasses (B_i's) so the resulting biomass budget equations become a system of simultaneous equations linear in the B_i's. The formulation of each term of the biomass budget equation is presented in detail below.

Biomass Production

Production (P) for a cohort of animals over a period of 1 year is defined as:

$$P = \int_0^1 N_t \frac{d}{dt} (w_t)\, dt$$

and mean annual biomass (B) for the cohort is defined as:

$$B = \int_0^1 N_t w_t dt$$

where

N_t is the number of animals and w_t the mean individual weight at time t.

Allen (1971) investigated the production to biomass (P:B) ratio for a cohort over a range of mortality and growth functions. For a number of mortality and growth functions, including negative exponential mortality and von Bertalanffy growth, the ratio of annual production to mean biomass for a cohort is the annual instantaneous total mortality (Z_i). For a species group which consists of n cohorts or species with instantaneous annual total mortality (Z_i) for cohort or species i, where mortality is determined by a negative exponential function and growth by a von Bertalanffy growth function, the total species group production

(P) is the sum of the cohort production (P_i) and can be expressed as:

$$P = \sum_{i=1}^{n} P_i = \sum_{i=1}^{n} Z_i B_i \ . \qquad (2)$$

Under the assumption that the Z_i's are all equal to say Z, then total species group production can be expressed as P = ZB, where B is the mean annual species group biomass.

Allen (1971) also showed that when growth in weight is linear for a range of mortality functions, the P:B ratio is equal to the reciprocal of the mean age. For a number of other growth and mortality functions the ratio of cohort P:B can be the reciprocal of the mean lifespan. Thus, for a range of growth and mortality functions, total species group production can be expressed as P = CB, where B is the mean annual species group biomass and C is a parameter. In the subsequent application of the ECOPATH model to an ecosystem where there is very little fishing mortality, the P:B ratio for fishes and crustaceans is taken as the annual instantaneous natural mortality (M), whereas the P:B ratio for primary and secondary producers whose growth is more likely to be linear rather than the von Bertalanffy is estimated as the reciprocal of the mean age.

Predation Mortality

Predation mortality is the fraction of the biomass of a species group which is consumed by all predators. The ECOPATH model computes this mortality in the same fashion as the PROBUB model. Two types of information are needed. First, the food web or predator-prey relationships must be defined. A diet composition matrix DC_{ij} must be specified where an entry DC_{ij} from this matrix refers to the proportion (by weight) of prey j in the diet of predator i. The primary source of this information is the analysis of stomach contents. The second type of information needed to ascertain predation mortality is the food requirements of the predator. The PROBUB model expresses the total food required (R_i) by a species group (i) as:

$$R_i = b_i B_i + a_i P_i$$

where

B_i is the annual mean species biomass, P_i is the annual production of species group i, and a_i and b_i are parameters to be estimated from energetics studies. The component b_i B_i is the food required to maintain the biomass B_i, and the component a_i P_i is the food required to support the biomass production P_i (Laevastu and Larkins, 1981).

In the ECOPATH model the production of species group i is $P_i = C_iB_i$, so the food required for species group B_i is

$$R_i = b_iB_i + a_iP_i$$

$$= b_iB_i + a_iC_iB_i$$

$$= (b_i + a_iC_i)\ B_i\ .$$

Thus the amount of species group j consumed by predator species group i is given as:

$$R_iDC_{ij} = (b_i + a_iC_i)\ B_iDC_{ij}\ .$$

Nonpredation Mortality

All mortality attributable to causes other than predation such as fishing mortality, spawning mortality, and disease is considered together under the category of nonpredation mortality. In the ECOPATH model this is determined as a fraction (d_i) of the mean annual biomass B_i.

For n species groups the biomass budget equation (1) becomes a system of n simultaneous equations as follows:

$$C_1B_1 - \sum_{k=1}^{n} (b_k + a_kC_k)\ B_kDC_{k1} - d_1B_1 = 0$$

$$\vdots$$

$$C_iB_i - \sum_{k=1}^{n} (b_k + a_kC_k)\ B_kDC_{ki} - d_iB_i = 0$$

$$\vdots$$

$$C_nB_n - \sum_{k=1}^{n} (b_k + a_kC_k)\ B_kDC_{kn} - d_nB_n = 0\ .$$

With input estimates for parameters C_i (usually M_i), b_i, a_i, DC_{ij}, and d for all i and j, this system of equations is a system of n simultaneous equations linear in the unknown B_i's. This system of equations can be expressed in matrix form as $AB = 0$, where A is an n x n matrix of coefficient, B is an n-dimensional vector of mean annual species group biomass, and 0 is the null vector. Typically the matrix A will be of full rank and will only have a trivial solution:

$B_i = 0$ for all i .

It is therefore necessary to provide an estimate of at least one of the species group biomass B_i before there exists a unique nontrivial set of B_i's which solves the biomass budget system.

The following is an application of the ECOPATH model to obtain estimates of biomass and production for the component of the marine ecosystem at French Frigate Shoals (FFS) in the NWHI.

FRENCH FRIGATE SHOALS

French Frigate Shoals is located at lat. 24°50'N, long. 166° 10'W, approximately midway along the chain of islands and banks comprising the NWHI. It is described by Bakus (1979) as a "crescent-shaped reef on a circular submerged platform about 18 mi in diameter (almost an atoll). The shoals form a large lagoon, bordered on one side by 12 sand islets (total area 56 acres) with a small rock pinnacle (La Perouse Pinnacle, ca. 1 acre) near the center of the platform. The highest elevation is generally 5 ft above sea level except for La Perouse Pinnacle (135 ft high)." The area is an important nesting ground for the green turtle, Chelonia mydas, various species of seabirds, and the Hawaiian monk seal, Monachus schauinslandi.

The ecosystem of interest to the model is the reef and nearshore community from shoreline to a depth of 365 m (200 fathoms). This habitat describes a circular area with a radius of approximately 20 km and a total area of approximately 1,200 km^2. The reef habitat in this region defined as the area from shoreline to 55 m (0 to 30 fathoms), consists of approximately 700 km^2.

Fifteen species groups have been identified as the major component of the ecosystem within the region down to the 365 m depth around FFS. These species groups which will subsequently be described in detail are seabirds, monk seals, tiger sharks, reef sharks, sea turtles, small pelagics, jacks, reef fishes, lobsters and crabs, bottomfishes, nearshore scombrids, benthic algae, heterotrophic benthos, zooplankton, and phytoplankton.

The parameters which are required as inputs to the ECOPATH model are (for each species group): the P:B ratio C_i (usually M_i), the energetic parameters a_i and b_i, the diet vector DC_{ij}, and the nonpredation mortality d_i. In addition, as discussed earlier, it is necessary to enter an estimate of at least one of the species group biomass values to have a nonzero solution to the biomass equations. The logical apex predator to drive the system is the tiger shark, Galeocerdo cuviere. However, in addition to the tiger shark biomass as a fixed input, biomass estimates for birds and monk seals will be treated as fixed inputs since they are based on visual censuses and are considered reliable.

Many of the estimates for input parameters are determined from field data collected at FFS. In some cases, however, data to estimate parameters were not available from FFS, or anywhere in the NWHI, so estimates from the literature were used. This was almost exclusively the case for the estimate of the nonpredatory mortality d_i. The d_i exclusive of fishery mortality used in a Gulf of Alaska simulator ranged from 0.019 to 0.029 (Livingston, 1977); thus a mean value of $d_i = 0.024$ was used in the ECOPATH model in the absence of any other information.

Typically the value C_i was estimated as annual instantaneous natural mortality (M_i) in the absence of fishing mortality. In some instances only von Bertalanffy growth parameters were estimated from field work and then M_i was estimated from a regression equation proposed by Pauly (1980) as:

$$\log_{10} M_i = 0.0066 - 0.279 \log_{10} L_i + 0.6543 \log_{10} K_i + 0.4634 \log_{10} T_i$$

where

L_i is the asymptotic maximum length (cm) of the stock, K_i the von Bertalanffy annual growth coefficient, and T_i the mean environmental temperature (°C) for the stock.

There is a shortage of energetics work on tropical stocks. Estimated food uptake for a temperate North Sea stock of cod based on a study of stomach contents suggests that the stock consumes an average of 0.75 percent of its body weight per day (Daan, 1973). For faster-growing fishes such as salmon, food consumption may be as high as 2.0 percent of its body weight per day (Laevastu and Larkins, 1981). Consumption relative to net production, or ecological efficiency, has been examined for a number of stocks and found to range from 10 to 25 percent (Crisp, 1975). Ecological efficiencies for three size groups of a Bermuda reef fish, Epinephelus guttatus, ranged from 15 to 25 percent (Menzel, 1960).

In the absence of any energetics input to estimate a_i and b_i, the value of b_i used was 2.0 from Laevastu and Larkins (1981). Since the amount of food needed for the maintenance of a species group i is b_iB_i, $b_i = 2.0$ implies that tbe species group must annually consume twice its biomass for maintenance. The food required to support production (P_i) is a_iP_i. In the absence of any food requirement information, a value of $a_i = 5$ was used, which, with the range of P:B values used in the model, results in ecological efficiencies and total consumption rates which are in agreement with the previously mentioned values.

Seabirds

Studies by the Fish and Wildlife Service indicate that the following seabirds are found in abundance at FFS: sooty tern,

Sterna fuscata; black noddy, Anous tenuirostris; brown noddy, A. stolidus; great frigatebird, Fregata minor; red-footed booby, Sula sula; masked booby, S. dactylatra; wedge-tailed shearwater, Puffinus pacificus; Laysan albatross, Diomedea immutabilis; and black-footed albatross, D. niaripes. An estimated peak population of 320,000 birds and a mean residence time of 6 months produce a mean annual seabird population estimated at 160,000 birds. Of this population 25 to 50 percent of the birds (mean individual weight of 0.31 kg) feed in the 1,200 km^2 area around FFS (Harrison et al., 1983). Thus, the estimated mean density for seabirds is 15.4 kg/km^2. Their diet composition vector is 0.68 small pelagics, 0.15 reef fishes, 0.10 jacks, 0.02 nearshore scombrids, and 0.05 zooplankton, and they consume an average of 80 times their biomass annually (Harrison et al., 1983).

Monk Seal

The second apex species is the Hawaiian monk seal. The estimate of biomass for the seal population in the 1,200 km^2 region around FFS, obtained from a visual census, is 75,500 kg, which results in a density of 63 kg/km^2 (W.G. Gilmartin, 1982: personal communication). The diet is estimated to consist of 0.85 reef fish and 0.15 lobster and crab, and it is estimated that the monk seal must consume on the average 45 times its weight in food per year to support growth and maintenance (W.G. Gilmartin, 1982: personal communication).

Tiger Shark

The tiger shark is the predominant apex predator at FFS. The stomach contents of 27 tiger shark suggest a diet vector consisting of 0.30 seabirds, 0.01 tiger shark, 0.28 reef fish, 0.01 turtles, 0.08 monk seal, 0.14 lobsters, 0.05 jacks, 0.08 small pelagics, 0.03 reef sharks, and 0.02 nearshore scombrids (DeCrosta, 1981). The tiger shark population at FFS is estimated at 504 individuals with a mean individual weight of 100 kg (DeCrosta, 1981). These values result in a density of 42 kg/km^2 for tiger shark biomass over the 1,200 km^2 area at FFS.

Reef Sharks

This is a group of nearshore warm-water sharks other than the tiger shark. Based on observations and catches at FFS, this group includes the gray reef shark, Carcharhinus amblyrhynchos, the galapagos shark, C. galapagensis, the small blacktip shark, C. limbatus, the sandbar shark, C. milberti, the dusky shark, C. obscurus, and the whitetip reef shark, Triaenodon obesus. They occur in greatest numbers in the deeper waters outside of the reef, but also work their way into the shallow waters of the inner reef. These sharks prey primarily on the smaller reef fishes, but their diet also includes pelagic fishes, bottom-dwelling fishes, stingrays, crustaceans, squid, and octopuses. Based on an analysis of stomach contents (DeCrosta, 1981), their diet is estimated as 0.90 reef fishes, 0.05 lobsters, and 0.05

jacks. Mortality estimates are not available for reef sharks in the NWHI. However, Holden (1977) presented estimates of annual instantaneous natural mortality for a number of shark species. These estimates generate a range of annual natural mortality from 0.1 to 0.25. The midpoint of this range 0.175 was used as an estimate of reef shark natural mortality and as the estimate of the P:B ratio.

Sea Turtle

This species group consists of the Hawaiian green sea turtle, Chelonia mydas. The diet of the green turtle is estimated at 0.90 benthic algae and 0.10 zooplankton (G.H. Balazs, 1982: personal communication). The annual instantaneous mortality is estimated at 0.15 and the annual food requirement for growth and maintenance is estimated at 22 times the mean annual biomass (G.H. Balazs, 1982: personal communication).

Small Pelagics

This group consists of small surface pelagic fishes and squid including flyingfish, Exocoetidae; opelu, Decapterus spp.; akule, Selar crumenophthalmus, needlefish, Belonidae; and halfbeaks, Hemiramphidae. The bulk of the biomass for the group consists of akule, opelu, squid, and flyingfish. Based on a von Bertalanffy growth parameter of L_∞ = 27 cm and k = 0.215 for akule in Hawaii (Kawamoto, 1973), M = 0.65 was estimated. The growth parameters for opelu in Hawaii are estimated at L_∞ = 35 cm and k = 0.82 (Yamaguchi, 1953), resulting in an estimate of M = 1.50. An average value of M = 1.1 is used as the P:B ratio. The flyingfish, squid, akule, and opelu feed almost exclusively on zooplankton.

Jacks (carangids and large carnivores)

This is a group of active, fast-swimming carnivores including the white ulua, Caranx ignobilis; omilu, C. melampygus; ulua, Carangoides ferdau; and barracuda, Sphyraena barracuda. This group is found both in the reef and nearshore regions. Based on an analysis of stomach contents (Sudekum, 1981) it is estimated that their diet is 0.80 reef fish, 0.12 lobster and crab, and 0.08 small pelagics. Based on estimated growth parameter for Seriola dumerili of L_∞ = 149 cm and k = 0.31 (J.H. Uchiyama, 1982: personal communication), M is estimated as 0.52 and this is used as the P:B estimate.

Reef Fishes (and octopuses)

This group consists primarily of the coral reef fishes, excluding the snappers, groupers, and carangids. Their habitat ranges from the surge zone down to depths of 55 m (30 fathoms).

Based on analysis of stomach contents from reef fishes collected at FFS, the diet is estimated at 0.17 zooplankton,

0.248 benthic algae, 0.459 heterotrophic benthos, and 0.123 reef fishes (J.D. Parrish, 1981: personal communication). Typically, members of this group have a relatively high natural mortality. For the kumu, Parupeneus porphyreus, the growth parameters are estimated at L_∞ = 49 cm and k = 0.54 (Moffitt, 1979) which yields an estimate of M = 1.0. The butterflyfish, Chaetodon miliaris, has growth parameters L_∞ = 12.7 cm and k = 1.13 (Ralston, 1976) which yields an estimate of M = 2.3. As a rather arbitrary average the value of M = 1.5 was used as the P:B estimate for this large reef fish species group.

Lobsters and Crabs

This group includes the spiny lobsters, Panulirus marginatus and P. penicillatus, the slipper lobster, Scyllarides squammosus, and various crabs including the kona crab, Ranina ranina. The M for the spiny lobster, P. marginatus, at FFS has been estimated from tagging studies as 0.32 for males and 0.71 for females (C. MacDonald, 1982: personal communication). An average value of M = 0.52 is taken as the P:B estimate for this group. The diet of this group is 100 percent heterotrophic benthos. Production and consumption rates were estimated for the spiny lobster, P. homarus, on a reef off South Africa by Berry and Smale (1980). They estimated the P:B ratio as 0.42, the production to consumption ratio as 0.45, and the consumption to biomass ratio as 9.5. To approximate these consumption and efficiency rates, the values of a = 2 and b = 12 were used in the food requirement equation.

Bottomfishes

This is a commercially important group of food fishes including opakapaka, Pristipomoides filamentosus; kalekale, P. sieboldii; gindai, P. zonatus; onaga, Etelis coruscans; ehu, E. carbunculus; uku, Aprion virescens; hapuupuu, Epinephelus quernus; kahala, Seriola dumerili, and butaguchi, Pseudocaranx dentex. Fishermen report that these bottomfishes are caught predominantly between depths of 75 and 220 m (40 and 120 fathoms). They are all active, carnivorous fishes which prey on small fish, shrimp and other crustaceans, and macrozooplankton.

Stomach contents were examined for the predominant species lex, and a mean diet vector for this group is estimated as 0.125 small pelagics, 0.469 reef fishes, 0.018 lobsters and crabs, 0.026 bottomfishes, 0.104 zooplankton, and 0.258 heterotrophic benthos (S.V.D. Ralston, 1982: personal communication).

A detailed analysis of growth and mortality for the opakapaka, provided an estimate of M = 0.32 (Ralston, 1981). This mortality estimate is used for the bottomfish species group P:B estimate.

Nearshore Scombrids (and other carnivores)

This is a group of commercially important tunas and tunalike fishes, including skipjack tuna, Katsuwonus pelamis; kawakawa, Euthynnus affinis; yellowfin tuna, Thunnus albacares; wahoo, Acanthocybium solandri; dolphin, Coryphaena hippurus; and the rainbow runner, Elagatis bipinnulata. The members of this group are all pelagic or nearshore pelagic species which largely occupy the surface waters. The kawakawa, an inshore pelagic fish, has been observed foraging over the reefs in shallow water at FFS. These fishes are all active, fast-swimming carnivores and are opportunistic feeders. Their diets have been observed to consist predominantly of small fish, juvenile fish (tunas, snappers, carangids), squid, stomatopods, and megalops (Yoshida, 1979). Trolling from the RV Townsend Cromwell around FFS yielded 277 scombrids in 366 line-hours. The relative biomass catch vector for the 277 scombrids was 0.58 kawakawa, 0.27 wahoo, 0.12 yellowfin tuna, and 0.03 skipjack tuna. The diet for each of these fishes caught around Oahu based on analysis of stomach contents is presented in Tester and Nakamura (1957). An average diet vector weight by the relative biomass of each of these fishes yields a species group diet vector of 0.91 small pelagics and 0.09 zooplankton.

Preliminary estimates of growth parameters for kawakawa are L_∞ = 58.0 cm and k = 0.42 (J.H. Uchiyama, 1982: personal communication). The estimated M = 0.66 from these growth estimates served as the estimate of the P:B ratio.

Zooplankton (including fish larvae)

The P:B ratio for zooplankton is size-specific, ranging from 18 to 91 (J. Hirota, 1982: personal communication). The geometric mean for this range is 40, the value used for the P:B ratio. The zooplankton diet is 0.95 phytoplankton and 0.05 benthic algae.

Phytoplankton

Because the model is predator driven, the only parameter needed for phytoplankton is the P:B ratio which is estimated at 70 (J. Hirota, 1982: personal communication).

Heterotrophic Benthos

This group consists of all the invertebrates, bacteria, and protozoans living on the benthic substrate. The P:B ratio is estimated at 3.0 (J. Hirota, 1982: personal communication). The diet is 0.15 heterotrophic benthos and 0.85 benthic algae.

Benthic Algae

This group consists of fleshy algae, turf algae, and corals. The only parameter required for this species group is the P:B

ratio which is estimated at 12.5 (J. Hirota, 1982: personal communication).

A summary of all the input parameter estimates are provided in Tables 1 and 2.

RESULTS AND DISCUSSION

The ECOPATH estimates of mean annual biomass and annual production for the species group at FFS are provided in Table 3 and a simplified ecosystem food web is schematically presented in Figure 1. As might be expected the reef fishes group is the largest in terms of biomass after the primary producers and heterotrophic benthos. The biomass and production for this group of reef fishes can be checked from current field studies on reef habitat and reef transects at FFS (H. Okamoto and Hobson, 1979: personal communication; R.W. Grigg and J.D. Parrish, 1979: personal communication). These studies suggest that 12 percent of the area from the 0 to 18 m (0 to 10 fathoms) depth is rich in reef fishes, 17 percent is moderate, and 71 percent is sparse. It is assumed that the area in depths from 18 to 55 m (10 to 30 fathoms) is entirely a sparse habitat. A total of 36 transects produced estimates of fish biomass as follows: for a rich habitat 163,666 kg/km^2; for a moderate habitat 16,815 kg/km^2; and for a sparse habitat 1,569.4 kg/km^2. This gives an average density of reef fishea at FFS of 15,000 kg/km^2 which compares with the model estimate of 24,163 kg/km^2 over the reef habitat. Production of fishes from a reef in Bermuda was estimated at 22,000 kg/km^2/yr (Bardach, 1959) which is also comparable with the model estimate of 36,244 kg/km^2/yr (Table 3).

Although an estimate of density for bottomfishes is not available to check the model value, an estimate for maximum sustainable yield (MSY) of bottomfishes at Penguin Bank in the Hawaiian Archipelago has been obtained based on the Schaefer surplus production model. The estimated MSY, which is a lower bound because it does not take into account a recreational fishery, is 272 kg/nmi of 100-fathom isobath (Ralston and Polovina, 1982). Using Gulland's formula MSY = 1/2 M B_O, with the value M = 0.32 used in the model and the model estimate of B_O = 387 kg/km^2, an estimated MSY of 62 kg/km^2 is obtained. Since the bottomfish habitat is approximately 300 km^2 and the length of the 100-fathom contour at FFS is 65 nmi, the estimated MSY of 62 kg/km^2 is equivalent to an MSY of 286 kg/nmi of 100-fathom isobath which is in agreement with the Penguin Bank value.

TABLE 1. DIET (PERCENTAGE BY SPECIES GROUP) OF SPECIES GROUPS AT FRENCH FRIGATE SHOALS

Birds	
Small pelagics	68
Jacks	10
Reef fishes	15
Nearshore scombrids	2
Zooplankton	5
Tiger sharks	
Birds	30
Monk seals	8
Tiger sharks	1
Reef sharks	3
Turtle	1
Small pelagics	8
Jacks	5
Reef fishes	28
Lobster and crabs	14
Nearshore scombrids	2
Small pelagics	
Small pelagics	6
zooplankton	94
Reef fishes	
Reef fishes	12.3
Zooplankton	17
Heterotrophic benthos	45.9
Benthic algae	24.8
Bottomfishes	
Small pelagics	12.5
Reef fishes	46.9
Lobsters and crabs	1.8
Bottom fishes	2.6
Zooplankton	10.4
Heterotrophic benthos	25.8
Monk seals	
Reef fishes	85
Lobsters and crabs	15
Reef sharks	
Small pelagics	5
Reef fishes	90
Lobsters and crabs	5
Turtles	
Zooplankton	10
Benthic algae	90
Jacks	
Small pelagics	8
Reef fishes	80
Lobsters and crabs	12
Lobsters and crabs	
Heterotrophic benthos	100
Nearshore scombrids	
Small pelagics	48
Reef fishes	8
Bottom fishes	8
Zooplankton	36
Heterotrophic benthos	
Heterotrophic benthos	15
Benthic algae	85
Zooplankton	
Phytoplankton	91
Benthic algae	9

TABLE 2. INPUT PARAMETERS FOR THE ECOPATH MODEL

Species Group	Production/ Biomass	Food for Production Biomass	Food for Maintenance Biomass	Nonpredatory Mortality	Biomass for Apex Species (kg/yr^2)
Birds	5.40	15	2	--	15.4
Monk seals	3.00	15	2	--	63.0
Tiger shark	0.25	10	2	--	42.0
Reef sharks	0.18	10	2	0.024	--
Turtles	0.15	10	2	0.024	--
Small pelagics	1.10	5	2	0.024	--
Jacks	0.47	5	2	0.024	--
Reef fishes	1.50	5	2	0.024	--
Lobsters and crabs	0.52	12	2	0.024	--
Bottom fishes	0.32	5	2	0.024	--
Nearshore scombrids	0.66	5	2	0.024	--
Zooplankton	40.00	7	2	0.024	--
Phytoplankton	70.00	--	--	0.024	--
Heterotrophic benthos	3.00	5	2	0.024	--
Benthic algae	12.50	--	--	0.024	--

TABLE 3. MEAN ANNUAL BIOMASS AND ANNUAL PRODUCTION ESTIMATE FROM ECOPATH MODEL

Species Group	Biomass Per Habitat Area (kg/km^2)	Annual Production Per Habitat Area (kg/km^2)	Habitat Area (km^2)	Ecological Efficiency (Production/ Consumption)	Consumption/ Biomass
Birds	15	83	1,200.00	0.07	83.0
Monk seals	63	189	1,200.00	0.06	47.0
Tiger sharks	42	11	1,200.00	0.06	4.5
Reef sharks	38	7	1,200.00	0.05	3.8
Turtles	15	2	1,200.00	0.04	3.5
Small pelagics	1,883	2,071	1,200.00	0.15	7.5
Jacks	421	147	1,200.00	0.09	3.8
Reef fishes	24,163	36,244	700.00	0.16	9.5
Lobsters and crabs	2,327	1,210	700.00	0.06	8.2
Bottom fishes	387	124	300.00	0.09	3.6
Nearshore scombrids	62	41	900.00	0.12	5.3
Zooplankton	912	36,486	1,200.00	0.14	282.0
Phytoplankton	3,345	234,157	1,200.00	0.00	0.0
Heterotrophic benthos	289,181	867,543	700.00	0.19	52.0
Benthic algae	342,598	4,282,471	700.00	0.00	0.0
Total biomass	390,604				
Total production		3,294,960			

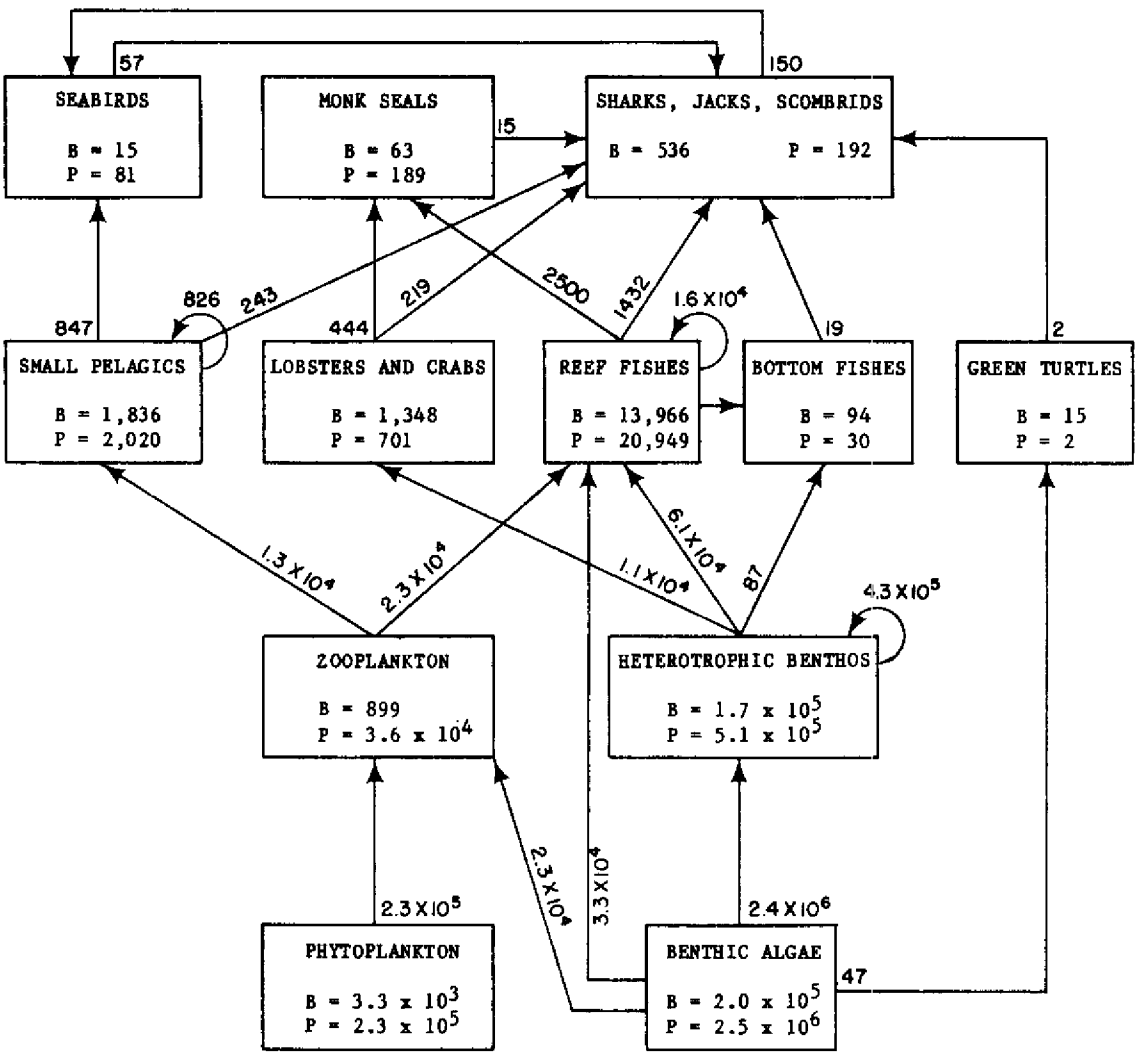

Figure 1. Biomass budget schematic for major prey-predator pathways. Annual production denoted as P and mean annual biomass as B with values in units of kg/km^2 based on a habitat area of 1,200 km^2 for purposes of trophic comparisons and will differ from estimates of B and P given in Table 3 when the habitat area is less than 1,200 km^2.

An estimate of the biomass of the reef shark population at FFS can be determined from population and mean weight estimates from DeCrosta (1981). The results of intensive fishing at FFS provide an estimate of the population of galapagos shark at 703 individuals and the gray reef shark at 826 individuals. With these population estimates and estimated mean weight of 60 kg for the galapagos shark and 20 kg for gray reef shark, the estimated biomass for the reef shark population is determined to be 48 kg/km^2. This compares with the model estimate of 38 kg/km^2. Hirota et al. (1980) estimated the primary production in the nearshore region in the NWHI at 670 metric tons (MT) biomass/ km^2/yr. The model estimates that 234 $MT/km^2/yr$ of phytoplankton production is needed to support life in the reef and nearshore ecosystem.

An estimate of net benthic primary production over a 700 km^2 habitat at French Frigate Shoals based on field measurements is 4.1×10^6 $kg/km^2/yr$ (see expanded abstract in this proceedings by R. Grigg). The model estimates the net benthic algal production necessary to support the ecosystem at French Frigate Shoals at 4.3×10^6 $kg/km^2/yr$ (Table 3).

The biomass of prey consumed by each predator is presented in Table 4. From Figure 1 and Table 4, it can be determined, for example, that monk seals consume most of the lobster and crab production but that they still constitute only a small portion of the monk seal diet compared with the portion of reef fishes.

SENSITIVITY ANALYSIS

To determine the sensitivity of the mean annual species group biomass estimated by the ECOPATH model to uncertainty or error in the inputted parameter estimates, a simple sensitivity analysis was performed. The set of input parameters used for the FFS biomass estimation served as the baseline values.

For a specific parameter, say the P:B value, the parameter for species group i was perturbed by a percentage p with all other parameters fixed at their baseline values, and the mean annual biomass for species group i was computed based on the perturbed parameter. The percentage of change of this new mean annual biomass from the baseline biomass for species group i was computed. This procedure was repeated for all i where each time the parameter for a new species group, say i + 1, was perturbed, the parameter value for species group i was returned to the baseline value. Let B_{io} represent the baseline mean annual biomass for species group i and B_{ip} represent the mean annual biomass for species group i when one of the input parameters was perturbed by p percent. Then a measure of the sensitivity of the estimate of mean annual biomass to a p percentage of change in a specific input parameter is the average absolute value of the change in mean annual biomass averaged over all species groups (avg B)

TABLE 4. PREDATOR CONSUMPTION VECTOR (KG/KM^2) BASED ON A HABITAT AREA 1,200 KM

Birds	
Small pelagic	869
Jacks	128
Reef fishes	192
Nearshore scombrids	26
Zooplankton	64
Tiger sharks	
Birds	57
Monk seals	15
Tiger sharks	2
Reef sharks	
Turtles	2
Small pelagics	15
Jacks	10
Reef fishes	53
Lobsters and crabs	27
Nearshore scombrids	4
Small pelagics	
Small pelagics	847
Zooplankton	13,272
Reef fishes	
Reef fishes	16,470
Zooplankton	22,763
Heterotrophic benthos	61,461
Benthic algae	33,208
Bottomfishes	
Small pelagics	15
Reef fishes	163
Lobsters and crabs	6
Bottomfishes	9
Zooplankton	36
Heterotrophic benthos	90
Monk seals	
Reef fishes	2,517
Lobsters and crabs	444
Reef sharks	
Pelagics	7
Reef fishes	127
Lobsters and crabs	7
Turtles	
Zooplankton	5
Benthic algea	47
Jacks	
Small pelagics	126
Reef fishes	1,263
Lobster and crabs	
Heterotrophic benthos	11,187
Nearshore scombrids	
Small pelagics	117
Reef fishes	20
Bottomfishes	20
Zooplankton	88
Heterotrophic benthos	
Heterotrophic benthos	260 x 10
Benthic algae	1.5 x 10
Zooplankton	
Phytoplankton	234 x 10
Benthic algae	23 x 10

where

$$\text{avg } B = \sum_{i=1}^{15} |B_{io} - B_{ip}| / 15\ B_{io} .$$

Similarly the sensitivity of the estimated total ecosystem mean annual biomass (TB) to change in the input parameters can be measured by the average change in TB when a specific parameter is perturbed for one species group at a time. If TB_{ip} represents the total ecosystem mean annual biomass when a parameter for species group i is perturbed by p percent, and if TB is the total ecosystem mean annual baseline biomass, then a measure of the sensitivity of the total biomass to change in a single parameter is the average absolute change in total biomass (avg TB) where:

$$\text{avg TB} = \sum_{i=1}^{15} |TB - TB_{ip}| / 15\ TB .$$

The values of avg B and avg TB for changes in P:B, d, a, b, and the apex B's are given in Table 5. The estimate of mean annual biomass and total ecosystem biomass is relatively insensitive to change in the input parameters a, b, d, and the apex B's. For example, an increase in the value of a, the ratio of food required for growth, by 25 percent only results in a 1.8 per cent change in the average mean annual biomass and a 2.8 percent change in total biomass. However, the estimate of mean annual biomass is quite sensitive to changes in the P:B value. A 25 percent increase for a specific species group results in almost a 22 percent change in the average mean annual biomass, and a 25 percent decrease results in almost a 40 percent change. Fortunately, this sensitivity is restricted only to the species group for which the parameter is being perturbed since the average change in total ecosystem biomass is relatively small for the P:B parameter.

Thus far a parameter has been perturbed for only one species group at a time. The sensitivity of the estimated annual species group biomass and total ecosystem biomass to perturbation in the P:B value and food required (a and b together) for 10 percent changes in all species groups simultaneously is given in Table 6. Due to the prey-predator interactions a 10 percent change in all food consumption values or a 10 percent change in all P:B values can have a substantially greater effect on the estimated species group biomasses and the estimated total ecosystem biomass.

TABLE 5. AVERAGE CHANGE IN MEAN ANNUAL BIOMASS AND TOTAL ECOSYSTEM BIOMASS AS A FUNCTION OF CHANGE IN INPUT PARAMETERS

	Perturbation Relative to Baseline Value							
	0.75	0.80	0.85	0.90	1.10	1.15	1.20	1.25
				Parameter a				
avg B	0.016	0.013	0.010	0.006	0.007	0.011	0.014	0.018
avg TB	0.026	0.021	0.016	0.011	0.011	0.017	0.022	0.028
				Parameter b				
avg B	0.046	0.038	0.030	0.021	0.026	0.041	0.059	0.080
avg TB	0.049	0.040	0.031	0.021	0.024	0.038	0.053	0.070
				Parameter d				
avg B	0.014	0.011	0.008	0.006	0.006	0.009	0.012	0.015
avg TB	0.005	0.004	0.003	0.002	0.002	0.003	0.004	0.005
				P:B ratio				
avg B	0.394	0.292	0.204	0.127	0.101	0.144	0.183	0.219
avg TB	0.076	0.056	0.039	0.024	0.019	0.027	0.034	0.040
				Apex B's				
avg TB	0.083	0.067	0.050	0.033	0.033	0.050	0.067	0.083

TABLE 6. CHANGE IN MEAN ANNUAL BIOMASS AND TOTAL ECOSYSTEM BIOMASS AS A FUNCTION OF SIMULTANEOUS CHANGES IN A PARAMETER FOR ALL SPECIES GROUPS

	Perturbation Relative to Baseline Value	
	0.90	1.10
	Parameter Jointly a and b	
avg B	0.14	0.19
avg TB	0.23	0.32
	Parameter P:B	
avg B	0.25	0.17
avg TB	0.32	0.21

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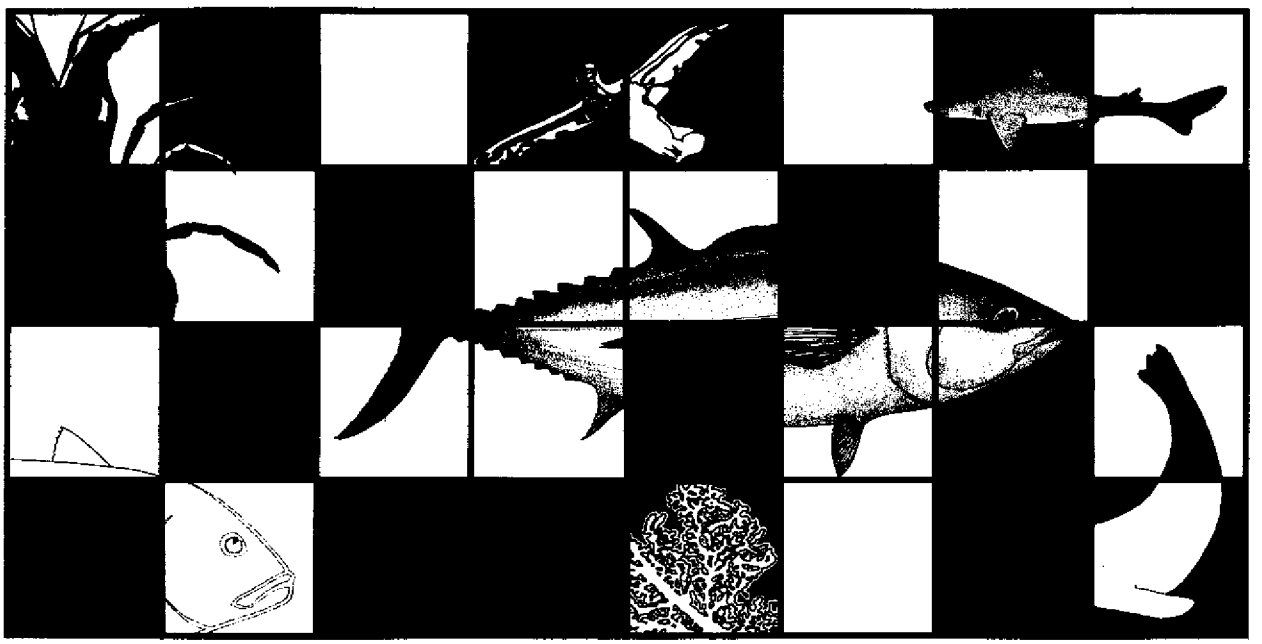

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ECONOMICS AND ENVIRONMENTAL VALUES IN THE MANAGEMENT OF THE NORTHWESTERN HAWAIIAN ISLANDS' FISHERY AND ENVIRONMENTAL RESOURCES

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ABSTRACT

The primary objective of this study was to provide information to and study the response of decisionmakers involved in making choices for the allocation and management of the living resources in the Northwestern Hawaiian Islands. This was accomplished by (1) creating an information base of impacts of various fishery/management alternatives; and (2) using this information base to determine individual utility functions and group choice criteria for a Fisheries Development Coalition and a Wildlife Conservation Coalition.

Impacts of the implementation of the fishery/management alternatives were evaluated in five dimensions called "attributes" through Delphi procedures. Individual utility functions determined by logit analysis and group weights for the five attributes elicited by Delphi/Delbeq procedures indicated that the protected wildlife held considerable value. These results implied that the establishment of the fishery development facilities studied would not generate expected revenues large enough to offset the adverse environmental impacts on the protected wildlife.

economics
policy
trade-offs
decisionmaking
utility functions

INTRODUCTION

The Problem

The extended jurisdiction provisions of the Magnuson Fisheries Conservation and Management Act of 1976 focused local and national attention on fisheries development and management of the Northwestern Hawaiian Islands (NWHI) and surrounding waters. These islands present a special problem for development and management due to possibilities of conflict between fisheries development and protection of the area's unique flora and fauna (some of which are legally defined as "endangered" or "threatened").

The development of policy becomes difficult in the case of the NWHI because such goods as natural resource environments and wildlife species are non-market goods. Methods are needed to evaluate the worth of these resources to society. Although economists have developed various kinds of indirect estimates of the value of non-market public goods, these rely on user or potential user information as the basis for measurement of resource values. In the case of the Northwestern Hawaiian Islands, these methods do not appear to be appropriate, since those people who vote to protect the flora and fauna are not active or potentially active users. To determine the appropriate emphasis on development and on environmental protection in the development of policy, another method of evaluation is needed.

The method of evaluation chosen for this study is decision-analysis. This technique investigates the preferences and attitudes of decisionmaking entities and recognizes the "personal element in decision-making" (Anderson et al., 1977, p. 11) and attempts to insure that decisions made "best corresponds to the beliefs, attitudes, and preferences of the decision-makers" (Mohayidin, 1981, p. 30).

Objective of the Study

The overall objective of this study is to devise methods to provide decisionmakers with information and insights into the nature and consequences of making choices among alternatives for the development and management of the Northwestern Hawaiian Islands. The following set of procedures was followed to accomplish this objective.

1. Create an information base for use by decisionmakers regarding the attributes of various alternatives' outcomes of fishery development
2. Model the decisionmaking process of the individuals involved in the study
3. Determine the trade-offs between development benefits and preservation benefits by persons identified as having a role in the decisionmaking process both on an individual and group basis

4. Examine the social, economic, and management implications of the decision modeling results

MANAGEMENT ALTERNATIVES STUDIED

Table 1 shows a matrix of development/management options that were under discussion at the time this study was initiated. The fishery facility options of "Midway Islands," "Tern Island," and "Mothership" are based on proposals made by various public agencies for the development of the area. The "Shoreline," "10 Fathom," "20 Fathom," and "3 Mile" delineations of protected waters are based on a proposal by the National Marine Fisheries Service for the designation of a critical habitat for the Hawaiian monk seal under the Endangered Species Act of 1973. For this study, it is assumed that no fishing will be allowed within the protected waters. The "No Development" facility and the "Shoreline" regime (which is defined as the boundary of the Hawaiian Islands National Wildlife Refuge as claimed by the Fish and Wildlife Service) are also included in this table. These are the status quo development and management strategies operating at present in the area.

TABLE 1. DEVELOPMENT/MANAGEMENT ALTERNATIVES FOR THE NORTHWESTERN HAWAIIAN ISLANDS

Outside Development Facilities	Management Regimes			
	Shoreline	10 Fathoms	20 Fathoms	3 Miles
No Development	IA	IB	IC	ID
Midway Islands	IIA	IIB	IIC	IID
Tern Island	IIIA	IIIB	IIIC	IIID
Mothership	IVA	IVB	IVC	IVD

Only one Midway alternative was retained in the study -- the Midway Islands/3 Mile alternative. The Midway facility was assumed to primarily service the albacore fishery. Since the albacore fishery is located approximately 500 to 1,000 miles north of Midway, it was assumed that the vessels utilizing this facility would not be fishing closer to the refuge than 3 miles. The only difference between the No Development alternatives and the Midway Islands/3 Mile alternative would be due to the increased catches of albacore.

Estimated Attributes of the Alternatives

The five attributes of importance to the decisionmakers were assumed to be: (1) the cost of establishing and constructing a fisheries facility within the Northwestern Hawaiian Islands area; (2) the average annual expected revenues from the commercial fisheries over the 10 years following the construction of the facility; (3) the change in the monk seal population at the end of 10 years; (4) the change in the green turtle population at the end of 10 years; and (5) the change in the seabird population at the end of 10 years.

Estimates of the costs (in terms of a likely range) of establishing the three proposed fishery facilities were available from the Division of Aquatic Resources. It was necessary to estimate wildlife impacts and potential fisheries catches to determine the other four attributes.

PROCEDURES FOR DEVELOPING FISHERIES CATCH AND WILDLIFE IMPACTS

Catch estimates of various species were required to estimate the expected revenues attribute. At the time this study was being conducted, only a small portion of the information needed to determine the fishery resource potential and wildlife impacts associated with development regimes was available. A number of studies were underway and a large pool of technical experts had been involved in ongoing and previous studies. Theoretically, this pool of expertise, individually and collectively, represented the state-of-knowledge of the area and its resources. The Delphi technique was determined to be an appropriate one to elicit the needed data from the experts.

In general, the Delphi technique relies on expert opinions on the investigated topic and involves a structured and consistent procedure to elicit data. It has three features: anonymity, controlled feedback, and statistical group response. These features reduce "noise" and "dominance effects" of strong personalities in an interactive group and allows evaluation of opinions on the merits of its rationale and not on the status of the person presenting the argument. The Delphi method has been used in previous studies as a forecaster of land use (Ervin, 1977; Farkas and Wheeler, 1980), air travel and air technology (English and Kerman, 1976), manpower forecasting (Milkovich et al., 1972), and recreational fishery catch (Zuboy, 1981).

In summary, it was assumed that two distinct sets of expert/researchers had access to the best available information regarding the commercial fisheries and the protected wildlife; thus, two Delphis, one for the fisheries and another for the wildlife, were needed to provide the catch and wildlife impact data.

The first step towards conducting the Delphis was the identification of experts. To assure that the information was

"trustworthy," decisionmakers were polled and asked to identify experts. The decisionmakers polled were directly responsible for the management of the resources in the studied area (e.g., director of the Western Pacific Program, National Marine Fisheries Service; director of the Division of Aquatic Resources, Department of Land and Natural Resources; and administrator of the Pacific Islands Office, U.S. Fish and Wildlife Service). An "expert" was asked to participate in a Delphi if his/her name appeared on a minimum of two lists. The list for the Wildlife Delphi included 18 experts of which 14 agreed to participate and the list for the Fisheries Delphi included 24 experts of which 21 agreed to participate. Both lists included one expert from the mainland who participated throughout the Delphi procedures.

The Fisheries Delphi and the Wildlife Delphi were conducted in three rounds each. During the first and second rounds of each Delphi, participants were asked two basic questions: (1) If a given alternative were implemented, what would be the impact over a 10-year period on certain species? and (2) Why do you feel that this impact will occur? Participants were given the option of answering the first question graphically or in a narrative form; the second question had to be answered in narrative form.

When the questionnaires were returned by the experts, their responses for each species for each alternative were separated into categories of increasing, decreasing, or constant trend curves. This categorization was done visually by using the points on the individual experts' curves at the first, fifth, and tenth years. Information on the range and mean for each trend curve and the number of experts who had predicted the trend curve, along with summaries of the rationales, were fed back to the experts.

In the third round of the Delphis, the participants were asked to estimate the probabilities associated with each trend curve. It was felt that this was the appropriate time to ask for them since all the information (predictions and rationales) should have been fully communicated by then. The sum of the probabilities of the trend curves for each species within each alternative equalled 1.00.

The length of time required for each Delphi was approximately 7 months. During these periods a number of participants dropped out of the procedures. The Fisheries Delphi began with 21 experts, with 17 participating in the second round and 14 in the third. The Wildlife Delphi began with 14 experts, with 12 participating in the second round and 11 in the third.

The Fisheries Delphi and the Attribute of "Expected Revenues"

Expected catch estimates of eight fisheries species (or categories of species) were generated by the Fisheries Delphi. These included four tuna species (skipjack, albacore, bigeye, and

yellowfin), the bottomfish species category, the seamount category (alfonsin and armorhead), the baitfish category (akule and opelu), and the species of spiny lobster. The fisheries experts were asked to estimate the catches for all eight species for all alternatives proposed except the Midway Islands/3 Mile alternative. Since the Midway alternative was assumed to be specifically designed to service the albacore fishery, the experts were asked to only estimate the catches of albacore. Each fisheries expert predicted 97 trend curves in each of the first two rounds.

The means of total catch of the trend curves (over 10 years) used for the estimation of expected catch were the results of the second round and were estimated using the following formula:

$$\frac{\sum \left[(C_{ij1})(2.5) + (C_{ij5})(5) + (C_{ij10})(2.5)\right]}{N_k}$$

where

C_{ij1} = predicted catch of species i by expert j for year 1
N_k = number of experts who predicted that trend curve

Estimated average annual expected catches are presented in Table 2 with the estimates of the same species as developed in the Hawaii Fisheries Development Plan (DLNR, 1979). There appeared to be a wide divergence between the Delphi and HFDP estimates. The latter estimates were based on "resource potential" rather than "expected catch" which may account for some of the differences.

Using the prices given by the Hawaii Fisheries Development Plan, the expected revenues for each species was estimated using the following formula:

$$\sum (P_{it}\ EC_{it})$$

where

P_{it} = price of fish species i in year t
EC_{it} = expected catch (in pounds) of fish species i in year t

A "0" discount rate and constant price throughout time were also assumed in the calculation of the "expected revenues" attribute. The sum of all of the expected revenues for each species over a 10-year period was defined as the expected revenues of a proposed alternative. This was then divided by 10 to estimate the annual amount. It was this figure that was used as the basis for the decisionmakers' individual rankings (Table 3).

TABLE 2. EXPECTED AVERAGE ANNUAL CATCH ESTIMATES OF COMMERCIAL FISHERIES SPECIES (MILLIONS OF POUNDS)

Development Facility/ Management Regime	Species							
	Skipjack Tuna	Albacore Tuna	Bigeye Tuna	Yellowfin Tuna	Bottomfish Species	Seamount Species	Akule/ Opelu	Spiny Lobster
HFDP[1]	26.8	21.6[2]	15.5[3]	4.6[3]	5.1[4]	7.0[3]	2.8[5]	1.1[3]
No Development/								
Shoreline	5.4	3.0	0.6	2.0	1.2	0.8	0.4	0.7
10 Fathom	4.8	3.0	0.6	2.0	1.2	0.8	0.3	0.7
20 Fathom	4.5	3.0	0.6	2.0	0.9	0.8	0.0	0.3
3 Mile	5.0	3.1	0.6	2.0	0.6	0.8	0.0	0.2
Midway Islands/								
3 Mile	5.0	5.7	0.6	2.0	0.6	0.8	0.0	0.2
Tern Island/								
Shoreline	6.8	5.7	0.6	2.5	1.7	0.8	0.6	0.8
10 Fathom	5.8	5.8	0.6	2.5	1.7	0.8	0.5	0.8
20 Fathom	5.8	5.7	0.6	2.5	1.3	0.8	0.4	0.4
3 Mile	5.7	5.7	0.6	2.5	1.0	0.8	0.4	0.4
Mothership/								
Shoreline	6.2	6.4	1.0	2.1	1.8	0.8	0.5	0.7
10 Fathom	6.3	6.4	0.9	2.1	1.7	0.8	0.4	0.7
20 Fathom	6.0	6.4	0.9	2.1	1.2	0.8	0.3	0.5
3 Mile	5.6	6.4	0.9	2.1	1.2	0.8	0.2	0.3

[1] Hawaii Fisheries Development Plan, Department of Land and Natural Resources, State of Hawaii, 1979, p. 42
[2] Average of ranges for surface and subsurface groups
[3] Average of estimated range
[4] Average of ranges for deepsea and inshore groups
[5] Sum of averages for estimated ranges

TABLE 3. DEVELOPMENT/MANAGEMENT ALTERNATIVES' ATTRIBUTES FOR THE NORTHWESTERN HAWAIIAN ISLANDS

Development Facility/ Management Regime	Attributes[1]				
	FC	ER	MS	GT	SB
No Development/					
Shoreline (D)[2]	0.0	8.7	-22	-24	-10
10 Fathom (H)	0.0	8.3	- 5	- 9	- 5
20 Fathom (B)	0.0	7.1	- 7	- 3	- 4
3 Mile (K)	0.0	7.0	- 5	0	- 4
Midway Islands/					
3 Mile (F)	2.0	8.7	-10	- 5	- 7
Tern Island/					
Shoreline (M)	0.5	11.9	-48	-38	-18
10 Fathom (E)	1.0	11.4	-32	-34	-16
20 Fathom (A)	3.0	10.4	-32	-34	-16
3 Mile (I)	2.0	10.1	-33	-25	-15
Mothership/					
Shoreline (J)	2.5	11.7	-22	-23	-13
10 Fathom (G)	4.0	11.9	-14	-12	- 9
20 Fathom (C)	5.0	10.8	-11	- 9	- 7
3 Mile (L)	3.0	10.3	-10	- 3	- 5

[1] Key for attributes: FC = Facility cost (in millions of dollars), ER = Average annual expected revenues (in millions of dollars), MS = Change in monk seal population (in percentage), GT = Change in green turtle population (in percentage), SB = Change in seabird population (in percentage)

[2] Letters within parentheses represent the alphabetical order in which the alternatives were presented to the decisionmakers

The Wildlife Delphi and the Wildlife Attributes

The Wildlife Delphi was conducted to predict the attributes of "[percentage of] change in monk seal population," "[percentage of] change in green turtle population," and "[percentage of] change in the seabird population." The experts were asked to estimate the impacts of the proposed alternatives on the wildlife species over a 10-year period. A major assumption made by the experts was that the wildlife populations at year 1 were constant and stable and could be described as being at 100 percent.

Since the attributes were defined as the percentage of change in the wildlife species at the end of the 10-year period, only the expected population proportion at the end of the tenth year was needed. The formula for the estimation of the percentage of change in the population is:

[(Expected Population at end of Year 10) - 100%]

The expected population was estimated by summing the products of the mean of each trend curve (defined as the mean proportion at the end of the tenth year) and the mean probability associated with it which was estimated in the third round (Table 3).

DECISIONMAKING AND POLICY DEVELOPMENT

At the onset of the study it was generally believed that the public decisionmakers and private interests concerned with the development and management of the resources of the Northwestern Hawaiian Islands fell into two groups. These groups (called "coalitions" in the study) would advocate either the goals of wildlife preservation or those of fishery development, according to the mandates of offices, positions, or values they held (Figure 1). Political science theory states that it is the interaction between the coalitions which will determine the policy that finally develops. Since the goals of wildlife preservation and fishery development may conflict with one another, the interaction between the two coalitions was assumed to be competitive. It was hypothesized that these coalitions were faced with a prisoner's dilemma, i.e., the Wildlife Conservation Coalition preferred alternatives that would be highly restrictive to fisheries development, and the Fisheries Development Coalition preferred alternatives that would adversely affect the wildlife of the area. The identification of compromise alternatives was needed to help resolve the management issue.

PROCEDURE FOR THE ASSESSMENT OF INDIVIDUAL AND GROUP UTILITY FUNCTIONS

The determination of the individual decisionmakers for the Northwestern Hawaiian Islands began with a survey of persons representing various agencies who were involved in the management of the resources of the area. Those decisionmakers whose names

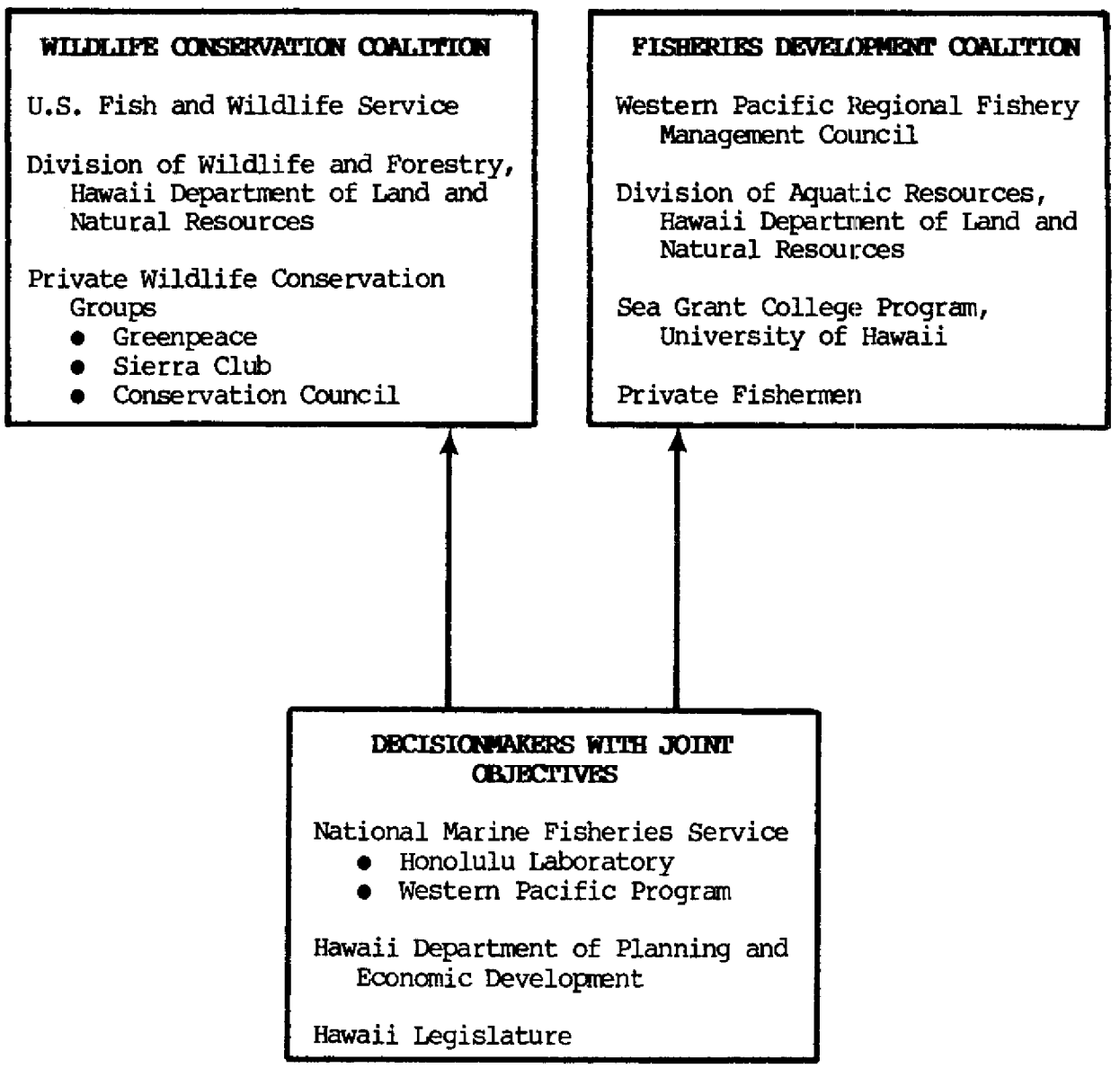

Figure 1. Coalition of public decisionmakers in the Northwestern Hawaiian Islands problem

were proposed, were in turn surveyed for names of other decision-makers as well. If a decisionmaker's name was proposed by two different agencies, his or her name was then placed on the list of those who were asked to participate in this study. This procedure was identical to that used to identify the experts who participated in the Delphi procedures. Twenty-five decision-makers were included on the list, and some of the agencies listed on Figure 1 were represented by more than one individual.

In order to determine the utility functions of the individuals, each decisionmaker was asked to rank the 13 alternatives from most preferred to least preferred based on the 5 attributes discussed above. These rankings were then transformed into data that were used in a logit model which estimated linear utility functions of the decisionmakers. Discussions of the logit model may be found in Amemiya (1981); Pindyk and Rubinfeld (1981); and Theil (1971).

In Figure 1 the composition of the Wildlife Conservation Coalition and the Fisheries Development Coalition is given. The private conservation groups and the private fishermen were placed in their respective coalitions according to what appeared to be their vested interests. Eight individual decisionmakers were placed in only the Wildlife Conservation Coalition, twelve were placed in only the Fisheries Development Coalition, and five were placed in both coalitions due to their joint responsibilities.

Each coalition was asked to arrive at a consensus regarding the importance ranking of the attributes through a series of rounds where they were allowed to interact verbally. After consensus was reached the members of the coalition were then asked to give weights to the attributes. In the first weighting vote, the top ranked attribute was assigned an importance weight of 100 and in the second weighting vote the least ranked attribute was given a weight of 10 with no weight higher than 1,000. Each member of the coalition assigned weights to the other attributes proportionate to their relative utility to the base attribute. The weights could be of any magnitude but the order of the weights could not differ from the group consensus of the attribute ranking.

This procedure used to elicit the coalitions' weightings of the attributes included aspects of both the Delbeq and Delphi technique procedures. Both techniques consist of structured communication procedures among a group of individuals to arrive at a consensus. The main difference between these two techniques is that the Delbeq technique allows direct interaction among the participants, even though the communication is still well directed and structured. Communication among participants in a Delphi procedure is channeled only through the analyst who summarizes the responses then feeds them back to the group.

RESULTS

The affiliation of the 25 decisionmakers represented are shown in Table 4. Public agencies were represented by 48 percent of the decisionmakers and the private sector (private conservation groups and private fishermen) by 28 percent. The state legislature and University of Hawaii were represented by 16 percent and 8 percent of the decisionmakers, respectively.

TABLE 4. AGENCY REPRESENTATION OF THE INDIVIDUAL DECISIONMAKERS

Category	Number	Percentage
Public agencies		
U.S. Fish and Wildlife Service	3	12
National Marine Fisheries Service	3	12
Western Pacific Regional Fishery Management Council	2	8
Hawaii Department of Land and Natural Resources	3	12
Hawaii Department of Planning and Economic Development	1	4
Hawaii Legislature	4	16
University of Hawaii	2	8
Private wildlife conservation groups	4	16
Private fishermen	3	12
TOTAL	25	100

Individual Decisionmakers' Rankings and Utility Functions

In the set of alternatives that was presented to the decisionmakers in this study, the "status quo" policy of No Development/Shoreline regime, alternative "D," was included. The results of the individual rankings which are summarized in Table 5 show that the continuation of this alternative is not highly preferred compared with the other alternatives (i.e., rankings given were not above "7" except for only one individual). Another result is that, based on the magnitudes of the given attributes, the alternatives with the Tern Island facility are not acceptable for most of the decisionmakers, regardless of the management boundary imposed with its establishment. The most preferred of the alternatives studied for a majority of the individuals was alternative "K," No Development/3 Mile, and

TABLE 5. FREQUENCY OF INDIVIDUAL RANKS FOR ALTERNATIVES A THROUGH M

Alternative	Rankings				
	13-11	10-8	7	6-4	3-1
A	0	1	0	3	21
B	18	1	0	5	1
C	3	14	4	1	3
D	0	2	4	17	2
E	1	0	1	14	9
F	4	21	0	0	0
G	5	6	12	1	1
H	16	7	0	1	1
I	1	1	0	9	14
J	0	5	3	16	1
K	19	2	1	2	1
L	8	14	0	2	1
M	0	1	0	4	20

Note: 13 = most preferred alternative, 1 = least preferred alternative

alternative "H," No Development/10 Fathom. However, both of these alternatives received low rankings from three and two decisionmakers, respectively. On the other hand, alternative "F," Midway Islands/3 Mile, did not receive the highest rankings, but all the decisionmakers ranked it above "7."

Utility weights for the five attributes determined by the logit analysis are presented in Table 6. A summary of Spearman's rho and Kendall's tau statistics between the actual and predicted rank orders are also included. A Spearman's rho coefficient of .89 and a Kendall's tau value of .74 was defined as the criteria of strong correlation. This amounts to the ranks of five sequentially ranked alternatives in one set being interchanged in the other ranked set.

TABLE 6. UTILITY WEIGHTS OF INDIVIDUAL DECISIONMAKERS

Decision-maker	Constant	Facility Cost[1]	Expected Revenues[1]	Change in Monk Seal Population[2]	Change in Green Turtle Population	Change in Seabird Population	Rho[3]	Tau[4]
1	26.03	- 4.77	37.91	32.19	9.94	4.11	.98	.92
2	-62.18	- 4.37	-10.90	33.32	- 6.01	- 3.51	.98	.90
3	- 1.39	-24.35	- 7.29	16.04	1.91	- 7.91	1.00	1.00
4	-12.53	7.49	-19.81	3.28	.03	16.29	1.00	1.00
5	1.99	.20	1.46	1.64	.70	- .24	.96	.90
6	8.90	-11.39	6.84	- .04	10.48	4.93	1.00	1.00
7	.27	- .51	1.71	.05	.08	.22	.84	.67
8	- .05	.21	.43	.16	.06	- .11	.89	.72
9	-21.78	-34.48	.72	13.45	6.71	-11.76	.98	.92
10	- .08	1.21	3.53	.25	.38	1.27	.97	.90
11	.31	- 1.46	.58	.53	.20	- .19	.98	.92
12	-21.09	-14.49	-29.77	25.30	- 1.86	-23.29	.99	.95
13	2.71	- 2.61	2.27	.32	1.04	- .56	.97	.87
14	- .87	- 2.57	- 3.79	.41	.12	- 1.01	.97	.87
15	- .25	- 1.69	1.49	- .03	.21	.31	.89	.72
16	- 7.27	-10.90	- 2.21	2.07	3.71	11.10	1.00	1.00
17	- .46	- .75	.81	.29	.02	- .16	.57	.44
18	-62.18	- 4.37	-10.90	33.32	- 6.01	- 3.51	.98	.90
19	-66.57	-10.41	-22.41	27.59	- 9.65	10.05	.98	.92
20	.61	- 1.99	1.34	.41	.22	- .72	.91	.80
21	20.79	-11.38	-23.77	27.60	- 4.61	49.82	.98	.92
22	.25	- 1.73	.72	.21	.45	- 1.70	.83	.67
23	19.75	-42.83	17.14	8.06	9.14	-15.10	1.00	1.00
24	-21.15	13.16	-15.69	10.86	7.81	- 1.82	.99	.95
25	.09	2.13	.24	- .17	.33	- .27	.96	.87

[1] In millions of dollars
[2] In percentage
[3] Spearman's Rho correlation coefficient
[4] Kendall's Tau correlation coefficient

The additive form of the utility function appears to adequately describe the utility functions of the decisionmakers and the estimated weights determined by the logit analysis appear to give accurate predictions of the alternatives' rank orders. Of the 25 decisionmakers' actual and predicted rankings, 5 were perfectly correlated, 16 were strongly correlated, and 3 were moderately correlated with one another. Only one of the decisionmakers' predicted and actual rankings was weakly correlated.

Coalitional Groups

Agency representation in the Wildlife Conservation and Fisheries Development Coalitions is shown on Table 7. The number of

TABLE 7. AGENCY REPRESENTATION OF DECISIONMAKERS BY COALITION

Category	Wildlife Conservation Coalition		Fisheries Development Coalition	
	Invited	Participated	Invited	Participated
Public agencies				
U.S. Fish and Wildlife Service	2	2	0	0
National Marine Fisheries Service	2	1	2	2
Western Pacific Regional Fishery Management Council	0	0	1	0
Hawaii Department of Land and Natural Resources	1	1	2	0
Hawaii Department of Planning and Economic Development	1	0	1	0
Hawaii Legislature	1	0	4	1
University of Hawaii	0	0	2	2
Private wildlife conservation groups	3	2	0	0
Private fishermen	0	0	3	1
TOTAL	10	6	16	6

Note: Invited = invited to participate in coalition, Participated = actually participated in coalition decisionmaking

decisionmakers participating in the Wildlife Conservation Coalition represented 60 percent of the individuals invited, whereas only 37.5 percent of the invited decisionmakers participated in the Fisheries Development Coalition.

All the members of the Wildlife Conservation Coalition had individual rankings that were strongly correlated with one another. Of the 16 members of the Fisheries Development Coalition, 8 members' rankings were strongly correlated with one another (and with the Wildlife Conservation Coalition's members); the other 8 decisionmakers' rankings were not correlated with those of anyone else. This ratio of highly correlated and independent decisionmakers (50 percent) was maintained in the actual Fisheries Development Coalition meeting. Interestingly, the three public agencies who are responsible for the plans for fishery development did not participate in the Fisheries Development Coalition. If they had participated, the proportion of members with strong wildlife values would have increased to 55 percent and the proportion of independent decisionmakers would have dropped to 45 percent. This implies that a wildlife coalition exists almost "voluntarily" (in the sense that individual members hold common values and goals) and can be organized easily in the public arena. A fisheries development coalition would require much more effort and time to be organized into a cohesive unit due to the diverse value systems of its members.

Table 8 presents the means of the data generated in the coalitional meetings. The Wildlife Conservation Coalition's weights reflected its general concern with all the wildlife species, with 91.8 percent of the total group weight being placed on the wildlife attributes alone. The Fisheries Development Coalition, as was expected, gave the most weight to "expected revenues." However, it appeared to be "environmentally aware," with the total sum of the weights given to the wildlife attributes accounting for 55.4 percent of the group's weighting. The rank orderings of the alternatives based on both the coalitions' weightings were similar to one another and were highly correlated with one another. For both coalitions, the No Development/3 Mile alternative was the most preferred of all those studied. Also, all of the Tern Island facility alternatives were the least preferred.

This similarity between the group rankings also indicates that both coalitions felt that expected revenues of the fishery development alternatives did not justify the adverse impacts on the wildlife species. This was true even for the "economically minded" fishery development group, based on the estimated outcomes of the alternatives. Since the rankings of both groups were in close agreement with one another, there was no evidence of a conflict regarding the proposed alternatives, and the need to identify compromise alternatives did not exist.

TABLE 8. MEANS OF GROUP WEIGHTING VOTES

Attribute	Wildlife Conservation Coalition				Fisheries Development Coalition			
	Max. 100	Min. 10	Ave.[1]	SD[2]	Max. 100	Min. 10	Ave.[1]	SD[2]
Facility cost	-.067	-.014	-.041	.047	-.081	-.025	-.053	.061
Expected revenues	.067	.014	.041	.047	.341	.443	.393	.181
Change in the monk seal population	.352	.412	.382	.059	.253	.259	.256	.084
Change in the green turtle population	.300	.341	.321	.042	.184	.161	.172	.052
Change in the sea-bird population	.213	.218	.215	.075	.142	.111	.126	.048

[1] Ave. = average of the "Max. 100" and "Min. 10" votes
[2] SD = standard deviation of the average weight

The "Shadow Price" of the Wildlife Populations

Implicit in the preference scheme, reflected in the coalitions' rankings (based on utility weights) and most of the individual decisionmakers' rankings, is the "shadow price" of the wildlife species as defined by Mishan (1976). Mishan states that "the term [shadow price] has been extended to estimates of social benefits, or social losses, that are either unpriced or not satisfactorily priced. Unpriced, or inadequately priced benefits or losses may be valued . . . by calculating the price for a good or a 'bad', that is implicit in government decisions to undertake particular projects." So the act of choosing No Development/3 Mile over No Development/Shoreline implies that decisionmakers value 17 percent of the monk seal population, 24 percent of the green turtle population, and 6 percent of the seabird population by at least $1.7 million per year, which is the expected annual revenue lost by choosing the more restrictive management regime.

EXTENSIONS OF THE FINDINGS

An important advantage of the analysis is that a criterion is available to evaluate alternatives as new information is generated or some assumptions regarding the implementation of the alternatives are changed. The following reflect the assumptions that (1) management regimes (i.e., the boundaries of protected waters) cannot be changed; (2) the private sector will finance the establishment and construction of the facility (i.e., the public facility cost is "0"); and (3) the prices of the commercially harvested species change, thus changing the attribute of "expected revenues" for all the alternatives.

The "Status Quo" Alternative as a Baseline Alternative

If the critical habitat designation is significantly delayed due to institutional and political constraints, the establishment and operation of a development facility may be as acceptable as the "status quo," No Development/Shoreline, for both coalitions and their members if an increase of expected revenues were large enough to offset the associated adverse wildlife impacts. Using the group weighting of the two coalitions, Table 9 presents the expected revenues that would need to be generated for a development facility to be preferred over the status quo (utility weights in this table were determined by using group weights, but each individual decisionmaker's requirement in terms of expected revenues can be determined by using their individual utility weights as determined by the logit analysis).

Table 9 points to a potential conflict that may occur regarding which facility should be established. For the Wildlife Conservation Coalition, the status quo is still the preferred alternative compared with any other development facility alternative. For the Fisheries Development Coalition, the status quo is not as attractive as the alternatives of establishing the

TABLE 9. ADDITIONAL EXPECTED REVENUES REQUIRED FOR A DEVELOPMENT FACILITY TO BE AS PREFERRED AS THE STATUS QUO

Development Facility/ Management Regime	Present Utility		Additional Revenue	
	WCC	FDC	WCC	FDC
No Development/Shoreline	-17.9	- 7.6	0	0
Midway Islands/Shoreline	-18.0	- 7.1	0.3	0
Tern Island/Shoreline	-33.9	-16.5	390.7	22.5
Mothership/Shoreline	-18.2	- 6.8	7.6	0

Note: WCC = Wildlife Conservation Coalition, FDC = Fisheries Development Coalition

Midway Islands facility or placing a mothership in the area, with the latter alternative being preferred over the former. In this situation a prisoner's dilemma exists.

The attributes used for the Midway Islands/Shoreline alternative equaled $2 million for facility cost, $10.4 million for expected revenues, -22 percent for change in the monk seal population, -24 percent for change in green turtle population, and -10 percent for change in the seabird population. The wildlife attributes' estimates were the same as estimated for the No Development/Shoreline alternative. Expected revenues were estimated by adding the difference between the No Development/3 Mile regime and the Midway Islands/3 Mile regime expected revenues to those of the No Development/Shoreline regime.

The Midway Islands facility may be an attractive compromise alternative, since only a small amount of additional revenue is needed for it to be acceptable to the Wildlife Conservation Coalition. In 1979 it was used as an albacore station. Since that time it has not been used as a fishery station, but the albacore fishery has remained in production. This has permitted some assessment of catches and impacts on the wildlife in the area with and without a facility.

No Facility Cost for the Public Sector

If other alternatives proposed for the Northwestern Hawaiian Islands area could be stated in terms of the attributes used in the study, the estimated utility weights would allow a comparison of these "new" alternatives with those that have already been studied. By using assumptions, such as (1) the private sector would reimburse the public sector for facility costs in 5 to 10

years or (2) private industry would construct the facilities with its own funds, the facility cost for all the alternatives becomes, effectively, "0". By recalculating the utility for each alternative based on this assumption, a new set of rankings for each coalition is determined (Table 10).

The new set of rankings for the Fisheries Development Coalition remained the same as its originally determined ranking. However, for the Wildlife Conservation Coalition, alternative "L," Mothership/3 Mile, and alternative "H," No Development/10 Fathom, have become reversed in their ordering from the original ranking. Thus, the utility weights can be applied to different alternatives as long as outcomes are defined as the attributes in the study model.

Changes in Price for the Commercial Fisheries Species

As new or more timely information becomes available and changes in the estimated amounts of the attributes are made, changes in the associated utility for the alternatives may easily be determined and a new set of rankings of the alternatives derived. The attribute of "expected revenues" was recalculated using prices based on the most recent data available (Table 11). Table 12 presents the utility of each alternative for both coalitions based on this new information along with the rankings.

Although the rankings of the alternatives remained very similar to the original rankings of the group, alternatives "I," Tern Island/3 Mile, and "E," Tern Island/10 Fathom, were reversed in the Wildlife Conservation Coalition's ranking from its original ranking and alternatives "H," No Development/10 Fathom, and "B," No Development/20 Fathom regime, were interchanged in the new ranking for the Fisheries Development Coalition. The higher preference given to the less restrictive regimes in the new rankings is due to the increase in expected revenues primarily generated by the most recent (April 15, 1983) spiny lobster price of $3.75 per pound which is more than twice the price estimated by the Hawaii Fisheries Development Plan. Thus, as more information becomes available, the rankings of the alternatives should be adjusted to reflect these changes.

TABLE 10. UTILITY WEIGHTS AND RANKINGS OF ALTERNATIVES BASED ON FACILITY COSTS OF "0" FOR THE WILDLIFE CONSERVATION COALITION AND FISHERIES DEVELOPMENT COALITION

Outside Development Facilities	Management Regimes			
	Shoreline	10 Fathoms	20 Fathoms	3 Miles
No Development	-17.887 6	- 5.53 10	- 4.207 12	- 2.487 13
	- 7.634 5	- 0.213 10	- 0.032 11	+ 0.96 13
Midway Islands				- 6.575 9
				- 0.897 9
Tern Island	-33.888 1	-26.093 3	-26.134 2	-23.432 4
	-16.465 1	- 9.605 4	-12.013 2	-10.704 3
Mothership	-18.092 5	-10.644 7	- 8.151 8	- 5.438 11
	- 6.664 6	- 2.129 7	- 1.021 8	+ 0.329 12

Note: The Wildlife Conservation Coalition estimated utility weights are given at the top of the box, the Fisheries Development Coalition estimated utility weights are given at the bottom of the box. Ranks of the alternatives are given below utility weights. 13 = most preferred alternative, 1 = least preferred alternative.

TABLE 11. PRICES OF FISHERIES SPECIES FOR THE NEW ESTIMATION OF EXPECTED REVENUES

Species	HFDP[1] Price Per Pound ($)	Recent Price Per Pound ($)
Skipjack tuna	.45	.45[2]
Albacore tuna	.61	.68[2]
Bigeye tuna	.70	.59[2]
Yellowfin tuna	.70	.59[2]
Bottomfish species	.75	.83[3]
Seamount species	.40	.39[4]
Akule/opelu	.40	.39[5]
Spiny lobster	1.75	3.75[6]

[1] Hawaii Fisheries Development Plan, Department of Land and Natural Resources, State of Hawaii, 1979

[2] Exvessel tuna prices at date of unloading, National Marine Fisheries Service, Fishery Market News Report T-14, February 21, 1983

[3] Based on the same proportion of catch value per pound of five bottomfish species as used by the HFDP (37 percent) and the most recent information (1980) provided by the Division of Aquatic Resources

[4] Seamount species prices and akule/opelu prices were assumed to be the same in the HFDP

[5] Based on the same proportion of catch value per pound of akule/opelu as used by the HFDP (39 percent) and the most recent information (1980) provided by the Division of Aquatic Resources

[6] Personal communication, National Marine Fisheries Service, Market News Service, Terminal Island, California, April 15, 1983

TABLE 12. UTILITY WEIGHTS AND RANKINGS OF ALTERNATIVES BASED ON NEW PRICES FOR THE WILDLIFE CONSERVATION COALITION AND FISHERIES DEVELOPMENT COALITION

Outside Development Facilities	Management Regimes			
	Shoreline	10 Fathoms	20 Fathoms	3 Miles
No Development	-17.836 6	- 5.475 11	- 4.188 12	- 2.472 13
	- 7.148 5	+ 0.312 11	+ 0.152 10	+ 1.101 13
Midway Islands				- 6.64 9
				- 0.838 9
Tern Island	-33.838 1	-26.063 4	-26.221 2	-23.481 3
	-15.814 1	- 8.988 4	-11.831 2	-10.492 3
Mothership	-18.128 5	-10.745 7	- 8.314 8	- 5.53 10
	- 6.158 6	- 1.734 7	- 0.879 8	+ 0.464 12

Note: The Wildlife Conservation Coalition estimated utility weights are given at the top of the box, the Fisheries Development Coalition estimated utility weights are given at the bottom of the box. Ranks of the alternatives are given below utility weights. 13 = most preferred alternative, 1 = least preferred alternative.

CONCLUSIONS

In summary, two major conclusions arise out of this study. The first conclusion is that according to the alternatives studied and their estimated attribute amounts, the expected revenues that the group of experts projected from fishery development facilities are not large enough to offset adverse wildlife impacts. The second conclusion is that the wildlife resources appear to hold high value for most of the decisionmakers identified as involved in the NWHI issue. This indicates that fishery development activities that are proposed and planned for the area must address the problem of adverse wildlife impacts as well as the economic benefits which may accrue to development. More resources in the planning and design phase for fisheries facilities should be allocated for the protection of the wildlife of the area. If adverse wildlife impacts could be reduced through effective planning and implementation, perhaps the expected revenues generated would be enough for a fisheries facility alternative to become an attractive option for decisionmakers.

Information and analysis play important parts in the planning and managing of both fisheries and wildlife resources. They also play an important part in public decisionmaking since many times decisionmakers are not the "experts" in the areas in which decisions by them are made. The Delphi procedures for both the wildlife and fisheries development attributes provided a consistent and complete base of information for the decisionmakers in this study. It was found that most of them were comfortable with information that was generated with this procedure, even though the Delphi estimates of expected catches did not agree with earlier estimates of the Hawaii Fisheries Development Plan.

A problem in applying this simulation to real life is, although the study attempted to reach most of the decisionmakers who are still involved in this issue, all critical decisionmakers may not have been included. Over time the status of decisionmakers included in the study or their attitudes and values and hence their weightings will change. As time passes the study's results can be expected to be less applicable.

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INSTITUTIONAL POLICYMAKING IN THE MANAGEMENT OF FISHERIES: CASE STUDY - STATE OF HAWAII

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ABSTRACT

This study empirically characterized the personal communication networks of key administrators of the two federal and one state agencies which are legally mandated to implement the Magnuson Fishery Conservation and Management Act (FCMA) of 1976 (PL 94-265) in Hawaii.

The implementation of the FCMA, particularly the development of fisheries management plans for the resources of the Northwestern Hawaiian Islands (NWHI) and the western Pacific, can be materially enhanced by the Western Pacific Regional Fishery Management Council (WPRFMC), the legal entity established for the cooperation of state and federal agencies and the fishing industry. It was found that the centrality of the WPRFMC in the information network of decisionmakers gives the chair and staff of the WPRFMC the potential power to broker cooperation among the governmental agencies.

institutional policymaking network anlaysis
fisheries management Hawaiian fisheries

INTRODUCTION

This paper provides a micro-examination of the information channels for decisionmaking in federal and state executive agencies in the implementation of legislative acts. The particular act which provides the context for this analysis is the Magnuson Fishery Conservation and Management Act of 1976 (FCMA), PL 94-265, which promotes vertical integration of federal and state governments in the management of fisheries within the

fisheries conservation zone. The FCMA, therefore, recognizes the need for management strategies to better fit the indivisible character of fisheries which extend beyond federal and state jurisdictional boundaries.

The FCMA designates the Department of Commerce as the lead implementation agency. For the purposes of this paper, the significant aspects of the FCMA are (1) the creation of regional fisheries management councils (Hawaii is a member of the Western Pacific Regional Fishery Management Council) and (2) the naming of the National Marine Fisheries Service, a line agency under the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce, to provide the required information to enable the councils to develop fishery management plans for waters within the fishery conservation zone (FCZ) which extend from the seaward boundaries of the 3-mile territorial sea, the extent of jurisdiction of a littoral coastal state, out to 200 miles. Although the fishery and seabed resources of the FCZ are under federal jurisdiction, under international maritime law, the surface waters fall under the regime of high seas and, thus, are international waters.

The research question can be posed as follows: Given known characteristics of organizations, as described by administrative and organizational theories, how and where will the federal and state agencies charged with the implementation of the FCMA in Hawaii obtain information to develop operational policies to manage fishery resources?

Several a priori assumptions underlie the question. First, organizational behavior of federal and state agencies, which can be characterized as complex organizations, is explainable by extant theories of organizations. Second, there is perceived need for information by the organizations and they will attempt to obtain it. Third, it is possible to track inflow of information into an organization by identifying interfacing boundaries and mapping the information intake network of administrators at key decisionmaking nodes in the organization. And lastly, federal and state cooperation is desirable in the development of management plans for fisheries.

ORGANIZATIONAL THEORIES

A comprehensive review of extant theories of organization is beyond the scope of this paper. However, there are numerous general works on public administration practice and theory which are readily available. Only a short review of a few more directly relevant works is provided here to give some contextual background for this paper. The present focus is confined only to the involvement of executive agencies in the policymaking realm related to the implementation of the FCMA; therefore, the basic problem which is being examined is the cooperative behavior of complex organizations as a function of information networks of decisionmakers or actors in the formulation of operational

objectives to implement the broad goals of the FCMA to "take immediate action to conserve and manage the fishery resources found off the coasts of the United States" [FCMA, Section 2 (b)(1)]. The literature dealing with organizational decision-making is not confined to the discipline of public administration alone, but can be found in micro- and macro-economics, political science, and international relations.

In general, the rational actor model, based on economic and statistical decision theory, is not considered here because of the nonmarket conditions in which decisions of public sector organizations operate and because of the difficulties associated with the primary premise of the model that all options are known and that choices are made by a single individual's judgment without considering the effect of the organizational environment or the bureaucratic politics of decionmaking (Allison, 1971). Furthermore, rationality is difficult to define because it is almost impossible to separate subjective and objective criteria of rationality. March and Simon (1958) discuss "boundaries of rationality" as a limiting factor in the ability of human beings to handle complex problems. This limitation triggers the compensatory behavior they have described as "satisficing" to replace "optimizing." While the course of action based on satisficing may be rational to the decisionmaker, it may not be rational to others. Waldo (1980), has published an excellent summary of the themes and theories of public administration in the light of futuristic issues of technology. Taking a normative approach, he suggests the need for changing present-day social values, which are based on abundance and growth, to cope with the transition of American society from industrialism to postindustrialism, i.e., from abundance to scarcity. He particularly focuses on the problems of system overload in public sector organizations brought on by escalating demands for services and predicts a future in which pressures will worsen rather than improve. However, while offering three possible scenarios, ranging from confusion and disorder to disintegration and integration, i.e., unity and centralization, direction and control, he does not predict a future except to note Bell's (1977) observation that the nation state is too small for large tasks and too large for small tasks.

La Porte and others (1975), discuss complex organizations from the standpoint of structural and functional complexity. The role of knowledge and the consequences of both the requirement of increasing levels of knowledge and the problems associated with knowledge explosion in terms of coordination cause the evolution of complex organizations. They see the non-fit of traditional organizational structure for the management of professional and scientific personnel.

Metlay (1975), concludes that the result of an "increasing organized social complexity is an inability to predict, for all practical purposes, the behavior of the system" (p. 247). He takes issue with the homeostatic analog used extensively by

planners because such a construct assumes only small changes over an extended period. In a complex system, Metlay is fearful that deviations based on a "simplified image" of a system will not be sufficient or fast enough to enable a response to changes which could be profound. He prescribes Lindblomian incrementalism, monitoring, and reevaluation of organizational behavior to cope with ambiguity.

Thayer (1981), suggests that the role of both leaders and followers should be to become "'professional citizens,' for the creative act of building consensus [which] can be defined as the primary act of citizenship for each individual" (p. 38). He depicts the policy process as a horizontally linked venn diagram. The process involves five individuals who will link the various interrelationships of a nonhierarchical flat structure extending from city, to substate region, to state, to subnational region, to nation, and, finally, to other nations. Hence, he predicts a probable future of more structure, but he proposes structural models that are free of conventional bureaucratic hierarchy to minimize alienation of human beings.

Bureaucratic Policymaking: Is It Legitimate?

Waldo (1980), notes symbolic and legal problems associated with the recognition and legitimation of policymaking by the bureaucracy. He contends that at the federal level the present conditions of bureaucratic policymaking cannot be fully legitimated by democratic ideology which supplements the Constitution and, further, that while such policymaking has been formalized by deriving authority from the elected chief executive, this "overhead democracy" does not answer all problems. However, Reigel and Owen (1982) state that since the Supreme Court's decision on Panama Refining Co. v. Ryan, 293 US388, 430(1935), and the days of the New Deal, "it is improbable that a federal court would find that a statute conferring rulemaking power to a federal agency is unconstitutional delegation of congressional power."

Waldo raises these confusing points while fully recognizing that public administrators do make policy "by deciding what has been decided after basic decisions have been made by political authorities; by deciding what further needs to be decided; by defining and weighing alternatives; and by making further decisions" (pp. 180-181). In this context, Waldo discusses the confusion stemming from the traditional vertical channel of authority flowing from the elected official to the administrator down to the bureaucracy and the authority vested in knowledge which manifests itself as a horizontal organizational structure.

Thayer (1981), on the other hand, appears to argue that questions of constitutional legitimation are moot. Political democracy, because of its "peculiar historical development[,] has [been] . . . the principal vehicle through which we continually increase alienation" (p. 75). Hence, under current structural manifestations of "democracy," Thayer's contention is that "all

'democracies' we know about have been tyrannical" (p. 75) and, therefore, it is not importan to put the blame for public alienation on any branch of government because all hierarchical structures are oppressive.

The prevailing rationale is that there is a necessity for hierarchy in which elected officials exercise control over the bureaucracies to enable the public to maintain control of government. This notion is credited to Drucker (1971). Lowi (1971), a strong advocate of centralization, goes even farther in strengthening the legislative branch. He proposes that all legislation should be so detailed as to make administration almost automatic. If this were the case, the bureaucracy would then be removed from the policymaking arena [12]. But Lowi's proposal is naive. No major national policy has been enacted without a wide bse of support, a condition which necessitates compromise and results in an end product which is generalized to allow much latitude in interpretation during administrative rulemaking.

Thus, administrative structures are societal artifacts reflecting processes and physical manifestations which promote social values. As technology brings about changes, organizational theorists recognize that traditional bureaucratic structures, which current bureaucracies are modeled after, are not appropriate. Katz and Kahn (1966) note that empirical research on authoritarian bureaucracies suggests that linking "hierarchy with efficiency and authority with authoritarian behavior are errors of great importance and great human cost" (p. 215).

THEORIES OF INSTITUTIONAL PROCESSING OF INFORMATION

Essential to the central research question reported in this paper are the works of Simon (1976) and Katz and Kahn (1966). Simon's work, a classic, deals with the understanding of organizations in terms of their decision processes. He

> analyzes organizations in terms of the decisionmaking behavior of their participants, but it is precisely the organizational system surrounding this behavior that gives it a special character. The roles of organization members are shaped by their goal identifications, and goal identifications, in turn, are a product of location in the organization (p. xxxiv).

He contends that administrative behavior can be predicted if the premises of decision are known in sufficient detail in some instances. In others, informational premises or still other premises are required. He dismisses Parsons' action theory as being "insufficiently subtle and flexible for the description of behavior" (p. xxxiv).

Simon (1976) applies "efficiency" as a criterion for defining what is meant by "good" or "correct" administrative behavior

rather than how outputs or accomplishments are to be maximized. In this context, he discusses the concept of "rationality." According to Simon, "rationality is concerned with the selection of preferred behavior alternatives in terms of some system of values whereby the consequences of behavior can be evaluated" (p. 75). Hence, rationality is a nebulous term. Like beauty, it is mostly in the eye of the beholder.

Possibly the most significant insight which Simon provides is the underscoring of the fact that difficulty in dealing with information lies not in scarcity of information, but in the limitation of the "processing capacity" within the organization, largely because information is generated by external organizations and may be only partly useful, if at all. He concludes that since the scarce resource is "attention", organizations must have the capacity to conserve the scarce resource by "provid[ing] for interfaces to handle information which originates outside the organization (pp. 294-295)."

Katz and Kahn (1966) note that "the closer one gets to the organizational center of control and decision-making, the more pronounced is the emphasis on information" (p. 223). However, more information is not necessarily better for an organization. No organization can cope with unrestricted inflow of information (Ashby, 1956). To alleviate the possibility of being swamped, organizations develop a coding system which limits the amount and type of information they receive from the external world. The information is then transformed to fit their systemic needs (Katz and Kahn, 1966). March and Simon (1958) call this behavior, "selective filtering." They note that it occurs not only at the boundary of an organization, but at "every stage in the transmission and elaboration of program proposals" (p. 189). Each stage, thus, becomes a boundary, having its own set of criteria for selective filtering. The filtering system of decision nodes where uncertainty is absorbed has the greatest influence on innovation, according to March and Simon. In this way, selective filtering is a gatekeeping system which maintains organizational equilibrium. Without this protective mechanism, organizational response will result either in such dysfunctional behavior as error and omission or adaptive behavior such as queuing or delay and filtering or selective receiving of information. These adaptive responses can become maladaptive, if they are used to escape from tasks at hand (Katz and Kahn, 1966).

Of interest to the present discussion is "upward communication" within an organization. Katz and Kahn note that communication in a hierarchical organization is characteristically downward. Upward flow of information is usually used for control purposes by supervisors. Hence, the information passed upward "not only tell[s] the boss what he wants to hear, but what [the subordinates] want him to know" (pp. 245-246).

While organizational decisions are complex, they are still made by individuals. Katz and Kahn cite the process of problem solution described by Dewey (1933):

1. Immediate pressures on the decisionmaker
2. Analysis of the type of problem and its basic dimensions
3. Search for alternative solutions
4. Consideration of the consequences of the alternative solutions

These steps are influenced by:

1. The nature of the problem
2. The organizational context
3. The basic personality characteristics of the policymaker
4. The cognitive limitations of human beings because of situational and personality factors

All parts of this process may or may not be active for any given decision, but they constitute a model of an individual's "fallibility" (Katz and Kahn, 1966, p. 274). Janis (1959) cites two other possible "fallabilities" in organizational decisionmaking:

> One [problem] is . . . the emotional impulses which can move into the conscious sphere; the other stems from deeper defensive needs of which the individual has no awareness.

Katz and Kahn conclude that in an autocratic structure the defensive mechanisms of leaders are enhanced because they are supported by the organization. As noted above, subordinates will protect their own positions by sending through only information which feeds the emotional biases of the leader. Hence, the "whole institutional environment may become modified to confirm the pathological tendencies of the men on the top" (p. 293). Janis (1979) has dubbed this phenomenon "groupthink."

Janis defines groupthink thusly:

> One of the most common norms [of groupthink] appears to be that of remaining loyal to the group by sticking with the policies to which the group has already committed itself, even when those policies are obviously working out badly and have unintended consequences that disturb the conscience of each member (p. 237).

Thus far, the discussion has centered on bounds of human capability in decisionmaking in an organizational setting, a condition which exists because of "limits of human intellective capacities in comparison with the complexities of the problems that individuals and organizations face" (March and Simon, 1958, p. 169). Over time, the organization simplifies communication

for programmed activities by developing (1) a repertory of standard responses, (2) a classification of program-evoking situations, and (3) a set of rules to determine the appropriate response for each class of situations. However, it is organizational response to unprogrammed or new externally generated information that is of primary interest in the present study. March and Simon put forth the proposition that unprogrammed communication becomes "reified" as a technique for "uncertainty absorption." Reification occurs when raw data are edited to produce inferential information which may be abstracted several times over as it is transmitted through the communication network of an organization. They note that "a great deal of discretion and influence is exercised by those persons who are in direct contact with some part of the 'reality' that is of concern to the organization" (pp. 164-165) and, more so, if they serve the function of uncertainty absorption.

The logical end to simplification is the replacement of "optimizing" by "satisficing", according to March and Simon. They also note other manifestations of simplification: the search process is used to discover limited alternatives, standard responses are programmed by the organization, ranges or restrictions are placed on situations and consequences, and action programs are semi-independent and only loosely coupled.

Interfacing Boundaries and the Processes of Information Intake

Knoke and Laumann's (1982) definition of "policy domain" provides the operational parameters for the discussion in this paper. They define "policy domain" as the "substantive focus of concern of policy initiatives and debate" (p. 256). Further,

> members of a policy domain are complex formal organizations -- such as corporations, confederations, commissions, and committees -- rather than natural persons acting in their own right . . . . [T]he basic analytic criterion determining whether an organization belongs to a subsystem's [the elite or core organization] policy domain is the standard of relevance or fate whereby actors take each other into account in their actions. This mutual relevance criterion effectively excludes from the domain any actors whose actions or potential actions are inconsequential in shaping binding collective decisions for the subsystem" (p. 257).

This operational definition, modified somewhat, is used in this study to eliminate actors who are not influential in the decisionmaking activities of the administrators of the three agencies (the subsystems referred to by Knoke and Laumann above) involved in the implementation of the FCMA.

For the purpose of this paper, the boundary delimitations are those recognized by the actors themselves as members of the

three institutions which have functional responsibilities in the management of living resources in the Northwestern Hawaiian Islands: the Hawaii Division of Aquatic Resources, the U.S. Fish and Wildlife Service, and the National Marine Fisheries Service. (See Appendix A for a short description of the NWHI.) Hence, it is assumed that members of these agencies have a "we-feeling" characteristic of corporate groups about their own agency (Laumann et al., 1983). Thus, by definition, membership or participation is predetermined. What is being empirically tested is the relationship and makeup of the informational network which is used by the agency heads in obtaining technical information for normal and FCMA-related decisionmaking (Laumann et al., 1983).

Because there is little by way of empirical research of classifications of relationships, Laumann et al. note that the prevailing approach by researchers is "common-sense" justification. They point to the danger of "partial system fallacy" which results when relationships are considered without the entire set of actors. Relational inclusion, therefore, should be based on the "elements of focal interest" rather than using geographical boundaries, for example (Laumann et al., 1983). This potential methodological weakness was addressed in the present study by utilizing decisional nodes at three levels of the federal agencies which are located at different sites and at two levels for the state agency because decisionmaking at the lowest level operationalizes objectives promulgated by the next highest level, etc. (Circey-Wantrup, 1976).

THE METHODOLOGY

Personal interviews were utilized for the gathering of empirical data which were systematized with a questionnaire constructed by the researcher.

Underlying Assumptions

Two spheres of influence are assumed for each major "actor" or "node", the decisionmaker, around whom a network is defined (Knoke and Kuklinski, 1982). One is the decisionmaker's influence and authority within the sector of the agency he/she heads and the other is the decisionmaker's role as an interface or boundary for extra-agency interaction. Network analysis utilizes two assumptions about social behavior:

> Its first essential insight is that any actor typically participates in a social system involving many other actors who are significant reference points in one another's decisions . . . . Its second essential insight lies in the importance of elucidating the various levels of structure in a social system, where structure consists of 'regularities in the patterns of relations among concrete entities.' (Knoke and Kuklinski, 1982, pp. 9-10)

Thus, network analysis has a "dualistic quality" in its capacity to consider social structures as holistic artifacts while also enabling the examination of its details (Knoke and Kuklinski, 1982; Bell, 1977).

As stated by Knoke and Kuklinski, the significance of network analysis at the theoretical level is to explain the

> occurrence of different [linkages] and, at the nodal [or decisionmaking] level, to account for variation in linkages to other actors. The parallel task in network analysis is to detect the presence of such structure in empirical network data (pp. 12-13).

Obviously, it is not possible or desireable for any study to define the hundreds of people who come in contact with public agency heads. Hence, the field was narrowed to those individuals identified by decisionmakers, who were interviewed, as primary sources of information in two contexts: general decisionmaking and FCMA-related decisionmaking. McCallister and Fischer (1983) call these sources "core networks," which they define as the "set of people who are most likely to be sources of a variety of rewarding interactions." They found that the theory of exchange, which assumes a relation based on "rewarding interactions," (in this case information), to be borne out by their own research (p. 78).

Exchange theory is extended to apply to "macro-level" exchange processes by Cook (1982). She indicates that agents who are members of groups with the power to act for the group, can serve as relatively independent actors, as intermediaries, or as brokers. (See below for a discussion of brokerage behavior.) Leibenstein (1976) notes that agents typically have "split loyalties to their own ends and to [group] ends -- a problem frequently faced by boundary personnel in organizations" (p. 161). The dilemma of those who represent an agency on an interagency coordinating committee can be explained by similar split loyalties and the difficulty they face when the perceived "larger good" conflicts with agency positions or objectives. Leibenstein further notes that agents do not necessarily carry out transactions for gain. They may also be less willing to take risks in negotiations than individual principals acting on their own behalf.

The role of brokers exists because they function as "linking actors having complementary interests, transferring information, and otherwise facilitating the interests of actors not directly connected to one another" (Aldrich, 1982, pp. 288-289). Marsden (1982) points out that the persistence of brokerage behavior lies in the "functional equivalence of indirect ties to direct ties," that is, it is not mere "happenstance" (pp. 205-206). The brokers consider the needs of the actors at the periphery for sending and receiving information to one another. Furthermore, Marsden indicates that centrally positioned actors in an "access

network" will gain power when access is restricted because they are likely to be situated on unique linking systems joining peripheral actors.

Gain in power in communication networks through brokerage behavior has been identified by Freeman (1979) as a function of "betweeness" and "closeness." The equation he proposes is simple: overall gain is the excess remaining when outflow is subtracted from inflow. Hence, a central position of the brokeractor in enabling him to arrange transactions is significant. In other words, net gain accrues in inverse proportion to the number of ties with which an actor must interact in effecting a transaction, centrality is necessary; but it is not a sufficient requirement. The second criteria of closeness to peripheral actors is required if the broker is to have the ability to consummate the transaction without the cooperation of intermediaries.

Finally, Alba and Moore (1983) shed some light on the notion of "central circle," based on their study of elite integration in the United States. Most small groups can be explained by the "propinquity principle" (propinquity is defined as social propinquities and commonly shared issues and/or institutional sectors, e.g., individuals who are appointed office holders, or members of Congress, etc.). But an interesting aspect was the bridging function of the central circles which acted to facilitate "communication and interaction both within a large, diverse leadership group and between members of that circle and more specialized elite groups" (p. 259).

Research Design

Based on the assumption that institutional decisionmaking is done by persons, more specifically, by administrative heads, their communication network constitutes the basic unit of analysis in this study. The top administrators at three levels of the agencies (Hawaii, regional, and Washington, D.C.), which are separated geographically, thus, enhancing the discreteness of each unit, were also assumed to be the boundary interfacer. These administrators were considered to be the most significant intake point of information from extra-agency sources.

The hierarchical organizational structure of the agencies in a way simplified the identification of the appropriate decisionmaker at each level. Since location within the hierarchy coincided with the level of authority, i.e., the top of the organizational chart was occupied by the top decisionmaker, location on the agency's organizational chart was used to select the administrative decisionmaker at the national (Washington, D.C.-based), regional, and local or Hawaii-based offices.

Using interview data, the communication relations of the administrators were mapped; specifically, the network of information linkages between and among agencies and their sources of information was plotted.

THE POPULATION

Three decision nodes were identified for each of the federal agencies: the head office in Washington, D.C., the regional offices on the West Coast (NMFS regional offices are located in La Jolla and Terminal Island, California; FWS regional office is in Portland, Oregon), and the Honolulu office.

An unsuccessful attempt was made to interview the head of the state agency, the Department of Land and Natural Resources, which is the organizational structure within which the Division of Aquatic Resources is a component. The explanation given to the researcher was that all information pertaining to fisheries is provided to the head of DLNR by the DAR through its director; hence, the director of DAR was interviewed.

The respondents are:

1. Four administrators (two in Washington, D.C.) from U.S. Fish and Wildlife Service
2. Five administrators (two in California and two in Hawaii) from the National Marine Fisheries Service
3. One administrator from the State Division of Aquatic Resources

THE INSTRUMENT

An extensive survey instrument was developed by the researcher requiring both seven-point interval scaled and open-ended responses. The questionnaire consisted of three parts: (1) general information on the agency, such as organizational goals, perceived clientele, consonance of agency activity with societal values, etc., (2) the information sources used by the decisionmaker, including general patterns of intra- and extra-agency communication, and (3) the evaluation of the implementation of the FCMA.

This paper will focus only on part 2, the communication network of the administrators, and only peripherally with other aspects of the total survey instrument. The two questions asked to obtain the basic data to construct the information network used by the administrators were:

1. When you make decisions on questions/problems/issues related to the general function of your agency, name three to five persons you may actually consult to obtain information.
2. Name three to five persons from whom you get information on FCMA-related issues.

They were also asked to give the reasons for their choices as an open-ended question.

THE INTERVIEW

Personal interviews, requiring between 1 hour and 15 minutes to nearly 2 hours each, were conducted. Two exceptions need to be noted here. The FWS identified two administrators who had expertise in fisheries to be interviewed in place of the agency head in Washington, D.C. In Portland, the administrator in charge of general administration rather than the overall regional administrator was interviewed because of the health of the latter.

The responses of the administrators are plotted as networks with arrows pointing to the contact persons cited by interviewees in response to the two questions noted above. Separate networks were plotted for each administrator for each question, and these individual networks were then combined for the information network for each agency. In addition, as the third iteration, a composite tri-agency network was plotted to obtain an overview of inter-agency information linkages.

DISCUSSION OF THE RESULTS

Overall, the results of this study provide a description of the information channels through which agency heads seek data for decisionmaking. Both micro- and macro-organizational behavior can be seen by examining the information network of organizational decisionmaking when the network of individual administrators were combined to develop, first, a network for each agency and, second, a national or interagency network.

The National Marine Fisheries Service of the U.S. Department of Commerce

Three clearly defined central informational sources are identified for NMFS in Figure 1:

1. The American Tuna Foundation
2. The State Director of Fish and Game
3. The Western Pacific Regional Fishery Management Council Chairperson and Executive Director

The two regional administrators, the directors of the Southwest Region and the Southwest Fisheries Center, have a strong reciprocal link to each other, indicated by a two-way arrow. While they cite their own staff in the regional offices in Hawaii and California as sources, all administrators are in touch with extra-agency sources with the Honolulu-based administrator having the most diverse array of information sources. The citing of three University of Hawaii research-oriented faculty members, the directors of the Hawaii Institute of Marine Biology and the Sea Grant College Program and the chair of the Northwestern Hawaiian Island Research Coordinating Committee, probably reflects the cooperative efforts in fishery-related studies conducted by NMFS, FWS, DAR, and the University of Hawaii researchers over the past

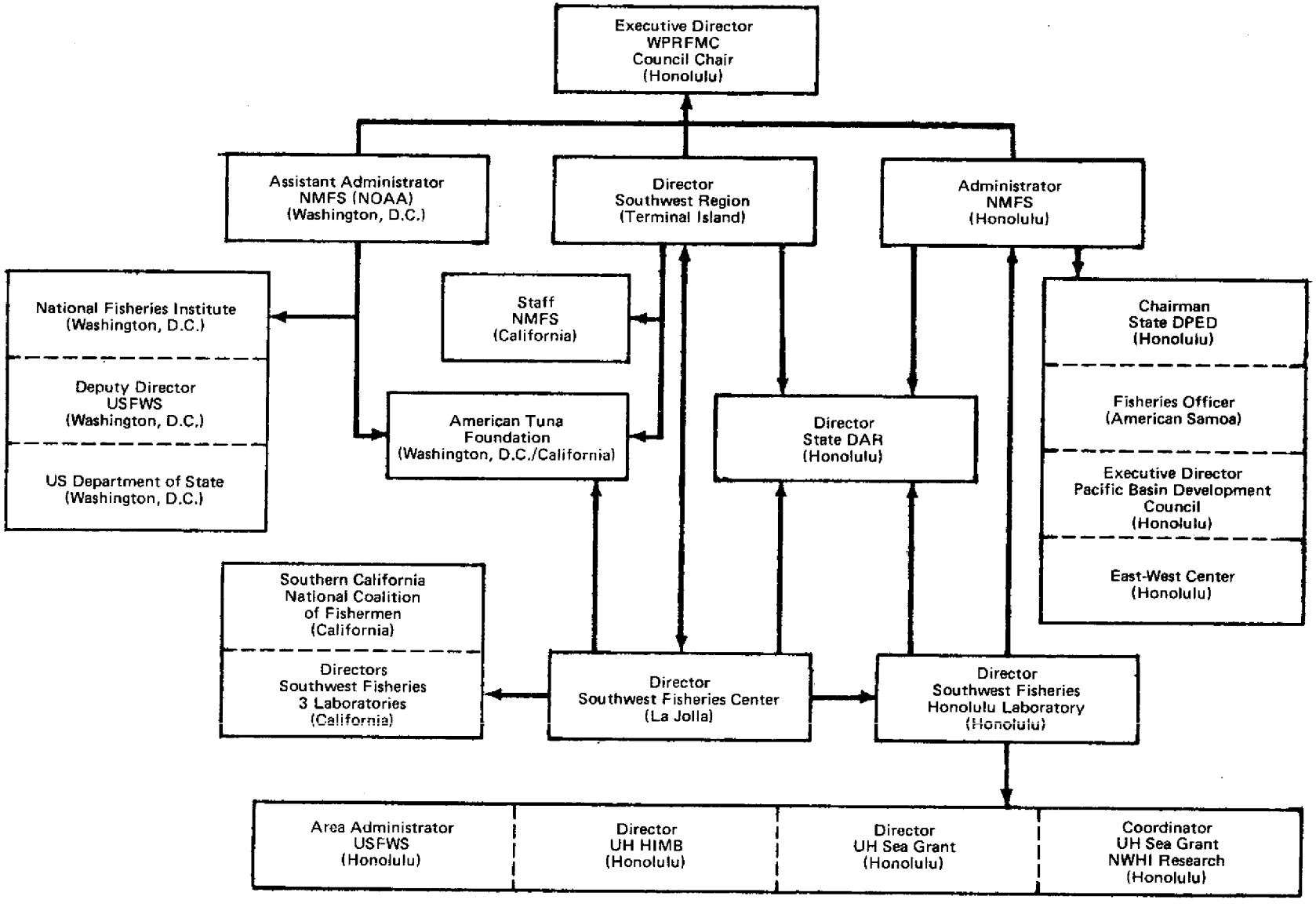

Figure 1. Sources of information for general agency decisionmaking

5 years. This is the only acknowledged contact with the University of Hawaii as a source of information by any administrator.

The three extra-agency information sources can easily become information brokers and may to an extent assume that role for the Washington, D.C. office. How strong or weak the broker function is depends on what is being sent "upward" concurrently along the hierarchical chain of command as standard reports. The well-connected intra-agency linkage among the four regional and Honolulu offices weaken the position of the WPRFMC and the state Division of Aquatic Resources somewhat as information brokers. However, the convergence on these two institutions and the American Tuna Foundation is a strong indication of the importance of these sources of information. But, perhaps of greatest significance is the absence of direct intra-agency linkage among the three levels of the organization. Decisionmakers at the three levels did not cite each other as sources of information with one exception, the director of the Southwest Fisheries Center and the director of the Southwest Region.

Figure 2 is a plot of NMFS's information sources for FCMA-related decisionmaking. The focal points of extra-agency information sources remain essentially the same, i.e., they are still focused on DAR and WPRFMC. The Washington, D.C. and Honolulu offices are linked by these two information sources and there is a direct downward linkage between the Washington D.C. administrator and the Honolulu Laboratory director. The regional administrators are not a part of the intra-agency network of the NMFS head in Washington, D.C.

However, there is a strongly interlocked core group (a clique?) at the regional level. The laboratory director of the Southwest Fisheries Center does not solicit information from outside sources, but he is linked to Honolulu-based agencies indirectly through the Honolulu Laboratory director, his subordinate, who is the boundary interface with DAR and WPRFMC. The three administrative levels [NOAA Assistant Administrator, Director of the SW Region, and NMFS Administrator (Honolulu)]in the NMFS hierarchy obtain information from the next higher level, i.e., there is a downward flow of information for FCMA-related decisionmaking among the offices of the organization in contrast to the free-wheeling configuration for regular agency decisionmaking (Figure 1).

The U.S. Fish and Wildlife Service of the U.S. Department of the Interior

The information network for general agency decisionmaking of FWS, shown in Figure 3, is a contrast to that of NMFS. Information sources cited by interviewees at the Washington, D.C. and regional levels are strictly intra-agency personnel, with the exception of the contact with wildlife organizations at the regional level. The three administrative levels are linked by the lower level providing information to the level above it;

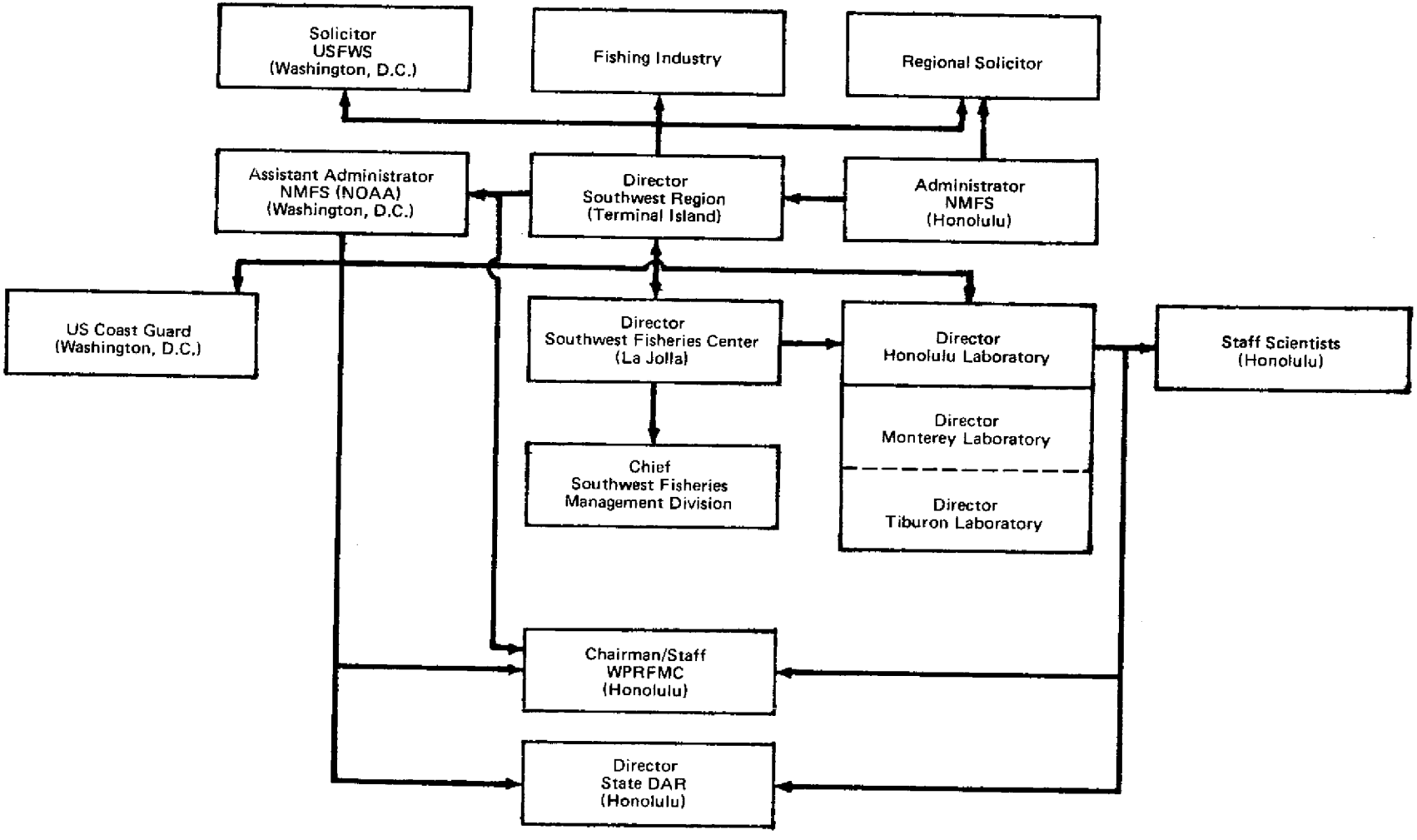

Figure 2. MFCMA-related information network of NMFS

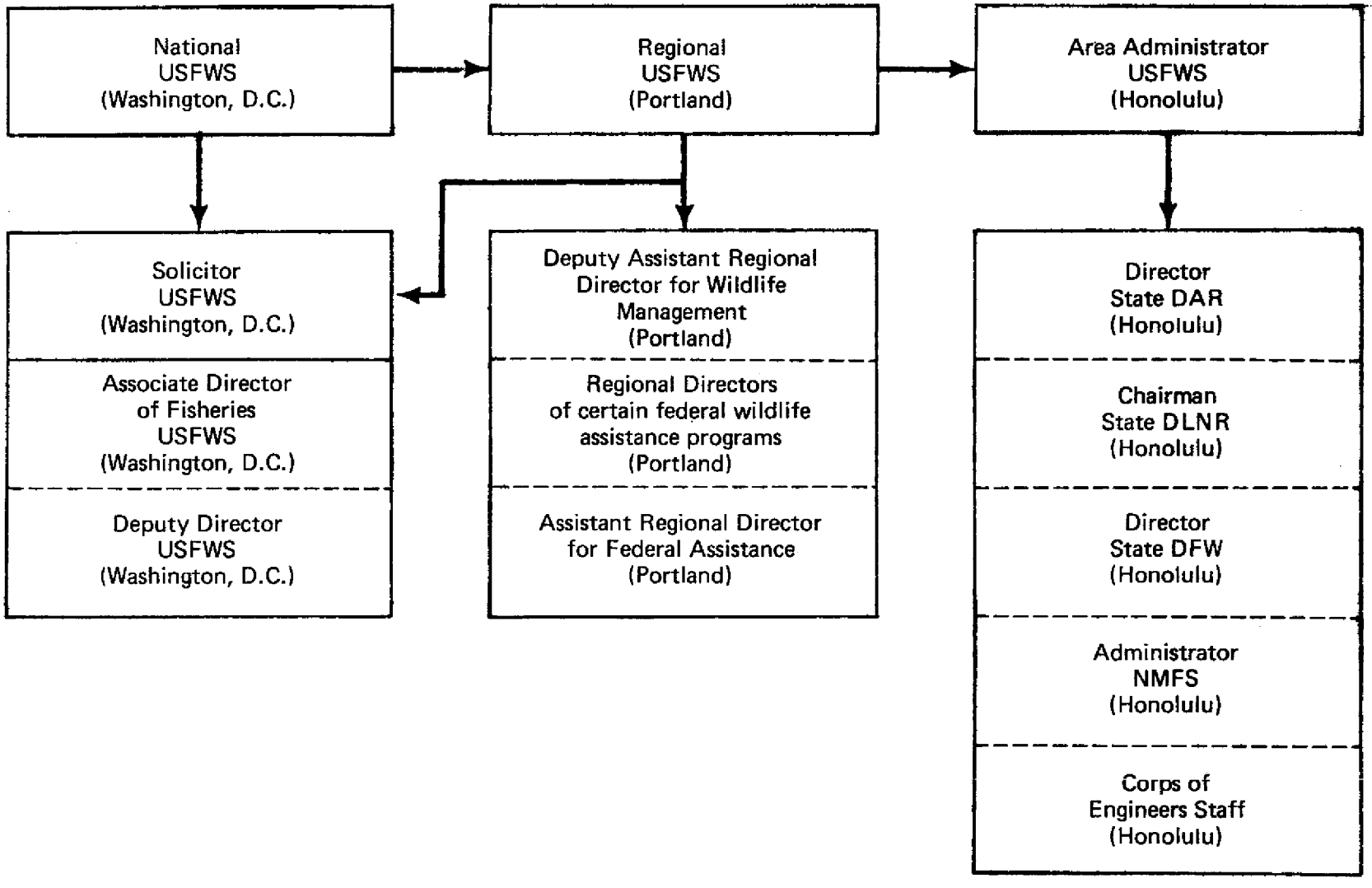

Figure 3. USFWS: Sources of information for general agency decisionmaking

hence, the information flow is upward. The boundary for the organization is the area administrator, based in Honolulu, who gathers information from relevant state and federal agencies. The regional and area offices are brokers and can exercise a great deal of discretion in the kind of information which is sent upward. The upper level administrators, without independent outside contacts, as in the case of the NMFS administrators, apparently have no way of readily testing the validity or accuracy of the information they receive.

In the information network for FCMA-related decisionmaking (Figure 4), the regional office becomes the broker which links the Washington, D.C. office with the local office. The regional office, however, has its own contact in the state through the Hawaii Division of Forestry and Wildlife. The area and regional administrators are linked through the Office of Federal Assistance to Regional Councils in Portland and the area administrator retains his role as boundary interfacer for the organization in FCMA-related matters. The area administrator represents the FWS as a non-voting member of WPRFMC.

Division of Aquatic Resources of the Department of Land and Natural Resources, State of Hawaii

The information network for general agency decisionmaking (Figure 5) includes not only relevant federal agencies and DAR's own staff, but its principal constituents -- fishers. The head of DLNR relies directly on the director of the DAR for reports and recommendations. This statement reflects the response received when information was solicited directly from the department head, who is a member of the Governor's cabinet and is above the director of DAR in the DLNR hierarchy.

The director's information network for FCMA-related issues, shown in Figure 6, indicates increased contact with NMFS by including the local administrator in addition to the laboratory director, but does not include FWS. The chairman and the staff of WPRFMC are additional contacts. The director of DAR represents the state as a voting member of the WPRFMC.

For both regular and FCMA-related decisionmaking, the director of DAR assumes both the boundary and broker positions vis-a-vis DLNR. This position is strategic since the head of the DLNR looks to the director as the sole source of information, other than that which the former might obtain incidentally, given the established organizational channels of information.

Tri-agency Network for General Decisionmaking

The administrative information network for general agency decisionmaking is assumed to be the established communication channels used by the agencies' decisionmakers. Further it was assumed that the decisionmakers also serve as the boundary interface through which new information can enter the organization at

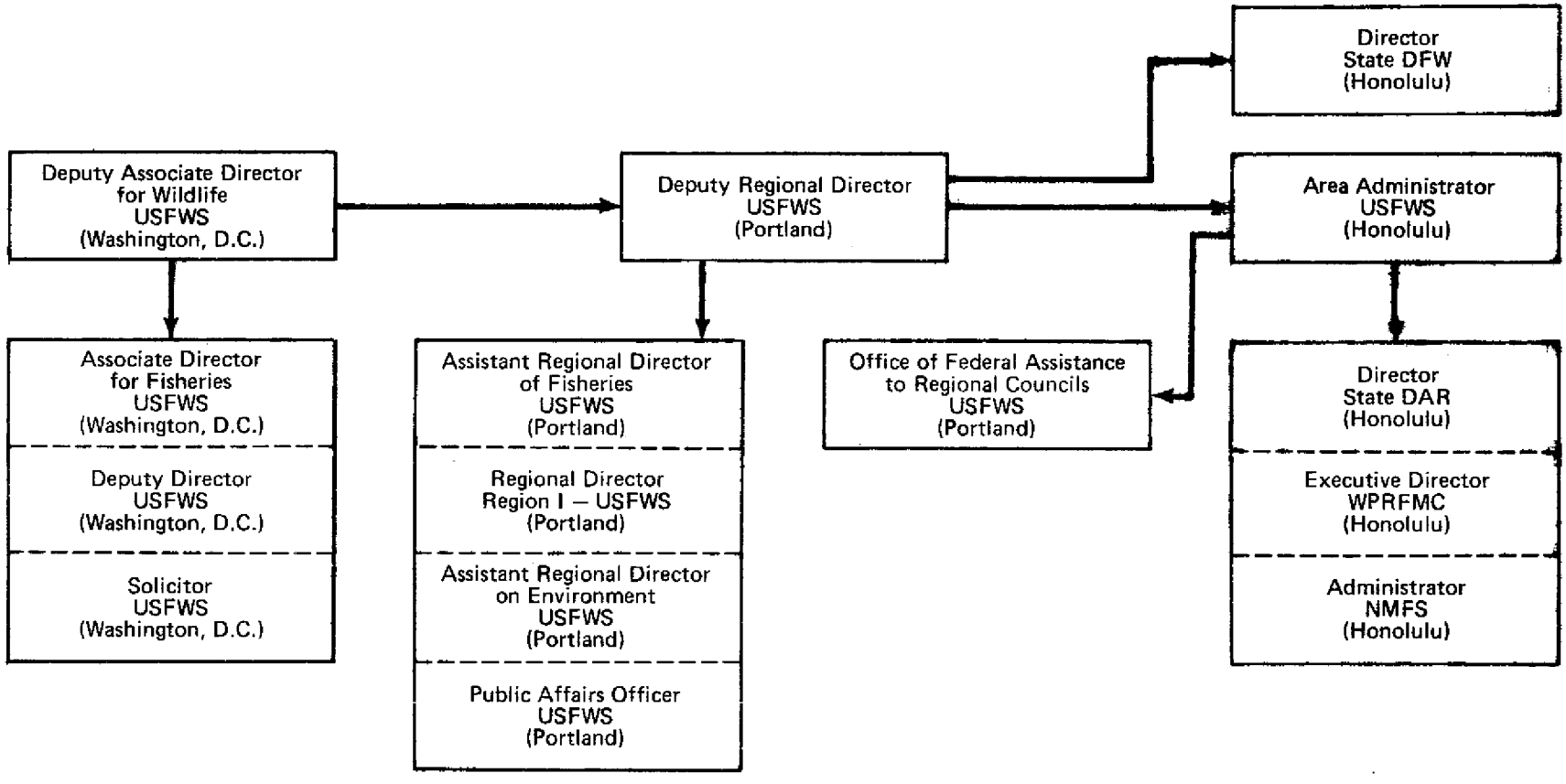

Figure 4. MFCMA-related information network of the USFWS

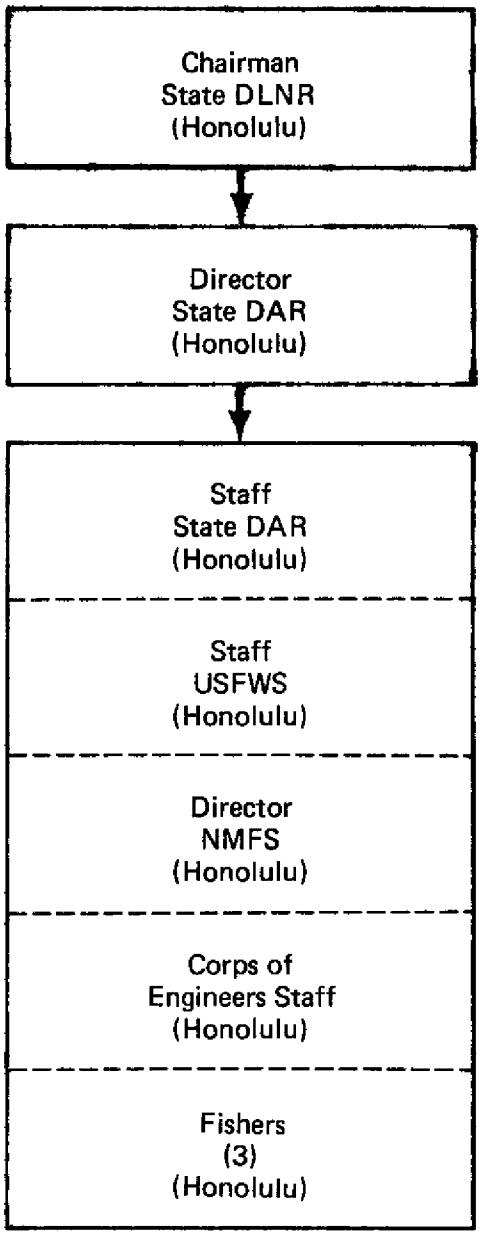

Figure 5. DAR: Sources of information for general agency decisionmaking

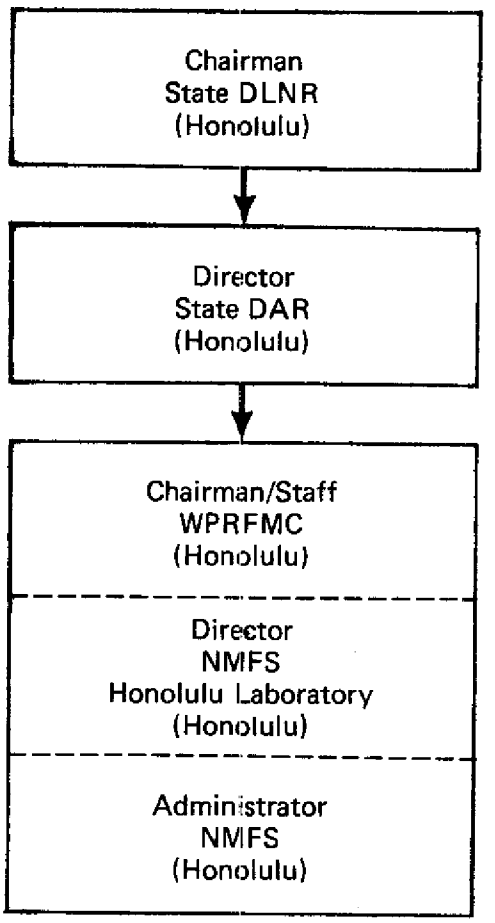

Figure 6. MFCMA-related information network of the DAR

a point where significant impact could be made on that organization's policies. Thus, the persons cited by the decisionmakers provides clues as to whether information is sought from within the organization or outside of it, as well as the kind of information being sought.

The reduction of intra-agency details in Figure 7 clarifies extra-agency linkages but linkages or lack of linkages between geographically separated offices of a single agency are preserved. The administrators of DAR and NMFS obtain information from many extra-agency individuals. While the Honolulu and regional offices of NMFS cite the director of DAR as an information source, the linkage is one-way. The DAR, however, has a strong link with FWS through a two-way channel, although the person cited by the DAR director is a staff member and not the area administrator. The Corps of Engineers, however, is a common information source for DAR and FWS. Overall, in openness to information from extra-agency sources, NMFS is the most open on the basis of sheer numbers and variety of individuals contacted by the administrators. However, there are intra-agency channel breaks between the Washington, D.C. office and the regional offices. The only intra-agency linkage cited was that between the regional and Honolulu offices with the arrow going downward -- from the regional to the Honolulu office.

Some observations can be made from these data concerning NMFS. Apparently the young age of NMFS, established under Reorganization Plan IV in 1970, has not yet solidified communications processes into standard operating procedures (SOPs) which limit outside informational sources at all levels. However, this diffusion may be costly in terms of strong intra-agency linkage. The breaks in the communication linkages among the top administrators within the organization may cause confusion, especially if extra-agency groups serve as brokers between two levels of the agency, e.g., the regional councils and the American Tuna Foundation serve as links between the regional and the Washington offices. The use of extra-agency brokers would be more beneficial to the agency if a strong linkage, i.e., a two-way channel, existed among the NMFS administrators also. If a strong intra-agency link were present, it would weaken the power of the broker, because of the diffusion of the information sources.

The position of DAR vis-a-vis the federal agencies is one of power, according to network theory. DAR's power is based on its position as one of the core actors and the sole source of information about the state. Obviously, such information is required by federal agencies. The power position of the director of DAR is further enhanced if the extra-agency contact of lower levels within its own hierarchy is constricted to such an extent that all information is channeled through the director's office. However, the negative consequences of such a constricted channel probably outweigh any possible gain, in terms of increasing institutional rigidity, etc.

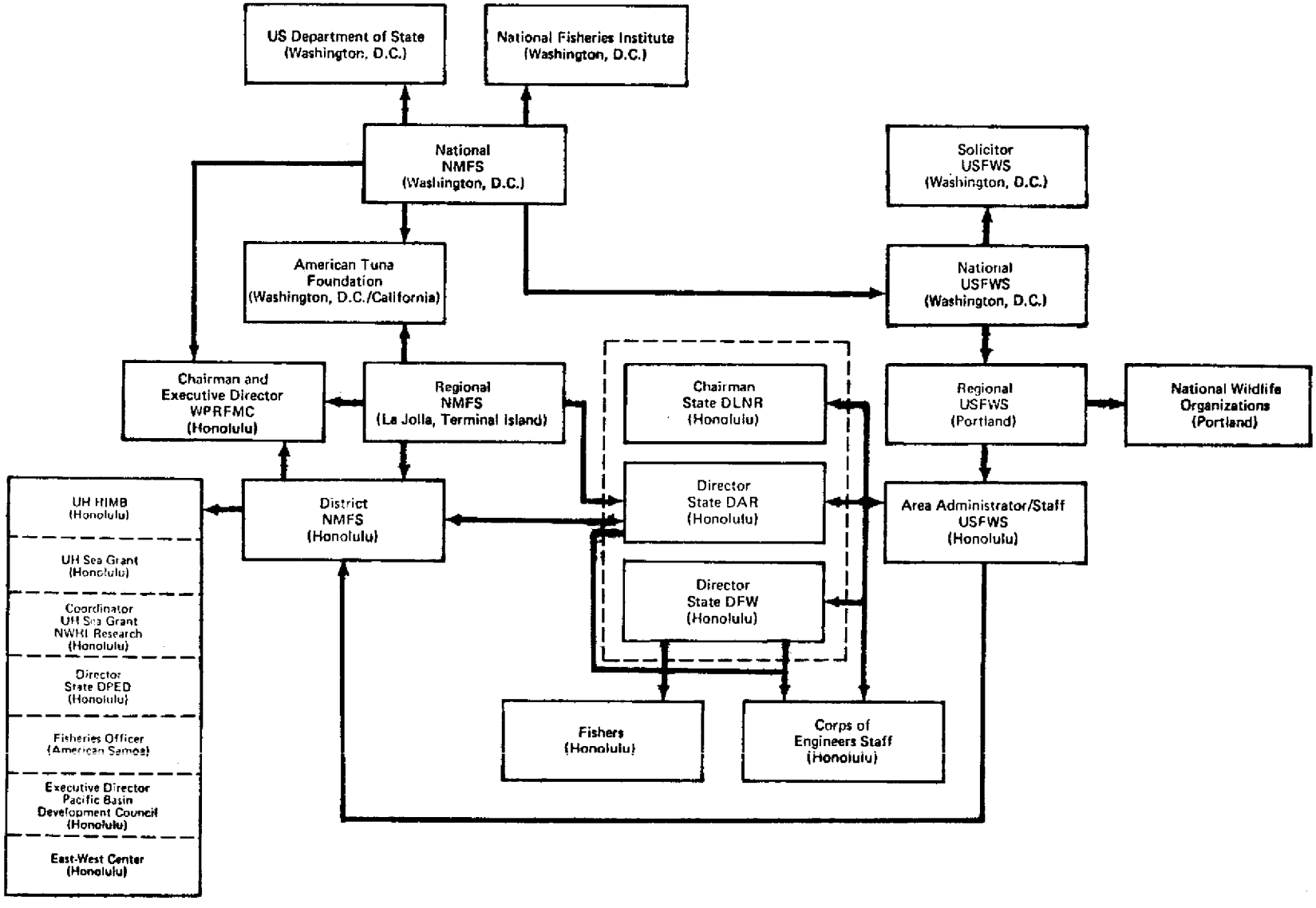

Figure 7. Triagency network for general agency decisionmaking

As indicated in Figure 7, the state agency is strongly linked to the FWS and NMFS by a two-way tie. The Corps of Engineers provides an indirect link between DAR and the FWS office in Honolulu. It is, however, probably safe to assume that DAR would not consider the Corps to be a bridge to the FWS.

Finally, in this scenario, the information network of FWS has interesting implications both for intra- and inter-agency or intergovernmental relations. Its neat communication channels are significant in several ways. Because the higher level administrator obtains information only from the immediate lower level, with the exception of the solicitor (who, however, is an intra-departmental lawyer) in Washington and regional office contact with wildlife interest groups, there are at least three potential levels of abstraction of data from the area administrator's office to the administrator in Washington. Without direct access to outside information there is no way for the reified information to be checked with details of the raw data by administrators at the upper levels of the hierarchy.

Three possibilities of error may occur in the reification process: (1) abstraction forces the deletion of information and interpretation may misconstrue information; (2) bias enters in the abstraction process through the personal value system of the abstractor; and (3) the interpretation of what may be perceived to be general departmental missional goals may vary at the different hierarchical levels.

A possible skewing in the network needs to be noted here. Since the persons interviewed for FWS in Washington, D.C. were not at the same administrative level as the administrator interviewed for NMFS, it is unlikely that there would be communication between the persons interviewed in the two agencies. Hence, there is a possibility that there could be a two-way or strong linkage between the Washington offices of the two heads of the agencies, similar to that existing in Honolulu.

Overall, there is a strong possibility, explainable through organizational theory, that the constricted information channels of the FWS may be an artifact of age since the placement of the FWS in the U.S. Department of the Interior occurred under Reorganization Plan No. II in 1939 and Reorganization Plan No. III in 1940. A case can be made for the setting of SOPs over a 40-year period, since it is well-recognized that organizations will tend to reduce uncertainty and increase "efficiency" by routinization.

Tri-agency Network for FCMA-related Decisionmaking

The tri-agency network of information sources for FCMA-related matters, shown in Figure 8, clearly shows the prominence of the WPRFMC, its chair, and Executive Director. The WPRFMC was established under the FCMA to develop management plans for fisheries within a 200-mile fishery conservation zone (FCZ), which was also defined under the FCMA. The state occupies a strong

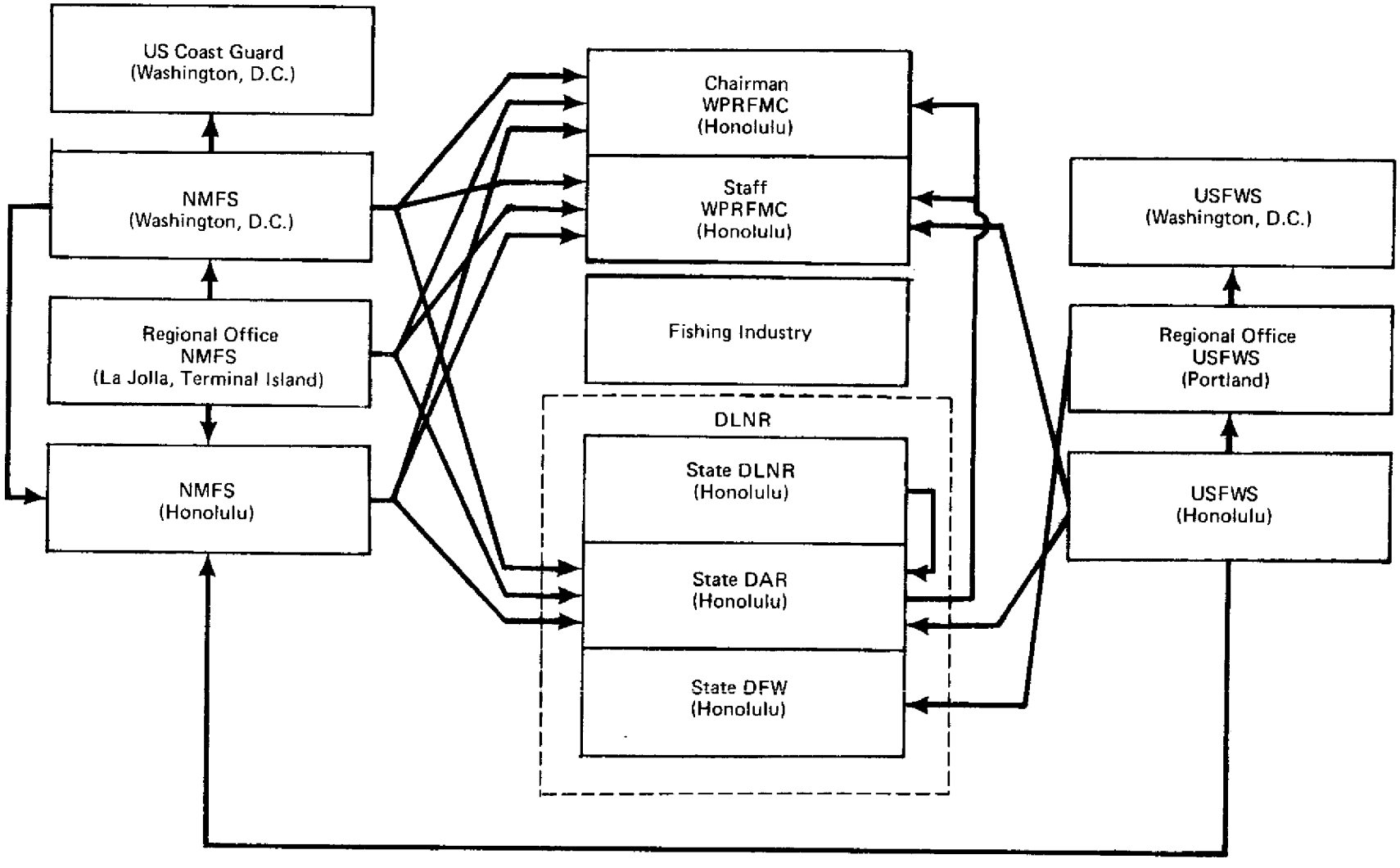

Figure 8. Triagency network for MFCMA matters

central position which is shared with the WPRFMC. However, the WRPFMC's position is probably stronger because it is a source of information for the DAR. Within the year that data were being gathered for this study, the executive director's position was vacated and is currently being filled by the former administrative assistant on an "acting" basis. It is noteworthy that even while occupying the position of administrative assistant, the acting executive director was frequently mentioned as a source of information by name.

The Honolulu offices of NMFS and DAR are shown to be strongly linked in Figure 8. The local NMFS offices sit in a position of centrality with direct ties to both the regional and Washington, D.C. offices. In addition, it is also the link with FWS. In essence, it serves nearly the same strategic function as does WPRFMC. However, the NMFS intra-agency network falls apart at the regional level. The regional administrators are ignored as a source of information by all; the linkage with the Honolulu offices is to the regional solicitor's office only. However, the regional offices obtain information from both the Washington and the Honolulu offices. The direct linkage between the Washington, D.C. and the Honolulu offices creates an enclave at the regional level. The regional level, therefore, does not appear to be a significant source of information for national-level decision-making. This is a puzzling finding because the voting representative of NMFS on the Western Pacific Regional Fishery Management Council is one of the regional administrators.

The FWS is totally ignored by the other two agencies, yet it is the legal administrator of all of the land mass in the NWHI, with the exception of Midway Islands and Kure Atoll. The area administrator of FWS cites the DAR, NMFS, and WPRFMC staff as sources of information; hence, fulfilling pretty much the same kind of function in this scenario as for normal agency operation indicated in Figure 7, i.e., he is the information intake point or boundary interface in Hawaii. The regional office is the source of information for both the local area and Washington, D.C. offices. It appears that for matters related to the FMCA, the regional office is the significant source of information for the FWS. However, for Hawaii, the link between the state Division of Forestry and Wildlife and the regional office underscores the primary concern of the FWS, the preservation of wildlife.

Finally, the powerful position of WPRFMC is abundantly evident. While there are possibilities for a brokerage function which can be carried out by the Honolulu office of NMFS or the DAR, they are not likely to be credible as impartial organizations.

WPRFMC, which was established by the Congress under the Fisheries Conservation and Management Act of 1976, is required to perform the following principal functions (Office of Technology Assessment, 1977):

1. Modify preliminary management plans prepared by NMFS for foreign fisheries
2. Prepare fishery management plans for domestic fisheries
3. Determine information, data, and analysis needed to prepare management plans
4. Test and evaluate techniques for determining optimum sustainable yield and other management factors
5. Secure information from NMFS and/or other regional sources to complete management plans

The composition of the councils, consisting of voting representatives of the states which constitute a "region," fishers and/or other representatives of the fishing industry and fishery experts, and federal agencies, NMFS (voting member) and the U.S. Department of State, U.S. Coast Guard, and FWS (non-voting members), was specifically designed to promote intergovernmental cooperation. Because the 200-mile FCZ is a composite of the 3-mile territorial sea, which is under the jurisdiction of the littoral coastal state, the internationally recognized 9-mile fisheries zone beyond the territorial sea, and beyond that the high seas up to 200 miles, the management of fisheries can only be done through federal-state cooperation because fisheries are fugitive resources which do not recognize jurisdictional boundaries.

CONCLUSIONS

The study of the behavior of organizations as information comsumers can be justified by the slippage between the amount of available research information and the actual use of this information by bureaucratic and other decisionmakers. It is clear that availability of information does not insure its use. This point was made in the present study when only one decisionmaker named University research-related persons as information sources. A study of organizational behavior, especially as information processing systems, provides insight to institutional administrators about their own organizations and to others, who are affected by institutional actions and interactions, about the operations of government which implement public policies.

The survey of the literature established several characteristics of organizations which can be considered as given:

1. Organizations are motivated by self-preservation.
2. Organizations are hierarchical in character with information usually flowing downward.
3. The more restricted the organization is in its boundary interface with the environment, power is enhanced at the decision nodes which act as uncertainty absorbers.
4. The rational actor model is too simplistic for explaining decisionmaking in complex organizations.

5. As information is passed from one level to another, it becomes reified because it is abstracted and reinterpreted at each level; hence, reification enhances the power of the decisionmaker who is doing the abstracting and interpreting.
6. Organizations are selective in the amount and kind of externally generated information they elect to receive.
7. "Central circles" composed of small groups having common interests can assume bridging functions among their members and with other groups.

The empirical data provide an explanation of intergovernmental relations, i.e., federal-state interaction in fisheries management, or the lack of such relationships from the narrow perspective of interpersonal communication of key administrative actors in the implementation of the FCMA. The FCMA was predicated on the notion that non-migratory coastal fisheries should be managed not only by federal and state bureaucrats, but also by fishers and/or experts of living marine resources by legitimizing their participation in the regional management councils on par with governmental representatives. Such a tripartite policy-making body which includes non-governmental members is a new concept in resource governance. Therefore, intergovernmental relations in fisheries management introduces the inclusion of private sector clients, who are normally external to the public decision-making process, as legitimate actors. The recognition and significance of these private actors in the decisionmaking process is evident in the central position of the chair and staff of the WPRFMC in the communication network of state and federal decisionmakers.

The empirical data obtained in this study show that the regional fisheries management councils can promote intergovernmental cooperation. It is a neutral body which provides all participants equal voice and vote. Besides this formal function, WPRFMC, as indicated in Figure 8, serves as the broker of information for all agencies. The WPRFMC's key position of centrality has potential for serving the "bridging" function among the actors as the central circle for the implementation of the FCMA.

Since the common forum for all parties is the Western Pacific Regional Fishery Management Council, its leadership should consider the bridging function, which only they can fulfill, as its most important function. The council's leadership can use its position of power to broker agreements and coalitions within the council and with the federal and state government decisionmakers. The NMFS decisionmakers are important to the approval process since the FCMA requires that all FMPs must be approved by the Secretary of the Department of Commerce, the parent organization of NMFS through the National Oceanic and Atmospheric Administration. The link between the leadership of the Western Pacific Regional Fishery Management Council and the NMFS Washington, D.C. office is present in the personal communication

network of the top administrator of NMFS. The WPRFMC leadership, therefore, can facilitate interactions between federal and state agencies. Because the WPRFMC's staff and chair are information sources of the three agencies, at one or more levels, they are in an opportune position for obtaining advance intelligence on trouble spots and for understanding existing and emerging viewpoints and problems.

In the final analysis, therefore, if the institutional policymaking process is considered to be the channel through which public policies are implemented, the effectiveness of the process must be judged not only on the basis of the success or failure of the policy being implemented, but also on the effectiveness of the process itself. In examining the role of information flow as one aspect of the institutional policymaking process, it was found that decisionmakers' information network provided a surprising abundance of data, both about the process of organizational interaction and the character of the institutions involved.

The present analysis of the communication network of decisionmakers of the three principal agencies, which are involved in the implementation of the FCMA, indicates that the Western Pacific Regional Fishery Management Council is indeed effective as a vehicle for promoting intergovernmental interaction. Based on data gathered on the agency-council interaction in Hawaii, there is high probability that a similar role is assumed by other regional fishery management councils. What may not have been effective in the past is the efficient use of the naturally occurring informal social system which has developed as a result of the implementation of the FCMA. The information network of the administrators who act for an agency can be utilized to develop and implement public policy, if the character and nature of the network are understood.

In evaluating the policymaking process, it is not enough to define problems and alternatives based on costs and benefits, but new configurations of the formal and informal organizations which evolve need to be considered. In addition, of equal importance is the knowledge of channels through which core actors can act and interact, especially when intergovernmental cooperation is being promoted.

ACKNOWLEDGMENTS

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APPENDIX A

The Northwestern Hawaiian Islands extend Northwestward for about 1,200 miles from Kauai, the last inhabited island under the jurisdiction of the state of Hawaii. Except for Kure and Midway Islands, the several dozen islets and atolls, totaling only 3 square miles, are part of the national wildlife refuge system (Grace, 1974). The waters surrounding the Northwestern Hawaiian Islands contain most of the state's "underdeveloped" fishery resources. According to the state's fisheries development plan, while potential tuna resources range out to 1,500 miles (the plan acknowledges that this figure is an arbitrary one), "essentially all of the bottomfish, lobster, shrimp, akule [big-eye scad], and opelu [mackeral scad] potential exists within the Leeward, or Northwestern Hawaiian Islands" (DLNR, 1979).

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STATE FISHERY REGULATIONS IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Use of the fisheries and aquatic resources of the Northwestern Hawaiian Islands is regulated by numerous federal and state laws, rules, regulations, and policies. Certain federal acts protect fish and wildlife species by prohibiting unauthorized harvest; other acts promote conservation through control of different activities. For implementation, these acts generally require cooperation, coordination, and in some cases concurrence with state agencies. In Hawaii, aquatic resources are managed through statutes and rules. The Hawaii Legislature enacts fisheries-related state statutory provisions; others are effected through administrative rules promulgated by the Department of Land and Natural Resources through the state's administrative procedures process. Statutes and administrative rules embody the state's management and control of fishery resources, including those occurring in waters of the Northwestern Hawaiian Islands.

INTRODUCTION

The purpose of the tripartite agreement between state and federal agencies was to implement a cooperative, intensive 5-year survey to assess the living terrestrial and aquatic resources and their habitats in the Northwestern Hawaiian Islands (NWHI) and formulate a basis for resource management decisions. The cooperative nature of the agreement, and of many of the field studies conducted thereunder, is appropriate in view of the overlapping character of federal and state laws and policies that currently regulate the use of resources in this vast and remote area.

An example of a federal law emphasizing state and federal cooperation is the Coastal Zone Management Act of 1972 which, among other things, provides that federally proposed actions should be consistent with that of the state's program implemented for such matters as resource management. The Endangered Species Act of 1973 also emphasizes cooperative effort between state and federal agencies, especially in managing endangered and threatened species.

There also exist federal policies intended to clarify relationships between state and federal authorities responsible for fish and wildlife management. The Department of the Interior, for example, has established a policy, with attendant rules and regulations, ". . . to reaffirm the basic role of the States in fish and resident wildlife management, especially where States have primary authority and responsibility, and to foster improved conservation of fish and wildlife" (Federal Register, 1983). The National Wildlife Refuge System Administration Act of 1966 provides that ". . . The regulation permitting hunting and fishing of resident fish and wildlife within the system shall be, to the extent practicable, consistent with State fish and wildlife laws and regulations . . ." (Committee on Merchant Marine and Fisheries, 1975). In state law, provisions of Sections 187-6 and 187-7, Hawaii Revised Statutes, encourage the Department of Land and Natural Resources to cooperate with other agencies for enhancing aquatic life and wildlife values through mutually agreeable means, and to utilize federal aid funds as may be available for cooperative fish and wildlife restoration and management programs.

The philosophical basis for governmental management of fish and wildlife resources is that these resources are held in trust by the government for the people to enjoy, appreciate, and gain social, economic, and scientific benefits. Since such a function is not reserved to the federal government by the Constitution, the individual states generally exercise primary responsibility and authority for managing and protecting fish and wildlife within their territorial boundaries. Many states view the right to regulate use of fish and wildlife to be independent of ownership of particular parcels of land or waters, inasmuch as the resources themselves do not respond to human delineations of real property ownership. Just as the Magnuson Fishery Conservation and Management Act of 1976 allows federal jurisdiction of regional management councils to extend into state waters when resources under management are known to migrate freely between state and federally controlled areas, so, too, can states regulate use of resources in extraterritorial waters when those resources contribute to stocks within state jurisdictions. Also, this principle forms the basis for "landing laws" since it enables enforcement of state regulations at the point of landing, especially when the precise origin of the catch is often impossible to determine.

State fishery regulations are established procedurally in Hawaii through two mechanisms: enactment of statutes by the legislature and adoption of administrative rules by the Department of Land and Natural Resources. Generally, statutory provisions are broad and provide authority for administration action; administrative rules implement the statutes more precisely for establishment of regulating use of fishery resources through size and bag limits, open and closed seasons, gear restrictions, and other limitations which may apply statewide or within specific geographical limits.

With the exception of statutes and administrative rules that apply only to specific geographical areas, most of Hawaii's fishery regulations have statewide application. State controls over the fishery resources applicable within the NWHI include the following statutory and administrative provisions, below abstracted from Chapters 187 through 195D, Hawaii Revised Statutes and Department of Land and Natural Resources rules Chapters 13-28 through 13-124:

General permit and license requirements apply to commercial harvests and allow monitoring of the resources from the NWHI

> First, each person taking marine life for commercial purpose must obtain a commercial marine license. Also required of each licensee is a monthly fish catch report used by fishery resource managers to monitor trends in commercial fishery harvests.
>
> Second, in order to fish in the NWHI by methods otherwise prohibited statewide, a licensed commercial fisherman may obtain from the Department of Land and Natural Resources a NWHI fishing permit. Such a permit may exempt the fisherman from provisions such as closed seasons, size limits, and prohibited gear, subject to conditions imposed on a case-by-case basis to safeguard against depletion of NWHI resources.

Bag limit provisions serve to limit the rates at which resources are harvested, including

> An individual may take a maximum of 50 moilii, 50 oama, and 15 moi per day.
>
> Except for commercial use with a commercial marine license, no more than 20 ulua, papio, or omilu, in aggregate, may be taken by an individual per day.

Size limit provisions generally protect pre-reproductive organisms and direct effort to individual sizes that will provide appropriate benefits.

> First, a fisherman may take an ulua, papio, or omilu only if it is at least 7 inches long.

Second, if taken for commercial purpose, each slipper lobster must weigh at least 1 pound, and each kuahonu and kona crab must measure at least 4 inches across or along its back.

Third, a spiny lobster may be taken only if it measures at least 3-1/4 inches in carapace length and may not be mutilated or de-tailed in the main Hawaiian islands. For the NWHI, the minimum size established for taking is 3 inches in carapace length, or if de-tailed, 2 inches in width across the first segment of the tail.

Fourth, an opihi may be taken only if it measures at least 1-1/2 inches in shell diameter or 1/2 inch in meat diameter.

Fifth, taken for sale, aholehole and manini must be each at least 5 inches long; mullet, moi, weke, moana, and kumu must be each at least 7 inches long; awa, oio, kala, and opelu kala must be each at least 9 inches long; and opakapaka, ulaula, uku, ulua, papio, uhu, and squid must individually weigh at least 1 pound.

Gear restriction is used to prevent the indiscriminate killing of resources, or the wasteful taking of small or undersized specimens, including

Spears may be used to take any of the finfish or octopus just mentioned only if the resource meet the standards indicated for sale; under no circumstances may sea turtles, crustaceans, or aquatic mammals be speared, or taken with firearms.

Nets and traps may be used for fishing only if made of netting with stretched meshes measuring at least 2 inches, and if the traps are both portable and each measures at most, 10 feet by 6 feet by 6 feet. However, persons fishing for sport may use throw nets with stretched mesh of at least 1-1/2 inches, and any fisherman may use nets of at least 1-1/2 inches in mesh size to take akule or halalu. Baitfishermen with an appropriate license may also use smaller mesh nets to take certain bait fish species. Trap fishermen taking lobsters in the NWHI must additionally use trap openings no larger than 10-1/2 inches in greatest diagonal or diameter at the larger end, and no larger than 6-1/2 inches in greatest diagonal or diameter at the smaller end.

Electrofishing devices, explosives, and poisonous substances may not be used for fishing anywhere in state waters.

Gill nets which have been deployed in the water for fishing must be checked at least every 12 hours.

Certain crustaceans, while carrying eggs externally, are prohibited from being taken in the NWHI. These include the spiny lobster, slipper lobster, kuahonu crab, and kona crab that should be immediately released if observed to be bearing eggs on their abdomen.

"Threatened" and "endangered" species on the federal list are also afforded protection by state statutes and administrative rules. In NWHI waters, three species of sea turtles, the Hawaiian monk seal, and three species of whales are protected through state provisions that include their prohibited taking.

Seasonal closures are invoked to protect fishery stocks during predictable periods of particular vulnerability such as spawning or mass recruitment.

Kona crabs, spiny lobsters, and slipper lobsters, are protected against any harvest from state waters during the months of June, July, and August.

Mullet are protected during the months of December, January, and February.

Halalu and akule, if smaller than 8-1/2 inches long, are protected from netting during the months of July, August, September, and October.

In summary, fish and wildlife resources depend for their existence on habitats which may include private lands, public property, or both, and may pass freely from one to the other. Accordingly, to be effective, management provisions intended to protect, maintain, enhance, and control use of fish and wildlife resources often must cut across jurisdictional limitations of laws, rules and regulations, and personal desires of private landowners. It is therefore esential that involved parties cooperate in recognition of mutual interests and with mutual respect for divergent concerns, in order to coordinate effective management of fish and wildlife resources. Moreover, obtaining the full cooperation of resource harvesters in abiding with regulatory provisions as discussed, must be accomplished for the protection and conservation of living renewable resources.

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MANAGEMENT PLANS FOR FISHERY RESOURCES IN THE NORTHWESTERN HAWAIIAN ISLANDS

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ABSTRACT

Five fishery management plans have been prepared since the Magnuson Fishery Conservation and Management Act (FCMA) of 1976 became operational. Each of these plans cover a variety of species that are grouped into management units on the basis of habitat similarities and on their susceptibility to capture with certain fishing gears. This paper describes the fisheries on each management unit and the management measures that are incorporated in the plans. In addition, this paper indicates how the plans are related to the NWHI and the degree of the relationship.

NWHI fisheries
federal fishery management plans
multi-species fisheries

INTRODUCTION

Five fishery management plans (FMPs) have been prepared for the western Pacific region since the Magnuson Fishery Conservation and Management Act of 1976 became operational. These plans cover a variety of species that are grouped into management units on the basis of habitat similarities and susceptibility to capture with certain fishing gears. The five units differ widely in the number of fishermen that participate in the fishery, in the type of gear employed by the fishermen to catch the management unit species, in the habitats where the management unit species live, and in the annual size and value of the catch.

A brief perspective of Hawaii's fisheries is presented below. Following this, each of the five fishery management plans that have been prepared by the Western Pacific Regional Fishery

Management Council (WPRFMC) and the National Marine Fisheries Service (NMFS) is outlined. In addition how the plans are related to the NWHI is discussed.

There is always the temptation to compare the annual volume and value of fish landings made in Hawaii with those of mainland states, and then to compare the present contribution of fisheries with the state's income. Such comparative imagery tends to discount the national significance of Hawaii's fisheries. If such imagery is extended by limiting the state's fishery to catches currently made by domestic fishermen only in NWHI waters, then the relative "significance" of the NWHI fisheries would border on trivia by, say, Californian of Alaskan standards.[1] In a way, it's like dealing with apples and oranges when trying to compare the fisheries of Hawaii with those of mainland states. This is so because there is no good common denominator between oceanic islands and continental states to form a basis for comparison.

It is safe to say that many people would agree that there is value in the fisheries of the NWHI when weighed on an island's scale. Otherwise, why would there have been a 5-year study?

PELAGIC SPECIES OTHER THAN TUNA

On the average, about 85 to 90 percent of the volume of commercial fish landings made in Hawaii are pelagic species. Of this relative amount, skipjack tuna (aku) roughly makes up about 50 percent of the annual commercial landings. Blue marlin, striped marlin, mahimahi, and wahoo (ono) are among the top 10 species in terms of the volume and value of annual commercial fish landings made in Hawaii, following the top three species -- skipjack, yellowfin, and bigeye tunas.

The prominence of skipjack tuna in the state's commercial catch has diminished in recent years. Landings have steadily declined and continue well below the long-term average for 1964-79. Cumulative landings of the larger pelagic species (e.g., yellowfin and bigeye tunas, billfish, mahimahi, and ono), on the other hand, have increased significantly due to the growth of the small-boat handline and troll fisheries and the expansion of the state's fish aggregation program.

In 1960, blue marlin contributed the largest percentage of the commercial troll landings followed by skipjack tuna, yellowfin tuna, ono, mahimahi, and striped marlin. Two decades later (in 1981) commercial troll-caught landings were led by yellowfin

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[1] Some world and continental fisheries are measured in hundreds of thousands of metric tons whereas the fisheries of Hawaii and many other Pacific islands are measured in hundreds or few thousands of metric tons.

tuna, followed by blue marlin, ono, mahimahi, albacore, skipjack tuna, and striped marlin. The fact that yellowfin tuna has displaced blue marlin as the top commercial species caught using trolling gear can be partially explained by the price increase of sashimi-quality tunas that can command $5 per pound in the round. It can perhaps also be explained by the apparent decline in the abundance of blue marlin in the Pacific. Catch rates of blue marlin taken on foreign longline gear in the fishery conservation zone (FCZ) surrounding Hawaii have declined significantly since the early and mid-1960s.

The commercial fishing license forms issued by the Division of Conservation and Resources Enforcement of the Hawaii Department of Land and Natural Resources indicate that roughly about 200 vessels and 240 fishermen trolled commercially during fiscal year 1981-82 and that about 1,000 vessels and 1,000 fishermen fished commercially at least sometime combining trolling with other types of fishing. Very little commercial trolling is done in the NWHI. Much of the fishing is done within 20 to 25 miles of the main islands. However, in recent years, albacore trollers have also trolled for ono, mahimahi, and yellowfin tuna in the NWHI prior to landing their catches in Hawaii. Also, an increasing number of bottomfishing vessels have been trolling the bank areas for ono, mahimahi, and yellowfin tuna on their run back from the NWHI to deliver their catches for sale in Honolulu's growing fresh-fish market.

The domestic tuna longline fishery captures the larger species of pelagic fish. Occupying a prominent position in Hawaii's fishery in the early 1950s, the fleet steadily declined in the 1960s and 1970s to about 15 to 20 vessels. However, the fleet has made a strong rebound during the past 2 years. At present there are about 30 vessesls that longline on a regular basis. A few of the boats that are new to the fleet are quite large, about 70 to 80 feet long. Most of the domestic longline fishing is done within 100 miles of the main islands, but some of the newer, larger vessels venture out to 200 miles or farther from Honolulu. The catches made by this fishery bring in exceptionally good prices. The fish are sold fresh mostly to the sashimi markets in Hawaii, the mainland, and even Japan. The price incentives have lured an increasing number of albacore boats to outfit themselves with longline gear and fish for sashimi-grade tuna during the off season for albacore.

The pattern of domestic fishing nearer to the main Hawaiian islands contrasts sharply to the pattern of foreign longlining in the NWHI in the recent past. For the average of the 5-year period, 1973-77, about twice as much fish was taken by the foreign longline fleet in the NWHI than in the FCZ waters of the main Hawaiian islands. This was to be expected since the NWHI are nearer to the home ports of the foreign fleets, since the FCZ waters in the NWHI are significantly larger than those surrounding the main Hawaiian islands, and especially since one of the world's best fishing grounds for bigeye tuna, a premium market

species in the sashimi trade, is within the FCZ of the NWHI and just north of it.

Seventy-five percent of the foreign longline catch made in the U.S. FCZ surrounding the Hawaiian islands during the winter is taken in the NWHI portion of the zone. Striped marlin and swordfish account for over 90 percent of the billfish catch, whereas bigeye and albacore tuna dominate the winter catch of tuna. However, during the summer when the domestic fisheries are most active, the foreign longline fishery directs its focus away from the waters of the NWHI to the waters of the main Hawaiian islands.

Historical foreign longline statistics reveal an apparent marked seasonal variation in abundance among the billfish, with striped marlin generally occuring in greater numbers during the winter and blue marlin during the summer. The seasonal variations in species composition are dependent upon the movements and local abundance of the fish. Both of these factors may be influenced by a number of environmental factors such as sea surface temperatures and the relative availability of prey. It appears, in general, that striped marlin and bigeye tuna (winter fish) may be responding to a different set of environmental factors than the blue marlin and yellowfin tuna which are mostly summer fish.

The foreign longline fishery has been inactive in Hawaiian waters since April 1980. Foreign fishermen claim that onboard observer requirements, check-in and check-out procedures, and other "onerous" requirements of the Preliminary Management Plan (PMP), which was implemented then, prevent them from economically fishing in the FCZ. Picking up an observer, according to foreign longline fishermen, does not make much economic sense when length of fishing of the average Japanese longliner in the FCZ was only 5 days in 1979. Foreign longline fishermen dip in and out of the FCZ to follow the fish.

Having discussed the fishery and fishermen, attention will now be turned to the WPRFMC's fishery management plan for billfish and other pelagic species. The FMP that the WPRFMC has prepared for pelagic species is relatively uncomplicated. The management program proposed would establish areas and season in which foreign longlining would not be permitted. Under the proposal for Hawaii, foreign longliners would be allowed to fish up to 100 miles of the NWHI year-round and up to 100 miles of the main Hawaiian islands during the winter months, November through February. During summer months, foreign longliners would be prohibited from fishing in the FCZ around the main islands. Foreign longline vessels would also have to obtain permits, submit catch and effort data as under the PMP, and carry observers when so directed by the regional director of the National Marine Fisheries Service acting under the advice and counsel of the WPRFMC. There would be no catch or effort restrictions on domestic fishermen, but they would be encouraged to keep records and their

catch would be sampled periodically to monitor catch levels and rates.

The underlying rationale for the area closures to foreign longline fishing around the main Hawaiian islands is to protect domestic fishermen by increasing the probability of transfers of billfish, mahimahi, ono, and inevitably tunas to domestic fishermen. There is a wide-held belief that catch competition or catch interaction effects exist between the domestic and foreign fisheries that capture billfish. Keeping foreign longlining out of the FCZ of the main Hawaiian islands during the months when the domestic fisheries are most active makes a lot of sense. Foreign fishing would be allowed up to 100 miles of the main Hawaiian islands during the "off season" for domestic trollers and handline fishermen. Foreign longlining up to 100 miles of the NWHI would be allowed year-round, thus making a good portion of the traditional fishing grounds for bigeye tuna also available to foreign fishermen.

There has been major difficulty in trying to balance the needs of various domestic and foreign participants in the fisheries for highly migratory pelagic species. Both the PMP and the proposed FMP, out of legal necessity, are based on an artificial distinction between one set of migratory fish in the management unit and a second set of "highly migratory species" legally defined as all tunas. This is the root of the problem. Trying to manage the pelagic fisheries by ignoring its largest component (the tunas) is unproductive and self-defeating in the long run.

The WPRFMC would like to see U.S. policy changed to include the tunas within the management planning purview of the regional councils. It recognizes that the area and season closures for foreign longlining proposed for species of billfish, mahimahi, ono, and oceanic sharks have a bearing on the U.S. posture when negotiating with nations in the eastern Pacific and elsewhere with respect to tuna fishing. It has considered both the positive impacts on the domestic fishery for pelagic species stemming from the proposed management scheme and possible ancillary impacts on distant-water tuna fisheries, both foreign and U.S. alike. A balancing of national interests is being sought.

SPINY LOBSTER

In contrast with its fisheries for pelagic species, the Hawaii spiny lobster commercial fishery is much smaller in terms of harvests, the number of fishermen that participate, and where the fishery is conducted. By far the most significant emphasis in commercial fishing for spiny lobster has been directed at the NWHI. Although for many years commercial catches have been made around the main Hawaiian islands by fishermen using tangle-nets as well as by trap fishermen capturing a wide variety of fish species, they generally do not specifically target spiny lobsters. Commercial lobster trapping operations have increased in

the main Hawaiian islands in recent years, but the levels of present and potential harvests there are and will continue to be way below the harvest levels of the NWHI. This is because there are fewer spiny lobster habitats in the main Hawaiian islands compared with the NWHI.

The distant-water commercial fishery for spiny lobsters expanded rapidly soon after research cruises by NMFS during 1975 demonstrated the presence of commercial concentrations around Necker Island and a few other locations in the NWHI. In 1977, 72,000 pounds were taken in the NWHI. The live, whole lobster market in Hawaii could not absorb this quantity, thus the fishing operations shifted to at-sea de-tailing and freezing of lobster tails for export. In 1979, 100,000 pounds of lobsters (round weight) were landed. In 1980, total landings shot up to 400,000 pounds (round weight). Landings continued to increase in 1981, when 10 vessels participated in the fishery, including three large vessels which entered the fishery in 1980. Landings were reduced to about 300,000 pounds (round weight) in 1982 when the larger boats left the fishery. Today, there are fewer boats in the fishery than in 1981. They are smaller, carry fewer traps, and make fishing trips of shorter duration than previously. From the beginning, the fishery has been characterized by a high turnover of participants probably because it has not produced income up to the expectations of the entrants. The simple fact is that the lobster resources are limited. Even the most optimistic projections of yield do not foresee the NWHI's spiny lobster fishery becoming very large compared with many of the world's other lobster fisheries. The potential annual average harvest of between 200,000 and 400,000 individuals simply will not support many vessels.

Any single-species fishery which involves travel to distant waters, and in which areas of proven concentrations are few, is economically risky. One of the major objectives of the Spiny Lobster Fishery Management Plan is to provide a stable fishery in which vessels can earn an income while exploring other fishery opportunities that are needed to diversify the resource base. This pattern is becoming more common now with a few boats combining lobster fishing with other fisheries. Economic projections in the WPRFMC's plan suggest that after initially high catch rates in the "virgin" lobster fishery are reduced, the relatively low density of NWHI's lobster populations will make it difficult, if not impossible, to achieve the scale of production large vessels need to recover operating costs, particularly with rising fuel prices and large quantities of fuel needed to travel long distances. This is why the larger boats have left the fishery and why more and more smaller boats are diversifying their operations into multi-species fisheries. Although there probably are some unexploited lobster stocks in the northern reaches of the NWHI, fishermen are currently harvesting lobsters in the southern and middle areas to keep operating costs down.

The population density of spiny lobsters in the NWHI is low in comparison with that of similar fisheries in areas of the world having continental shelves. The marked increase in lobster trappings in the early 1980s caused concern that the NWHI's lobster resources could be reduced to a level which would no longer support commercial fishing. Sustained biological damage to the lobster resource was, however, considered unlikely because declining catch rates would bring an end to the lobster fishery for economic reasons long before irreversible depletion of the lobster stock could take place.

The WPRFMC initiated research and planning for a spiny lobster FMP in 1977, but it took 3 years to reach agreement on the management measures for the fishery. The final plan was submitted for approval in 1981, but questions raised by NMFS about the interactions between the spiny lobster fishery and the monk seals delayed the plan's approval. Questions raised by the Hawaii Coastal Zone Management Program about the consistency of federal and state lobster fishing regulations also delayed implementation of the plan. The result has been a delay of a complete compilation of catches made in the fishery in recent years.

The CZM consistency problems will probably be solved soon through an amendment to the plan that extends the state's regulations for spiny lobsters to cover U.S. FCZ waters surrounding the main Hawaiian islands. Without the proposed amendment, the state would have difficulty prosecuting fishermen caught with undersized lobsters if the fishermen claimed that the catch was made in the FCZ surrounding the main Hawaiian islands rather than in state waters. The amendment to the plan closes this loophole.

The Spiny Lobster FMP for NWHI FCZ waters is now a reality. It was officially adopted on March 9, 1983. The regulations require a lobster fishing permit for federal waters and catch reports from fishermen. The regulations establish a minimum carapace length of 7.7 cm, gear restrictions on commercial fishing, and closures to lobster fishing in areas shallower than 10 fathoms and within 20 miles of Laysan Island. The areas closed to fishing will act as reserves from which recruitment to the lobster population can occur and also as buffer zones between the fishery and populations of "endangered" monk seals and "threatened" green sea turtles. Lobster trap opening dimensions are restricted to reduce the risks of monk seal entrapment. The state of Hawaii is currently amending its NWHI spiny lobster regulations to conform to the federal regulations.

Since much of the present spiny lobster catch goes to the frozen tail market, the FMP incorporates a tail width minimum size of 5 cm which statistically corresponds to the 7.7-cm carapace length measure, but a 15 percent tolerance factor is allowed. As with the state's regulations, the retention of egg-bearing lobsters is prohibited.

The FMP establishes an "optimal yield" or a potential annual harvest of spiny lobsters of between 200,000 and 400,000 "legal" animals. The range is not a quota, nor is it a harvest target or a harvest guarantee. The range is simply the best estimate of harvests that can be sustained in the long-run with other existing management measures. The potential harvest of between 200,000 and 400,000 lobsters is WPRFMC's best estimate of the "equilibrium yield" after the virgin stock is reduced. Simply put, the absolute level of harvest is immaterial, if reproductive capacity is protected through the conservation measures outline above. To make it complete, the plan recommends a research program to collect data to better define the life history parameters of the spiny lobster and to better monitor the status of lobster stocks, as well as to assess the effectiveness of the regulations in conserving lobster stocks. The rules are designed to keep the new industry from depleting the lobster population.

BOTTOMFISH SPECIES

Hawaii's multi-resource fisheries -- the fishery for bottomfish species, including snappers, groupers, and jacks (or uluas) -- form the basis for a small but locally important fishery in Hawaii. Some of these bottomfish are among the most valuable species in Hawaii. Some elements of the small-boat and medium-sized boat fisheries in Hawaii rely heavily upon sustained catches and incomes derived from harvesting bottomfish as a component of multi-species, multi-gear operations. The fishery includes commercial as well as substantial recreational components.

Traditional deepsea handline gear accounts for over 80 percent of the reported commercial catch of bottomfish species. Trap and bottom longline catches make up the remaining commercial catches. A few commercial bottomfish fishermen have found bottom longlining to be productive. Deep-water longlining and trapping are almost exclusively commercial undertakings because of the costly investment in gear.

About 33 percent of the 2,000 or so commercially licensed fishermen in Hawaii report using handline gear. Most of this group are made up of part-time fishermen who fish fewer than 50 days per year and who use other gear combinations like trolling in addition to deepsea handline gear. A small fleet of commercial fishing vessels (about 20 boats) which regularly fish for bottomfish operates out of Kewalo Basin on Oahu and Maui ports. They generally use larger, more seaworthy vessels than those operated by part-time commercial and recreational fishermen, and they have the capability to fish during periods of rough seas which severely restrict the operations of the smaller boats.

In the small-boat fishery for bottomfish around the main Hawaiian islands there is a tendency for nearby stocks to be fished much more intensively than distant-water stocks, and the past history of the bottomfish fishery in Hawaii has shown that

as each nearby location is subjected to heavy fishing, the catch rates decline and the boats move into other, more productive grounds. The long-lived, slow-growing species which characterize the bottomfish assemblage are more susceptible to stock reductions than are shorter-lived, faster-growing pelagic species. The potential habitat satisfying the depth requirements of bottomfish is very limited in Hawaii due to the narrowness of the shelf areas around the islands because the steep-sloping submerged portions of volcanic islands and atolls are close to shore.

The capacity for self-regulation of fishing pressure in the bottomfish fishery is rapidly diminishing. Fishing pressure is increasing as a consequence of (1) rising demand and prices for select bottomfish species which have gained great popularity in the tourist industry; (2) expanding export markets for fresh island-caught bottomfish; (3) an increasing number of recreational and part-time fishermen who have acquired the gear and skill to compete with commercial bottomfish fishermen; and (4) increasing use of large vessels (by Hawaii standards) to gain access to distant-water bottomfishing grounds, and re-outfitting of albacore vessels with bottomfishing gear to give them a fishing opportunity during the off-season for albacore.

Overall the bottomfish stocks near the main Hawaiian islands are thought to be fully exploited or near fully exploited, and some nearby stocks of opakapaka and possibly onaga are considered to be overfished. In direct contrast, the bottomfish stocks in the NWHI are considered to be underfished with a sustainable annual yield estimated to be worth a few million dollars. Without development of a multi-purpose, distant-water fishery, the fishing industry in Hawaii will lose commercial fishermen. The quantity of bottomfish marketed in Hawaii will decline sharply, bringing about extremely high prices for the limited quantities harvested around the main Hawaiian islands. The high price would then induce more part-time fishermen to put further pressure on already reduced stocks in the main Hawaiian islands, making the present-day management problems worse.

Although the immediate risk of overfishing bottomfish stocks in the NWHI depends on future developments, primarily in marketing, there could be a future economic incentive to overfish these resources. The WPRFMC is taking the framework approach in drawing up its fishery management plan for bottomfish. This approach essentially establishes a procedure in which certain conditions in the fishery would trigger a WPRFMC decision to reduce harvest levels of particular species, while increasing the monitoring and assessment of stock conditions for commercially important bottomfish species according to a previously developed program in the FMP. The snapper-grouper-jack complex is considered a management unit because there is overlap in the habitat of individual species, but there is no evidence of strong biological interdependence among individual species. Bottomfish species are generally not harvested together by commercial fishermen, but rather are

targeted by specific localities, bottom habit, depth, seasonality resulting from spawning aggregations, current conditions, and price discrimination by species. It is believed that individual species can be targeted by commercial fishermen with little incidental catch, thus a species-by-species approach may be the least complex form of managment.

Whenever the size structure of the catch indicates that a species is in or nearing the range of biological stress, the WPRFMC will decide if continuation of overfishing is justified on social and economic grounds and may restrict the harvest of that species by whatever method it selects provided that the method meets the national standards test embodied in the FCMA. Whenever monitoring of the size composition of the catch indicates that a species is not in or not approaching the range of biological stress, the species will be placed in a no action category until an in-depth analysis of overfishing can be performed. The remaining species in the bottomfish complex would be nonpriority species, and no individual species regulation would be necessary.

SEAMOUNT GROUNDFISH

The seamount fishery is carried out entirely by foreign trawlers and longline vessels. At various times, vessels of the USSR, Japan, Korea, and Taiwan have fished inside the FCZ north of Kure Atoll. The USSR was the first nation to commercially exploit the resources of this area. In November 1967, a Soviet commercial trawler discovered large concentrations of pelagic armorhead on the Emperor Seamount chain, and a large-scale fishery was initiated. Japanese trawlers of 1,500 to 4,000 gross tons entered the fishery in 1969. Their initial effort was mostly exploratory, but they set the stage for full-scale commercial operations by 1972. To assist in the development of the fishery, Japanese research vessels conducted extensive surveys in the 1972-74 period to determine the distribution of pelagic armorhead and alfonsin and their potential for development. They explored the central North Pacific for uncharted seamounts, described the topography and profile of known seamounts, and collected oceanographic data in the vicinity of the seamounts. The results of these surveys showed that the only seamounts suitable for trawling are located at the southern end of the Emperor Seamount chain, beginning with Kinmei Seamount and extending south-southeast to Hancock Seamounts in the U.S. FCZ.

In January 1977, the National Marine Fisheries Service put into effect a preliminary fishery management plan which regulates foreign fishing for groundfish on the Hancock Seamounts, which are located inside the U.S. fishery conservation zone. The regulations temporarily restrict the foreign fishery to a 2,000-MT annual catch quota by trawling or bottom longlining and to 60 vessel days of total effort. In addition, they establish a licensing procedure for foreign vessels and require the submission of detailed catch and effort data and the placement of U.S. observers on any foreign fishing vessel.

Under the plan, Japan and the USSR were each allocated 1,000 MT of seamount groundfish for 1977. In May 1977, a Soviet trawler was apprehended and cited by the U.S. Coast Guard for trawling in the Hancock area in violation of regulations defined in the plan. In recent years, Japan and Taiwan have each been allocated 1,000 MT. The Japanese allocation of seamount groundfish has never been fully taken, and the Soviet and Taiwanese vessels are not known to have fished inside the FCZ since implementation of the plan.

The plan does not prevent domestic vessels from harvesting seamount resources. No U.S. fishing vessels currently harvest or have ever harvested seamount groundfish in the central North Pacific, although the NOAA vessel Townsend Cromwell has conducted exploratory trawl and handline surveys there as part of the tripartite-Sea Grant Northwestern Hawaiian Islands investigations.

Considering the limited summit areas of the Hancock Seamounts, the number of domestic vessels which can be supported by the armorhead-alfonsin resources of the FCZ would be small. Although the foreign quota for armorhead-alfonsin resources inside the U.S. fishery conservation zone has been small, the data collected by U.S. observers in the 1978-81 period indicate that the catch rate of the Japanese trawler which fished there earliest in each year was invariably higher than that of the second vessel. Should domestic vessels enter the fishery, it would be advisable to reduce the annual Japanese allocation from 1,000 MT to a lower level in order to protect the first opportunity to the resource for U.S. fishermen. Available data suggest that the annual harvest quota imposed by the preliminary fishery management plan has been somewhat successful in allowing the Hancock Seamount stocks of armorhead and alfonsin to recover from heavy fishing prior to 1977. Catch rates at the Hancock Seamounts have generally improved since 1978, despite sustained heavy fishing outside the FCZ.

The economically more desirable alfonsin are a minor constituent of trawl catches. The large alfonsin inhabit rough bottoms which are not suitable for trawling, even with advanced techniques and gear. The principal fishing method for alfonsin is bottom longlining, and in 1972 or 1973, the Japanese initiated this type of fishery on Milwaukee Banks and other central North Pacific seamounts. Since that time, vessels from Korea and possibly from Taiwan have reportedly joined the bottom longline fishery. The vessels, ranging in size from 180 to 340 tons, make trips of up to 4 months duration to the central North Pacific grounds.

Catching alfonsin rather than less valuable species is said to require some degree of experience, which the Japanese have gained through fishing in home waters for over 30 years. Although alfonsin are widely distributed in the central North Pacific seamount chain, fishing is productive only in selected

areas. Alfonsin which has been quick-frozen onboard Japanese stern trawlers and bottom longline vessels is sold as sashimi in Tokyo's Tsukiji fish market. They are sold in size-segregated lots, and the Tokyo buyers apparently prefer large fish.

Armorhead and alfonsin taken in the Japanese seamount trawl fishery are headed, gutted, and frozen onboard the larger stern trawlers (1,500 to 4,000 ton class) which operate in the central North Pacific and Bering Sea. The heads and viscera are processed in fish meal factories onboard vessels. Those vessels lacking a fish meal plant discard all non-commercial species, as well as small alfonsin which have been damaged by long trawls.

As with other pelagic species it is unrealistic to attempt assessments for the Hancock Seamount stock of groundfish in isolation from the remainder of the central North Pacific seamount fishery resources. A cooperative effort between Japanese and U.S. fishery scientists will be necessary to determine stock recruitment relationships and maximum sustainable yields of the regionwide stocks. It is likely that truly effective resource management will be achieved only through an international agreement.

The impact of the foreign groundfish fishery on the precious coral stock at Hancock Seamounts is being adequately monitored by U.S. observers which accompany Japanese trawlers.

PRECIOUS CORALS

The management plan for precious corals covers domestic and foreign fishing in the FCZ. Six beds of precious corals have been located in the Hawaiian island chain, three of which are in the NWHI: (1) the 180 fathom bank, north of Kure Atoll; (2) Brooks Bank, near La Perouse Pinnacle; and (3) the WESPAC bed between Nihoa and Necker. The estimated area of these three beds of precious corals is less than 4 km^2.

The plan and regulations define areas around beds within which selective harvesting gear is required. These are the "established" beds, all in the main Hawaiian islands, which have been surveyed and for which estimates of maximum sustainable yield are reasonably precise. Only selective gear (submersibles or remote-controlled harvestor vehicles) is permitted in established beds. The known beds in the NWHI are labeled "conditional" beds. These are beds for which yields have been estimated by comparing their relative size to established beds and prorating yields on the assumption that ecological conditions at established beds are representative of all other beds. Unexplored portions of the FCZ in which coral beds are almost certain to exist are called "exploratory permit areas." Both selective and nonselective gear are permitted at the conditional beds and exploratory permit areas subject to a quota limitation on harvests. An exploratory area quota of 1,000 kg has been established to encourage the exploration and discovery of new

beds and to preserve an opportunity for low-investment dredge equipment in the fishery. A new bed located by exploratory fishing will become a "conditional" one when sufficient data have been collected to estimate the size and yield from the bed. A single "refugia" bed, the WESPAC bed, has been set aside to serve as a baseline study area and possible reproductive reserve. No coral harvesting is permitted in the refugia.

No domestic fishermen are known to have ever fished for precious corals in the NWHI. In 1965, Japanese coral draggers discovered a very large bed of precious corals in international water on the Milwaukee Banks of the Emperor Seamounts some 750 km northwest of Midway. And the race was on. In 1980, the "Midway" area produced 94 percent of the world's population of precious coral, but only about 10 percent of the grounds lie inside the U.S. 200-mile zone in the Hancock Seamount area. In 1981, there were 21 violations of the U.S. fishery conservation zone by Japanese and Taiwanese vessels. The U.S. State Department formally protested these incidents to the governments of Japan and Taiwan. No violations of the FCZ were recorded by the U.S. Coast Guard in 1982 although some fishing apparently did occur in the Hancock Seamount area according to Taiwanese fishermen. At the present time a quota of 1,000 kg exists for all species of precious corals in each of the FCZ exploratory areas of the different islands served by the WPRFMC. U.S. law requires that the surplus be made available to foreign fishermen. Approximately 40 to 50 vessels might be expected to fish on the high seas on the Midway grounds in 1983. To date, several foreign firms and one domestic firm have expressed interest in obtaining permits to fish the Hancock Seamount area where good quality coral is still found. Several foreign firms are interested in establishing a base in Honolulu in order to save fuel and crew costs for the long transit between Midway and Japan. The WPRFMC will explore the possibility of establishing a joint venture between a Japanese or Taiwanese firm and the domestic precious coral industry.

Management of the precious coral fisheries in the Pacific is a difficult problem because much of the resource exists in international waters. Conservation and management of precious corals could be handled through bilateral or multilateral approaches involving the WPRFMC, Taiwan, and Japan. The U.S. could seek to preserve the Midway-Emperor Seamount precious coral resources by entering into a multilateral treaty for their management under the common heritage principle. Articles of the Law of the Sea treaty urge agreement on measures for the conservation of living resources that occur both within the 200-mile exclusive economic zones and in areas beyond. In June 1982, the WPRFMC requested that the U.S. State Department look into the possibility of multilateral arrangements for managing precious coral fisheries in the Pacific. The WPRFMC is waiting for the State Department's thoughts and impressions on the need and workability of regional fishery management agreements for precious corals in the areas served by the WPRFMC and the adjacent high seas.

The abundance of precious corals on the Milwaukee Banks just northwest of the U.S. FCZ of the Hawaiian islands suggests that NWHI waters harbor more precious coral aggregations than the waters surrounding the main islands.

SUMMARY

The immediate role of the WPRFMC with respect to the fisheries of the NWHI, whether for precious corals, lobsters, bottomfish, seamount groundfish, or migratory pelagic species, is to promote development within the sustainable limits of the resources. The importance of the NWHI for fisheries development is paramount. Simple geography tells us that. One cannot expect to develop a fishery based in Honolulu when major stocks of albacore tuna, seamount groundfish, bigeye tuna, and smaller stocks of bottomfish, precious corals, and spiny lobster are 1,000 miles or more away from Honolulu. Opening portions of the NWHI for fisheries support purposes would appear to be essential for developing multi-species fisheries opportunities for domestic fishermen in the central and western end of the Hawaiian Archipelago, while at the same time decreasing the pressure on some overfished stocks in the main Hawaiian islands.

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MANAGEMENT OF THE HAWAIIAN ISLANDS NATIONAL WILDLIFE REFUGE

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ABSTRACT

Management of natural resources on federal lands demands accountability to the public. Yet, public "opinion" is not easily defined nor are differing opinions easily reconciled. Management decisions are further complicated when predictive capability is limited by the absence of relevant scientific data. Tripartite-Sea Grant studies in the Northwestern Hawaiian Islands (NWHI) provided data indicating the potential harvestability of various fishery resources, the anticipated direct and indirect effects of fishery development on fish and wildlife, the unique values of NWHI ecosystems, and the interrelationships of terrestrial and marine species and their habitats. These studies also demonstrated the need to apply an ecosystem approach to resource management acknowledging that fish and wildlife and the human activities that affect them have little regard for institutional boundaries. With this in mind, the U.S. Fish and Wildlife Service's (FWS) future role in the NWHI will address management needs both within and outside refuge boundaries, through the continuing cooperation of other agencies. Outside refuge boundaries, FWS will continue it's efforts to influence activities that jeopardize fish and wildlife and their habitats. Cooperative work on migratory birds and endangered species on Midway Islands and Kure Atoll will continue. Within refuge boundaries, wildlife populations will be closely monitored to document natural fluctuations and to assess the effects of fishery development. Methods to detect the presence and prevent the establishment of exotic pest species will be developed and tested. Access to refuge lands and waters will be controlled to minimize unnecessary disturbance to wildlife. Cooperative research programs will focus on species in jeopardy.

FWS's educational program will expand. The scheduling, ranking, and development of details for these and other programs will be a major focus of FWS's refuge master planning project, scheduled to begin immediately. Master planning for the Hawaiian Islands National Wildlife Refuge will ensure application of national policy, provide a basis for future budgeting, establish long-range management strategies, and provide continuity in refuge management. Public input will be assured throughout the planning process.

ecosystem	National Wildlife Refuge
master planning	resource management
endangered species	Northwestern Hawaiian Islands

INTRODUCTION

I have a distinct advantage over other speakers in that I have had the opportunity to hear all the presentations before my turn to participate in the tripartite-Sea Grant symposium. We've all heard some fascinating information about this unique part of the world we call the Northwestern Hawaiian Islands. We've heard about the terrestrial ecosystems that support unique assemblages of land birds, insects, and plants; diverse and abundant seabird populations; and monk seals and turtles that congregate to breed on small spits of land, but range widely in search of food. In the marine environment area, we've heard about the evolution of coral reefs and the Darwin Point, variation in reef fish and coral diversity and abundance along the archipelago, and the trophic relationships within the atoll ecosystem. Overall, we've learned through our combined efforts that the NWHI present unique potential for even greater understanding, a baseline or barometer against which to assess similar ecosystems around the world. Finally, we've also learned that only through continued study can we develop the tools to correct or reverse the disturbing trends in population and habitat condition that reflect former abuses.

In reflecting on what we have learned, I find it interesting to speculate on how we might interpret this information differently had the impetus for the tripartite-Sea Grant study been different. The driving force for the study was the desire to exploit: to determine if there was an economically harvestable fishery resource and, secondarily, to evaluate the possible effects of that harvest on other resources. What if the driving force had been the desire to seek a greater level of protection and recognition for the unique fish and wildlife resources of the NWHI, and only secondarily to determine how this protection might affect the development of commercial fisheries? Although this sounds like a semantics exercise, it's actually easy to see how this might have come about, perhaps during consideration of research natural area, wilderness area, or critical habitat designation. The important point to recognize is that the interpretation of scientific data cannot be entirely independent of

the perspective from which it is viewed. Both of the perspectives I have described are legitimate in their own right and should be fully considered in resource management planning.

Management of natural resources is an awesome responsibility. I find myself accountable to the public, to the resource, and to my own conscience. I am lucky enough to work for an agency with whom I share resource management philosophies, so my conscience can be satisfied relatively easily. It's also easy to convince myself that I am doing right by the resource, based upon the application of proven management methods. Only my accountability to the public is difficult to reconcile. Just who is this "public" that I'm accountable to? The "public," in fact, manifests itself in the form of a diverse body of opinion on how I should be doing my job. This opinion is not static in time nor is it always predictable. What is predictable is the fact that most often opinion is expressed as criticism, perhaps because those who are satisfied with the way things are going have other more pressing issues to worry about. My life on the job became easier when I accepted the fact that I could not satisfy all the varied desires and objectives of the public and still make amends to my conscience and the wildlife resource I am obligated to manage. It also helped to realize that public "opinion" is also manifested in the laws and regulations passed by elected officials, in spite of the fact that these mandates often seem to be in conflict with the most vocal constituency.

In making resource management decisions, it is also a given fact that one is inevitably forced to deal with less information than might be wanted or perceived to be needed. Stated another way, the outcome of future events is always predicted with uncertainty, sometimes far more than others. The purpose of the tripartite-Sea Grant study was to reduce uncertainty but it was clearly not feasible to eliminate that uncertainty altogether. In spite of the vast amount of data collected in this study, there still remains enough uncertainty to fuel a debate regarding the abundance and harvestability of certain fisheries, the anticipated impacts of expanded fishery development on various wildlife resources, and the effect of potential management actions, such as critical habitat designation, on fishery development.

SUMMARY OF STUDY RESULTS PERTAINING TO REFUGE MANAGEMENT

With that introduction behind us, let's review the study results without consideration of the original study objectives and see what we have learned. If I generalize I can summarize the results that are most relevant to refuge management in eight separate statements:

1. Certain fisheries outside refuge boundaries appear to have substantial potential for expanded commercial development, while others appear to hold less promise than anticipated.

2. The condition of refuge fish and wildlife and their habitats still reflects the direct and indirect effects of historical commercial resource utilization and other human activities in the NWHI.

3. Several of the proposed fisheries in the NWHI are unlikely to directly affect refuge wildlife. Yet, some conflict resulting from fishery development through the food web and through indirect habitat alteration is inevitable. The degree of conflict will likely vary when different wildlife species and their habitats are compared. In the case of seabirds, effects are anticipated to be localized and focused on a few species, depending upon which fisheries are developed. Effects on turtles and seals will likely be indirect, given appropriate fishery management measures, but certain subpopulations are particularly vulnerable through subtle effects of disturbance and habitat alteration. Terrestrial ecosystems are highly vulnerable to rapid and irreversible alteration, but risks associated with fishery development appear to be manageable, given sufficient user cooperation.

4. Terrestrial and marine ecosystems of the NWHI present unique opportunities for study, both as undisturbed areas and as sites whose history of human intrusion is well documented.

5. Terrestrial and marine ecosystems of the NWHI are inextricably linked without regard for refuge boundaries or other institutional considerations. Thus, security and well-being of refuge fish and wildlife cannot be ensured if waters and resources outside the refuge boundary are not properly managed.

6. Refuge fish and wildlife populations and their habitats are subject to natural fluctuations independent of fishery-related activities, both for reasons that have been documented and for reasons unknown. Some populations are increasing while others have experienced substantial declines.

7. Fishery-related impacts and problems unrelated to fishery development that affect refuge wildlife are additive, and potentially synergistic, in their effects.

8. Anticipated fishery-related impacts and the unrelated refuge resource problems can, to varying degrees, be monitored and mitigated.

REFUGE MANAGEMENT CONSIDERATIONS

Reflecting on this oversimplified summary of results, one can begin to see the complexity of the resource management issues surrounding the Hawaiian Islands National Wildlife Refuge (HINWR). This is not your everyday refuge. In fact, there are very few like it in the National Wildlife Refuge System (NWFS), and virtually all of those few that are at all similar are found in the Hawaiian and Pacific islands NWR complex. This refuge supports more threatened or endangered species (6) than most others and it is the only one in which the entire range of one or more listed species is confined to the refuge. The HINWR also has the dubious distinction of being the only refuge in the NWRS in which the extinction of wildlife species has been documented, and this refuge lost three. Together with the Aleutian Islands NWR, this refuge also supports a larger and more diverse nesting seabird population than all others in the NWRS.

So what has all of this got to do with the management of refuge fish and wildlife resources? Quite a lot, actually. The unique characteristics or attributes of the HINWR, as reflected in the results of the tripartite-Sea Grant studies, must be fully considered. I'll address a few of these characteristics and how they affect the evolution of site-specific management plans. Both biological characteristics and other more practical considerations are involved.

Endangered Species

The fact that six listed species inhabit refuge lands and/or waters is a significant factor in resource management. Among the interrelated characteristics of most listed species that inhibit recovery are the restricted or fragmented distribution, the unbalanced sex and age composition of subpopulations, and specialization in habitat requirements. These factors contribute to vulnerability and may prevent rapid recovery even in the absence of adverse human influence. Management actions to reverse population trends are complicated by limitations in relevant data. Often the very regulations enforced to protect the species make research to gather management data more difficult to accomplish than is the case for unprotected species. In the HINWR, logistical considerations inhibit our ability to detect and to react to problems in a timely way and add considerably to the cost of research and management programs. In the case of species which spend a large portion of their life at sea, such as the monk seal and green turtle, practical limitations on research itself inhibit development of management strategies. Of course, low populations to begin with provide less room for error and more urgency in action than other species. Finally, the legal mandates which are designed to protect these species provide relatively little flexibility in the consideration of otherwise legitimate resource utilization programs.

Migratory Birds

Although legislative mandates protecting migratory birds are less restrictive than those affecting endangered species, they are nevertheless a real factor in HINWR management programs. These mandates stem from international treaties; hence, involvement in management planning goes well beyond state or even national boundaries. It is important to note that the HINWR provides only a part, albeit a significant one, of the habitat required by NWHI seabirds. Most prey is taken outside refuge boundaries and, for some species, outside waters under U.S. jurisdiction. Historical evidence in the NWHI and elsewhere makes it clear that the apparent abundance of seabirds in their breeding colonies can be misleading. Seemingly insignificant alterations of habitat can and have led to population declines from which full recovery may require decades or may not be possible at all. Finally, we have also learned that seabird populations are subject to substantial natural fluctuations in productivity. These fluctuations are not easily detected in their earliest stages and the natural causes are not easily elucidated.

Small Insular Ecosystems

The vulnerability of terrestrial habitats in the HINWR to rapid alteration is intimately tied to their small size, isolation, and other biological characteristics. The seemingly insignificant introduction of an exotic insect, plant, or rodent can radically alter the terrestrial ecology of these islands, irreversibly in some situations. The value of these unique ecosystems as habitat of endangered land birds is at risk when any authorized or unauthorized human intrusion occurs.

Atoll Ecosystems

Atoll ecosystems are widely distributed in the Pacific so this cannot be considered an aspect of resource management unique to the NWHI. Yet, atoll ecosystems in the NWRS are virtually restricted to Pacific refuges, and the HINWR is the most endowed in this regard. Furthermore, tripartite-Sea Grant data confirmed the unique opportunity that NWHI atolls of variable age along a latitudinal gradient present for research. NWHI atolls are also distinct in comparison with most other Pacific atolls where the effects of centuries of resource exploitation are evident. Resource management within atolls, such as those in the HINWR, is a discipline lacking in the benefits of past experience that characterizes the terrestrial and wetland habitats found in most national wildlife refuges.

Protected Areas

Mechanisms for recognizing and protecting the unique attributes of areas which are relatively free from past human abuse and are extremely valuable for wildlife are found in specific

forms of authorizing legislation. National Wildlife Refuge designation, in itself, is one such form of area recognition that brings with it a host of implementing regulations designed to avoid adverse impacts on fish and wildlife resources and their habitat. The research natural area designation is an additional form of recognition that acknowledges the unique "natural" value of specific areas where research on essentially undisturbed ecosystems should be encouraged. Such contiguous research natural area designation for lands and waters of the HINWR in 1967 provides additional direction in resource management that is uncommon in the NWRS. Wilderness area status, pursuant to the Wilderness Act of 1964, specifically addresses the congressional mandate to identify those federal lands that should be maintained in perpetuity in their natural state. The HINWR was proposed for wilderness area status a decade ago. No action was taken on the proposal, not because it lacked merit, but as a result of opposing interests fearing that the action would prevent commercial fishery development. Similar concern was voiced in response to a 1978 proposal by the National Marine Fisheries Service (NMFS) to designate the area a critical habitat for the monk seal, pursuant to the Endangered Species Act. The issue of wilderness area or critical habitat designation is virtually certain to resurface in the future. Other forms of area designation, including potentially international recognition, are likely to be considered in the future as well. All of this adds up to a situation in which the management strategies for the HINWR must take into account the significance of existing or potential layers of formal recognition.

Shared Jurisdiction

Shared jurisdiction for fish and wildlife resources and their habitats in the NWHI is an issue directly affecting the Fish and Wildlife Service's resource management strategy, both within and outside the HINWR. Lands and waters of the HINWR, as defined by FWS, are also included within a State Wildlife Refuge. State statutes also protect migratory birds, endangered species, and other fish and wildlife in the HINWR, and state fishery regulations affect the taking of fishery resources in state waters immediately adjacent to the HINWR. NMFS and FWS share jurisdiction over marine turtles, depending upon whether they are on land (FWS) or in the water (NMFS). By interagency agreement, pursuant to the Marine Mammal Protection Act, NMFS was assigned primary jurisdiction for the monk seal. Yet, refuge regulations (50 CFR) provide FWS with shared enforcement and management authority for both seals and turtles within the HINWR. The FWS enforcement role, pursuant to the Migratory Bird Treaty Act, extends throughout U.S. lands and waters, and project review authority, pursuant to the Fish and Wildlife Coordination Act, affects all proposed projects in navigable waters. In the past, all of the shared jurisdictional responsibilities in the NWHI have led to some confusion and complication in the planning and implementation of management strategies. Conversely, they have also provided opportunities for additional expertise, manpower, program

funding, enforcement capability, and logistical support. Broader legislative authorities, even when duplicative to some degree, also provide additional safeguards in the management of species in jeopardy.

Geographic Area

One final practical consideration affecting the HINWR management program is worthy of note. In the NWRS, only the Aleutian Island NWR is more widely distributed geographically than the HINWR. More than 1,000 miles separate the western extreme of the HINWR at Pearl and Hermes Atoll from Nihoa, the eastern end of the refuge. Hundreds of miles of open ocean isolate the rocky islands and atolls of the refuge from each other. While this presents unique opportunities for study, it also creates unique logistical problems that are difficult to overcome. Enforcement of refuge regulations, early detection and control of introduced pests or environmental contaminants, and wildlife population monitoring are all made more difficult simply by the distances and logistical support costs involved.

THE HINWR IN PERSPECTIVE

All of this is a preface to the real purpose of this paper -- to review management strategies for the HINWR and adjacent waters. It is important to clearly distinguish the refuge itself from surrounding waters. To put it in perspective, one should consider that the lagoon waters within the refuge (as defined by FWS) amount in area to less than 1/10 of 1 percent of the waters included within the fishery conservation zone. They also include less than 10 percent of the water within the 100-fathom contour. Yet, in spite of the small fraction of area involved, the refuge is clearly the focal point of management controversy because of the potential role of refuge land for logistic support, the possibility of lagoon fisheries, and the potential direct and indirect impacts of fishery activities in adjacent waters.

It is my opinion that FWS has a legitimate interest in the management of habitat and fishery resources both within the outside refuge boundaries. But the expression of that interest and management concern will take different forms. In the past, interest in the management of waters outside the HINWR has manifested itself in participation in the development of fishery management plans for the fishery conservation zone, in the support of shipping regulations to minimize the risks of hazardous cargo or oil spills and in the cooperative management of seabird and other wildlife resources on Midway and Kure atolls.

MANAGEMENT STRATEGIES OUTSIDE REFUGE BOUNDARIES

In the future, FWS participation in management planning outside the HINWR is anticipated to take several forms. Where data warrant restrictive fishery regulations to mitigate impacts to fish and wildlife species, such measures will be advocated by

FWS. Among the measures which will be considered are regulatory provisions with fishery management plans that would enable enforcement of short-term restrictions on specific commercial fisheries when the combined effects of natural factors and fishery-related factors would severely impact wildlife inhabiting the refuge. The very real growing risk of vessel groundings associated with fishery development and increasing shipping activity, in my opinion, justifies serious consideration of measures to monitor and, where appropriate, limit this vessel activity. Vessel monitoring could be accomplished through observers and reporting programs, but a system of satellite monitoring may prove more economical and effective. Such a system would also reduce safety hazards associated with groundings that would not otherwise be immediately detected. The sinking incident of the Keola at French Frigate Shoals in 1981 is an example where satellite monitoring of vessel position could have led to timely rescue of the crew. Rapid detection of groundings would also permit timely response to mitigate effects of oil spills and to avert the successful introduction of rodents to NWHI. Similarly, a program of boat inspections and required rodent control actions for vessels fishing in the NWHI may help to prevent exotic mammal introduction. FWS will also continue to work with the state of Hawaii, the Coast Guard, the Environmental Protection Agency, and the shipping industry to minimize risks of groundings and oil spills. Where current licensing regulations do not adequately insure competency of operators in hazardous waters, then modification of those regulations quite likely will be an FWS objective.

FWS will continue to play an educational role where such effort can help to avoid potential conflicts with shippers and fishermen. Effort is currently being made to meet with boat owners and captains unfamiliar with NWHI waters both to inform them of refuge boundaries and regulations and to make them aware of the FWS field station at Tern Island in case our support is needed.

In cooperation with other agencies, FWS will also continue to investigate the hazards posed by fishing and shipping activities well beyond the limits of U.S. jurisdiction. One such hazard, the discarding of trawl nets from North Pacific fisheries, is believed responsible for entanglement of seals and turtles in the refuge. Resolution of this problem may require State Department intervention.

FWS will also continue to share interest in the management of lagoon waters and islands at Kure and Midway with the agencies having primary jurisdiction. At Midway, FWS currently assists in wildlife management under a memorandum of agreement with the Navy. Ongoing programs to reduce predation on seabirds, to control avian disease, and to minimize bird-aircraft strike hazards are anticipated to continue. FWS is also reviewing other shared management alternatives at Midway that would protect and enhance wildlife populations, including endangered monk seals.

Midway will also continue to be an important site for seabird population monitoring due to the opportunities for year-round study. The FWS role at Kure Atoll will continue to be minor, compared with their role at Midway. However, it is anticipated that assistance in wildlife population monitoring using methodology developed in tripartite-Sea Grant research will occur.

MANAGEMENT WITHIN THE HINWR

Unquestionably, the management role of FWS within the HINWR will substantially differ from its role outside its area of primary jurisdiction. Despite the very real involvement of other agencies, FWS is ultimately the accountable agency when the success or failure of management programs is reviewed. The buck stops here. In my perspective, the HINWR is a trust fund and in my role as refuge manager, I act as a trustee. I look upon the refuge as an investment in the future which can prosper if properly managed or can falter is poorly managed.

Historically, management of the HINWR has been directed towards the maintenance of a "healthy ecosystem." Manipulation of habitat has been limited to that considered necessary to restore conditions which have changed through the direct or indirect effects of human use of the area. This approach is in direct contrast to the manipulative, intensive management of habitat that characterizes most wetland refuges in the system. Under the "healthy ecosystem" approach, directed work with wildlife has been focused on research to document and monitor population status and habitat condition.

Public use policy in the HINWR has been substantially more restrictive than in most other refuges in the NWRS, recognizing both the uniqueness and vulnerability of the area. As is the case on all national wildlife refuges, public use has been and will continue to be secondary to the primary objective of the refuge. Public use consistent with the wildlife management objectives has been permitted and even encouraged. The refuge was designated research natural area in 1967 in recognition of its unique value for legitimate scientific research. Extensive use of the Tern Island field station for tripartite-Sea Grant research has been another appropriate, but well controlled, use. Other public uses, including commercial fishery support, have been carefully scrutinized and, where appropriate, have been accommodated.

With the conclusion of tripartite-Sea Grant studies, we now embark on a new phase of resource management, hopefully with no less cooperation and mutual assistance than characterized the study period. Management actions on refuge lands and waters will reflect the results of the research and the plans of other agencies, including the prospect of expanded commercial fisheries in adjacent waters. Some historic management practices will surely continue, but our minds are open to consider virtually all

options that recognize primary refuge goals. Among the management actions underway or under consideration are the following:

1. Development and implementation of seabird and landbird populations and productivity monitoring programs

2. Development and testing of methods to detect and control, if necessary, introduced rodents, insects, and pest plants on refuge islands

3. Assessment and control, where appropriate, of disease among HINWR seabird and landbird species

4. Enforcement of restrictions on access to refuge lands and waters supporting particularly vulnerable or sensitive wildlife populations

5. Consideration of additional forms of recognition or resource protection, where appropriate, for individual species or geographical areas of the refuge

6. Development of protocol for avoidance, detection, and response to oil spills and other major pollutant sources

7. Completion and implementation of recovery plans for threatened and endangered species in the HINWR. Research on these species will focus on factors inhibiting recovery. Management actions to arrest and reverse downward population trends will be implemented.

8. Planning and implementation of both on-site and off-site environmental education programs

9. Documentation and study of cultural resources in the HINWR and implementation of necessary measures to ensure their protection

10. Involvement of FWS in the operation of the Tern Island facility, including the continued assistance to commercial fishermen. Review of alternative management strategies will also continue.

FUTURE PLANNING DIRECTIONS

Appropriately, the logical vehicle for making reasoned management decisions is the formal planning process. The involvement of the affected public and other agencies can only be assured through adherence to a well-conceived and structured planning process. As was anticipated, progress on various planning initiatives relating to the NWHI did not cease during the tripartite-Sea Grant study. The period was characterized by a flurry of planning activity, including the Tern Island study;

the state of Hawaii's fishery development plan; the monk seal critical habitat proposal; recovery plans for endangered land birds and the monk seal; fishery management plans for lobster, precious coral, bottomfish, and billfish; and planning studies for fishery support facilities at Tern Island and Midway. During this period, FWS also completed its regional resource plan, which included a focus on migratory birds, endangered species, and fishery resources in the Pacific area. The plan provides a general framework of objectives and strategies stepped down from the FWS mission statement, the FWS management plan, and the program management documents for individual FWS programs.

Given the backlog of previous paperwork in recent years, why then does it make good sense to initiate, as yet, another planning process? From the FWS perspective, additional planning for the refuge will provide a needed site-specific focus and will provide additional opportunity for public involvement. The vehicle for planning at the refuge level is the refuge master plan. Through this process, specific objectives of the refuge are clearly established and the type of management and development necessary to meet those objectives are identified. The process will help to:

1. Ensure that national policy direction is incorporated into management of individual refuges

2. Determine the capability of individual refuges to further FWS goals, objectives, and long-range plans

3. Provide a basis for developing budgets to implement appropriate management programs

4. Provide a systematic process for making and documenting refuge decisions

5. Establish broad management strategies to guide refuge management programs and activities

6. Provide continuity in the management of individual refuges and the refuge system as a whole

To achieve these objectives, FWS has developed a comprehensive planning process which includes three phases of inventory, analysis, and evaluation of alternatives or synthesis. During the inventory phase, priorities are set, data are collected and resource information is mapped, where appropriate. Results of tripartite-Sea Grant studies are fundamental to completion of this phase for the HINWR. In the analysis phase, the capability of the refuge to accommodate existing and potential uses is determined. In the synthesis phase, objectives are set, alternatives to achieve the objectives are developed and evaluated, and a final plan is completed. The steps of the planning process, shown in Figure 1, each involve specific tasks

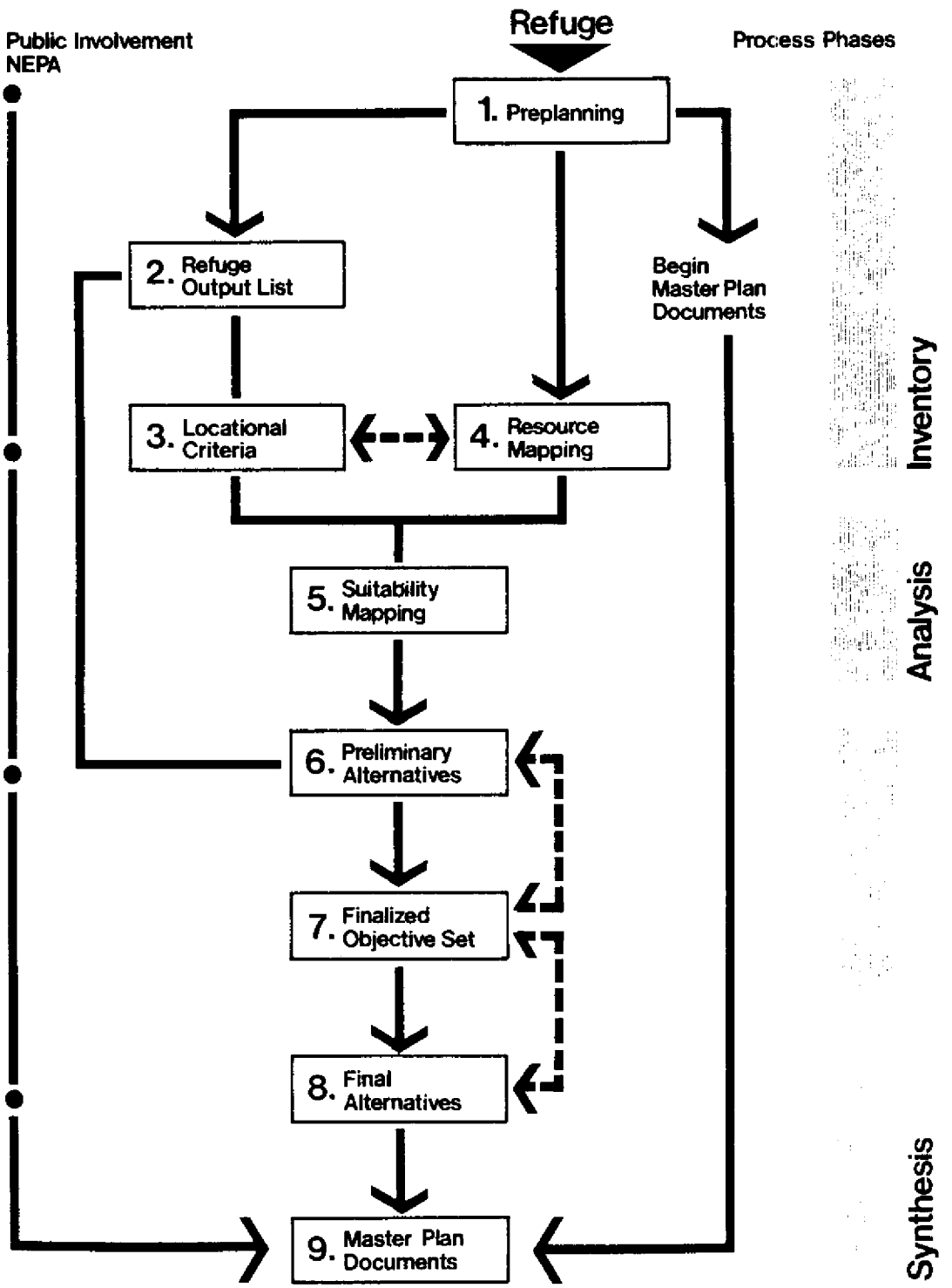

Figure 1. Master Planning Process

and products. Paralleling this process is the development and circulation of a draft and final environmental impact statement.

Products of the master planning process include (1) a resource inventory, (2) an output list (those things to be produced on the refuge) in priority order with numerical objectives where appropriate, (3) an objective documentation record, and (4) a long-range management strategy. This strategy is a description, in general terms, of refuge resources and management actions required to produce outputs in the quantities identified in the planning process.

In recognition of the concerns surrounding the management of the HINWR and the eagerness of the interested public and cooperating agencies to resolve lingering management issues, FWS has opted to schedule the HINWR for master planning during the 16-month period immediately following the NWHI symposium (Figure 2). This rapid schedule is feasible because of the related scoping effort initiated with the Tern Island study in 1979 and because the results of the tripartite-Sea Grant research provide a resource data base not usually available at the start of refuge master planning projects. Also, in contrast to many intensively manipulated wetland refuges, the range of potential active management options in the HINWR will be necessarily limited, reducing somewhat the complexity of the planning process.

Opportunity for public involvement will be provided in the planning schedule during scoping, in the development and review of outputs and preliminary alternatives, and in the review of the draft and final environmental impact statement. I strongly urge you to participate in this planning process, but at the same time I caution you to take your role seriously. With the privilege of public participation also goes a share in the responsibility for the results of the decisions made.

Victor Scheffer once defined wildlife management as "a process by which the closely related needs of wild animals and people are evaluated, reconciled and met." I see this as a desirable target towards which to shoot. Our tripartite-Sea Grant data provide a starting point for defining resource needs. Public involvement in planning will carry the process of defining human needs a step further. Together, these processes will not defuse or eliminate resource management controversy in the NWHI, but they will help to clarify and identify precisely which issues are in dispute and which are not. They will increase the likelihood that management decisions will be based upon the best available data and the informed consent of the interested public.

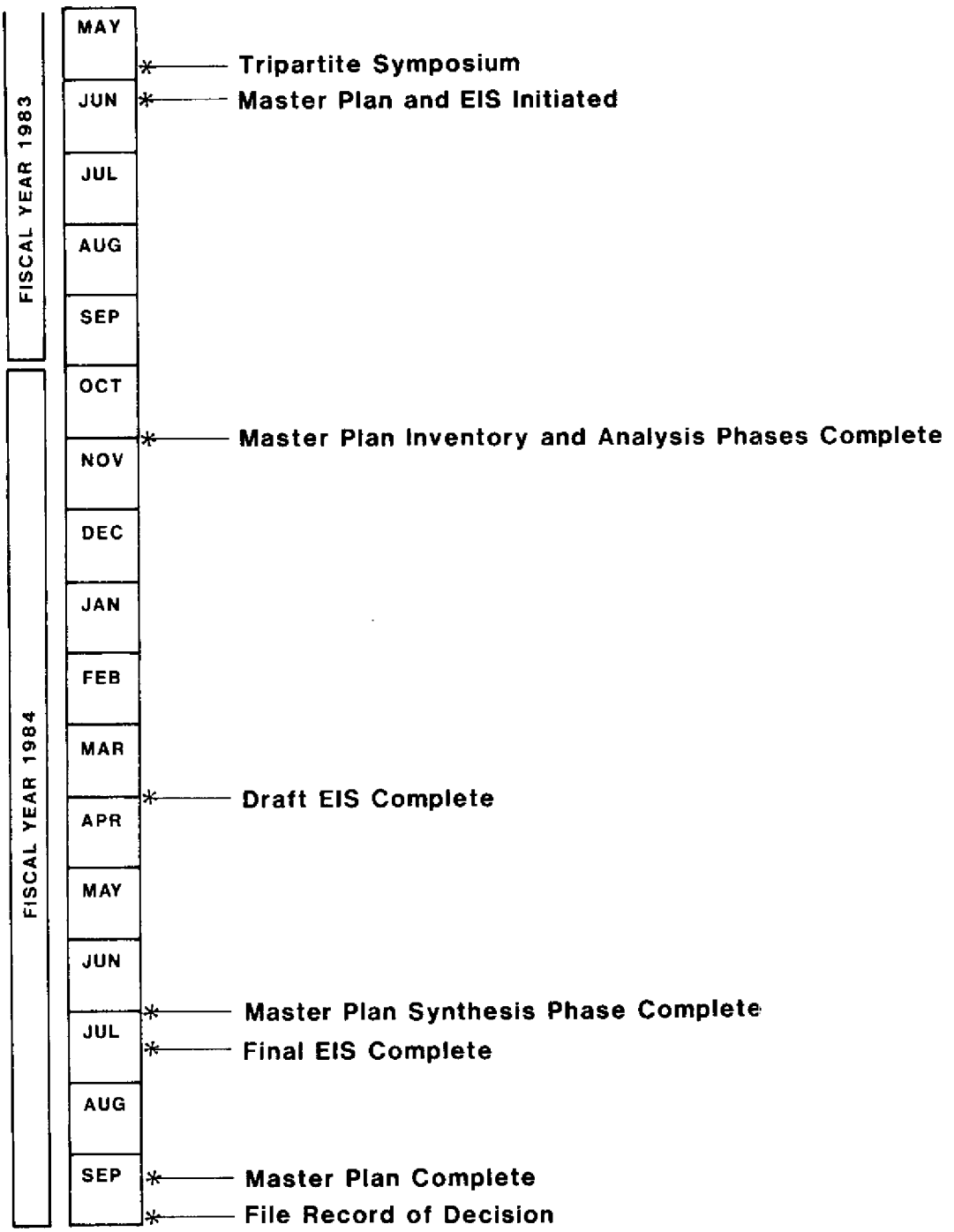

Figure 2. Master Plan Schedule